



European Organization for Nuclear Research



DEVELOPMENT OF ADVANCED MECHANICAL SYSTEMS FOR STABILIZATION AND NANO-POSITIONING OF CLIC MAIN BEAM QUADRUPOLES

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IWAA 2012 10-14 September 2012, Fermilab



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



Outline



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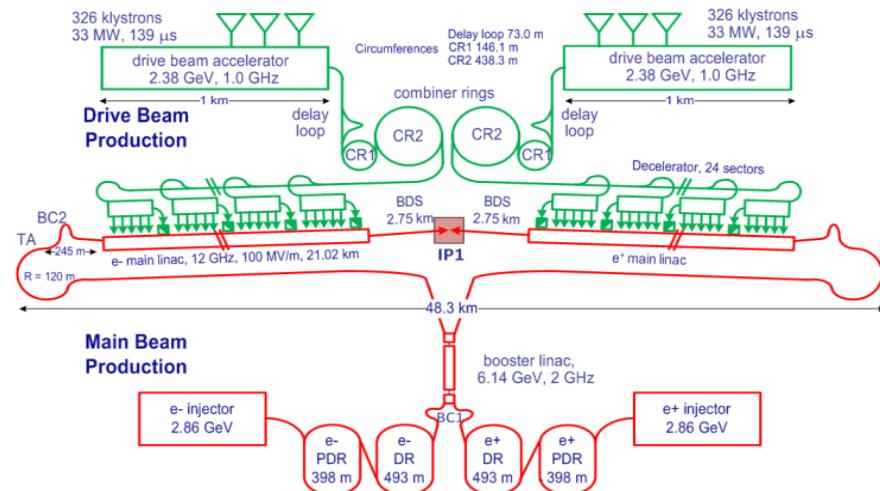
- Introduction & Requirements
- Active Support for Main Beam Quadrupoles
- Analytical & Finite Element models
- Experimental set-ups & sensors
- Future developments
- Conclusions



Luminosity, beam size and alignment

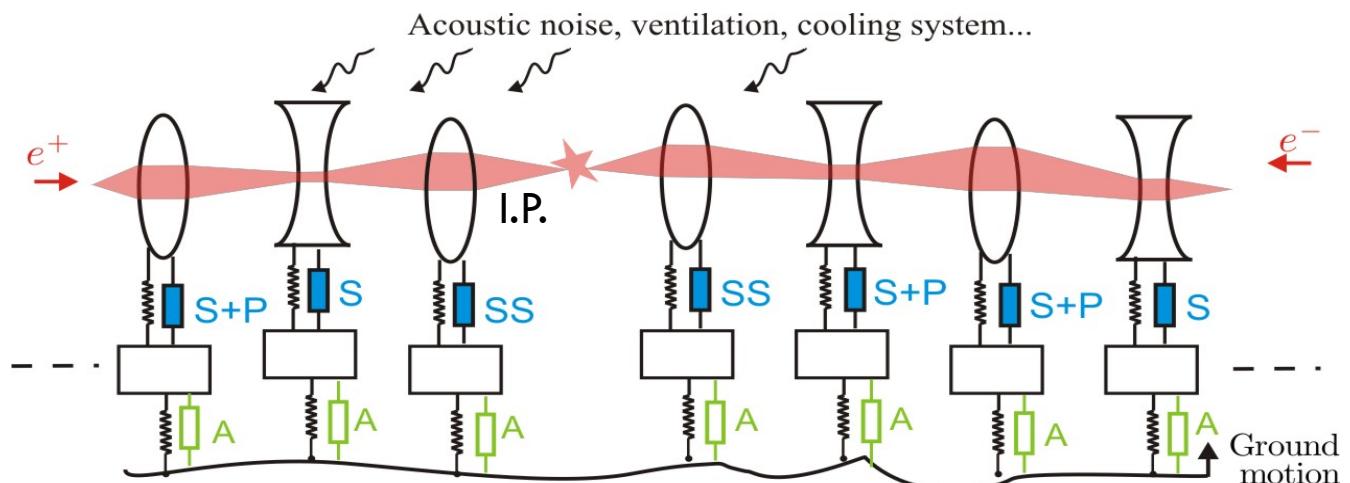


CLIC overall layout – 3 TeV



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

~ 40 nm

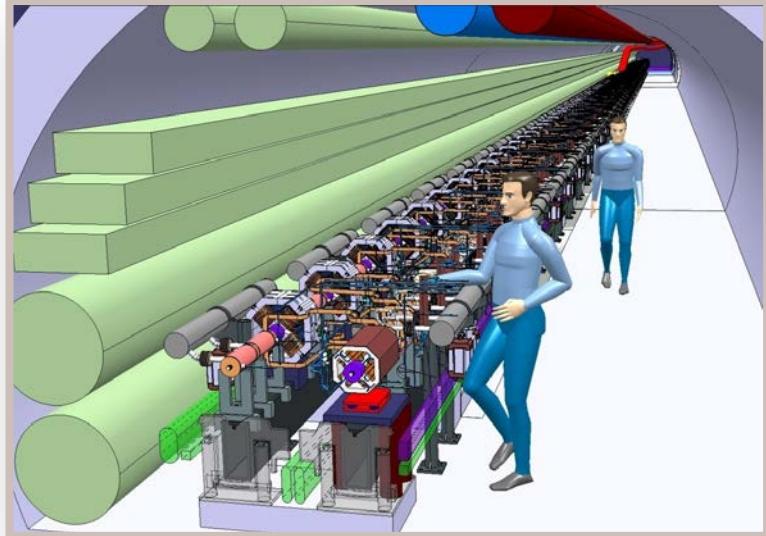


Alignment requirements



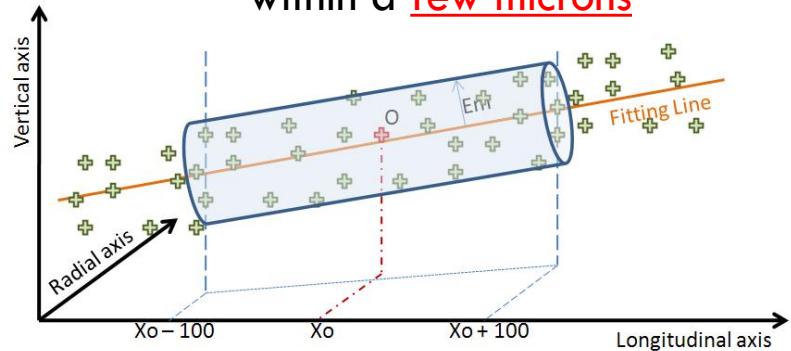
Contact: H. Mainaud Durand

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Mechanical prealignment ± 0.1 mm

Active prealignment of external references of the accelerating structures and quadrupoles within a few microns



Sliding window: zero of component shall be included in a cylinder with radius:
 17 μm for MB Quad over 200 m
 10 μm BDS over 500 m

Stability requirements

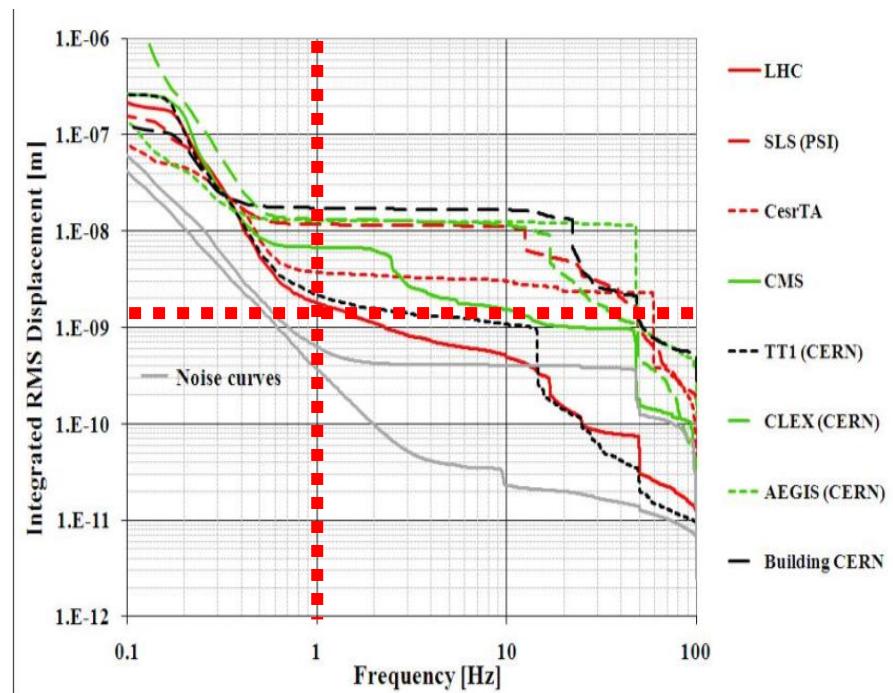
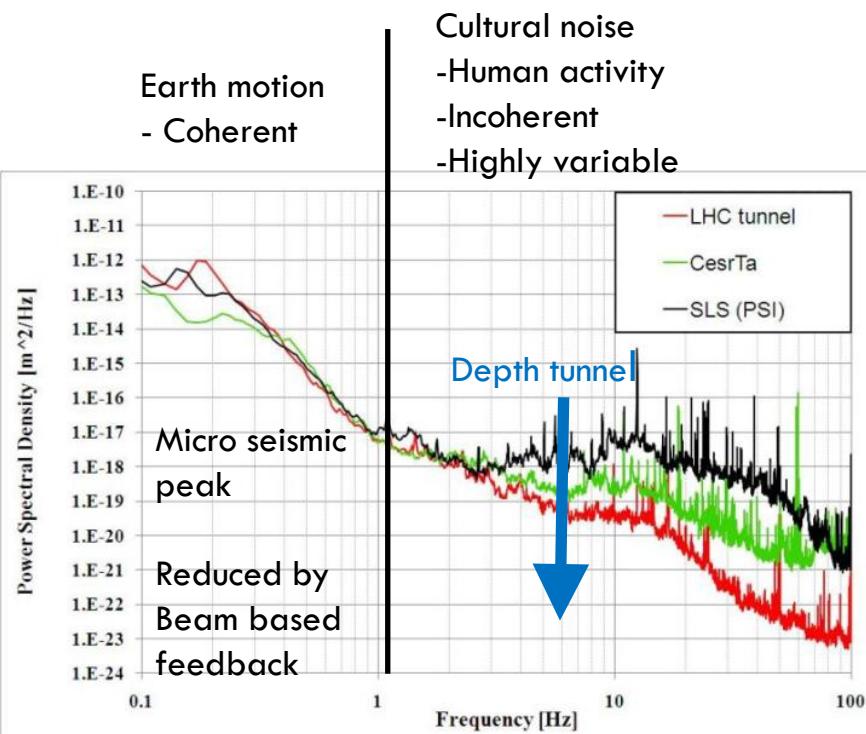


