Noise issues in vibration sensing and isolation for Advanced Virgo

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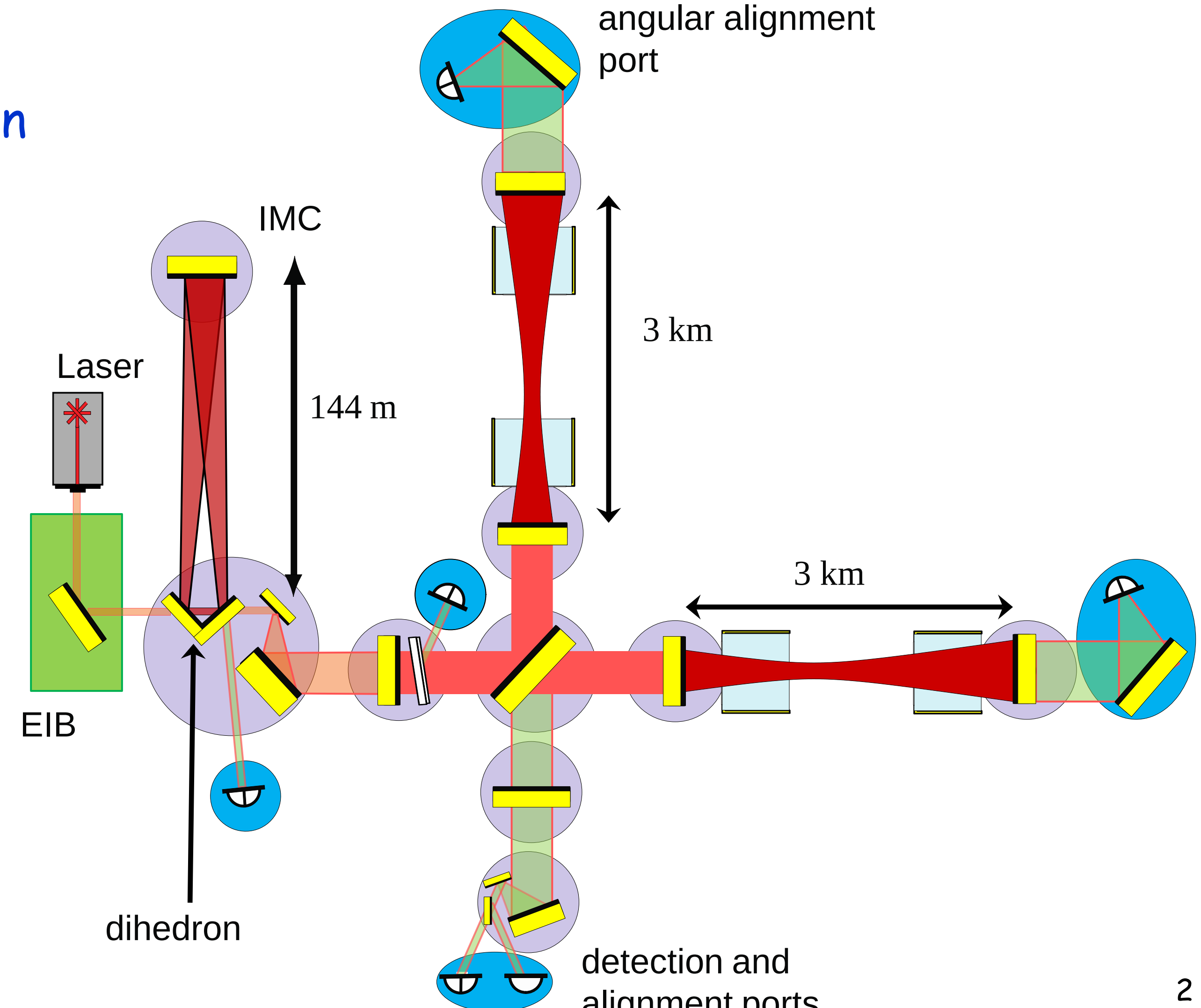
Nikhef 2011-2014 "vibration" activities on AdV

- External Injection Bench Seismic Attenuation (SAS)
- Isolation of 5 new suspended benches for linear alignment
- High sensitivity diagnostic accelerometer
- Input Mode Cleaner:
  - new End mirror + suspension
  - new Dihedron + support

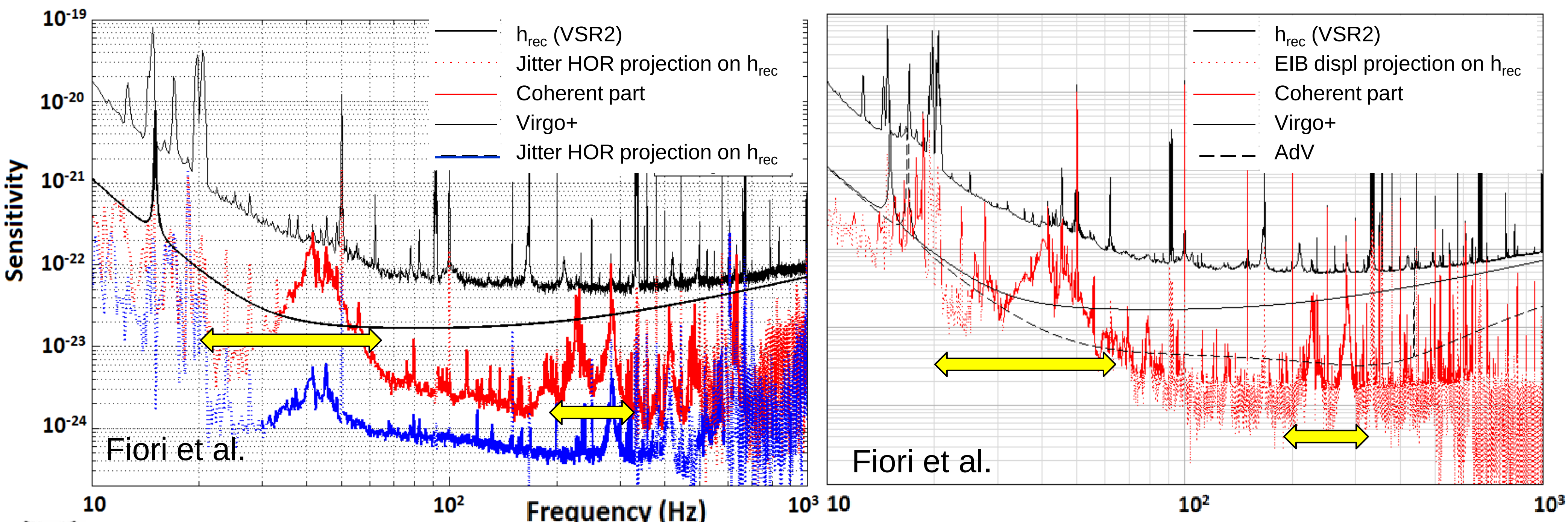


External Injection Bench (EIB) Seismic Attenuation (SAS)

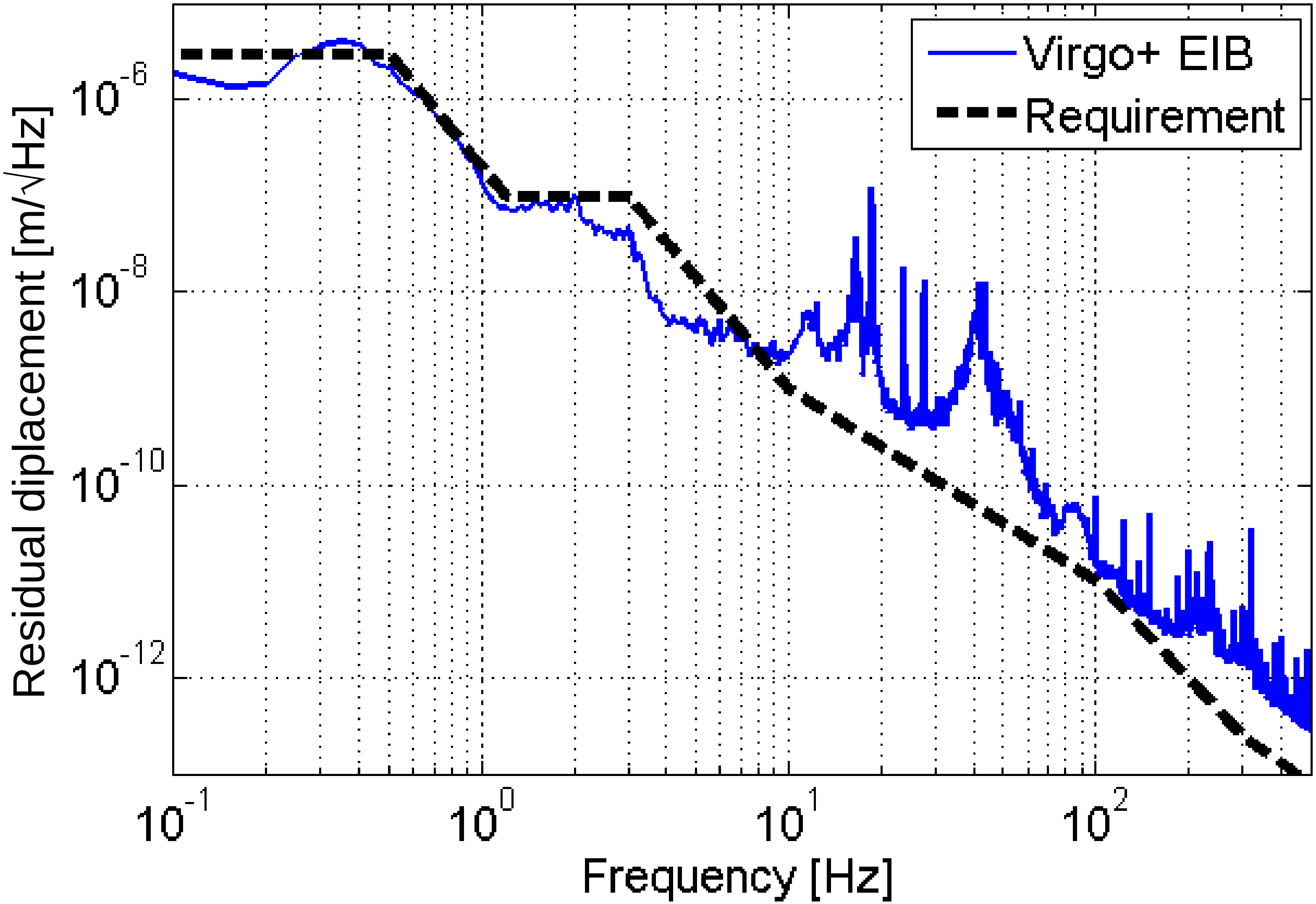
Motivation (since 2009):

- beam jitter noise is spoiling sensitivity
- Ascribed to mechanical modes of
  - bench frame (15-20, 30-60 Hz)
  - optical mounts (200-300 Hz)
- excited by both seism and "a bit of" sound
- to be minimized for Virgo+ and AdV

— Projection of vertical beam jitter on h_{rec} — Projection of EIB displacement on h_{rec}

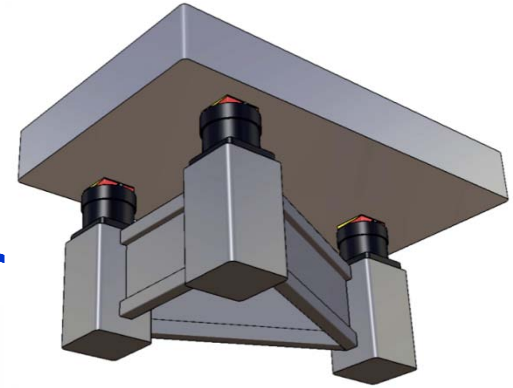


EIB-SAS Requirements



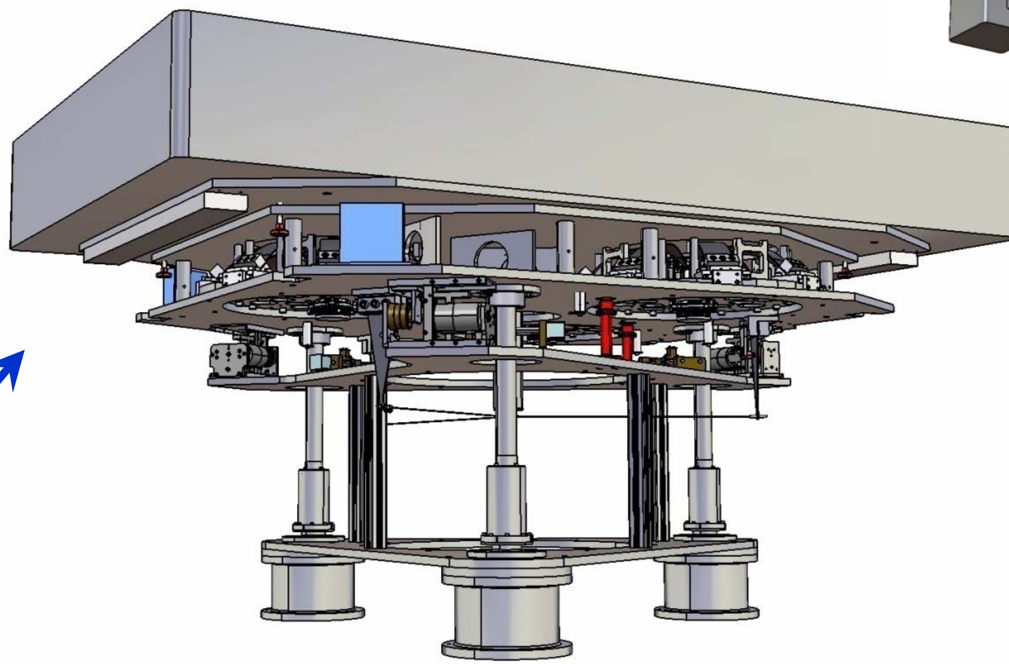
- Up to 40 dB attenuation > 10 Hz
- Long term stability (RMS 20 μm, 15 μrad, max 1 °C variations
- DC-control

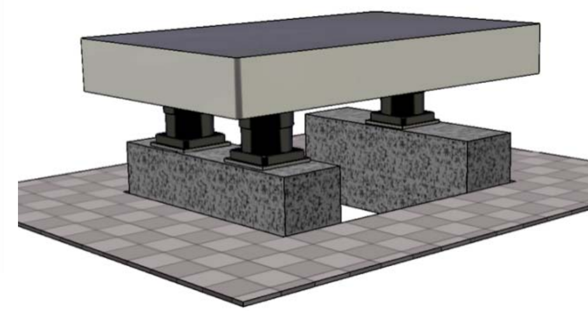
EIB-SAS Solution option history



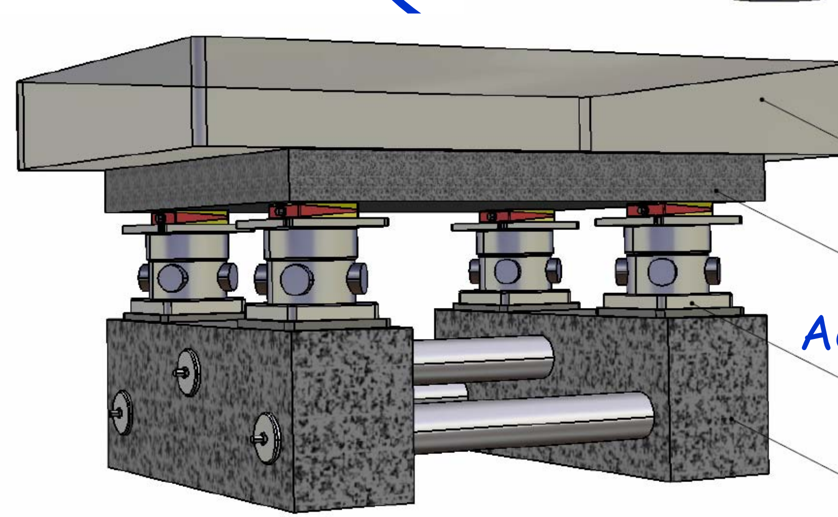
Stiffer legs

Chosen solution:
Highly-compliant suspension



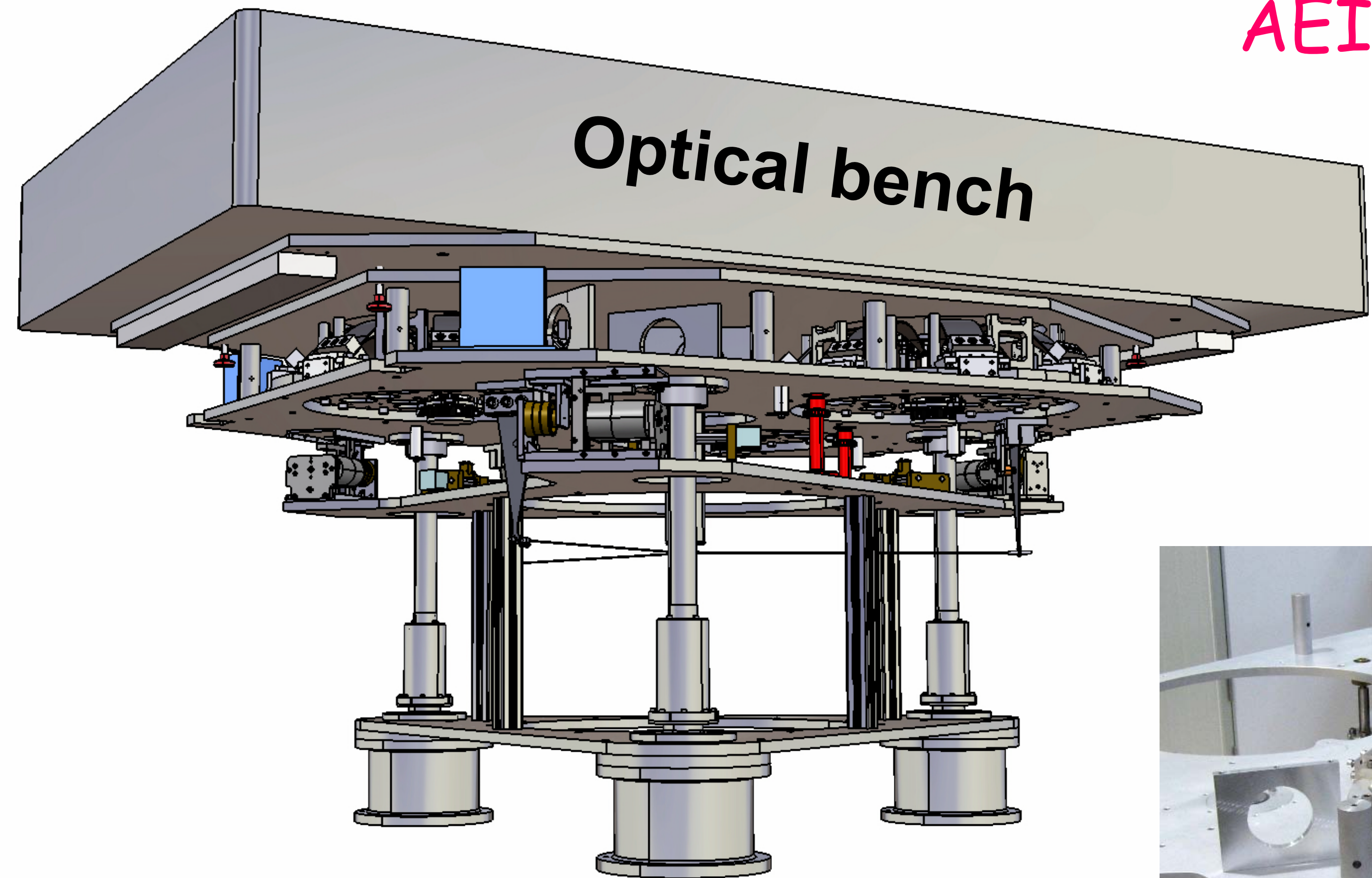


Stiffer support



Active isolation (TMC-Stacis)

