Impact of Controlled Cryogenic Payload modelling on present design

Majorana E., Pinto M., Ruggi P.

III Workshop on ET-LF TM Tower Integration - Elba - 28/09-30/09, 2025

Overview of what done in past two years

A significant activity concerning the ET-LF conceptual design of the seismic attenuation system was pursued.

After the conceptual baseline, a Virgo-like 17m-long *superattenuator* (2011, reviewed in 2020), a shorter configurations ~12 m height was examined and, going into deeper detail and optimization, it resulted suitable.

Moreover, longitudinal control and its technical noise have been studied, converging on a document that is close to publication.

- ❖ **We have baseline seismic isolation system**
- ❖ **A payload baseline system is included**
- ❖ **The method to model and analyse the system (in terms of performance and noise projections) is developed.**

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Einstein Telescope Low–Frequency Interferometer Test–Mass Suspension Conceptual Design Update

ET-xxxxX-25

Suspension Division
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The latest works and this workshop on ET-LF Tower bases.

- Cryostats and Cryostat content is the matter that should be investigated.
- We start from the core, baseline payload integrated to baseline seismic isolation

⇒ TM residual motion VS sensitivity has been studied

- ❖ Provided the good aspects of the double cavern, we focus on single cavern, and consider the preliminary modelling of tower bases.
- ❖ Tilt and hierarchical control (HC) must be considered as the mechanical content into the cryostats, constrained by cryogenics, is involved.
- ❖ So far, we focus on baseline Payload disconnected by the thermal links
- ❖ We derive preliminary considerations as intermediate milestones
- ❖ The next steps will be related to the links (started)

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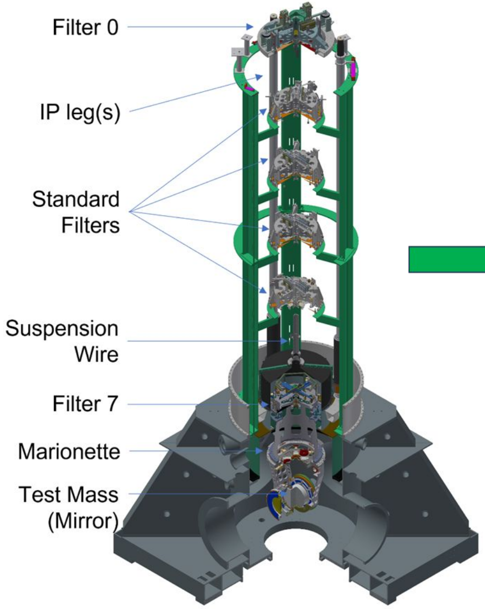
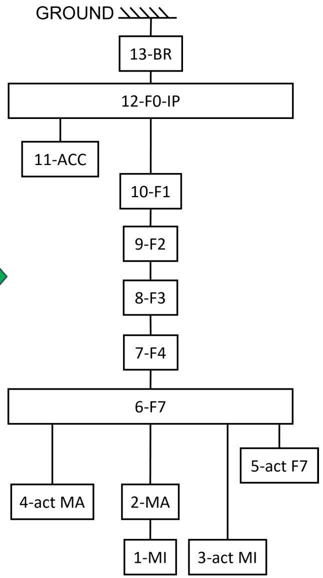
Outline

1. Interaction between tower and suspension:
    a. Effect of the tower design on the seismic noise propagation through the structure. Preliminar analysis.
2. Angular control noise budget: Cryo-Pay control
    a. Noise projection of SOFT (OpLev) and AA (WFS) control loop;
    b. Identification of the major contribution to the control noise budget;
    c. Consideration on possible design variations to the payload mechanics;
    d. Consideration on possible requirements derivation of hardware noise levels.
3. Open points and next steps
    a. Longitudinal actuation noise study on Reference solution+Cryo-PAY (HC4);
    b. Implementation of heat-links on mechanical model.