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Stability (magnetic axis):

Vertical	1.5 nm at 1 Hz
Lateral	5 nm at 1 Hz

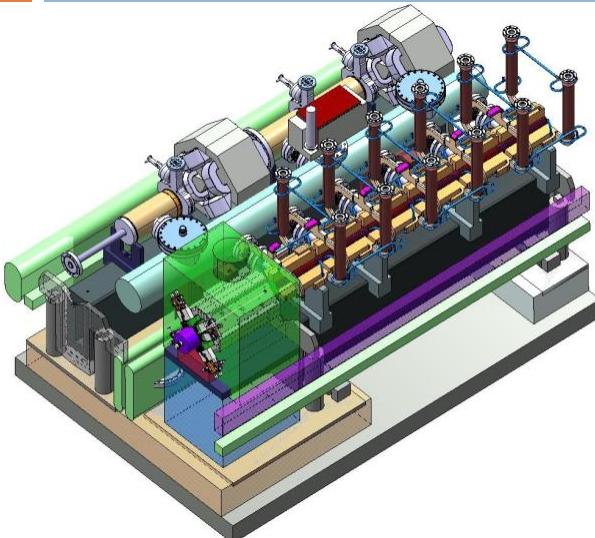
ground vibration



Other requirements



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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

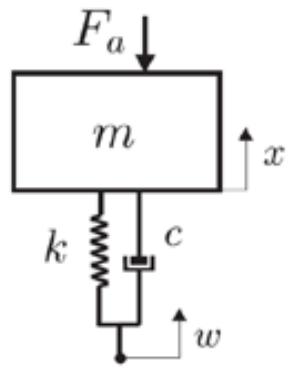
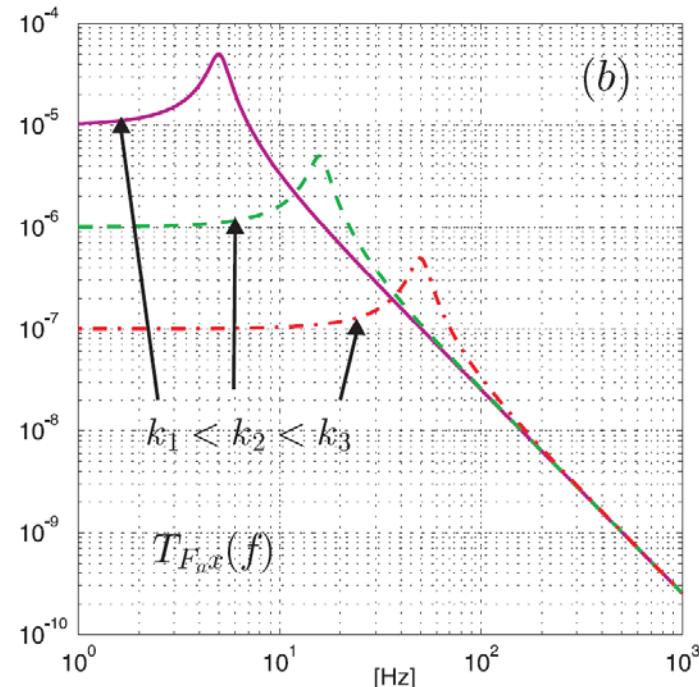
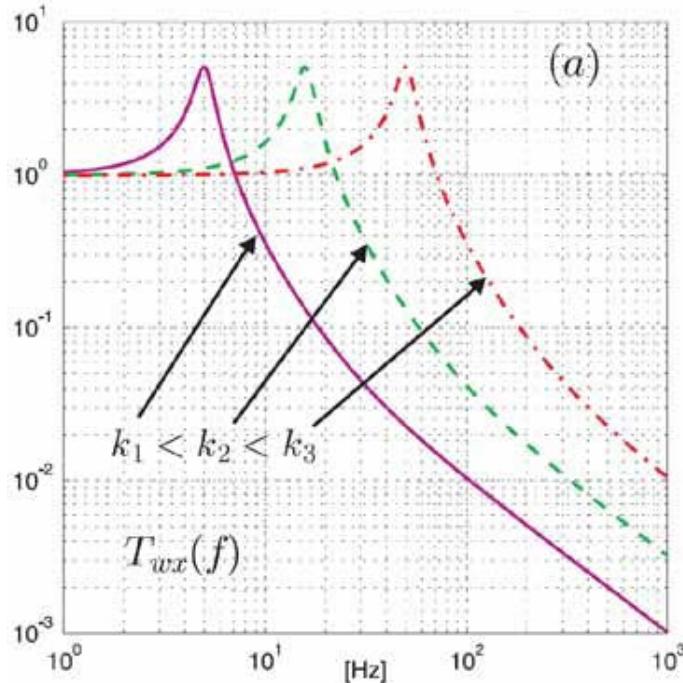
Accelerator environment

- High radiation
- Stray magnetic field

Soft or rigid support ?



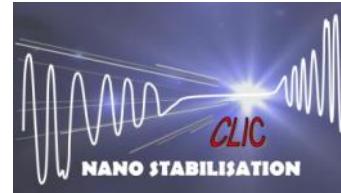
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Soft system is not robust against external forces \longrightarrow Active stabilization

- Artoos K. et al., "Status of a Study Stabilisation and Fine Positioning of CLIC Quadrupoles to the Nanometre Level", IPAC11
- Janssens S. et al., "System Control for the CLIC Main Beam Quadrupole Stabilization and Nano-positioning", IPAC11

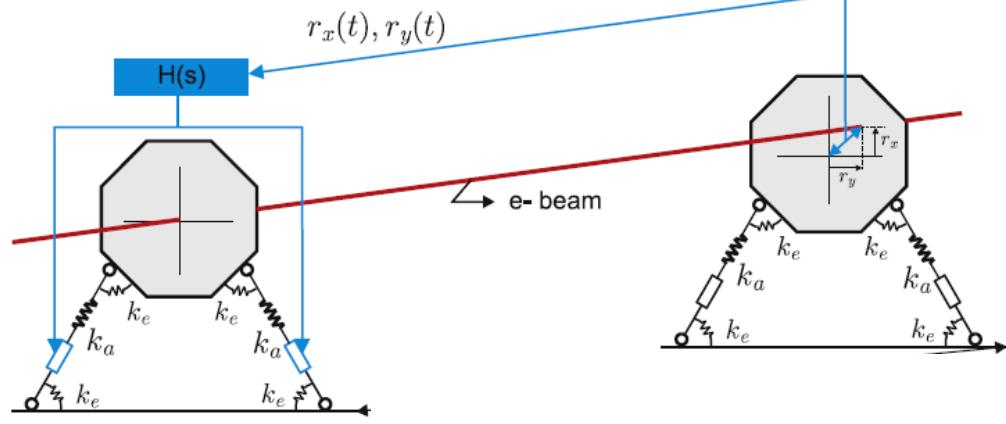
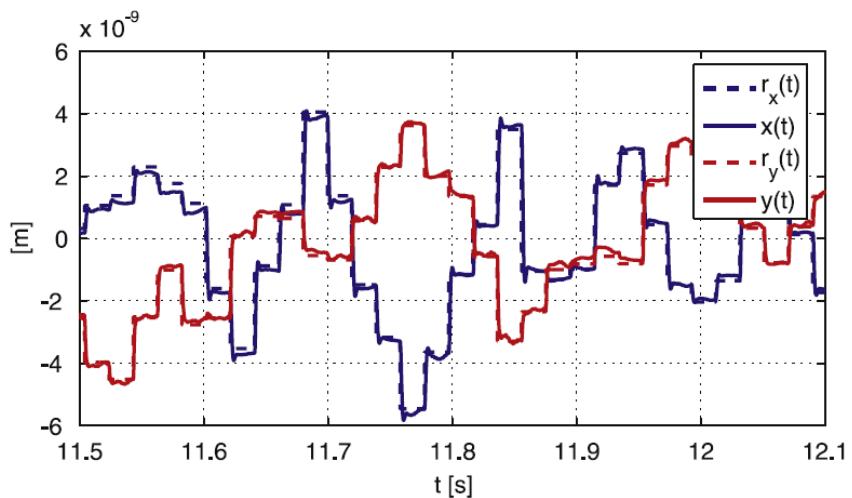
Nano-positioning



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Modify position quadrupole in between pulses (~ 5 ms)

Range $\pm 5 \mu\text{m}$, increments 10 to 50 nm, precision $\pm 1\text{nm}$



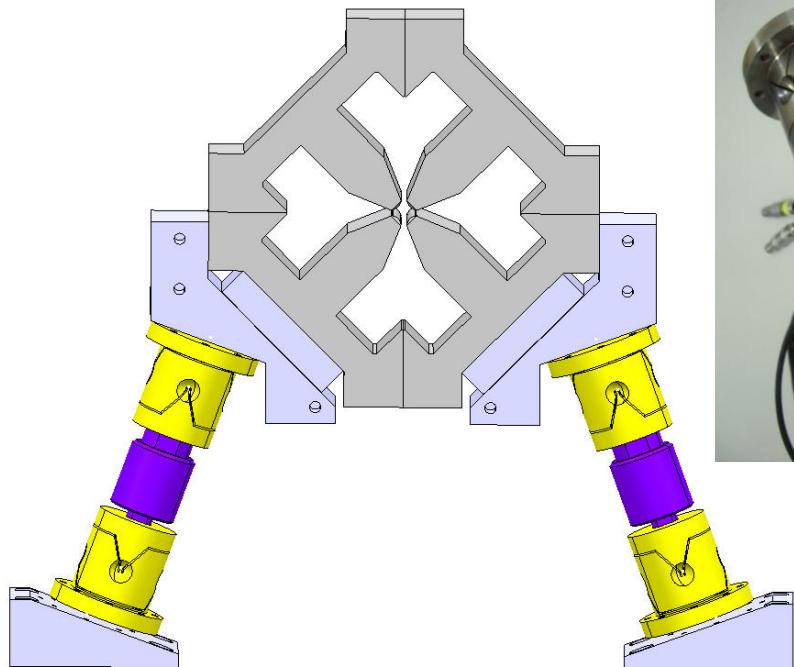
- In addition/ alternative dipole correctors
- Use to increase time to next realignment with cams