EIB-SAS: adopted from HAMSAS project (Caltech) & AEI-Hannover (2010)



6-DOF passive attenuation, anti-spring technology

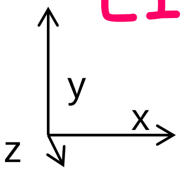
- 3 GAS filters, 3 Inverted Pendulum legs

Active positioning and low-f resonance damping

- 6 x LVDTs, 6 x geophones, 6 x voice coil actuator
- 800 kHz 18 bit ADCs
- 7 stepper motors

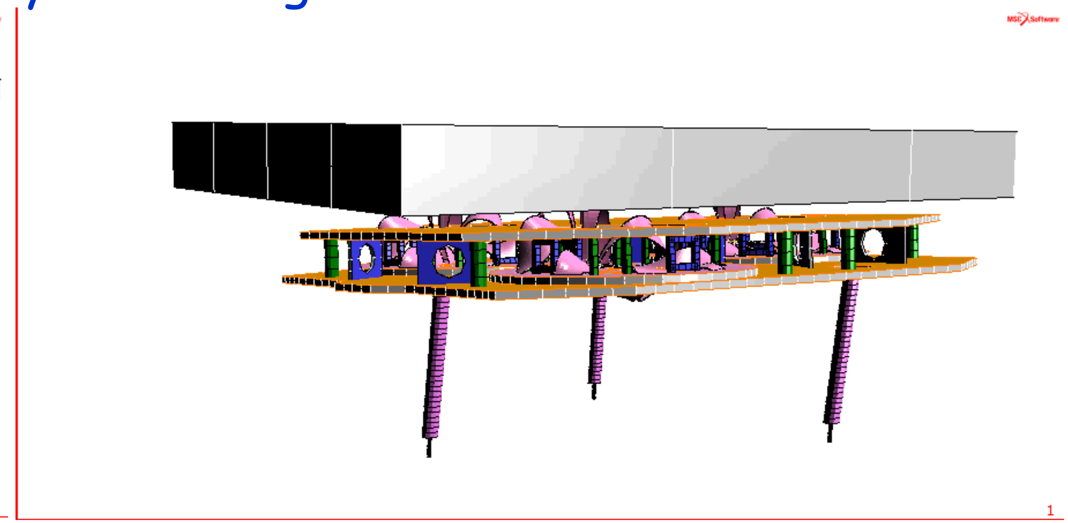
Built and tested at Nikhef, 2011

EIB-SAS complication: horizontal GAS modes < 20 Hz

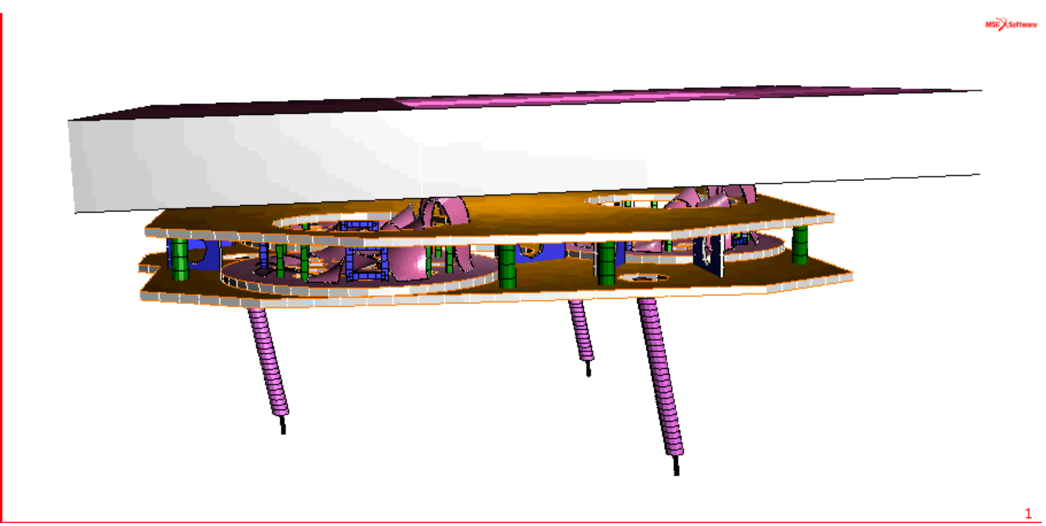


- Modes due to lateral GAS spring compliance
- Can be damped by extending control bandwidth

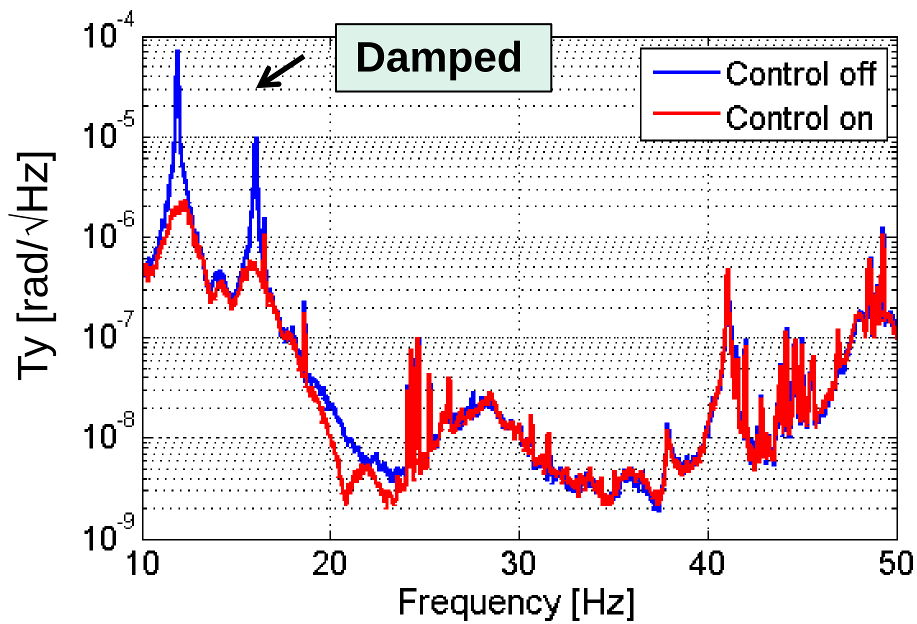
Yaw + z (12 Hz)



z + yaw +(bench) pitch (16 Hz)

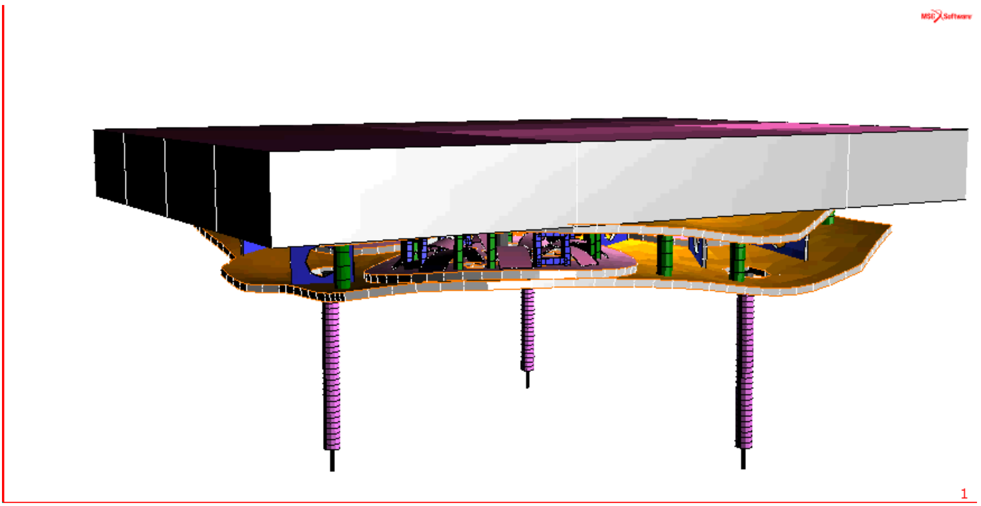


x + (bench) roll (18 Hz)

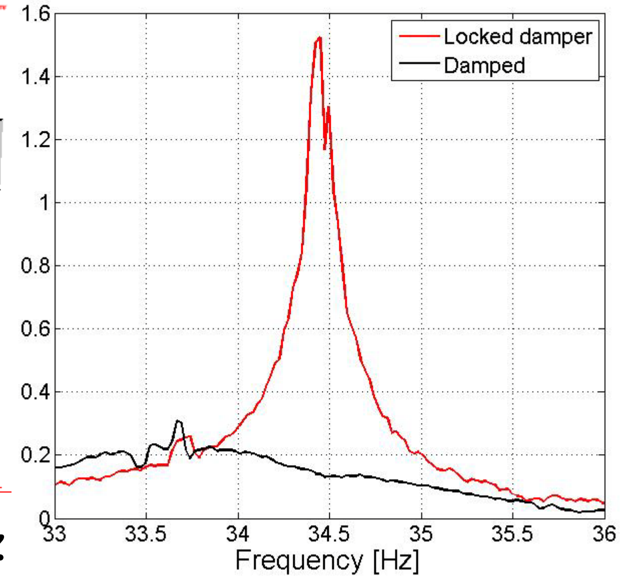


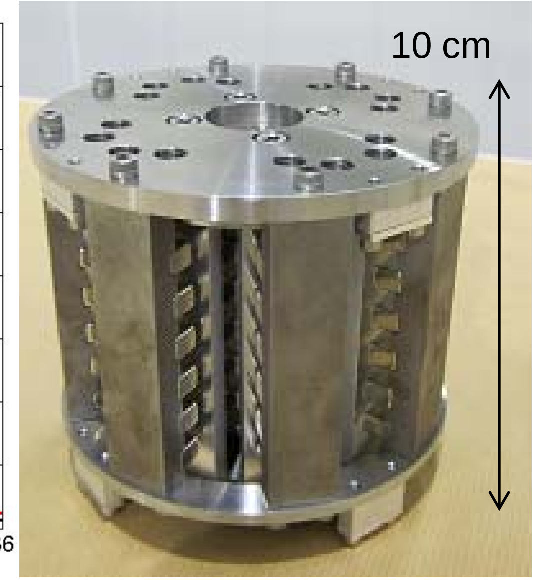
EIB-SAS complication: spring box modes 30-60 Hz

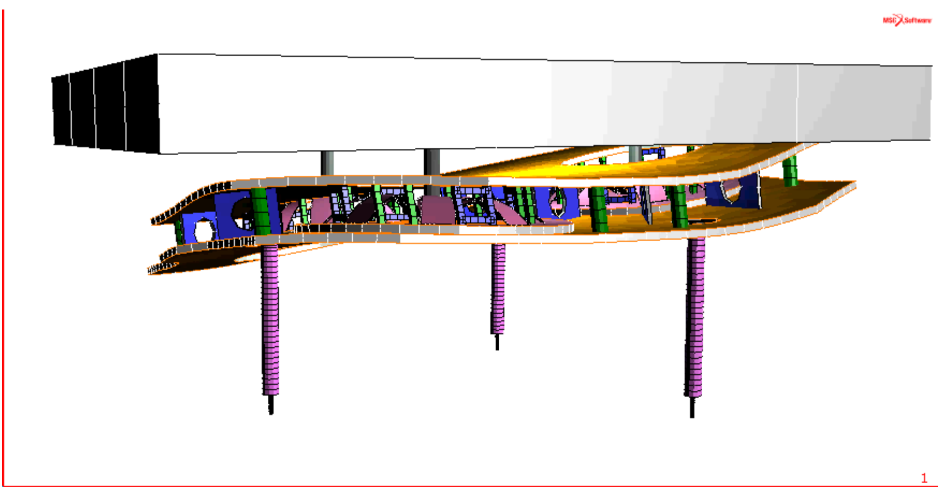
- Modes due to upper IP flex and spring box internal compliances
- Can partially be damped with eddy current damped resonators

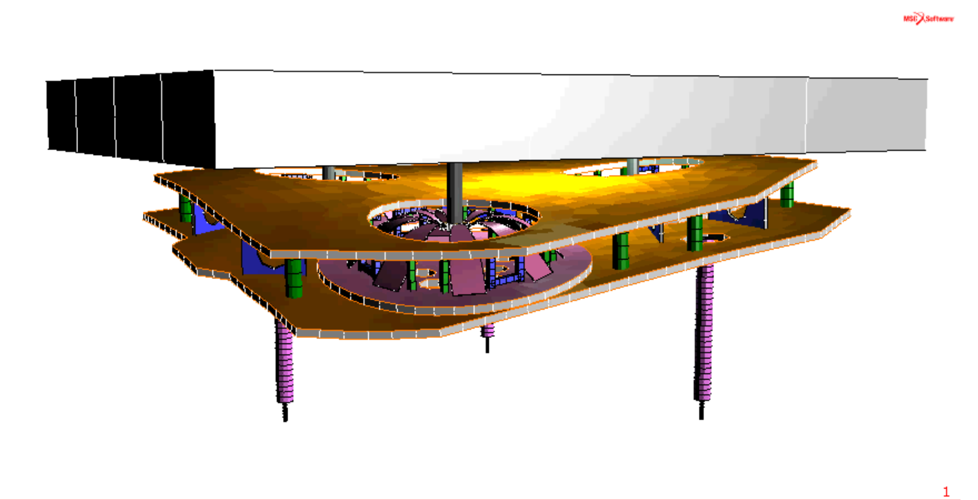


Springbox vertical bouncing mode ~ 50Hz



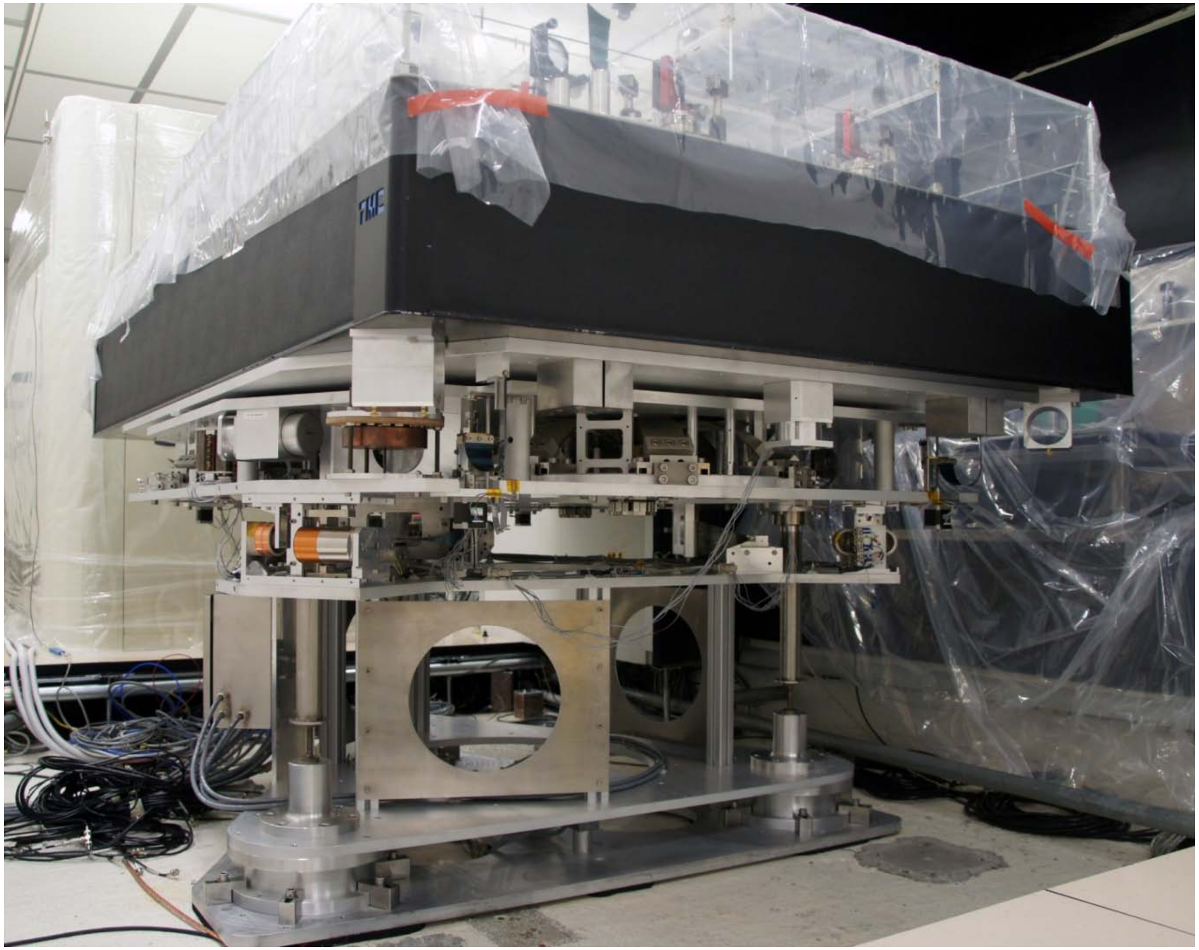






coupled tilt modes (~ 30-40 Hz)