Actuator support

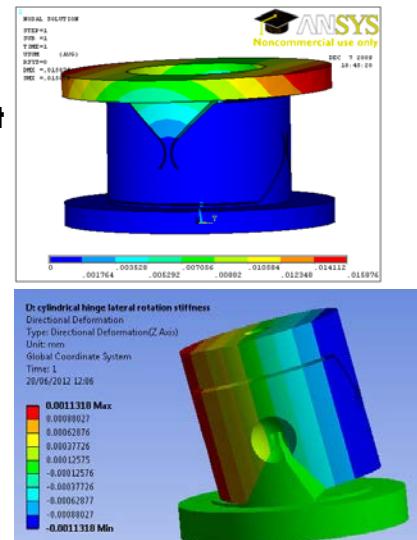


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stabilisation support section made of
Inclined stiff piezo actuator pairs with
flexural hinges (vertical + lateral motion)
(each magnet will have 2 or 3 sections depending on its length)



PI Piezoelectric Actuator
High stiffness ($480\text{N}/\mu\text{m}$)
Sufficient travel (15 μm)
Good resolution (0.15 nm)



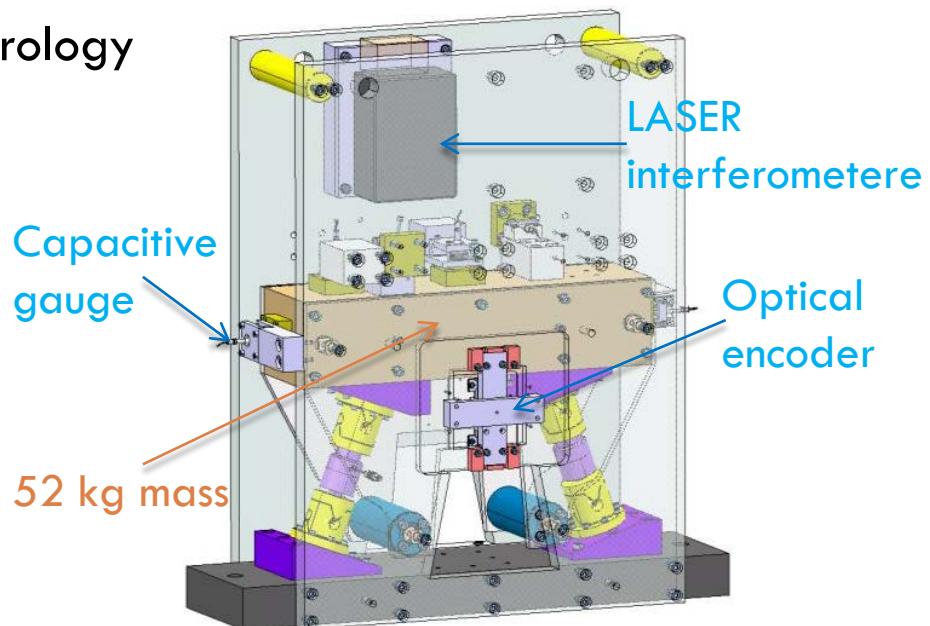
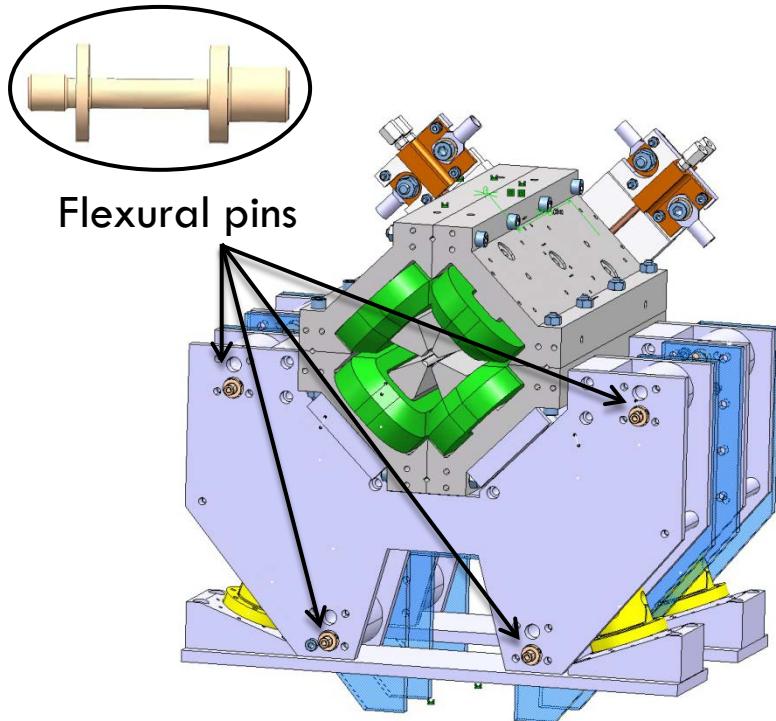
Universal Flexural Joint
2 rotation axes in the same plane
rotational stiffness ($k_e = 220\text{Nm}/\text{rad}$)
Axial stiffness ($k_{aj} = 300\text{N}/\mu\text{m}$)

X-y guiding mechanism



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- Blocks longitudinal movements
- Increases lateral stiffness by factor 200, no modes < 100 Hz
- Introduces a stiff support for nano-metrology
- Transportability



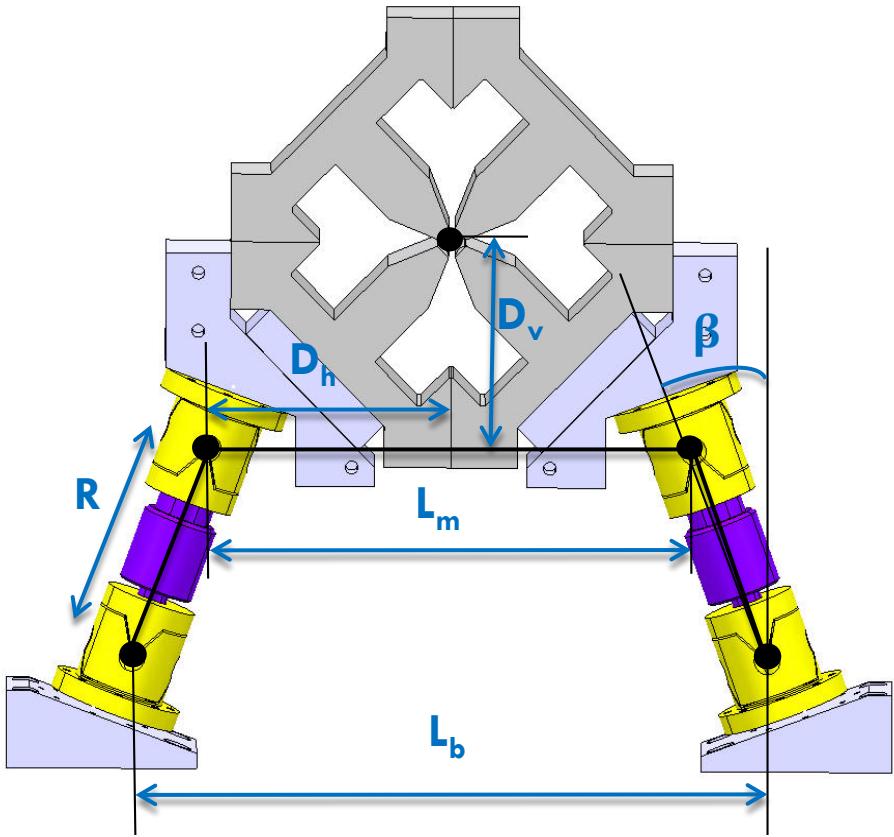
R. Leuxe

M. Esposito, IWAA 2012 Fermilab

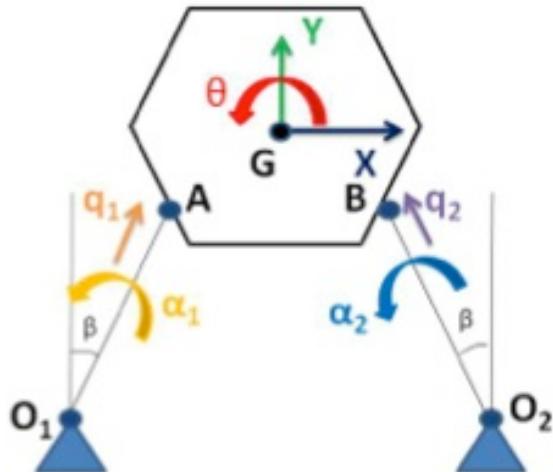
Analytical model (1)



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Coordinate systems



Coordinate transformation

$$\begin{aligned}
 q_1 &= \sin\beta x + \cos\beta y + (d_v \sin\beta - d_h \cos\beta)\theta \\
 q_2 &= -\sin\beta x + \cos\beta y + (-d_v \sin\beta + d_h \cos\beta)\theta \\
 \alpha_1 &= -\frac{\cos\beta}{r} x + \frac{\sin\beta}{r} y + \left(-d_v \frac{\cos\beta}{r} - d_h \frac{\sin\beta}{r}\right)\theta \\
 \alpha_2 &= -\frac{\cos\beta}{r} x - \frac{\sin\beta}{r} y + \left(-d_v \frac{\cos\beta}{r} - d_h \frac{\sin\beta}{r}\right)\theta
 \end{aligned}$$

Analytical model (2)



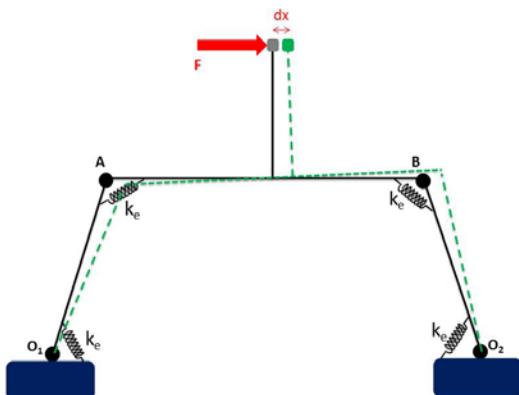
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Constraints

$$(R + q_1) * \cos(\beta - \alpha_1) + L_m * \sin(\theta) + (R + q_2) * \cos(\beta + \alpha_2) = 0$$

$$(R + q_1) * \sin(\beta - \alpha_1) + L_m * \cos(\theta) + (R + q_2) * \sin(\beta + \alpha_2) - L_b = 0$$

Stiffness calculation

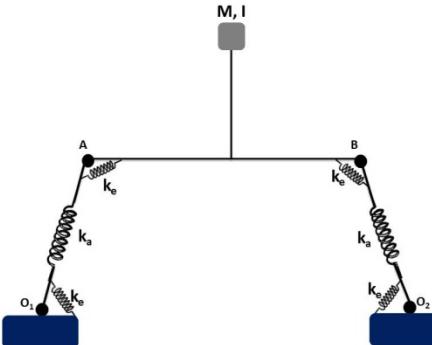


Principle of virtual work

$$F_x * dx = M_{O1} * d\alpha_1 + M_{O2} * d\alpha_2 + M_A * (d\beta - d\alpha_1) + M_B * (d\beta + d\alpha_2)$$

$$F_y * dy = (M_{O1} + M_{O2} + M_A + M_B) * d\alpha_1 + F_1 * dq_1 + F_2 * dq_2$$

Lagrangian method for Modal Analysis



$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{s}} \right) - \frac{\partial L}{\partial s} = 0 \quad \text{with} \quad L = T - V$$

$$\text{and} \quad T = \frac{1}{2} M \dot{x}^2 + \frac{1}{2} M \dot{y}^2 + \frac{1}{2} I \dot{\theta}^2$$

$$V = \frac{1}{2} k_a (q_1^2 + q_2^2) + \frac{1}{2} k_e [\alpha_1^2 + \alpha_2^2 + (\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2]$$

↓

$$M \ddot{s} + K s = 0 \quad s(t) = s_0 e^{-i\omega t} \quad -\omega^2 M + K = 0$$

ω^2 are the eigenvalues of matrix $M^{-1}K$

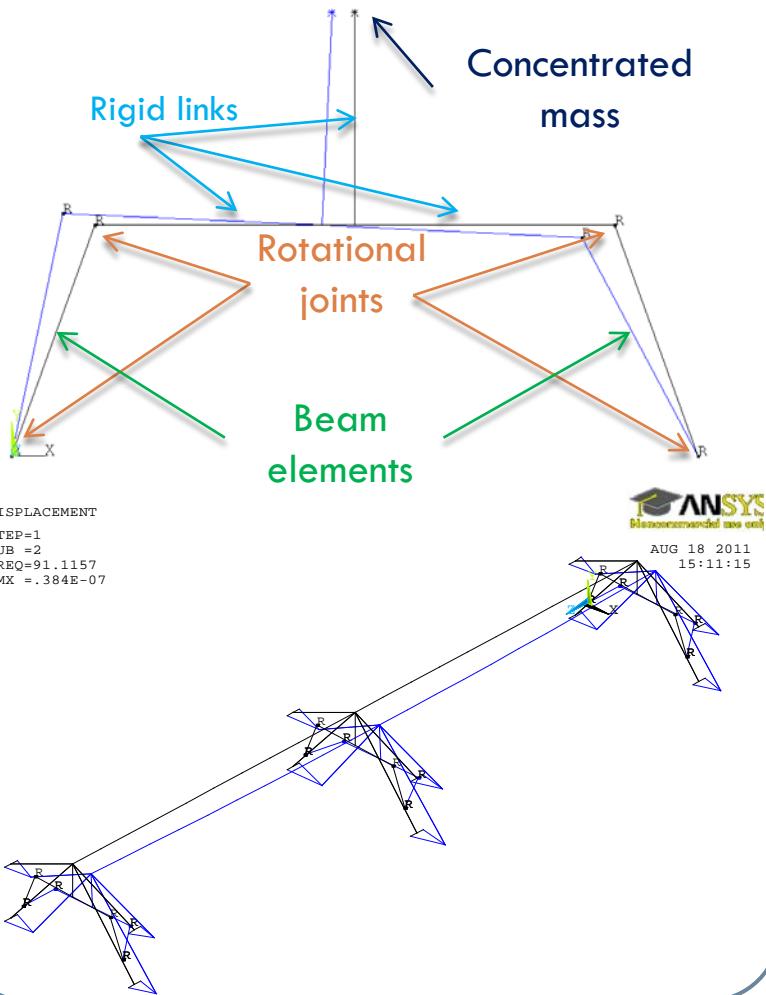
$f = \omega / 2\pi$

Finite Element models

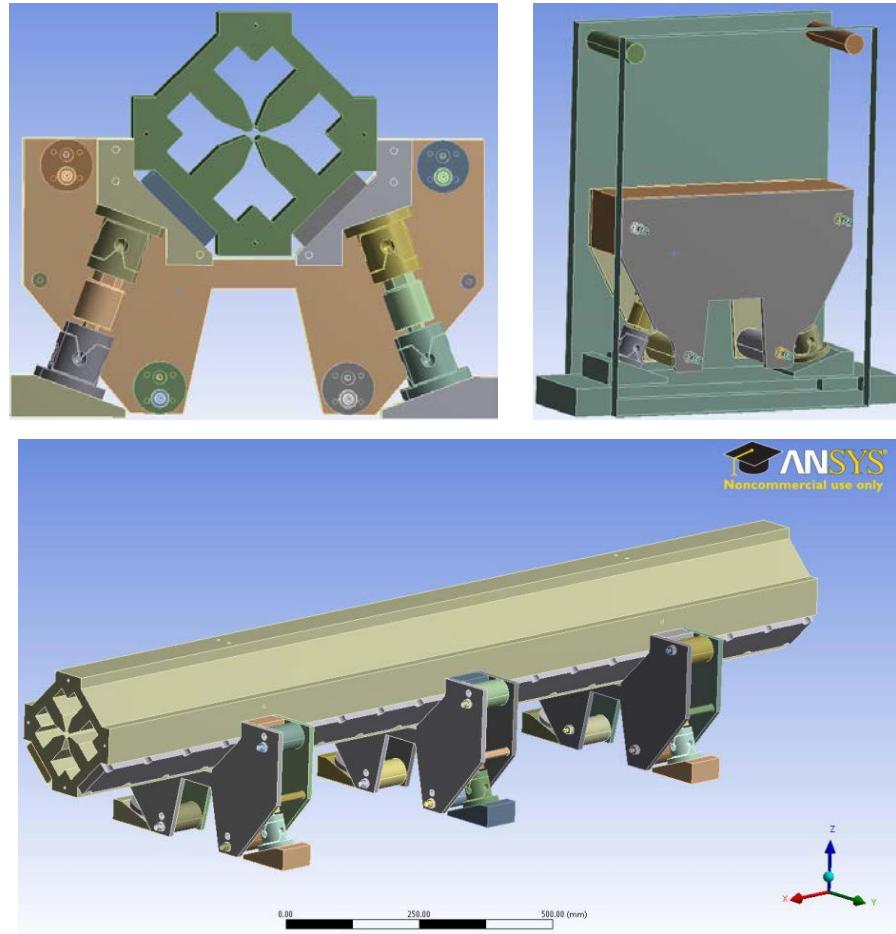


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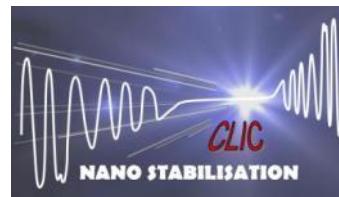
ANSYS Classic



ANSYS Workbench



Analytical & FE results



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	Hz k_h [N/μm]	Vt k_v [N/μm]	4-bar mode		θ mode		Vertical mode	
			f [Hz]	shape	f [Hz]	shape	f [Hz]	shape
Without xy guide	Analytical	0.21	203	9.2			319	
	Ansys classic	0.21	204	9.2				
	Ansys WB	0.21	203	8.3				
With xy guide	Analytical	35	229	153			339	
	Ansys classic	44	225	125				
	Ansys WB	38	220	145				
Type 1 MBQ with xy guide	$k_h=69$ [N/ μm]	$k_v=227$ [N/ μm]	119 [Hz]		303 [Hz]		319 [Hz]	

Longitudinal stiffness

Without xy guide
0.03 N/ μm

With xy guide
(pins totally fixed on 1
end)
278 N/ μm

With xy guide
(pins fixed to steel
plates)
48 N/ μm

Longitudinal mode

Without xy guide
3.4 Hz

With xy guide
(pins totally fixed on 1
end)
280 Hz

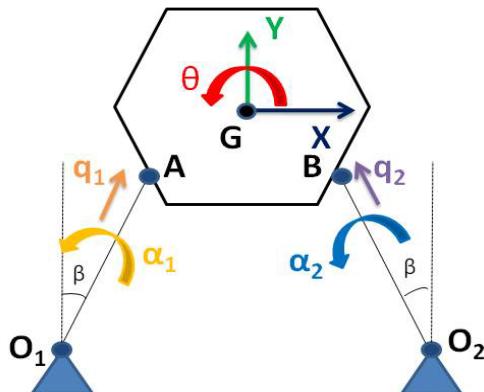
With xy guide
(pins fixed to steel
plates)
65 Hz

Simulated Kinematics (1)



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- 3 DOF system
- Only 2 DOFs are controlled



$$q_1 = \sin\beta x + \cos\beta y + (D_v \sin\beta - D_h \cos\beta)\theta$$

$$q_2 = -\sin\beta x + \cos\beta y + (-D_v \sin\beta + D_h \cos\beta)\theta$$

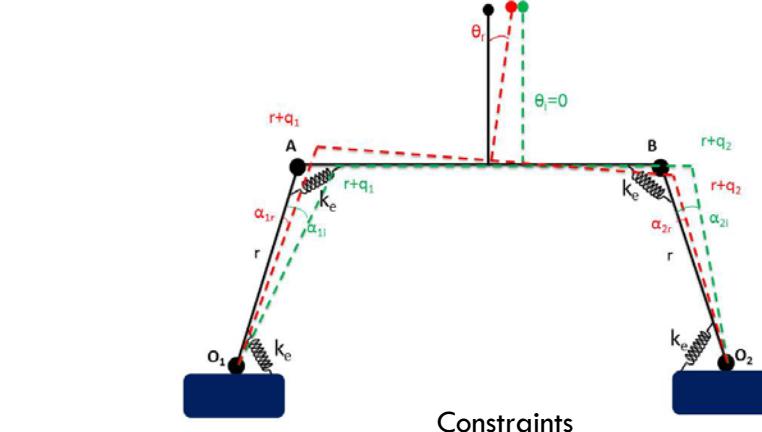
2 controlled DOFs

$$\alpha_1 = -\frac{\cos\beta}{R} x + \frac{\sin\beta}{R} y + \left(-D_v \frac{\cos\beta}{R} - \frac{D_h \sin\beta}{R} \right) \theta$$

$$\alpha_2 = -\frac{\cos\beta}{R} x - \frac{\sin\beta}{R} y + \left(-D_v \frac{\cos\beta}{R} - \frac{D_h \sin\beta}{R} \right) \theta$$