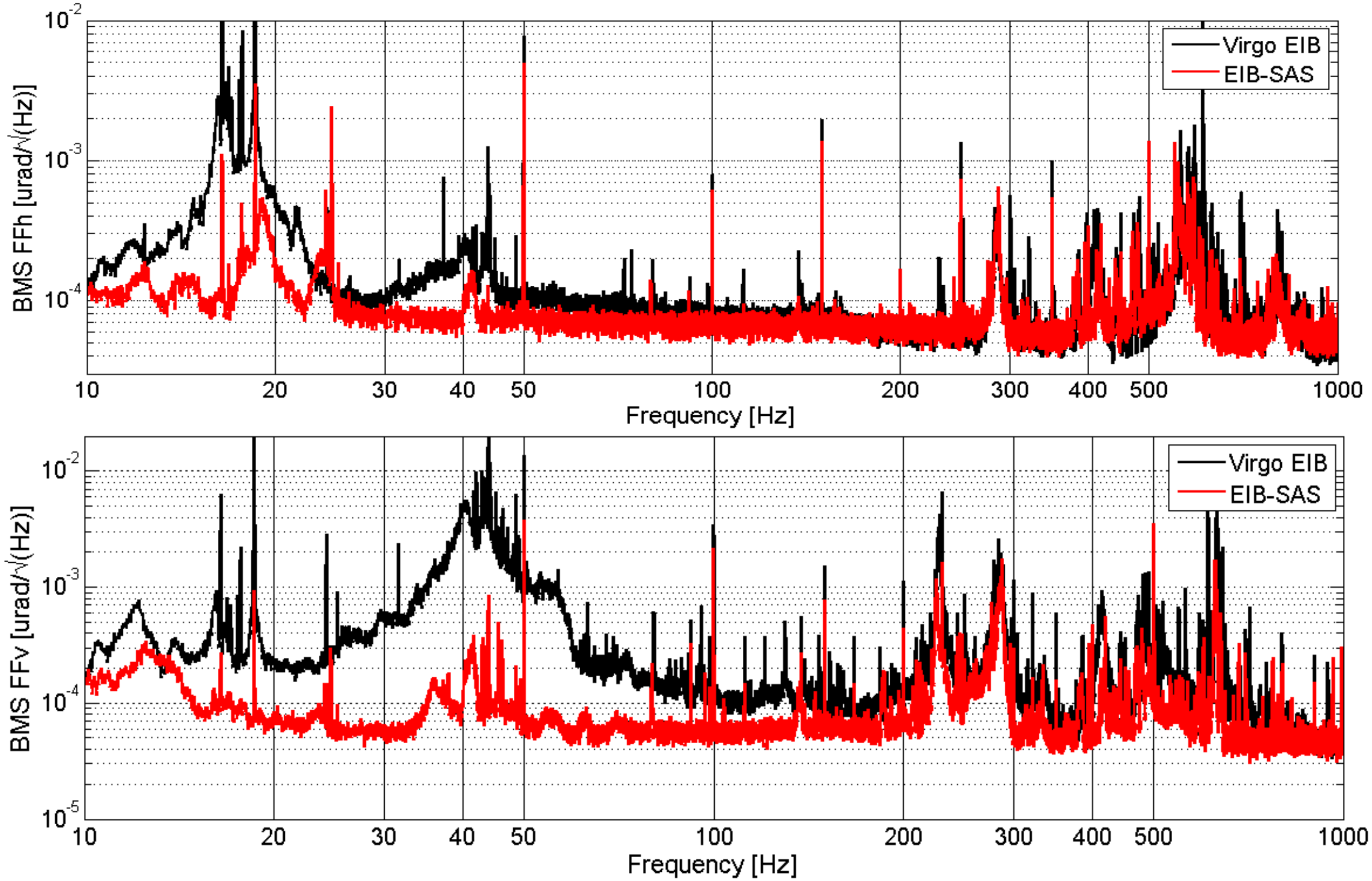
EIB-SAS: First major Advanced Virgo installation (Dec 2011)



EIB-SAS after installation

EIB in acoustic enclosure

EIB-SAS commisioning: beam jitter



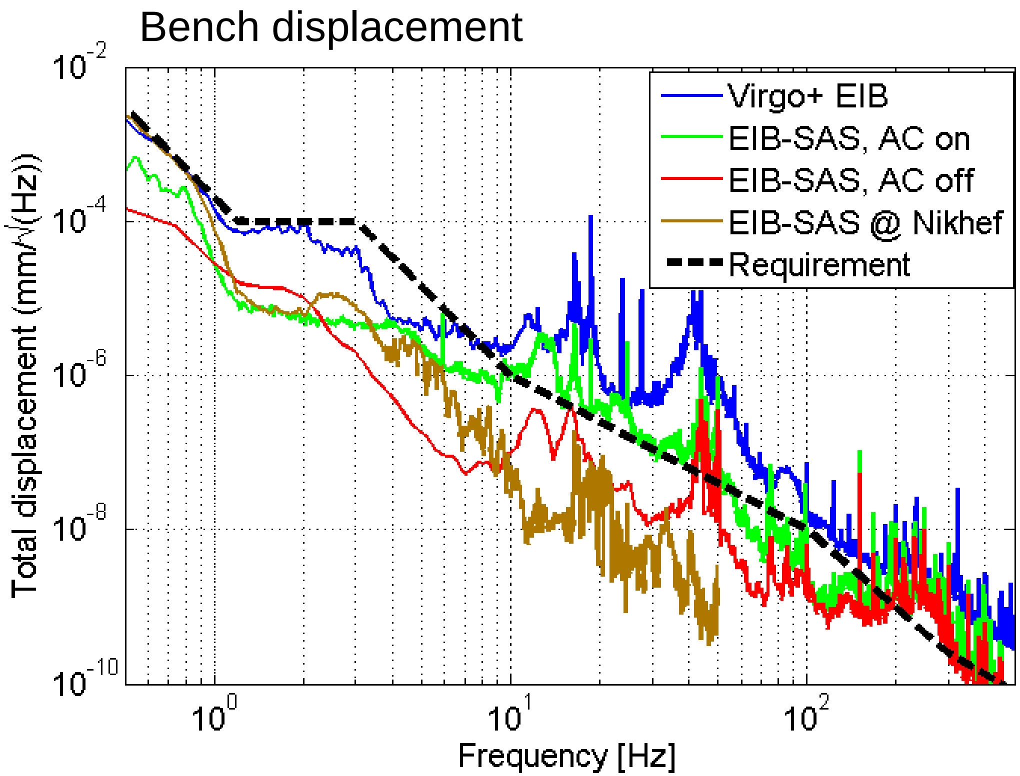
Fiori et al.

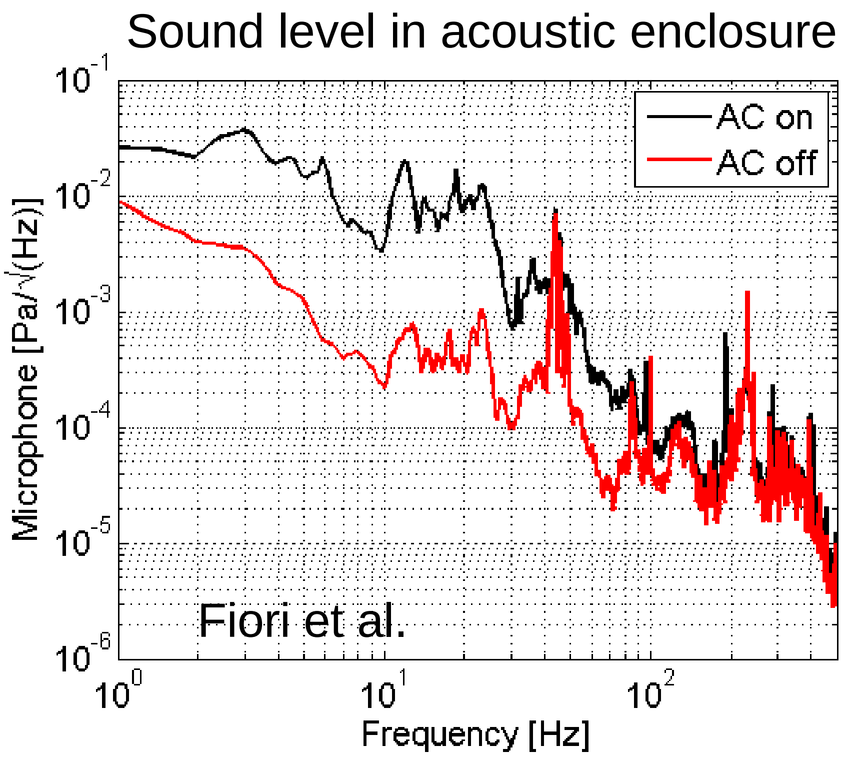
The good news:
Beam jitter significantly reduced < 100 Hz

But:
Optics mounts keep resonating (200-300 Hz)

And …

EIB-SAS commisioning: bench motion and acoustic noise

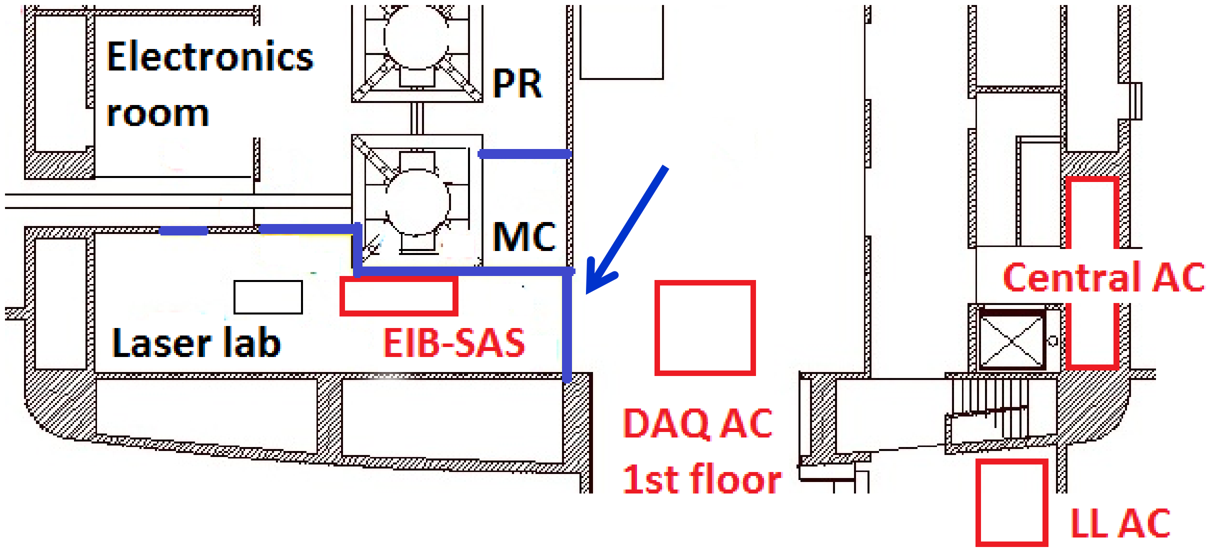




Conclusions after many tests

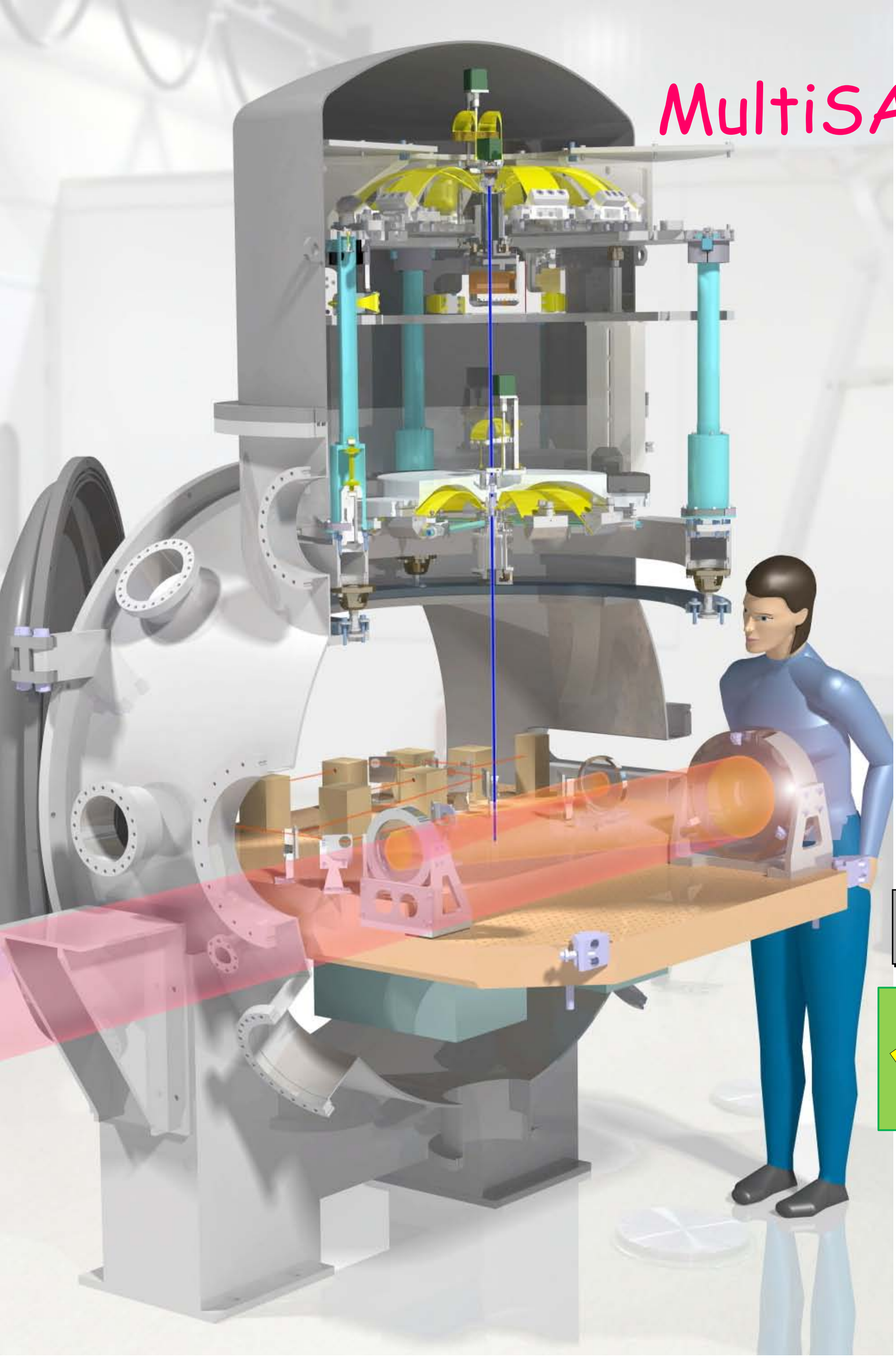
- 1 – 100 Hz: bench moved by acoustic noise from central building Airco
- 40 - 50 Hz: second noise source is present
- Limited shielding by acoustic enclosure
- Optical mounts are moved by sound

EIB-SAS: conclusions



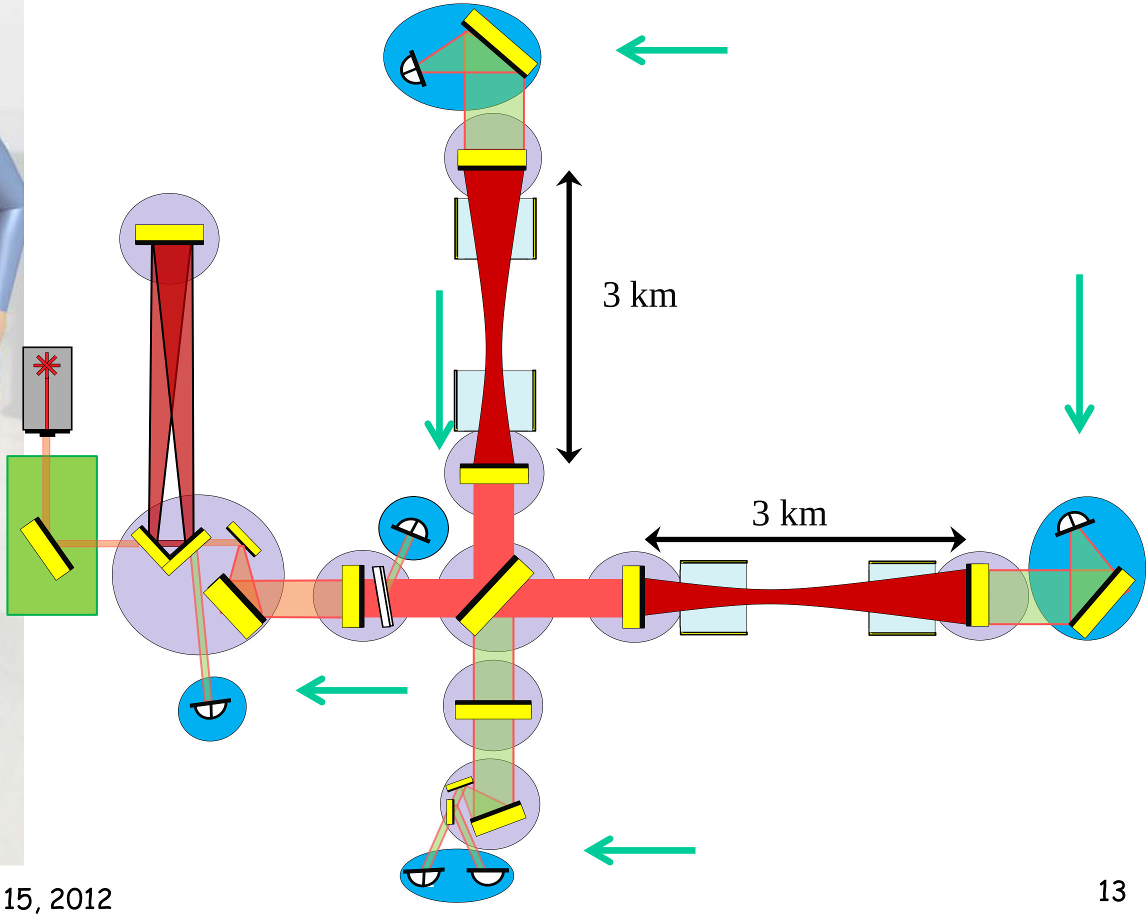
- Commissioning EIB-SAS revealed prominent roll of acoustic noise
- Laser lab walls are cleanroom walls → do not shield acoustic noise
- EIB-SAS is doing only most of the job, but ….
- It is usefeul for Advanced Virgo ..
  - **to replace these walls by concrete walls**
  - **to move Airco's outside main building**