2 equations necessary to fully describe the kinematics

The system is not fully determined without taking into account the reaction forces

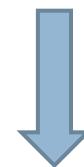


$$Cvt = (R + q_1) * \cos(\beta - \alpha_1) + L_m * \sin(\theta) + (R + q_2) * \cos(\beta + \alpha_2)$$

$$Chz = (R + q_1) * \sin(\beta - \alpha_1) + L_m * \cos(\theta) + (R + q_2) * \sin(\beta + \alpha_2) - L_b$$

Potential Energy

$$V = \frac{1}{2} k_a (q_1^2 + q_2^2) + \frac{1}{2} k_e [\alpha_1^2 + \alpha_2^2 + (\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2]$$



NMinimize[{V, Cvt == 0, Chz == 0, dq1 == 1, dq2 == -1}]

(find a minimum of potential energy respecting the constraint equations and fixing the input values of the actuator displacements)

Simulated Kinematics (2)



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		Hz movement		Vt movement	
8 PINS	Analytical model	x/q	1.3	y/q	1.06
		y/x	0	x/y	0
		$\theta/x \text{ [}\mu\text{rad}/\mu\text{m]}$	5.15	$\theta/y \text{ [}\mu\text{rad}/\mu\text{m]}$	0
	FE model	x/q	1.24	y/q	1.03
		y/x	0.05	x/y	0
		$\theta/x \text{ [}\mu\text{rad}/\mu\text{m]}$	5.25	$\theta/y \text{ [}\mu\text{rad}/\mu\text{m]}$	0
NO PINS	Analytical model	x/q	1.4	y/q	1.06
		y/x	0	x/y	0
		$\theta/x \text{ [}\mu\text{rad}/\mu\text{m]}$	4.64	$\theta/y \text{ [}\mu\text{rad}/\mu\text{m]}$	0
	FE model	x/q	1.15	y/q	1.06
		y/x	0.03	x/y	0
		$\theta/x \text{ [}\mu\text{rad}/\mu\text{m]}$	6.6	$\theta/y \text{ [}\mu\text{rad}/\mu\text{m]}$	0

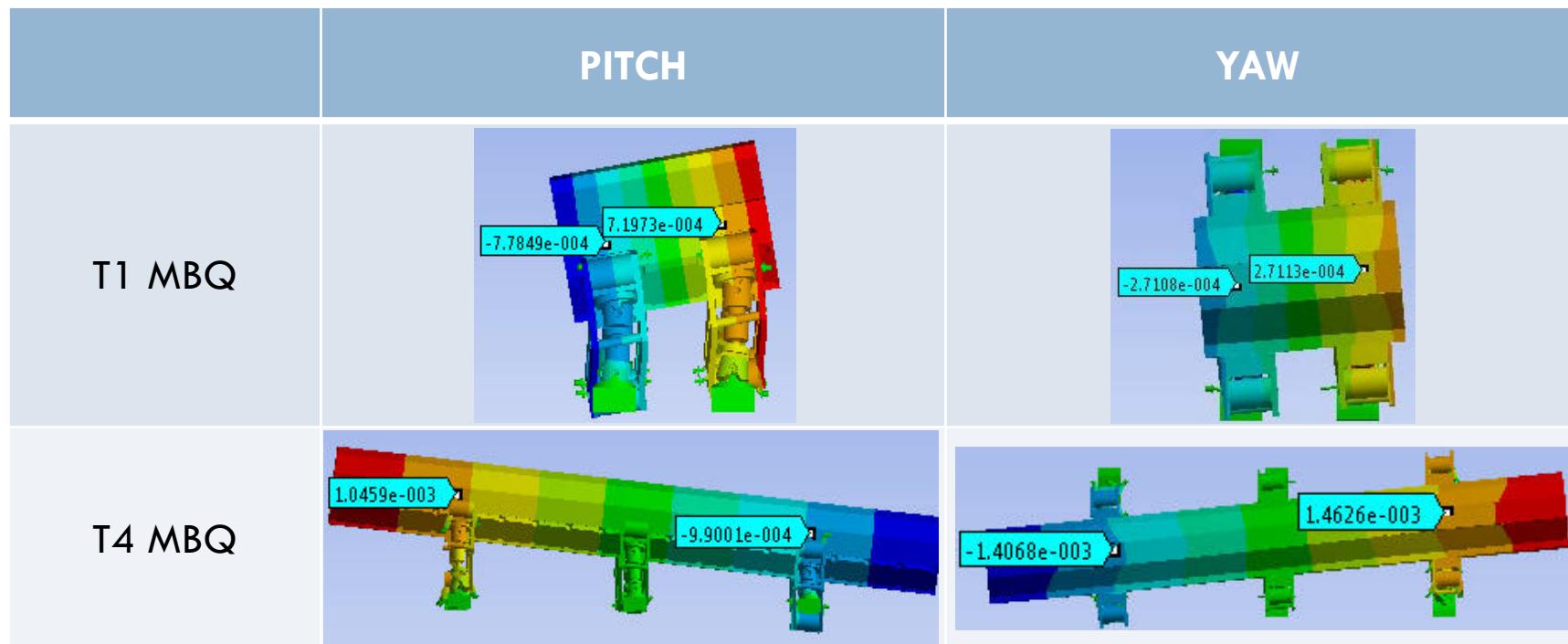
- Pins do not change the “shape” of the movement
- Less than 1% of coupling between horizontal and vertical
- $\approx 5 \mu\text{rad}/\mu\text{m}$ of roll per unit lateral displacement
- Translation/actuator elongation ratio is $\approx 1:1$ (Vt) and $\approx 1.4:1$ (Hz)



3D simulated Kinematics



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- No loss of translation range for T4
- About 25% of loss of vertical translation range for T1 pitch
- About 80% of loss of lateral translation range for T1 yaw

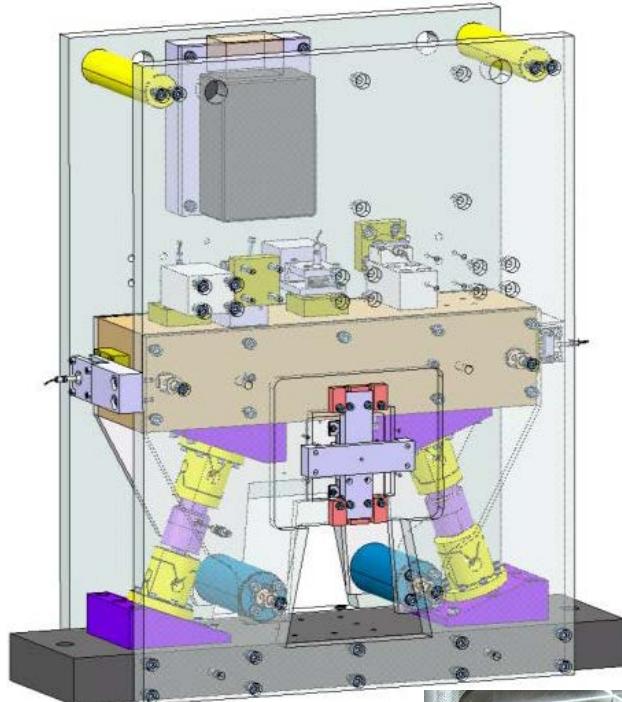
X-y prototype and sensors



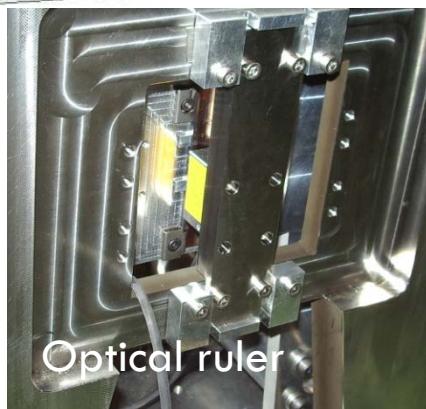
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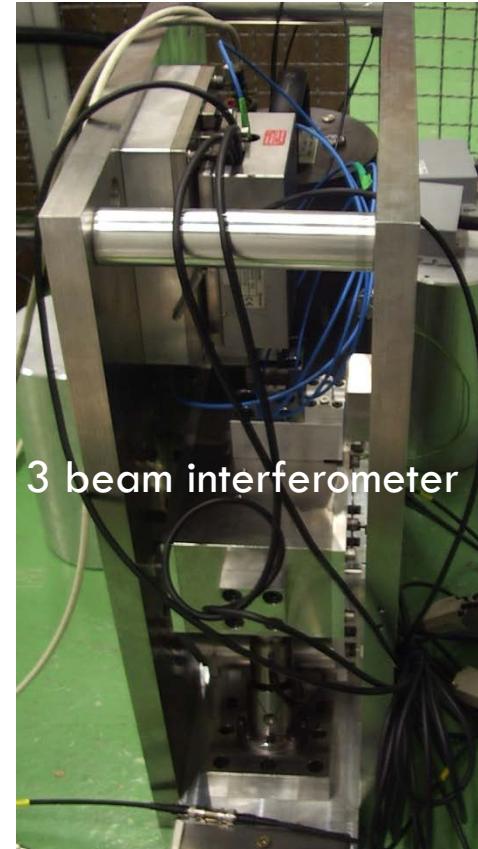
Capacitive sensor