MultiSAS: Isolating suspended benches for linear alignment

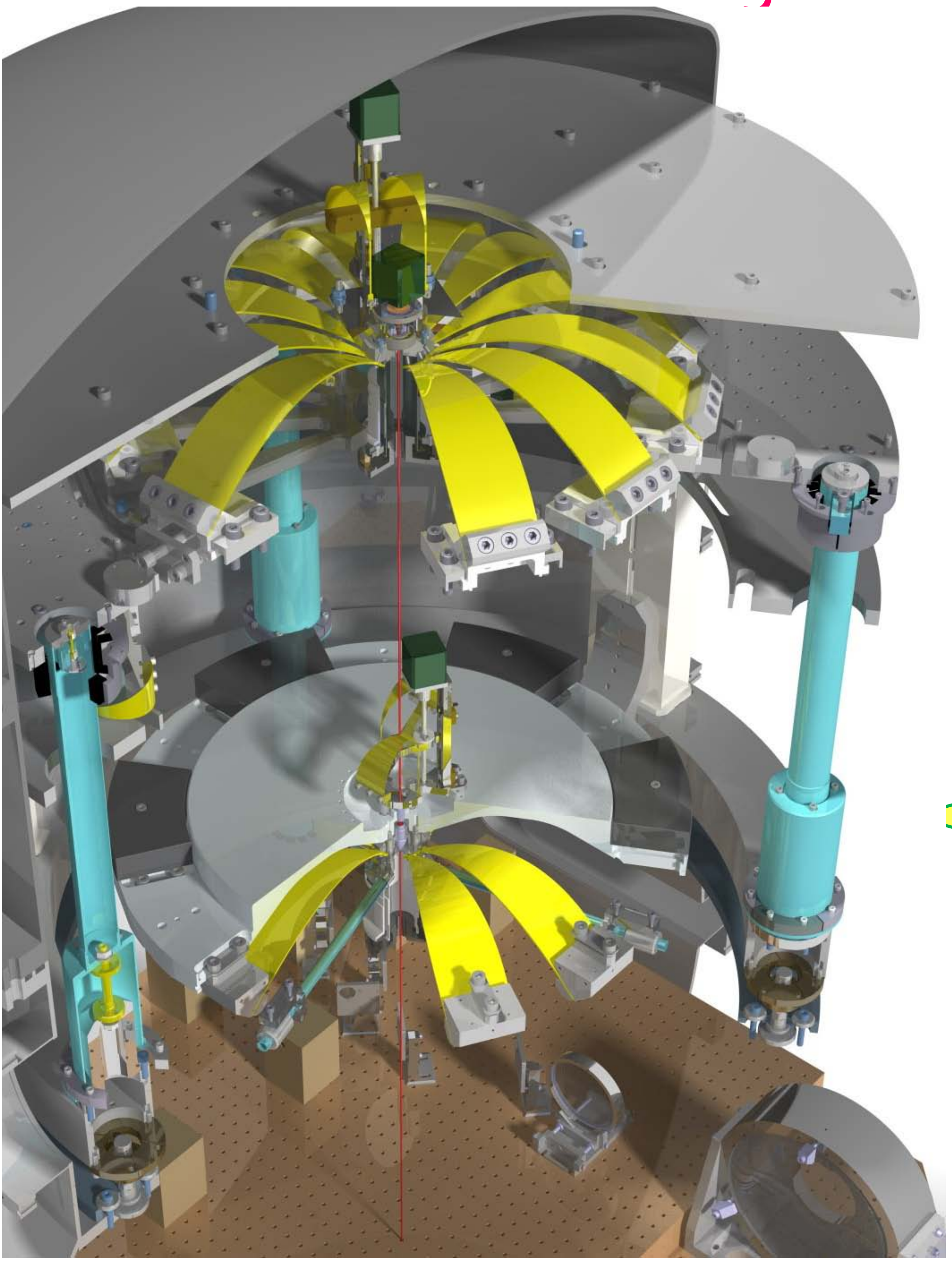


5 similar systems consisting of:

- MultiSAS (Nikhef)
- Optical bench (DET/LAPP)
- UHV vacuum mini-tower (LAPP)



MultiSAS: multi-stage 6DOF bench isolation & control



Requirements @ 10 Hz (VIR-0128A-12)	
δh	2 E-12 m/√Hz
$\Delta\theta$	3 E-15 rad/√Hz
h_{RMS}	2 E-5mm
θ_{RMS}	3E-9 rad

tough!

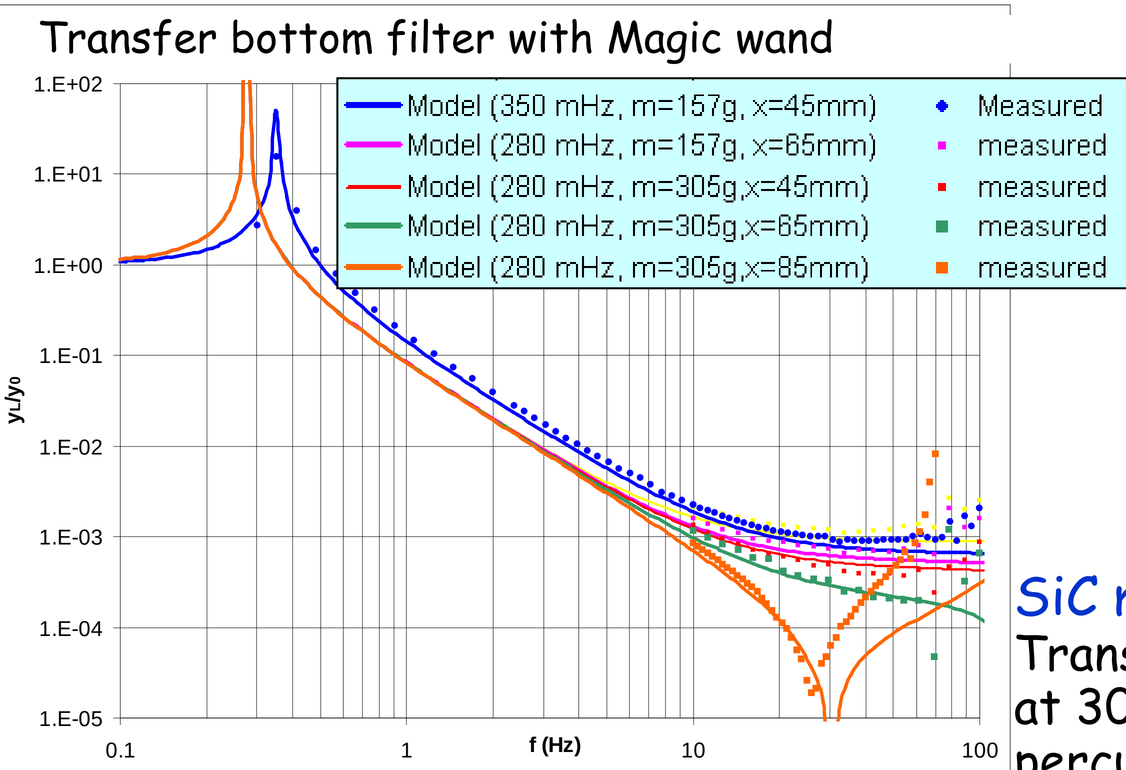
Characteristics

- two-stage vertical isolation (GAS)
- 3-stage horizontal isolation (IP, P, P)
- 320 kg single-wire suspended bench
- sensing/control technology like EIB-SAS

Schedule

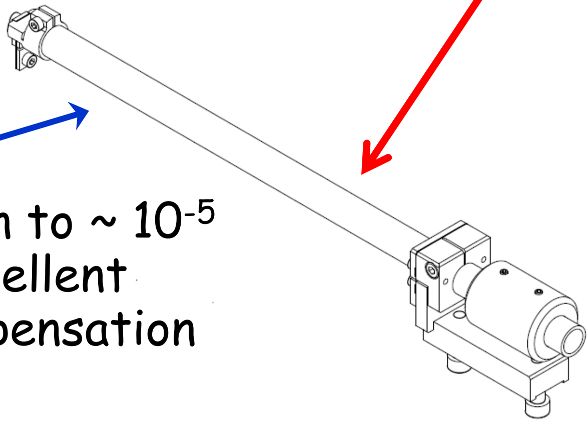
- Design approved
- Prototype assembled
- In-air testing started with dummy bench
- Integration test at Nikhef/LAPP from Sep 2012
- AdV production and first chamber installation 2013

MultiSAS: special GAS mechanics



Bottom GAS filter

GAS blades *below* Filter body

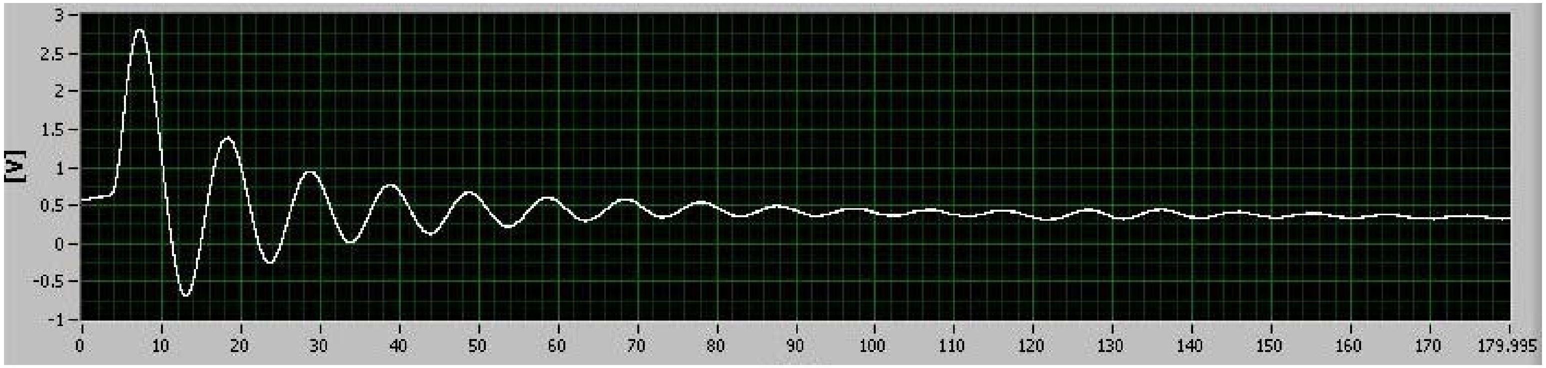


SiC magic wands

Transfer function down to ~ 10^{-5} at 30 Hz thanks to excellent percussion effect compensation

Top GAS filter

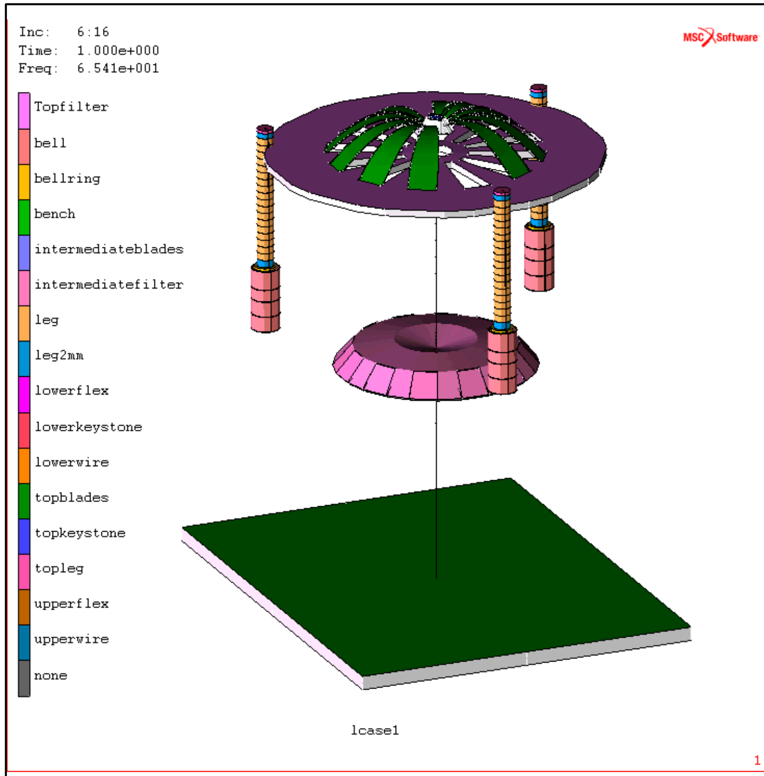
Down-tunable to 100 mHz thanks to combination of over-compression and hysteresis

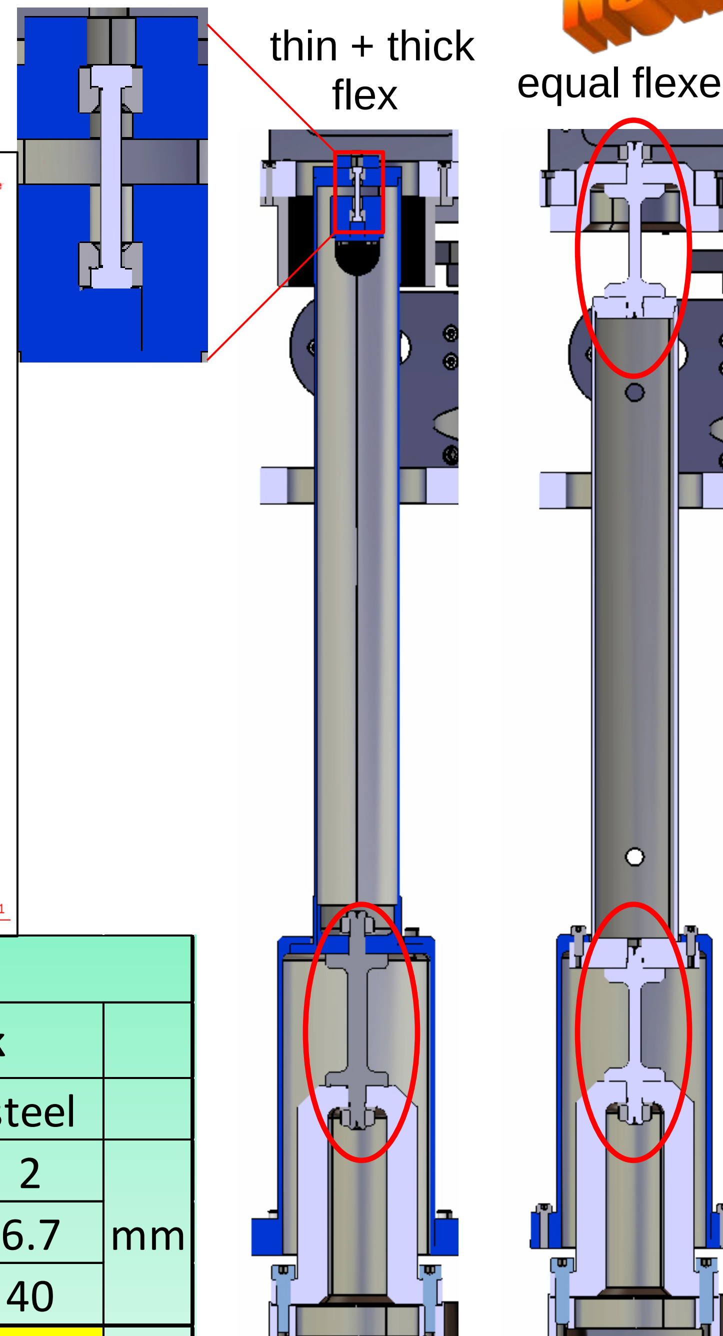


MultiSAS: IP equal bottom & top flexures (to be tested)

- Both flexures in compression
- Allows for significant raise of

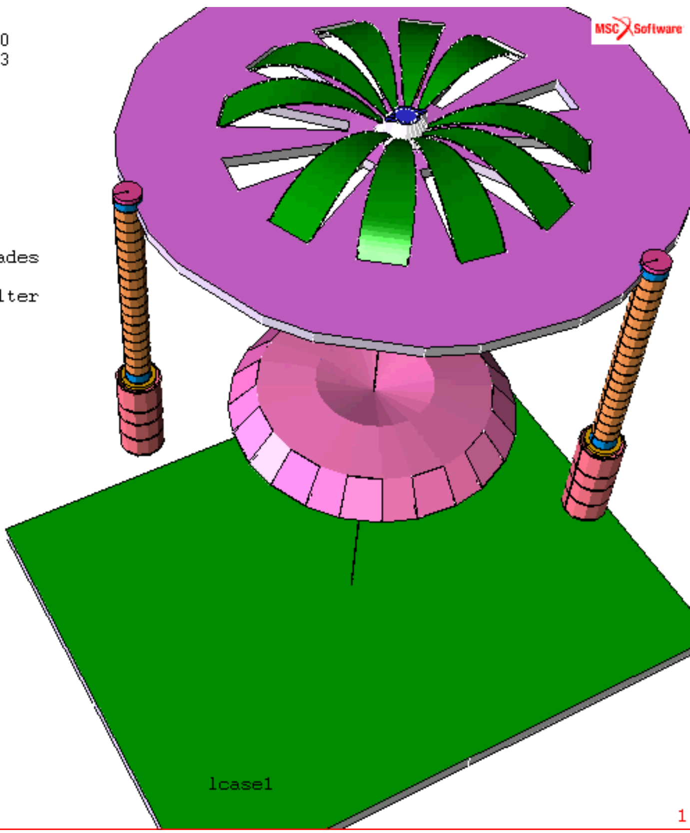
top plate bouncing → and rigid leg modes ↓



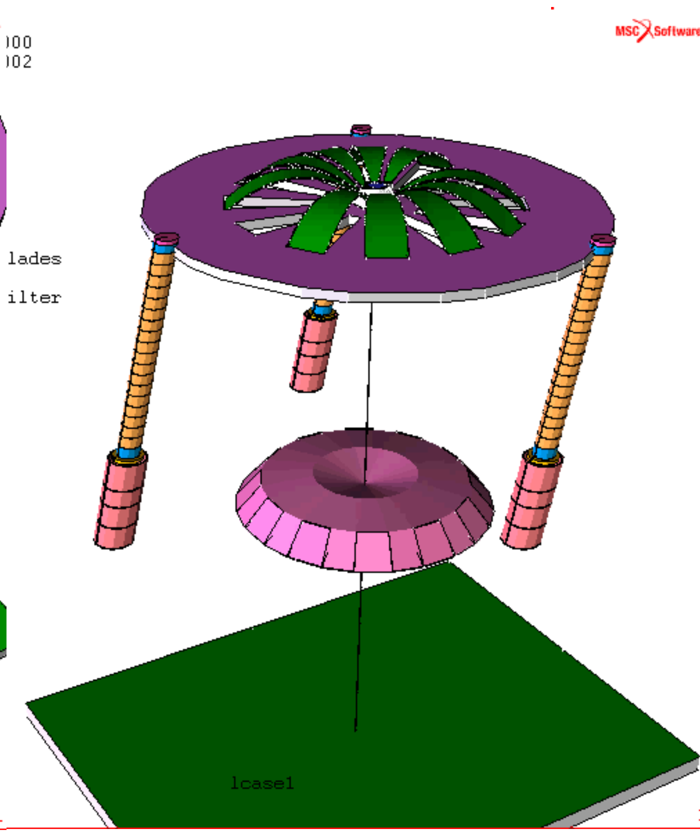


MultiSAS IP modes (FEM)						
upper flex		thin (2mm)		thick		
leg	material	alu	steel	alu	steel	
	wall thickness	1	2	1	2	
lower flex	thickness	8.7		7.4	6.7	mm
	length	60			40	
modes	*top plate y*	64	80	83	133	Hz
	rigid leg x/z	145	100	270	295	

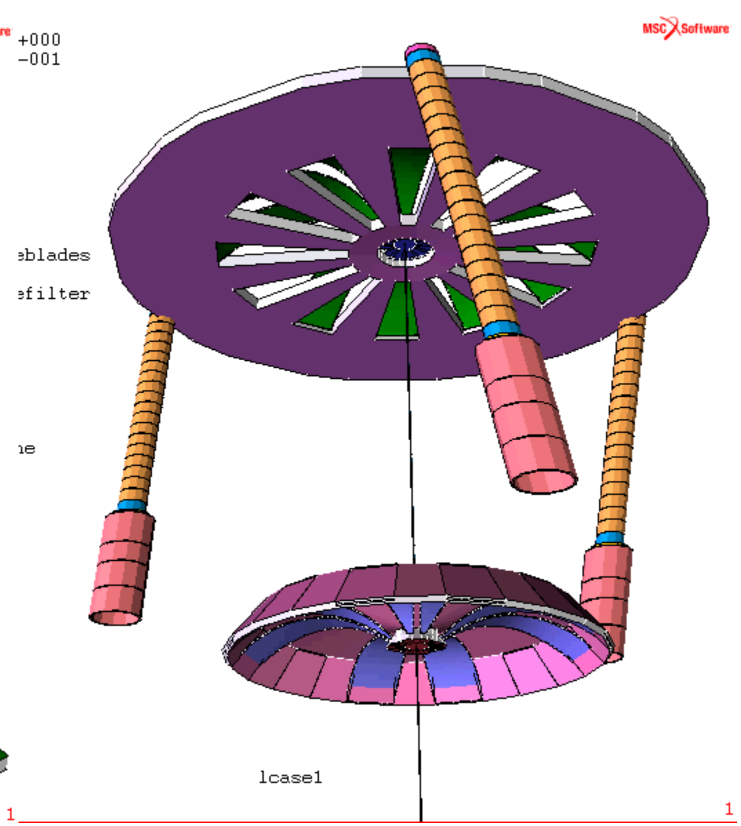
MultiSAS Modal analysis: modes < 250 mHz



Common yaw
(10 mHz)



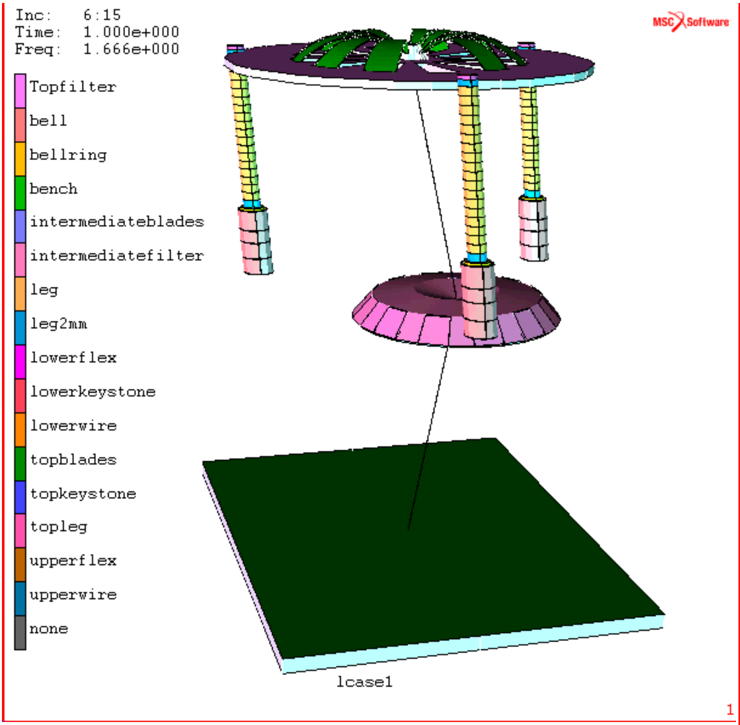
Common lateral
(80 mHz)



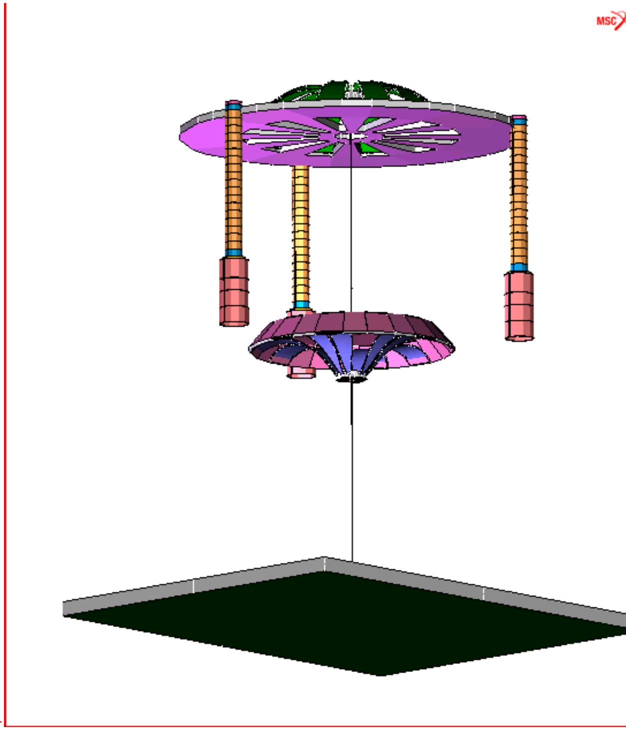
Top stage yaw
(230 mHz)

…. and 3 more

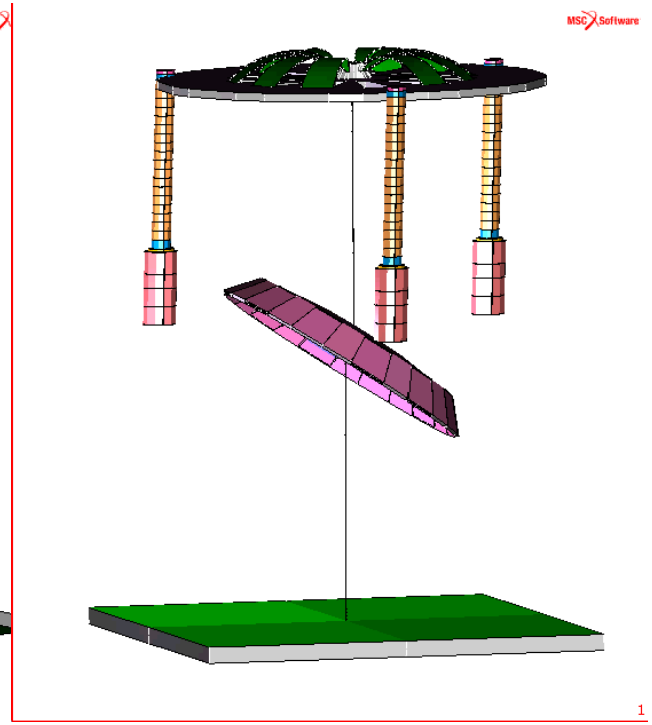
MultiSAS: Modal analysis: modes < 2 Hz



Pendulum mode
(1.7 Hz)



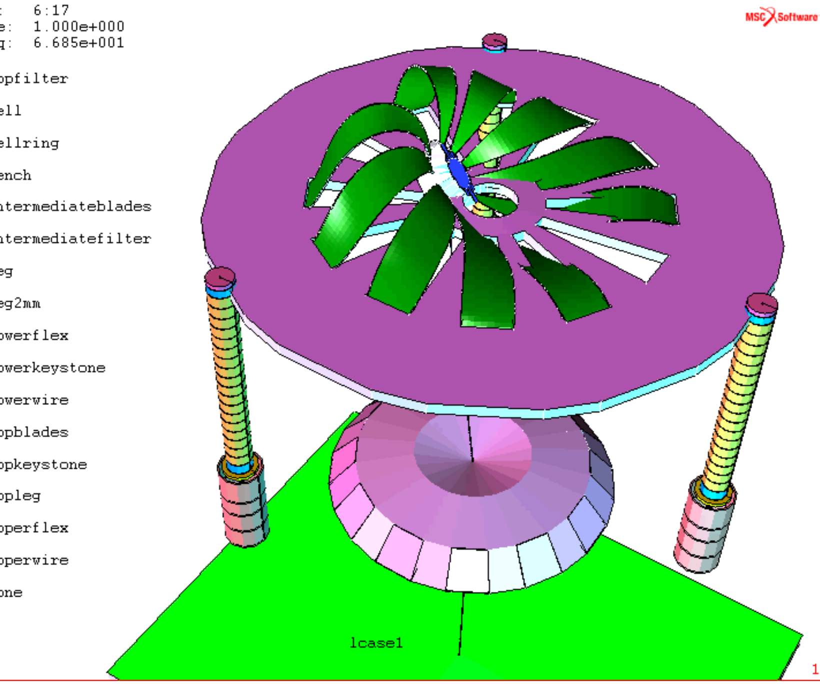
GAS mode
(0.5 Hz)



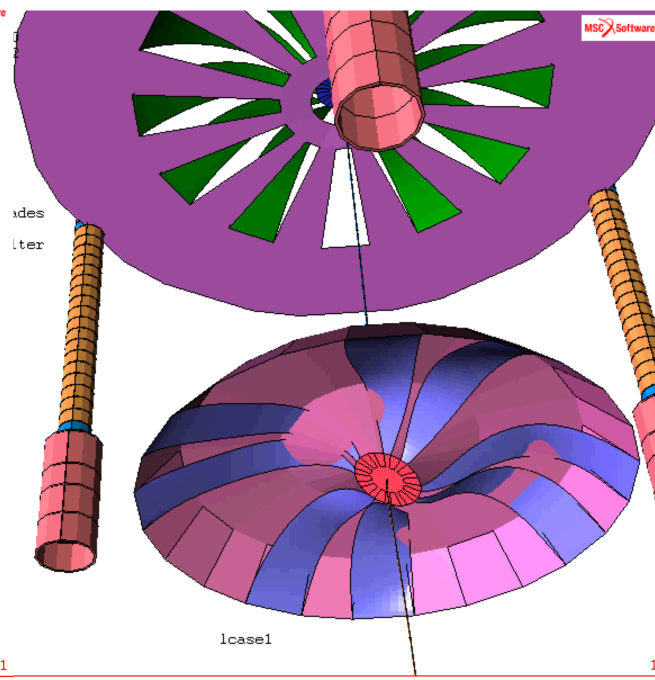
Filter tilt (0.43 Hz)
- coupling to horizontal

.... and 4 more

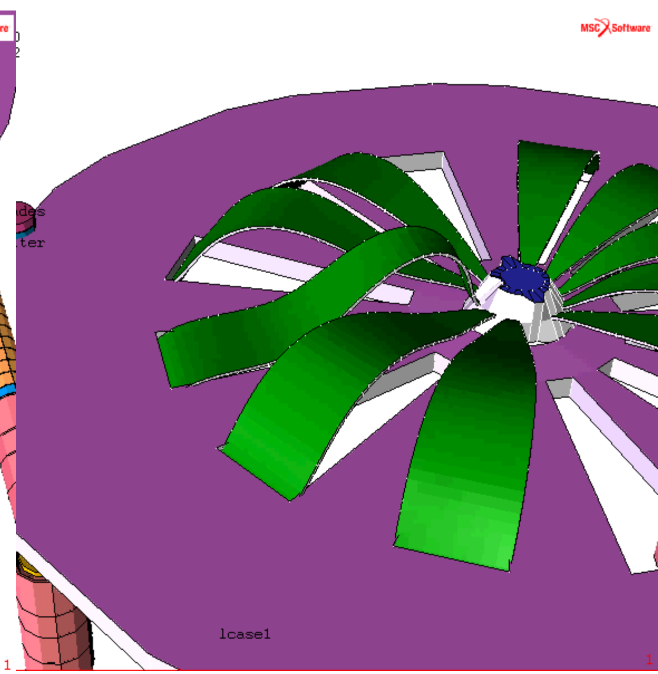
MultiSAS: Modal analysis > 60 Hz



Keystone coupled mode
(70 Hz)



Keystone rotation
(250 Hz)

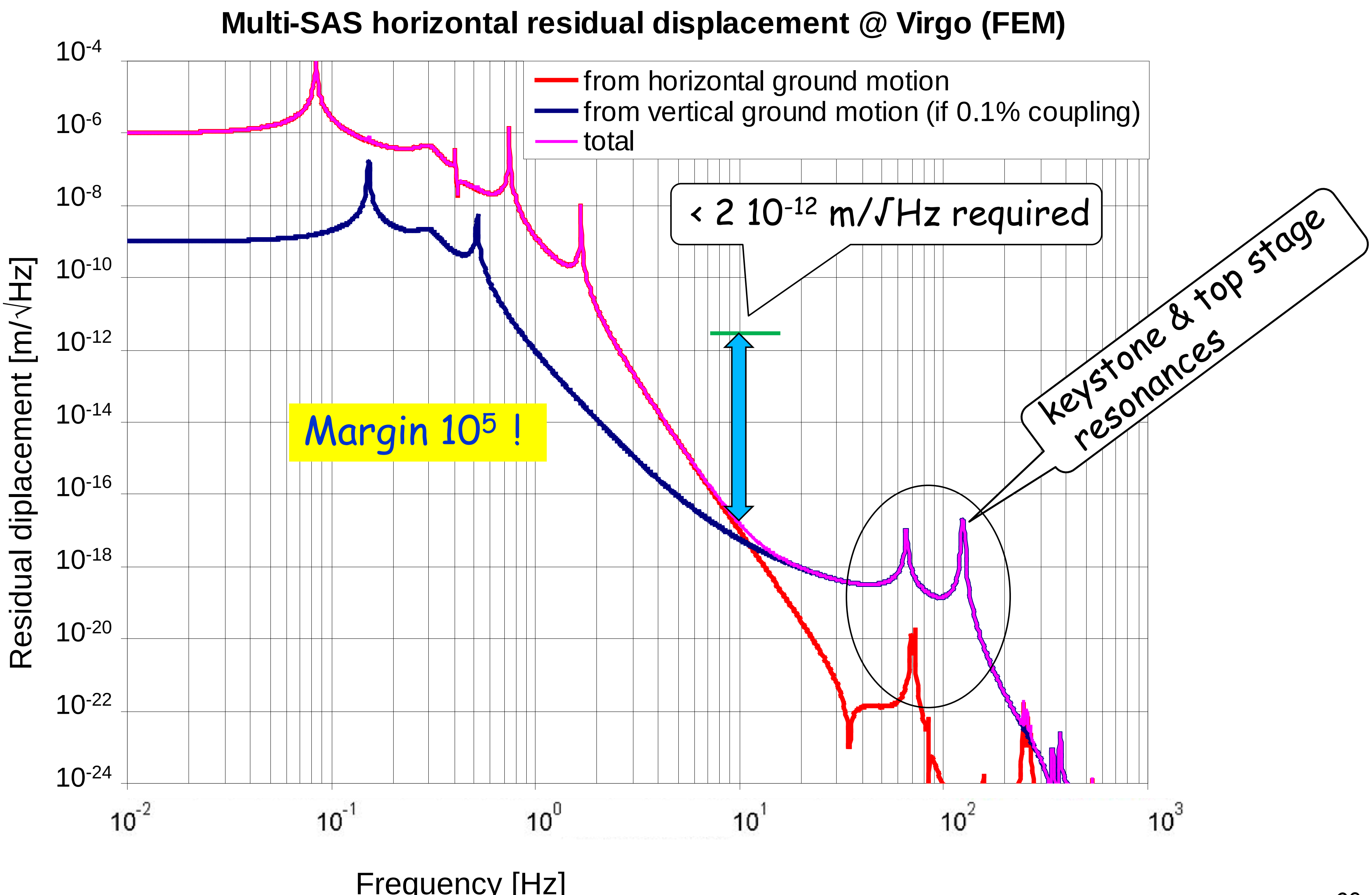


Blade mode
(340 Hz)