Actuators equipped
with strain gauges



Optical ruler

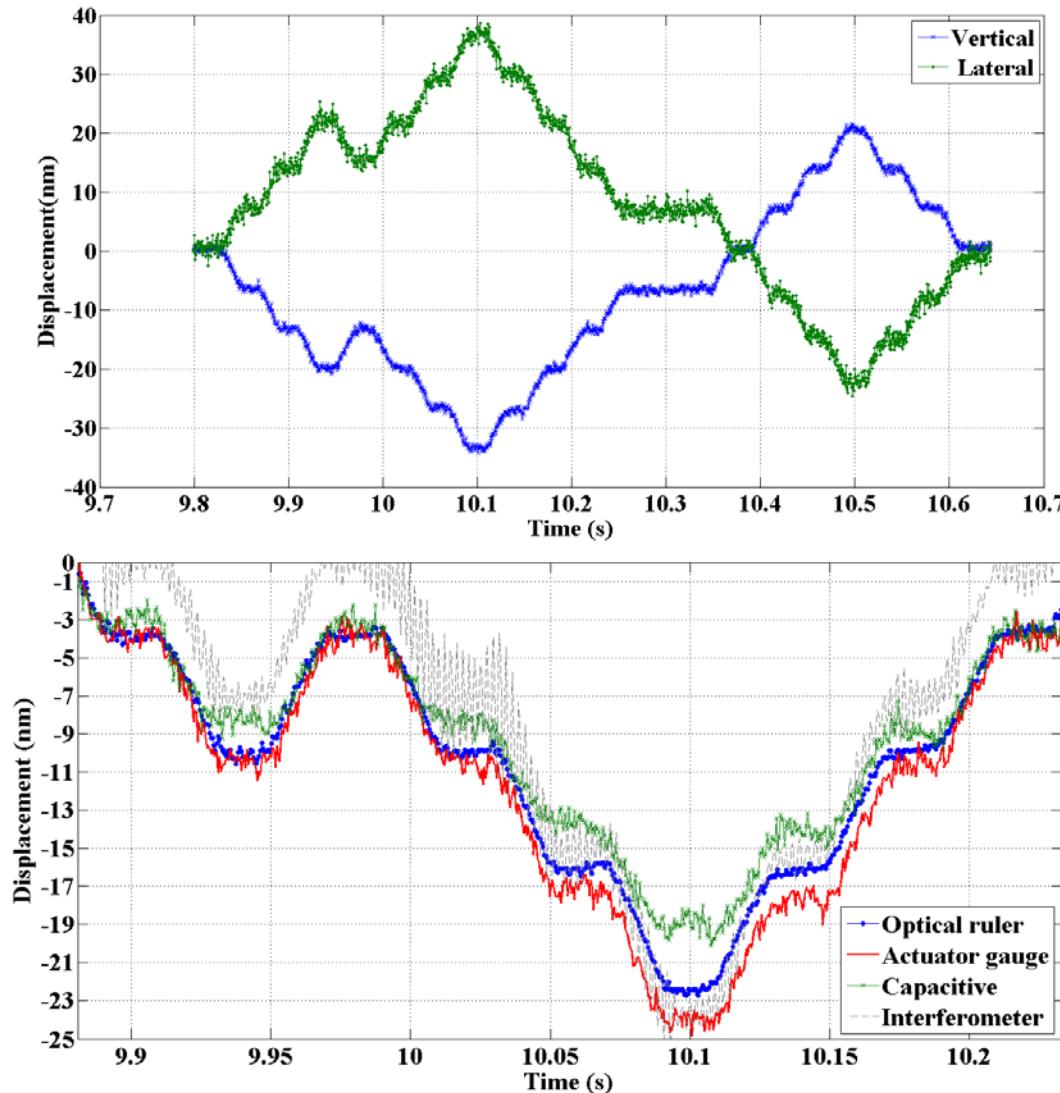


3 beam interferometer

X-y positioning: lateral and vertical 6 nm steps



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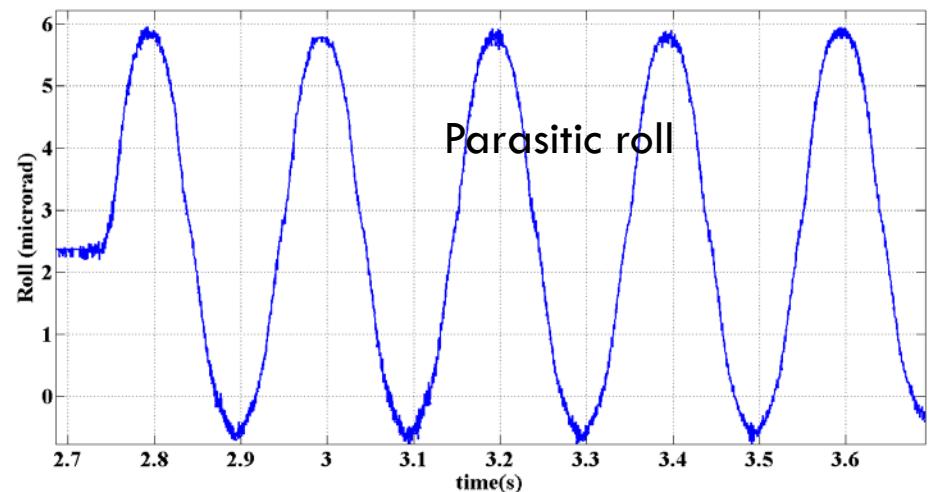
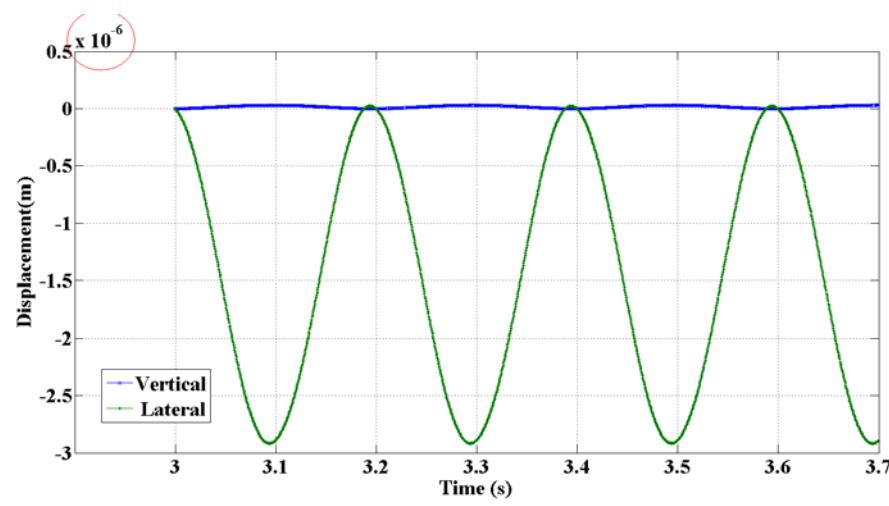
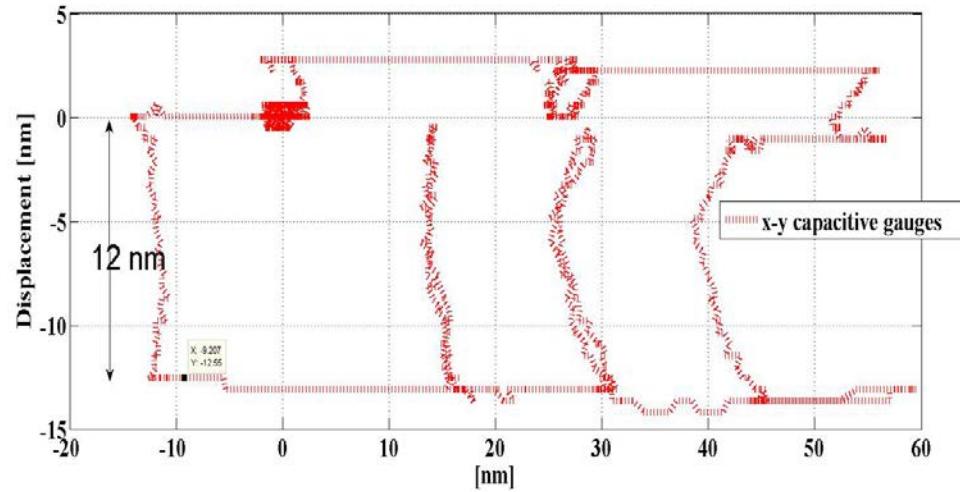
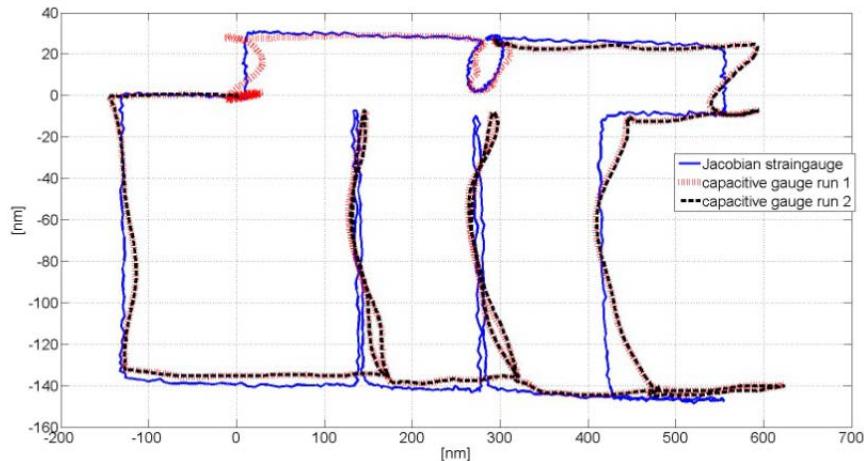




X-y Positioning



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Comparison sensors



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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	

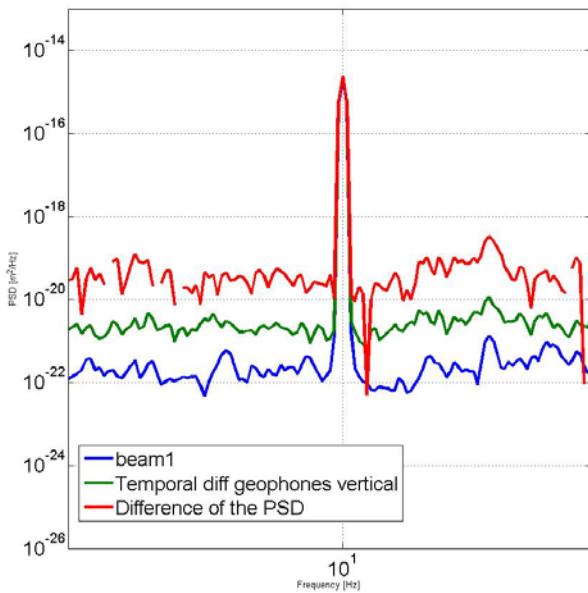
Noise level in frequency domain (PSD)