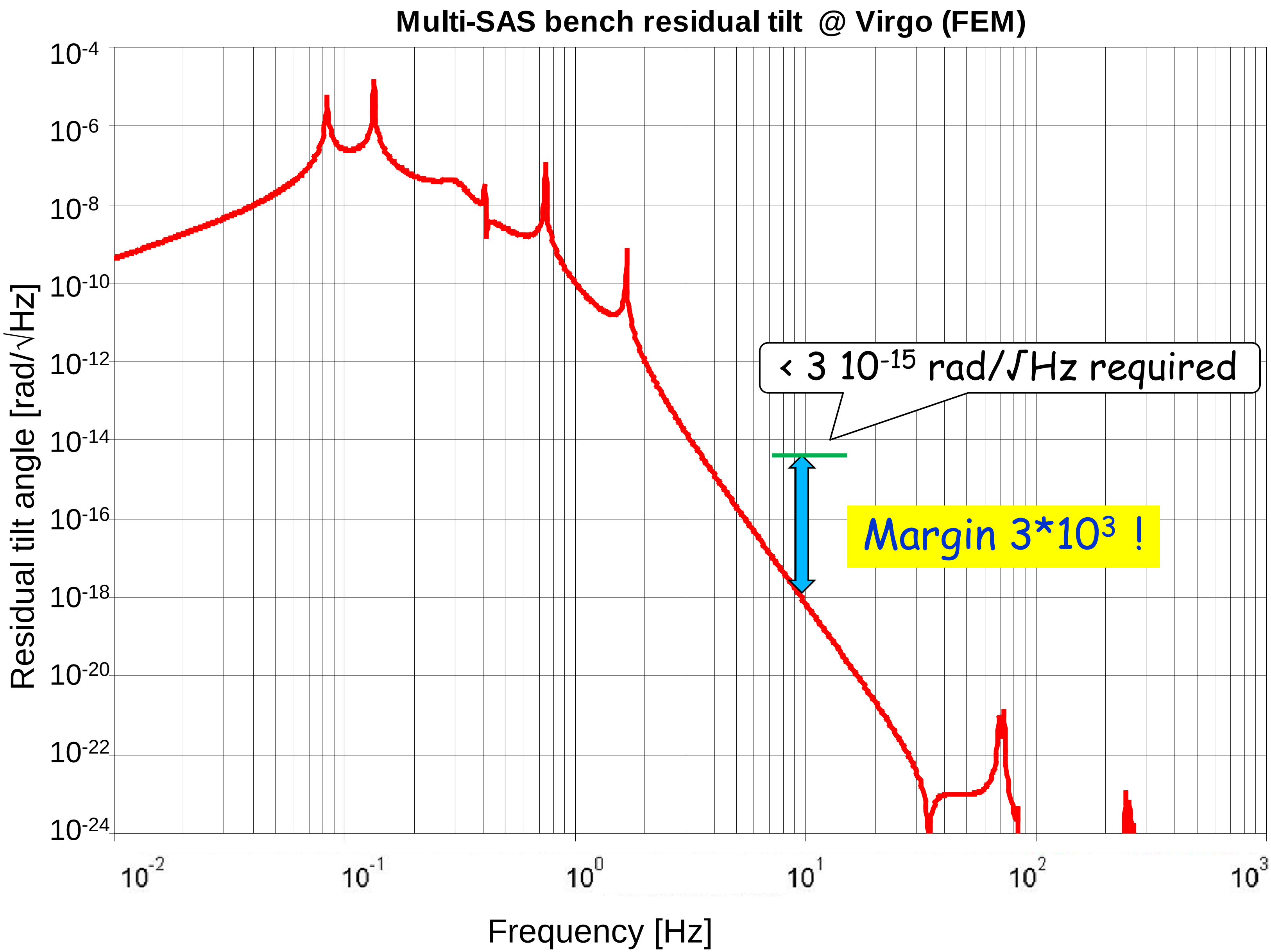
.... Etc etc

MultiSAS: residual horizontal displacement

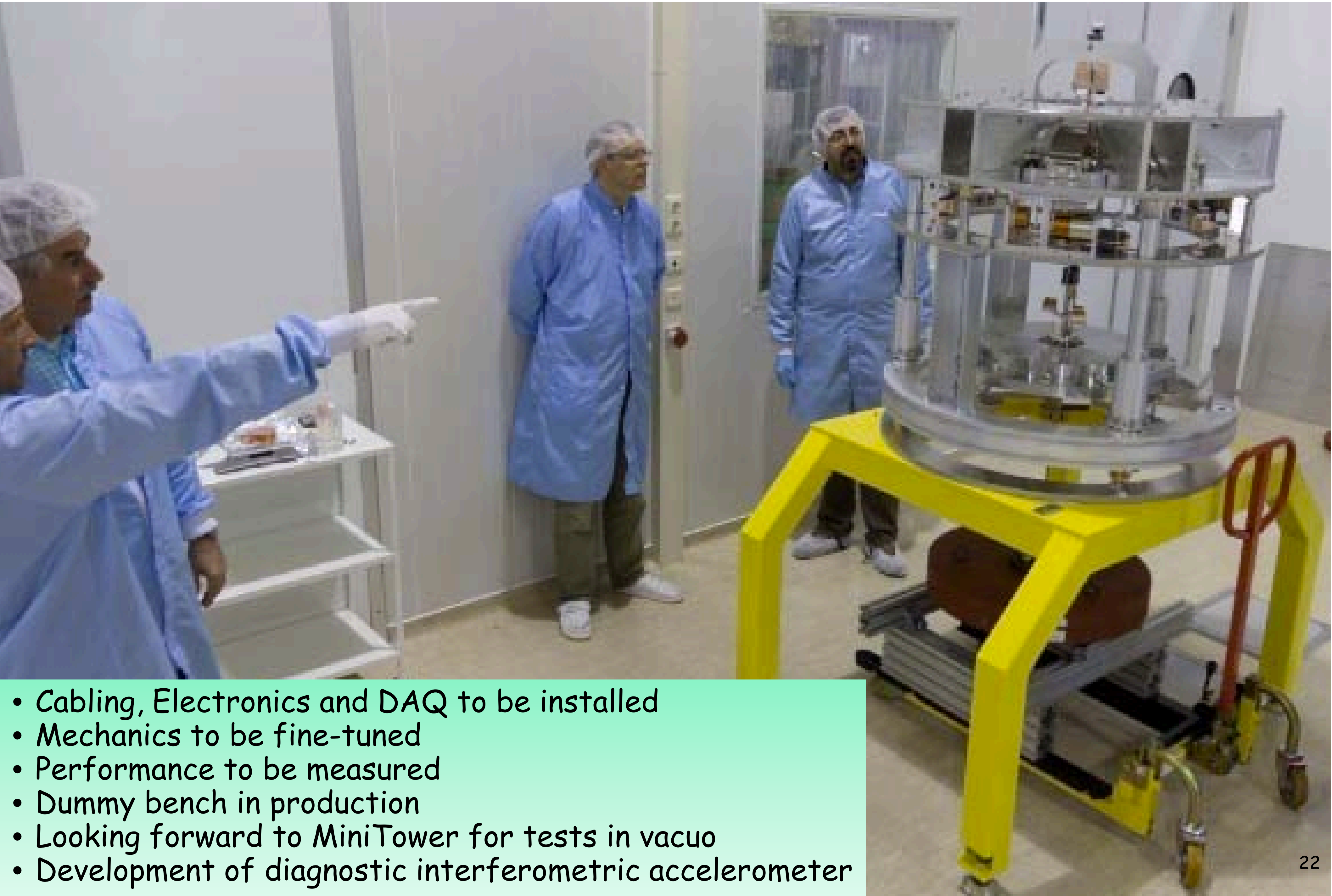
Calculated from FEM transfer functions (open loop)



MultiSAS: residual tilt (FEM)



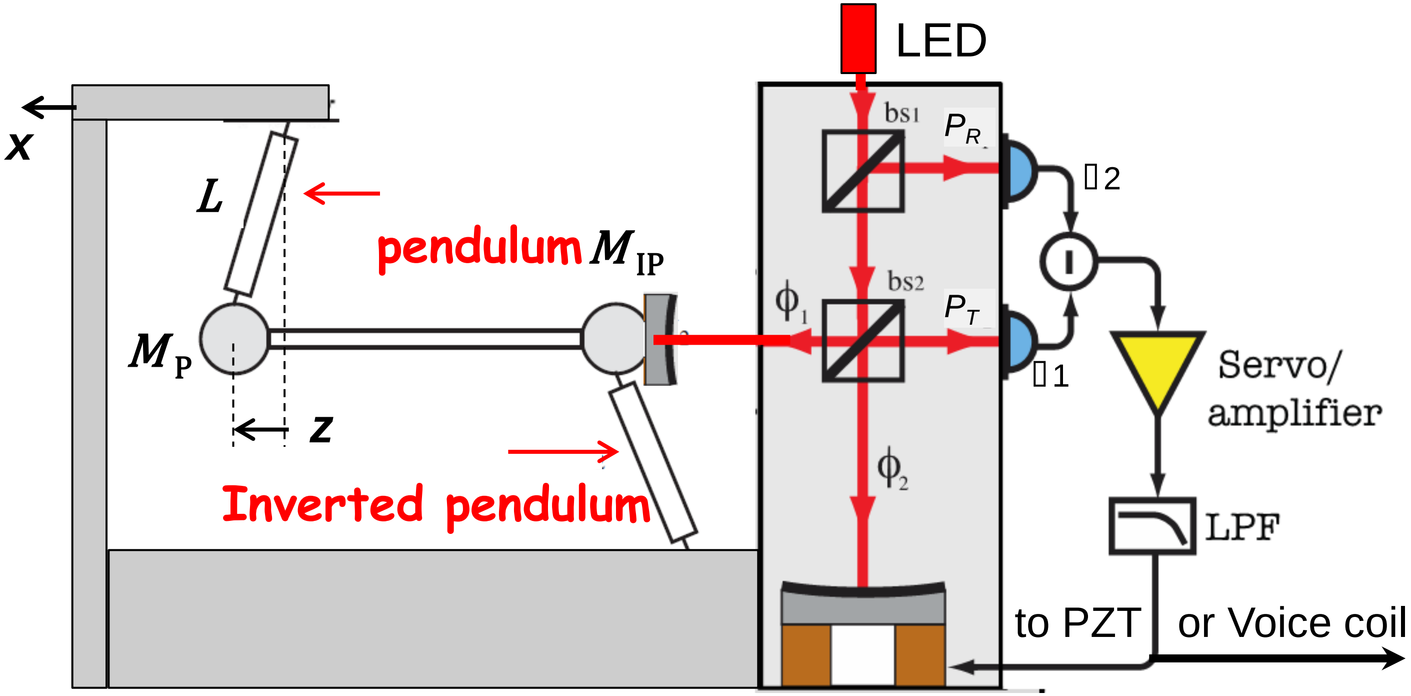
MultiSAS: current state of prototype



- Cabling, Electronics and DAQ to be installed
- Mechanics to be fine-tuned
- Performance to be measured
- Dummy bench in production
- Looking forward to MiniTower for tests in vacuo
- Development of diagnostic interferometric accelerometer

High-sensitivity diagnostic accelerometer

On behalf of
David
Rabeling



Mechanics: monolithic single-axis Watt-linkage oscillator (Bertolini, 2005*)

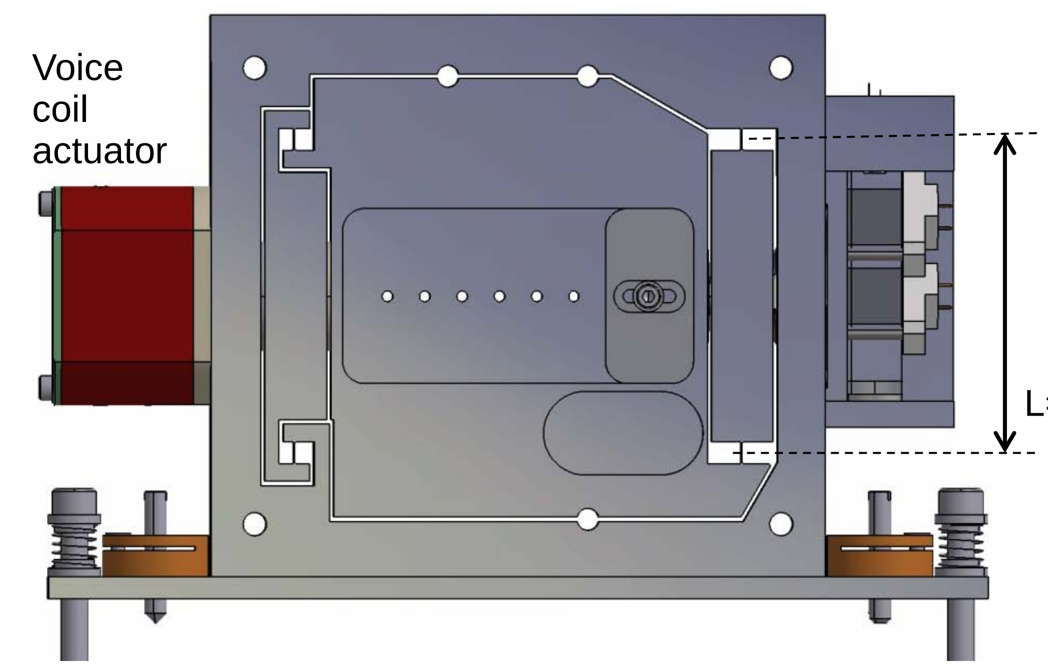
Projection of thermal noise x_{th} reduced by choosing
- low resonance frequency (~ 0.5 Hz)
- large quality factor (> 100)
- large mass (~ 1 kg)

Readout: based on balanced Michelson interferometer (Gray et al, 1998**)

- LED source allows for low Relative Intensity noise (RIN)
- Sensing of both reflected and transmitted beam → >40 dB RIN cancelling
- fringe locking by feed back loop to piezo actuator or voice coil

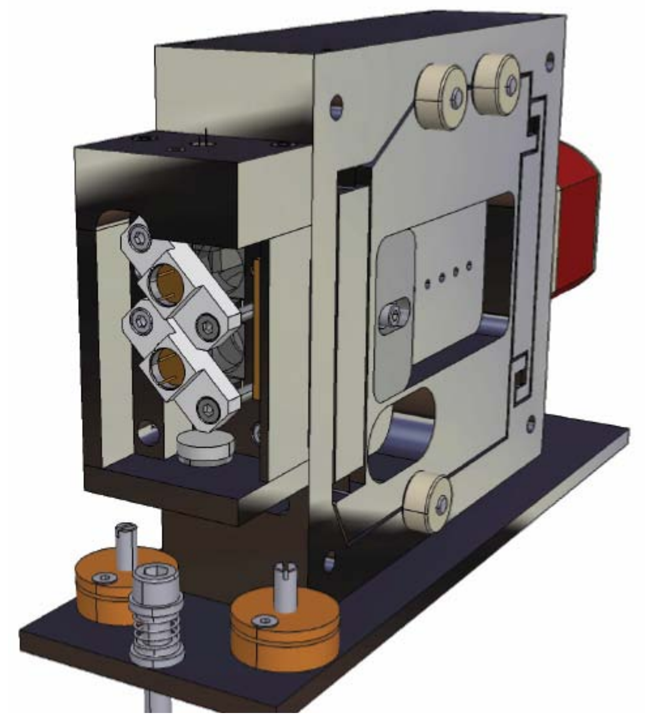
*Nuclear Instruments and Methods in Physics Research A 556, 2006, 616–623
**Optics & Quantum Electronics 31, 1999, 571-582

Accelerometer mechanics



Construction

- Wire-cut monolithic aluminum
- Symmetric pendulum + inverted pendulum
- All flexes (4x5x0.1 mm) in tension
- Adjustable mass distribution (tuning)
- Optional: voice coil actuator



Transfer function:

Mass-to-frame displacement

$$H(\omega) = \frac{Z(\omega)}{X(\omega)} = \frac{\omega^2(1-A)}{\omega_0^2 - \omega^2 + i\omega\omega_0/Q}$$

frame displacement

Projected thermal noise PSD:

$$X_{th}^2(\omega) = \frac{4k_B T\omega_0^2}{MQ\omega^5}$$

For structural damping:

$$Q = \frac{1}{\phi}\left(1 + \frac{gL(M_P - M_{IP})}{k}\right)$$

ω_0:resonance angular frequency
Q: Quality factor >>1
A : percussion factor <<1
K : total elastic stiffness
M: total mass (M_P+M_{IP})
k_B: Boltzmann's constant
ϕ : loss angle in flexes

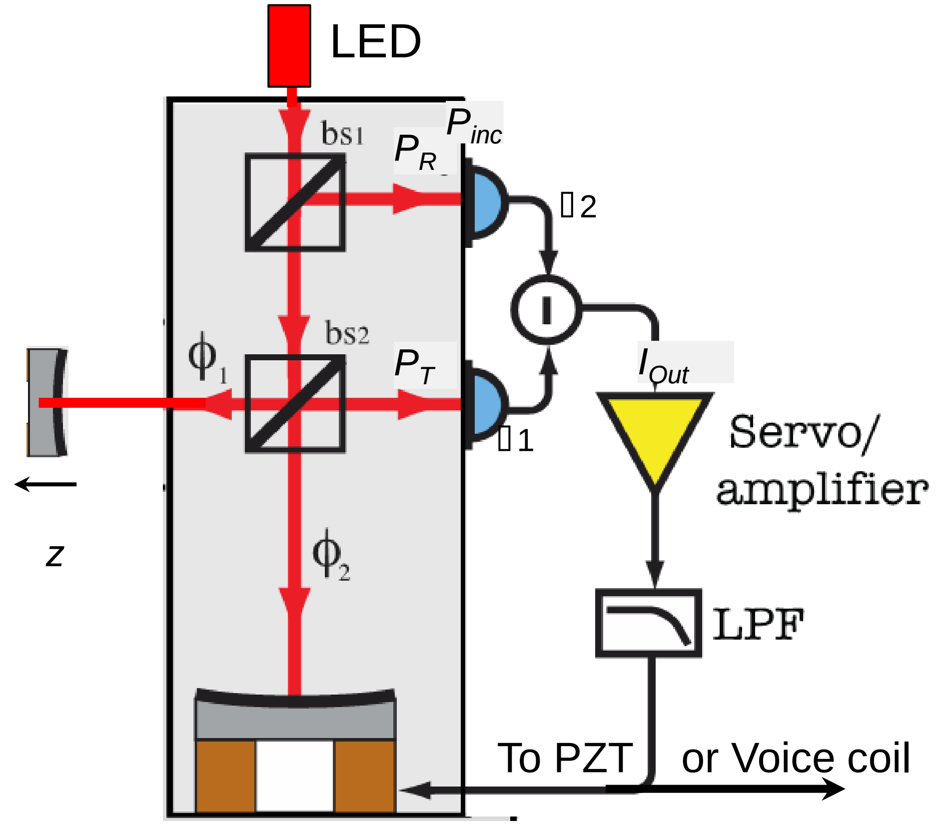
Interferometric read-out

Photodiode incident power

$$P_T = \frac{P_{inc}}{4}\left(1 + \mathrm{Re}(C(z/c))\cdot\cos\frac{4\pi z}{\lambda}\right)$$

$$P_R = \frac{P_{inc}}{8}\left(1 - \mathrm{Re}(C(z/c))\cdot\cos\frac{4\pi z}{\lambda}\right)$$

z : mass-to-frame displacement
P_{inc}: incident LED power
λ : carrier wavelength
C : complex temporal coherence