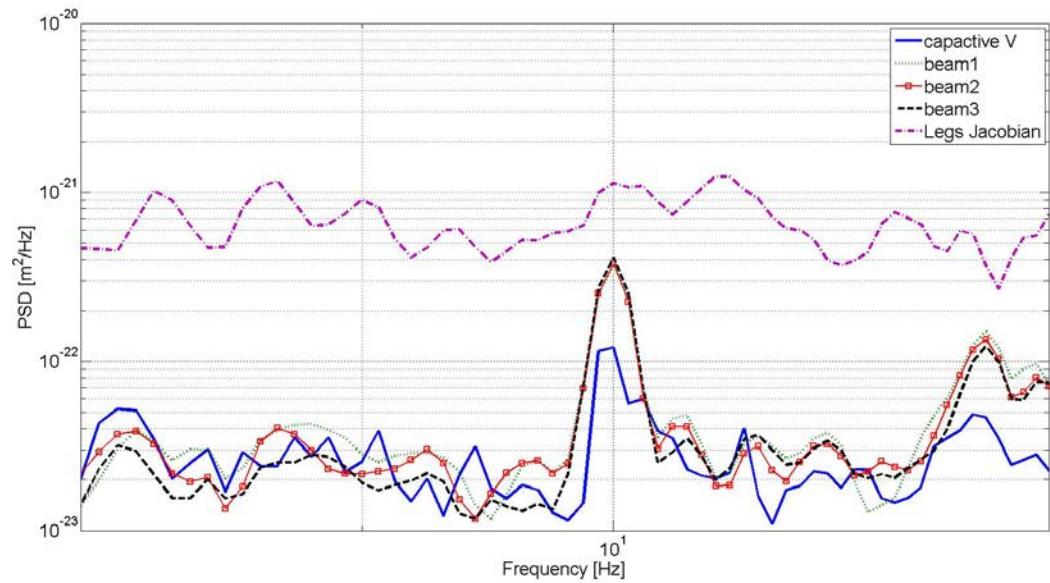
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Cross check between different instrumentation + resolution measurements

Irfu
cea
saclay



14 nm sine wave



14 pm sine wave

Stabilization on Type 1 MBQ



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- Water cooling 4 l/min
- With magnetic field on
- With hybrid circuit

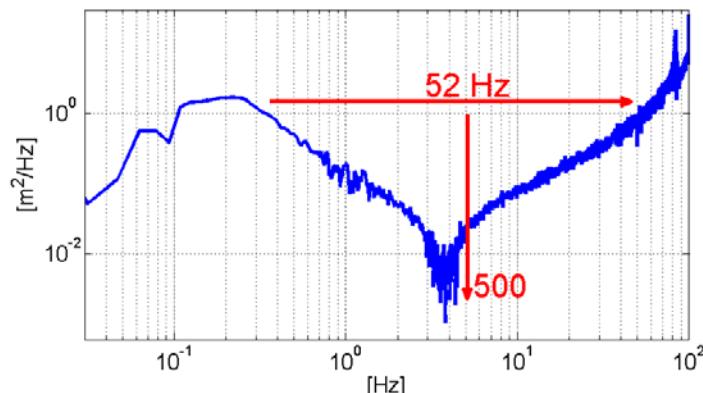
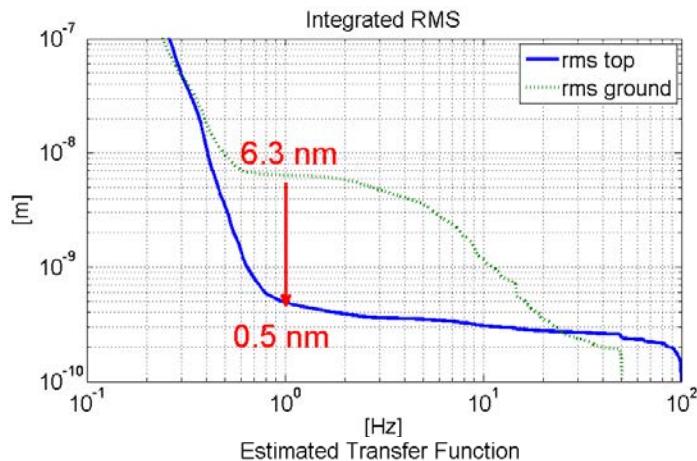


Figure	Value
R.m.s @ 1Hz magnet	0.5 nm
R.m.s @ 1Hz ground	6.3 nm
R.m.s. attenuation ratio	~ 13
R.m.s @ 1Hz objective	1.5 nm

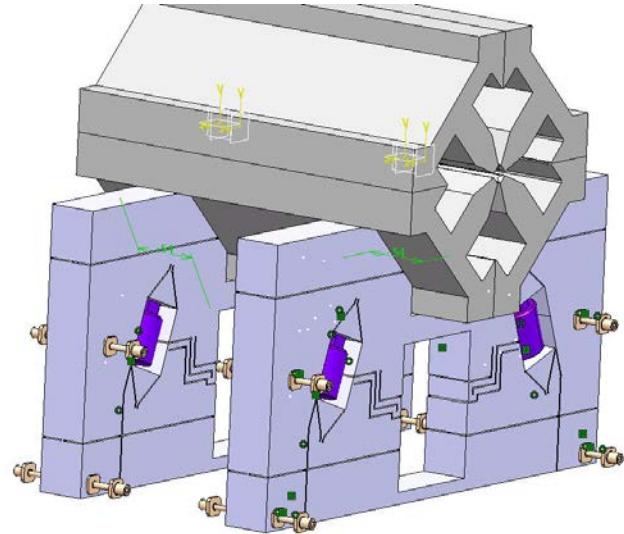
Future developments



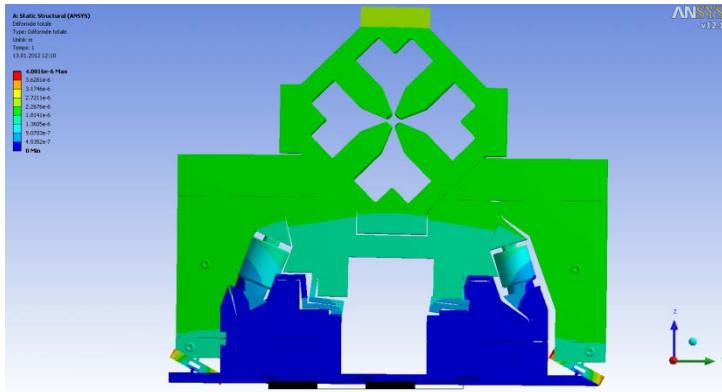
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Monolithic approach of the design:

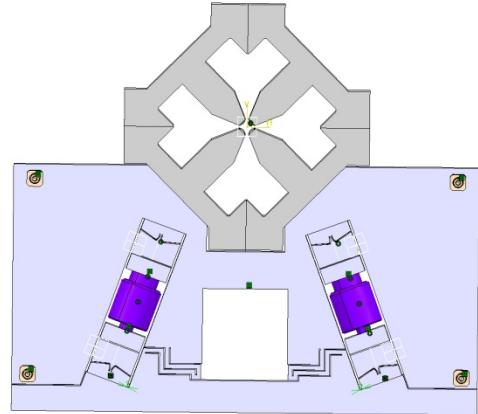
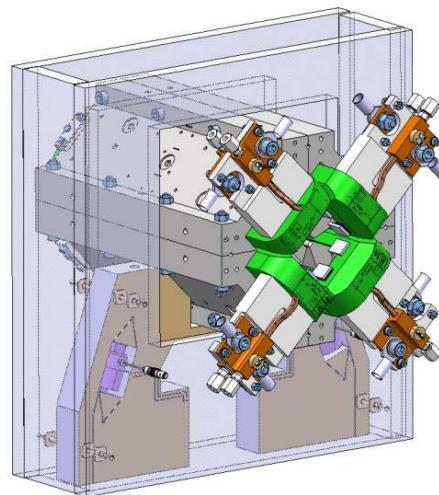
- To simplify the assembly + increase precision
- Reduce assembly stresses on actuator + magnet
- Improve sensor installation: inertial ref. mass and displacement gauges
- Optimise vertical, lateral and longitudinal stiffness
- Decrease parasitic motion if needed
- Mechanical locking for transport
- Improve interface with alignment



Work in progress: T1 test module



K. Artoos



M. Esposito, IWAA 2012 Fermilab

Conclusions

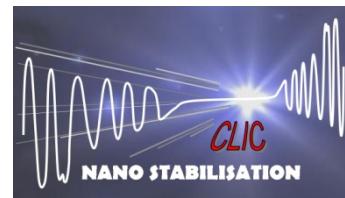


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- An actuator support for the stabilization and nano-positioning of CLIC MBQ is under development
- The mechanics has been studied in detail using Analytical and FE models
- A prototype has been built and measurements using 4 different types of sensors have been realized
- Experimental results show that the support and some of the sensors can reach sub-nanometre resolution



Publications



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<http://clic-stability.web.cern.ch/clic-stability/publications.htm>



The end



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Thank You for your attention!
(Questions?)



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Spare slides

Comparison



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Very Soft (1 Hz)



Soft (20 Hz)



Stiff (200 Hz)



- Pneumatic actuator
- Hydraulic actuator

$k \sim 0.01 \text{ N}/\mu\text{m}$

- Electromagnetic in parallel with a spring
- Piezo actuator in series with soft element (rubber)

$k \sim 1 \text{ N}/\mu\text{m}$

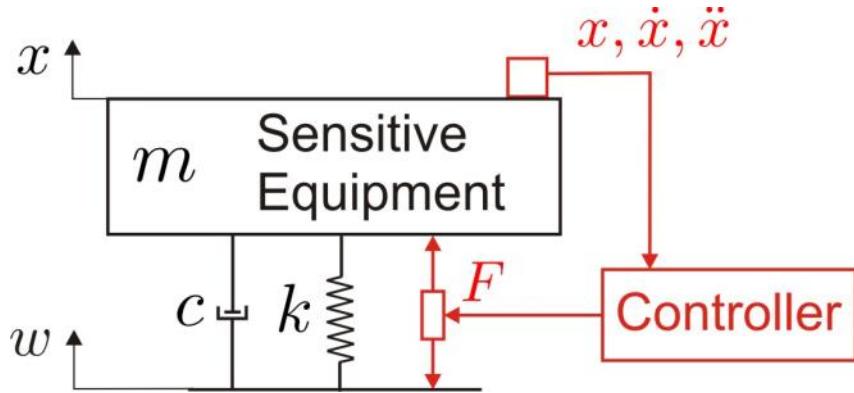
- Piezoelectric actuator in series with stiff element (flexible joint)

Piezo $k \sim 100-500 \text{ N}/\mu\text{m}$

COMPARISON

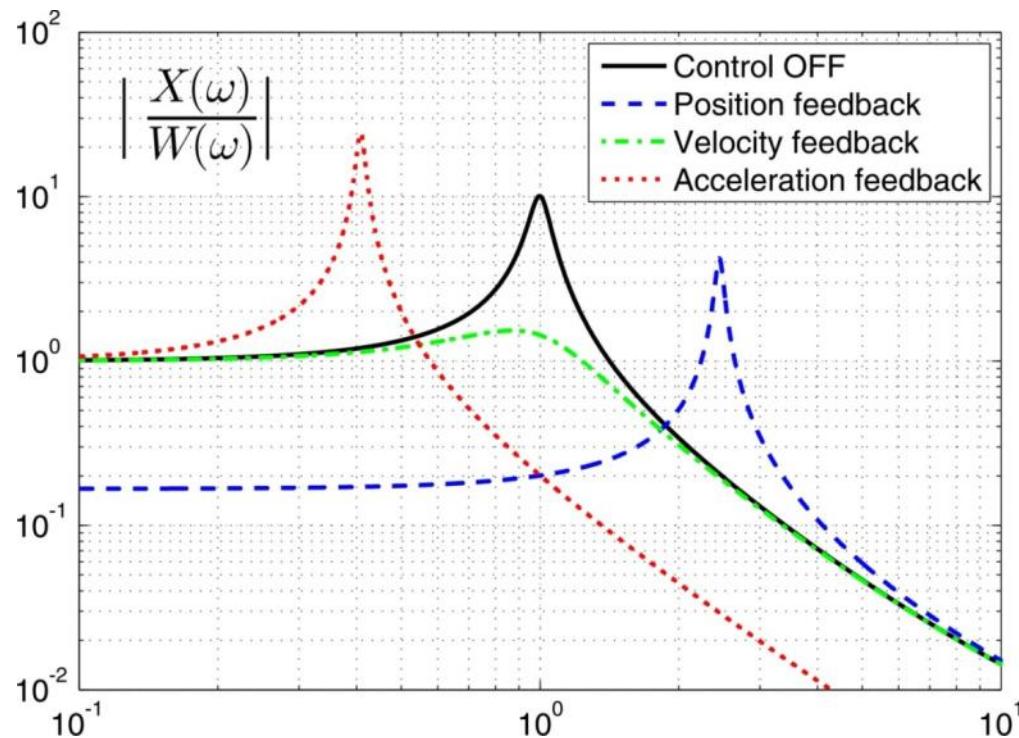
+ Broadband isolation	+ Passive isolation at high freq.	+ Extremely robust to forces
- Stiffness too low	+ Stable	+ Fully compatible with AE
- Noisy	- Low dynamic stiffness	+ Comply with requirements
	- Low compatibility with alignment and AE	- Noise transmission
		- Strong coupling (stability)

Feedback control principle



$$F(t) = k_d x + k_v \dot{x} + k_a \ddot{x}$$

$$\frac{X(s)}{W(s)} = \frac{cs+k}{(m+k_a)s^2+(c+k_v)s+(k+k_d)}$$

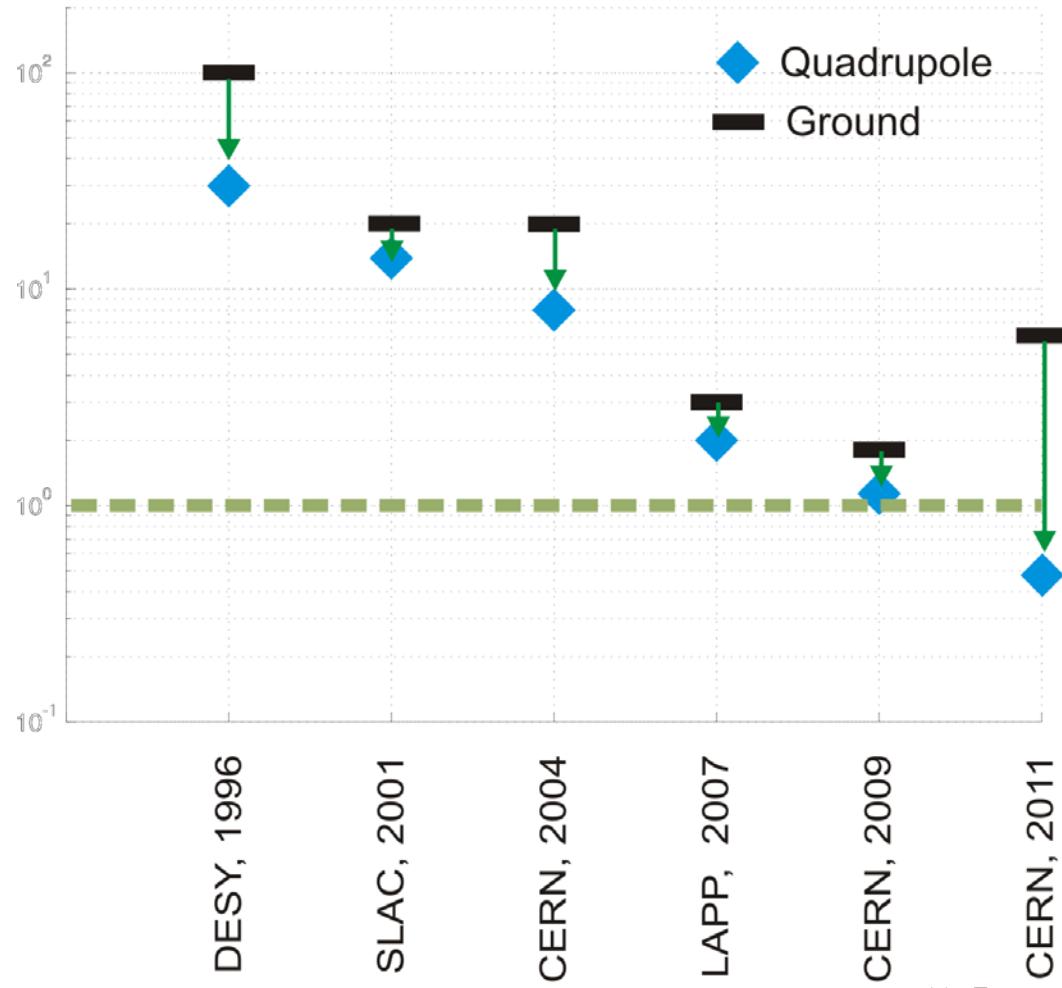


Comparison



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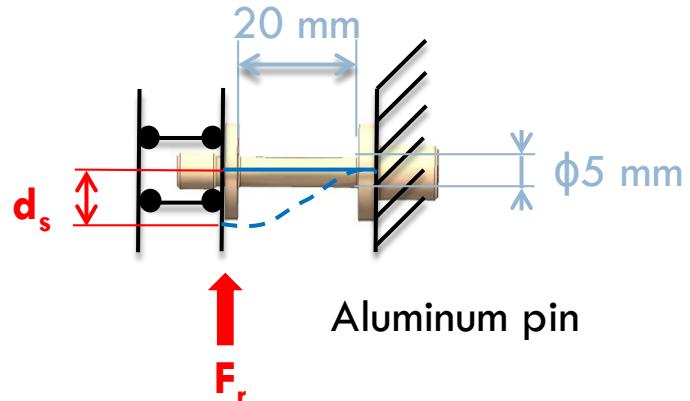
RMS integrated @ 1 Hz



X-y guide in the analytical model



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Flexural stiffness

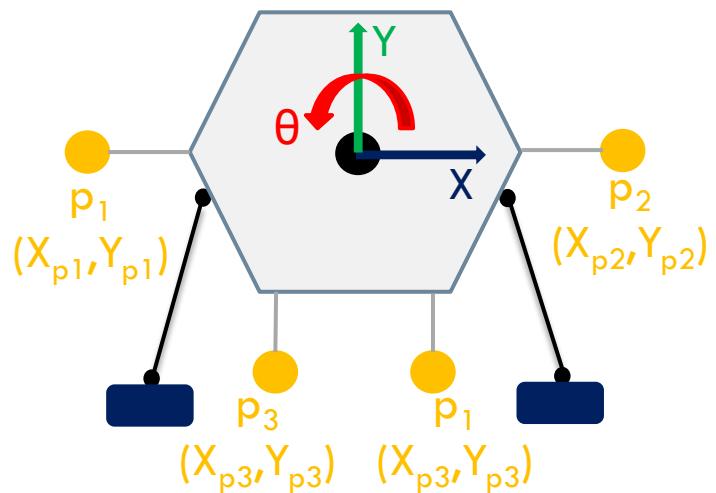
$$k_p = 3.2 \text{ N}/\mu\text{m}$$

Axial stiffness

$$k_a = 69 \text{ N}/\mu\text{m}$$

For each pin: $F_{ri} = k_p * d_{si}$

$$d_{si} = \sqrt{(x - \theta * y_{pi})^2 + (y + \theta * x_{pi})^2}$$



Potential Energy

$$V = \frac{1}{2}k_a(q_1^2 + q_2^2) + \frac{1}{2}k_e[\alpha_1^2 + \alpha_2^2(\alpha_1 - \theta)^2 + (\alpha_2 - \theta)^2 + k_p[(x - \theta * y_{p1})^2 + (y + \theta * x_{p1})^2 + (x - \theta * y_{p2})^2 + (y + \theta * x_{p2})^2 + (x - \theta * y_{p3})^2 + (y + \theta * x_{p3})^2 + (x - \theta * y_{p4})^2 + (y + \theta * x_{p4})^2]]$$