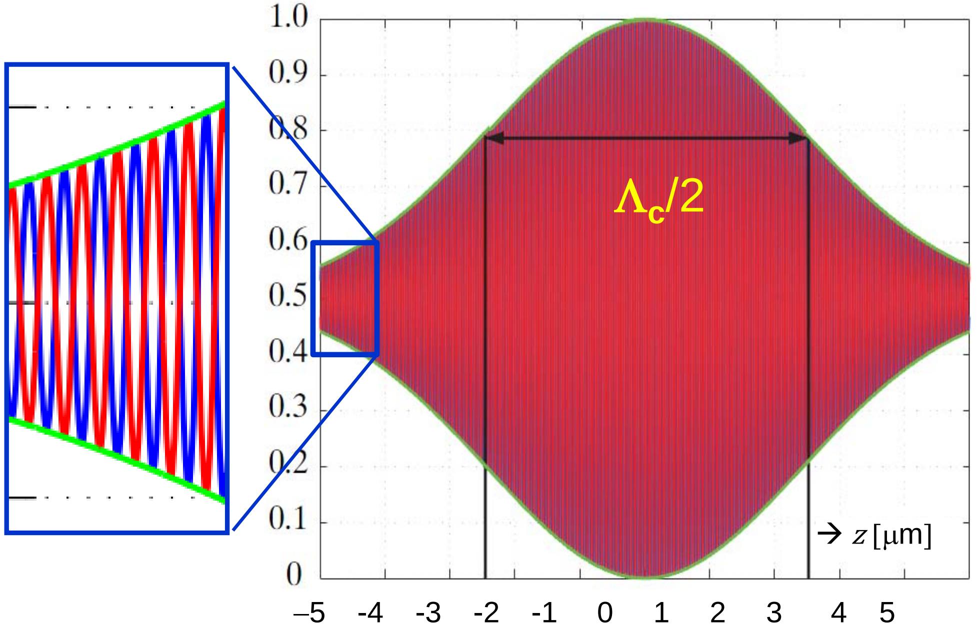
Coherence length Λ_c

Related to source bandwidth

$$\Lambda_c \approx 0.44\frac{\lambda^2}{\lambda_{BW}}$$

$$= 0.44\,\frac{(880\mathrm{nm})^2}{30\mathrm{nm}} \approx 11\,\mu\mathrm{m}$$

Relative PD intensity pattern (T and R)



Readout current sensitivity

Lock on half fringe:

$$\frac{dI_{Out}}{dz} = \frac{\rho\pi P_{inc}}{\lambda} = \frac{4\pi I_{T,DC}}{\lambda}$$

Optical and electronic readout current noise

Shot noise (SN) current

$$i^2_{SN} = 2q\rho(P_T + P_R)$$

Intensity noise

< -40 dB of shot noise (?)

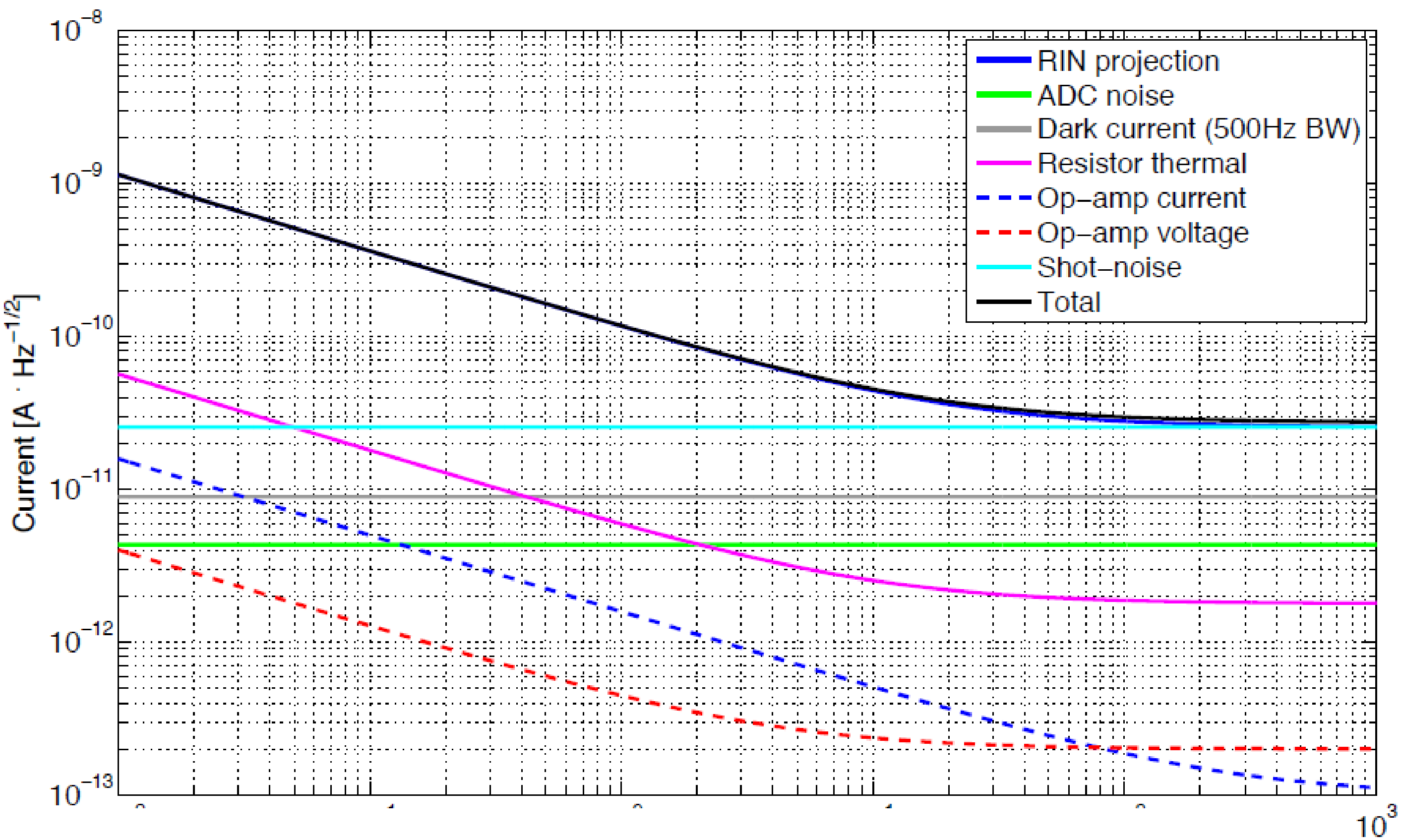
Dark current noise

$$i^2_{dark} = \frac{I^2_{dark}}{BW}$$

ADC noise

$$i^2_{ADC} = \left(\frac{V_{pp}}{2^{n+m}}\right)^2 \frac{1}{6 f_s r_f^2}$$

$$m = \log(\frac{f_{os}}{f_o}) / \log 4$$



Electronic noise

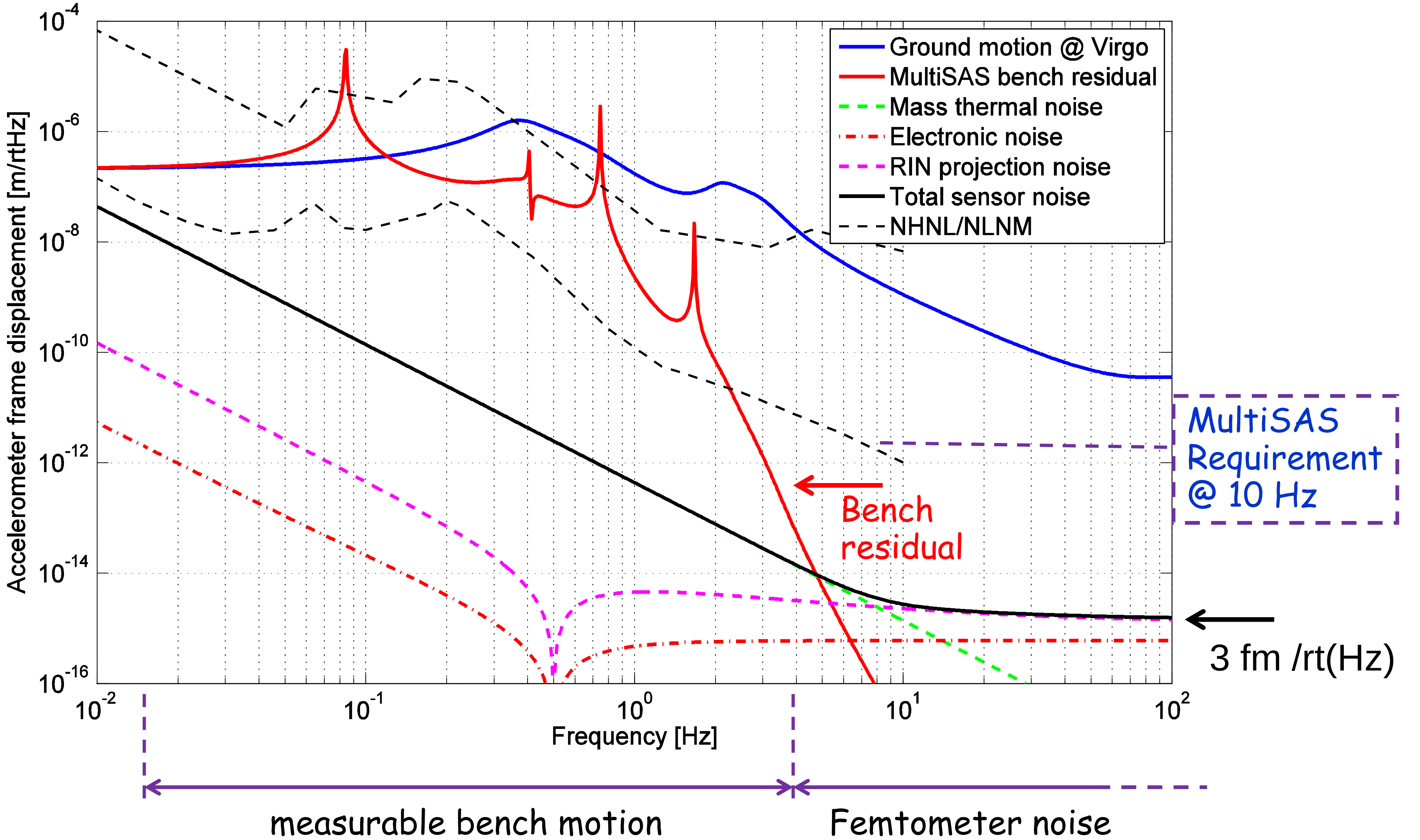
$$i^2_{OpAmp} = V^2_{op}\left(\frac{\omega_{cv}}{\omega} + 1\right) / r_f^2 + I^2_{op}\left(\frac{\omega_{ci}}{\omega} + 1\right)$$

$$i^2_{R,termal} = \frac{4k_B T}{r_f}\left(\frac{\omega_{cr}}{\omega} + 1\right)$$

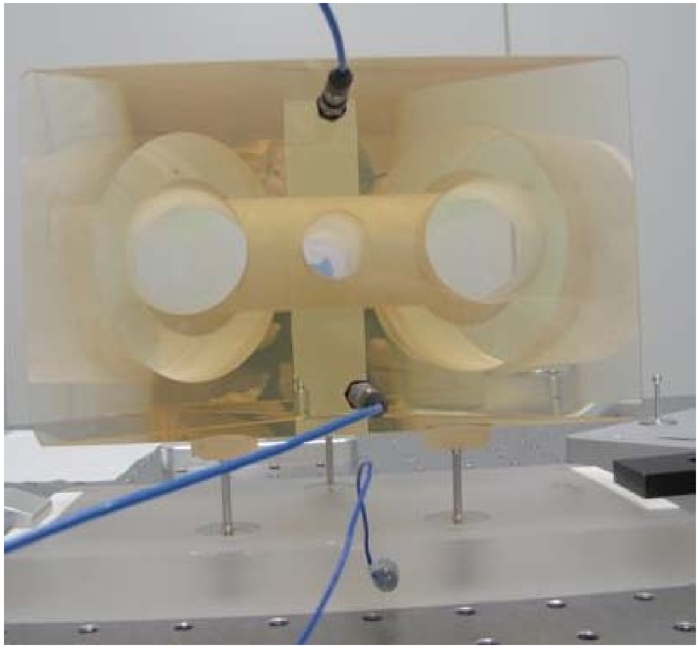
n : number of bits
f_s : sampling frequency
f_{os}: over-sampling frequency
r_f : transimpedance resistance
V_{op}, I_{op}: OpAmp noise levels
$\omega_{cv}, \omega_{cv}, \omega_{cv}$: corner frequencies
V_{pp}: ADC peak-peak voltage

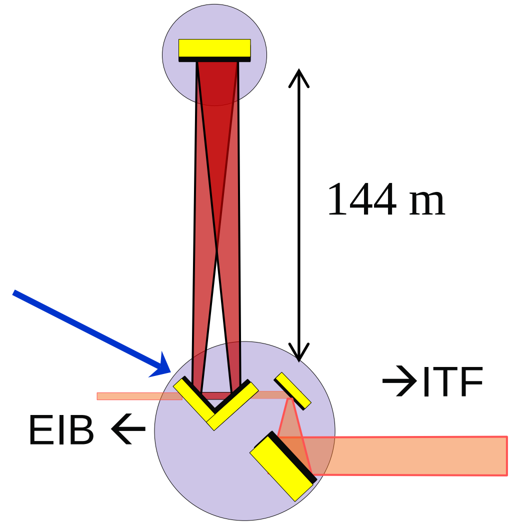
Projections of noise on frame displacement

For accelerometer with f0 = 0.5Hz, Q =100

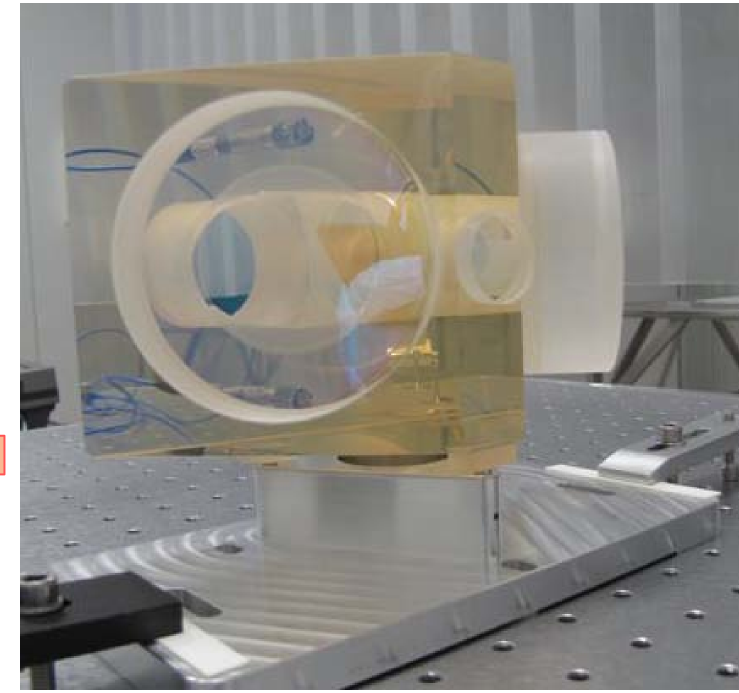


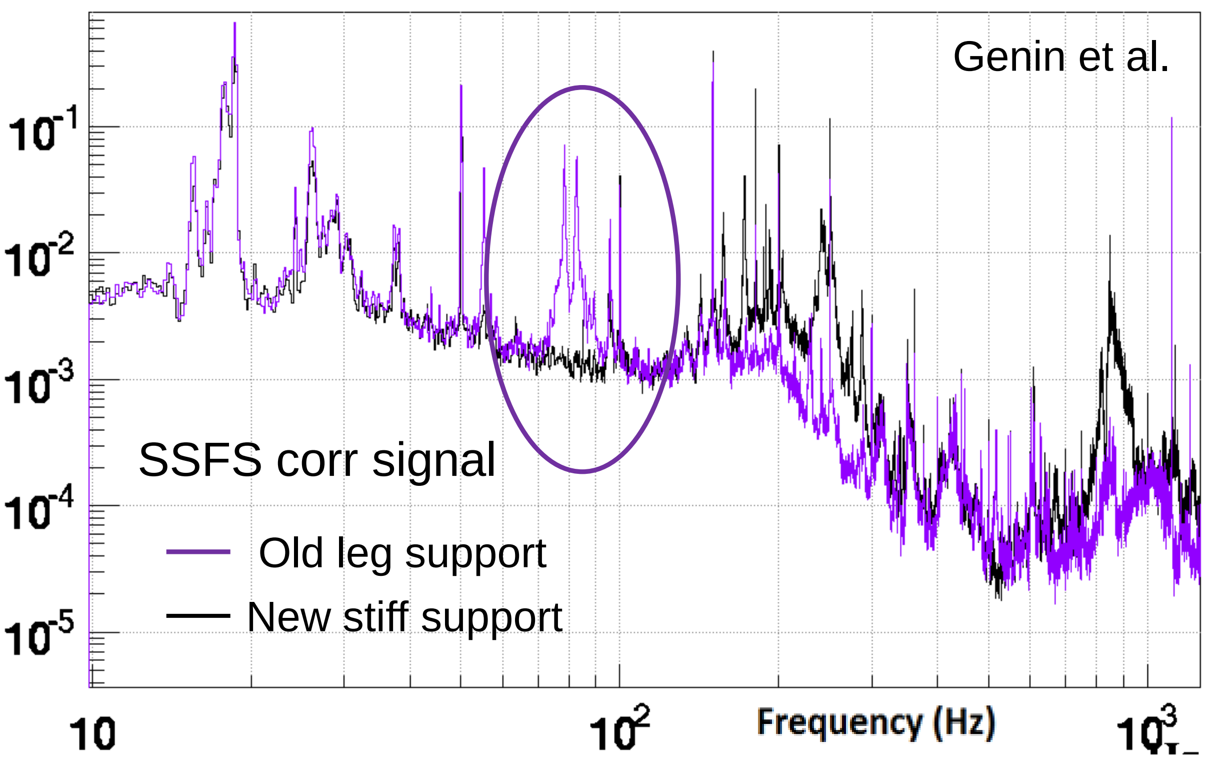
Input mode cleaner (IMC) modifications: 1. Dihedron support





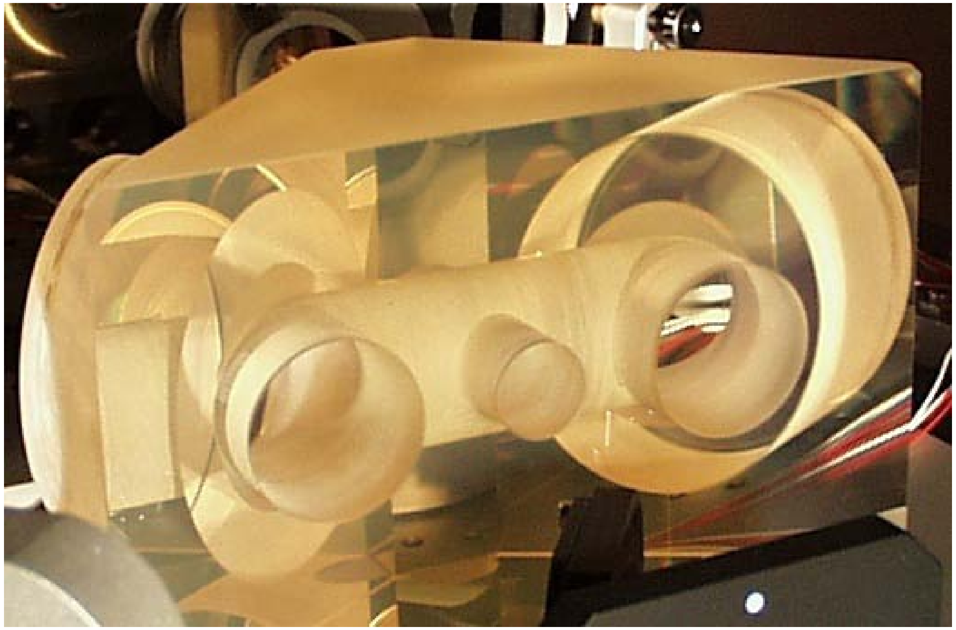
replaced Oct 2011

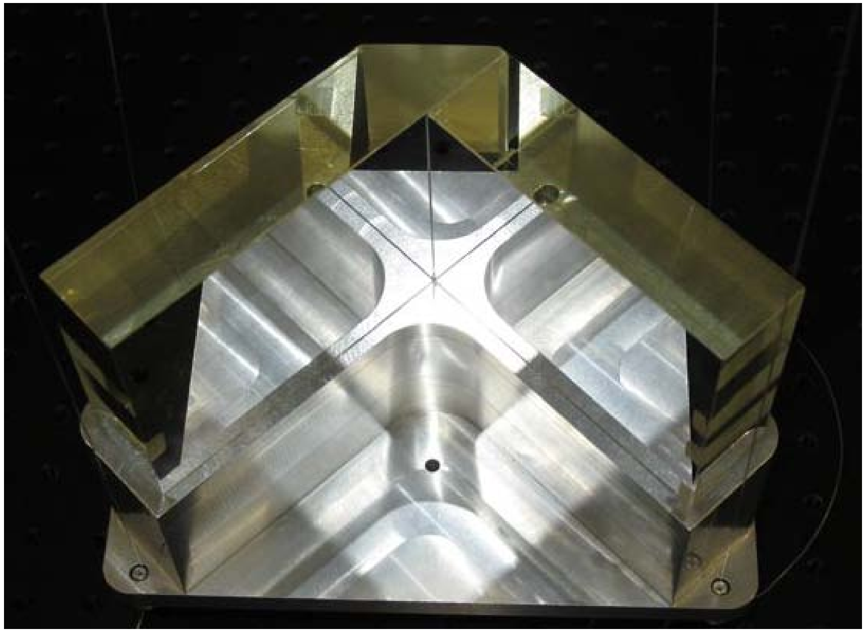




- modes 55, 78, 82 Hz disappeared
- new support: 240 Hz (Hertz contact)

IMC modifications; 2. New Dihedron

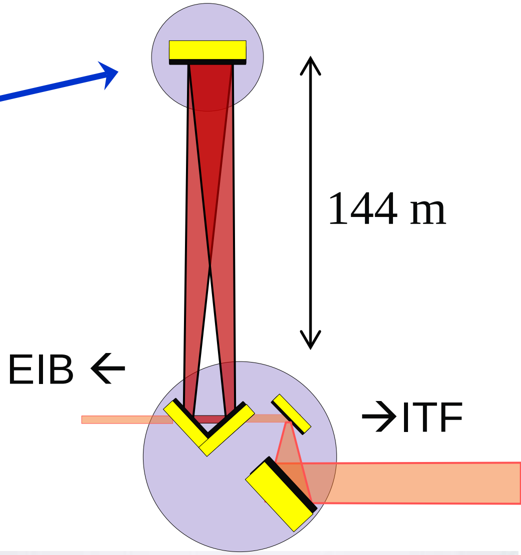


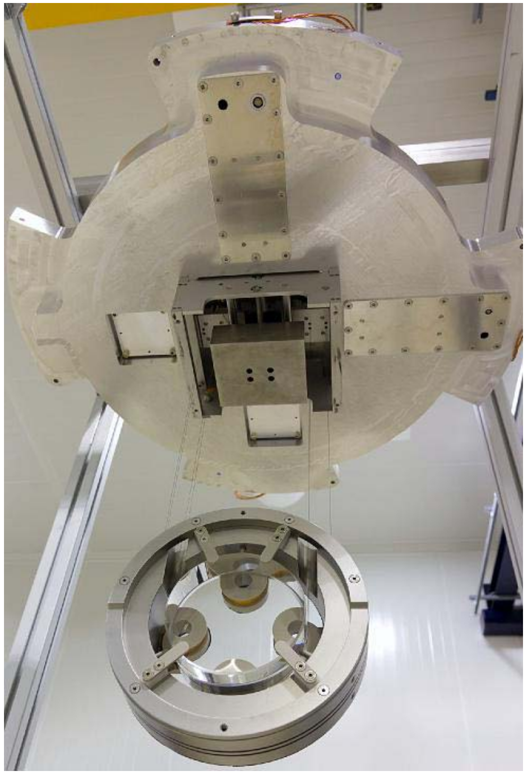


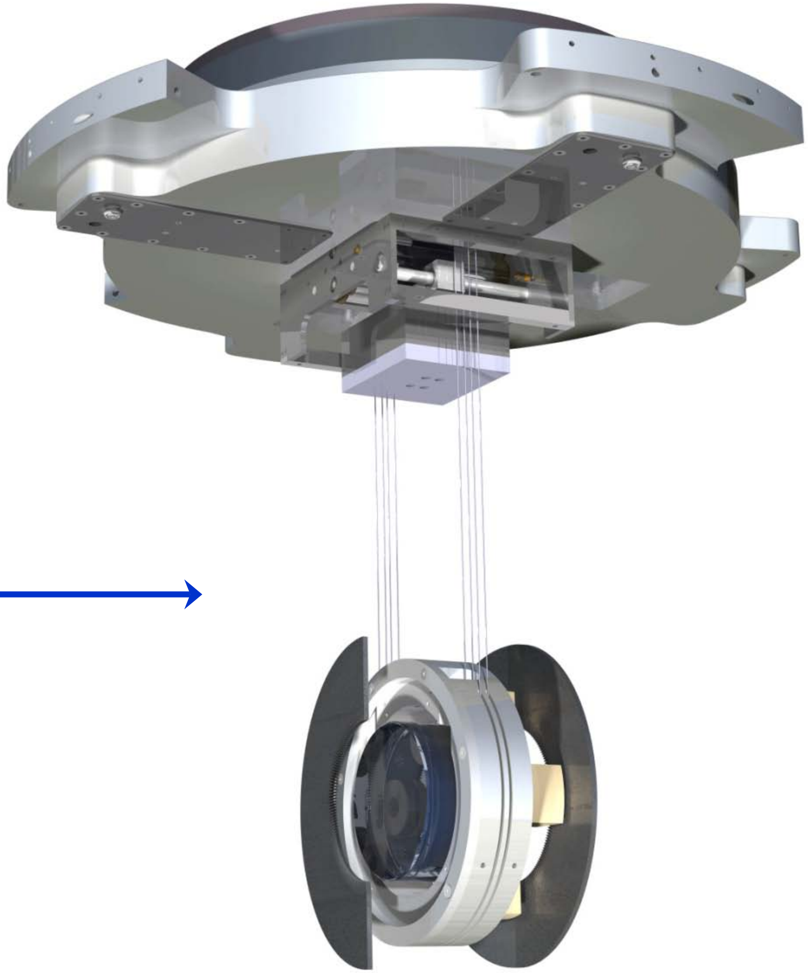
- Shaped and polished by Optronica (Den Helder, NL)
- Mirrors connected by Van der Waals bonds (no adhesive)
- Angle (89° 58′ 58″) machined to 0.4″ accuracy (max 2″ allowed)
- To be coated (by IPN-Lyon)
- To be installed in 2013

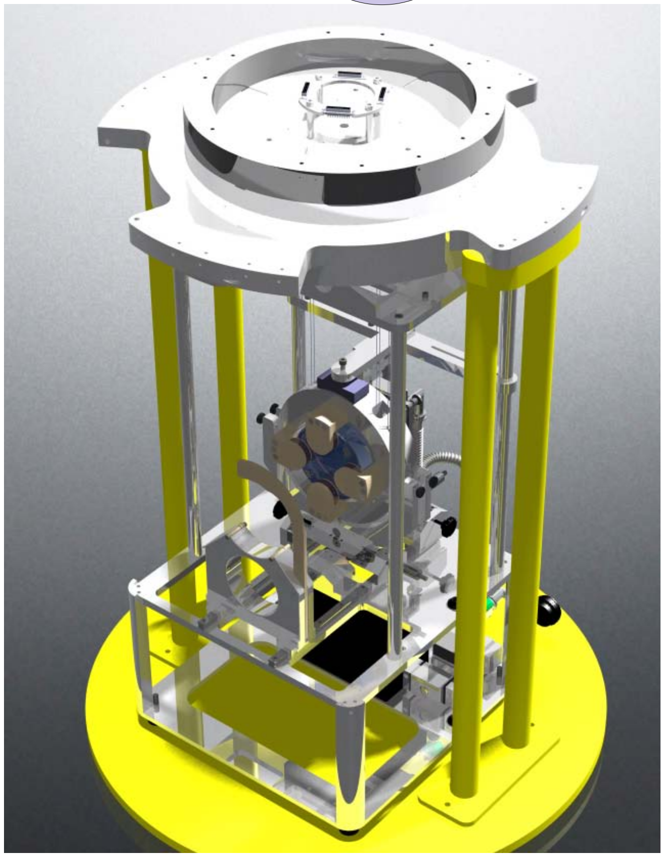
IMC modifications; 3. New End Mirror suspension

- mirror twice as thick
- including front (and back?) baffle
- adapting Marionette and gear box
- new installation procedure /tools
- largest challenge: connect baffles stiffly to reference mass







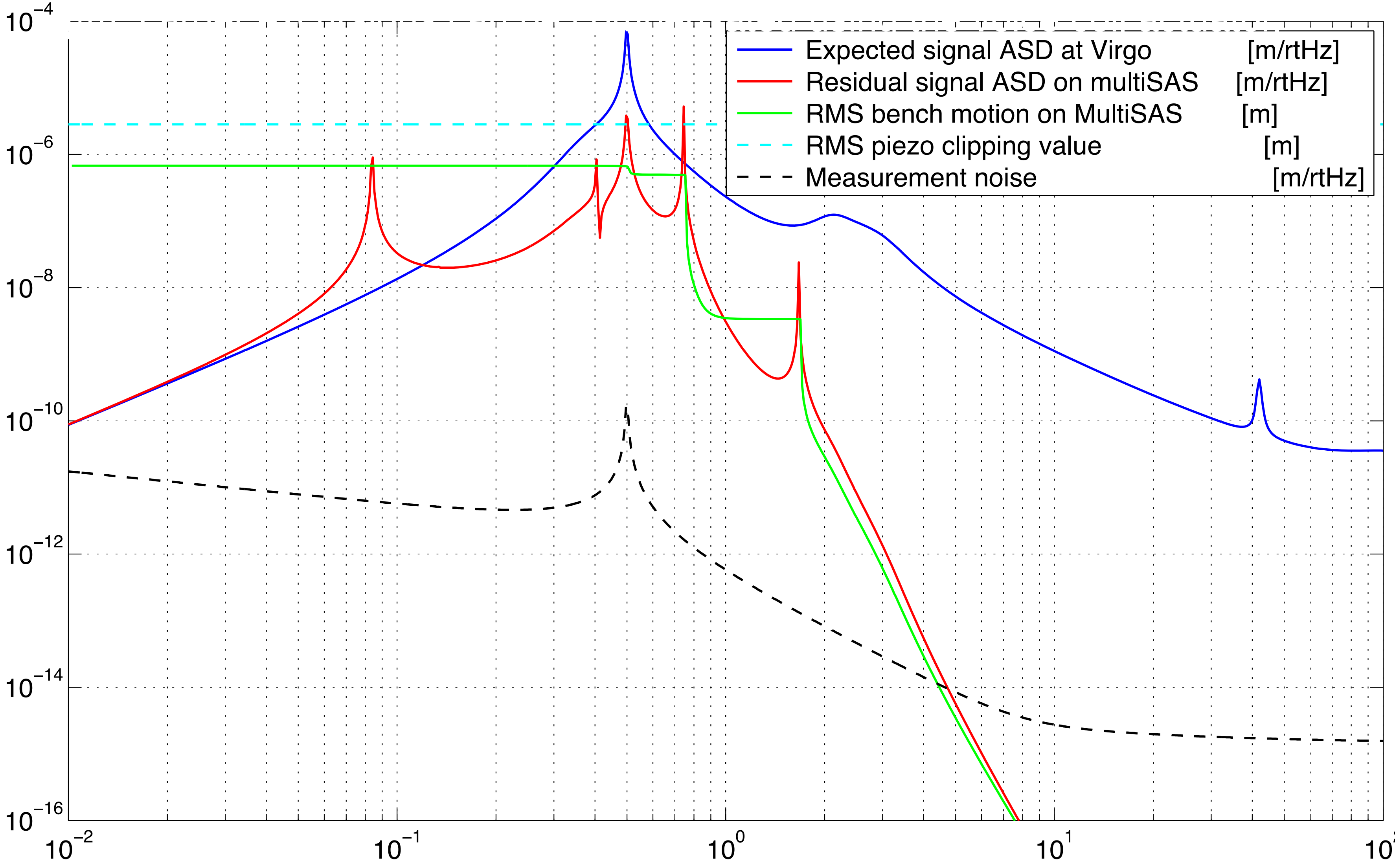


Summary

- EIB meets requirements, provided acoustic sources be removed or better shielded.
- MultiSAS prototype is working so far; performance to be fully tested
- New IMC dihedron mirror waiting for coating, than ready to be installed on its new support

  IMC end mirror suspension: a challenge regarding stiff baffle mounting
- Diagnostic accelerometer R&D looks useful tool for bench seismic attenuation performance testing

Projections of noise and bench residual on sensor displacement z



NIKHEF

System design parameters

Name	Symbol	Value	Unit	Type
Laser power	P_{inc}	5	mW	Hamamatsu LED
Laser wavelength	λ	880	nm	
Photodiode responsivity	ρ	0.6	A/W	Hamamatsu S2386-44K
Photodiode dark-current	I_d	0.02	nA	Hamamatsu S2386-44K
Accelerometer				
Resonant frequency	f_0	0.5	Hz	
Effective mass	M_e	0.85	kg	
Quality factor	Q	100		
Damping ratio	ζ	0.005		
Data acquisition				
Sampling frequency	f_s	1	kHz	Virgo DAQ
Oversampling frequency	f_{os}	800	kHz	Virgo DAQ
Voltage range	A	20	V_{pp}	Virgo DAQ
ADC bits	n	18	bits	Virgo DAQ
Read-out circuit				
Transimpedance amplifier resistance	r_f	8000	Ω	
Corner freq. resistor current noise	f_{cr}	10	Hz	
Corner freq. op-amp current noise	f_{ci}	100	Hz	LT1024
Corner freq. op-amp voltage noise	f_{cv}	0.08	Hz	LT1024
Op-amp voltage noise	V_{op}	6	$nV/\sqrt{Hz}$	LT1024
Op-amp voltage noise	I_{op}	0.1	$pA/\sqrt{Hz}$	LT1024

Component list

Name	Type	Vendor	Cost	Units
Light sources				
SLED	Superlum 38HP	Superlum	X €	1
LED	Thorlabs	Thorlabs	320 €	1
Diode laser	ρ	Thorlabs	X €	1
Laser driver	I_d	Thorlabs	X €	1
Electronics, diodes, and actuators				
Lock-box	Lock-box	Vrije Universiteit	2000 €	1
HV-amplifer	WMA-280	Falco systems	1490 €(excl tax.)	2
Photodiode	S5971	Hamamatsu	6.50 €	2
Amplifier	LT1028	Farnell	10 €	1
Resistors	X	Farnell	10 €	1
Connectors	BNC	Farnell	4 €	1
PCB fabriaction	X	X	200 €	1
Piezo	HPCh 150/12-6/2	Piezomechanik	145 €	2
Optics and mechanics				
Beam splitters	BS008	Thorlabs	123,41 €	2
Mirrors	X	Thorlabs	X	2
Fiber colimators	X	Thorlabs	X	2

Table 2: Table of costs (to be updated).