The methodology





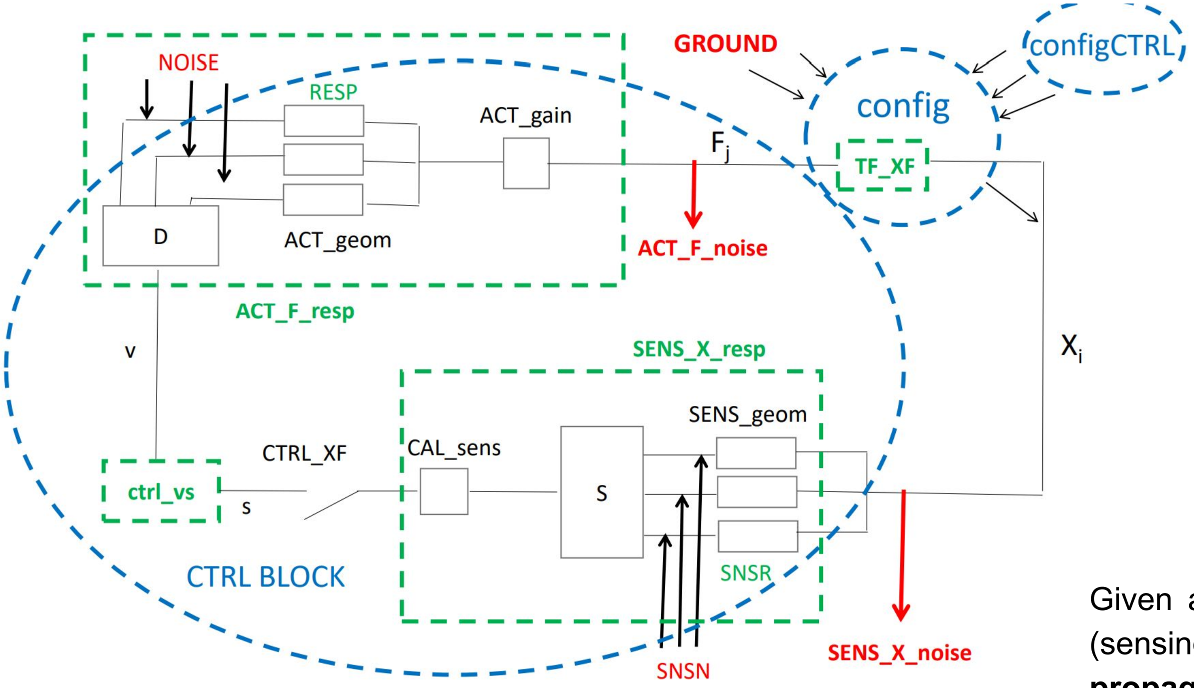
- Use of the **OCTOPUS*** simulation software.
- representation in block schemes of the physical layout of the mechanical system.
- estimate the behaviour of specific designed systems, in terms of performance and general requirements achievement.
- Implementation of **feedback control loops.**

Each block is a node of the representation: the dynamical variables (displacement, rotation, force, torque) of an arbitrary pair of nodes are connected by frequency domain functions.

Consideration on the effect of **control noise** is of extreme importance, since it is the real limitation to reduce the TM motion down to the requirement for a LF GW detector.

- * P. Ruggi, M. Pinto, L. Trozzo, G. Cella, E. Majorana, G. Losurdo, P. Chessa, A. Longo, A. Vicerè. *Mechanical simulation tool based on impedance matrices* – Phys. Rev. D 112, 022002.

The methodology



A control system works converting sensor outputs in forces, applied to the sensed bodies or others.

The hardware used to control a mechanical system is a **specific source of noise**, whose level depends by many factors.

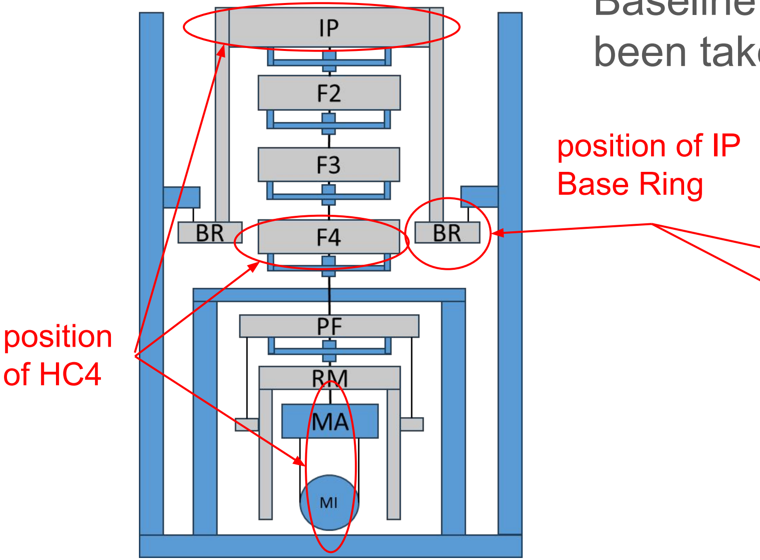
The tool allows to include the main parts which constitute a control loop, such as: number of **sensors**, number of **actuators**, their gain, **frequency response models** and their **noise levels**.

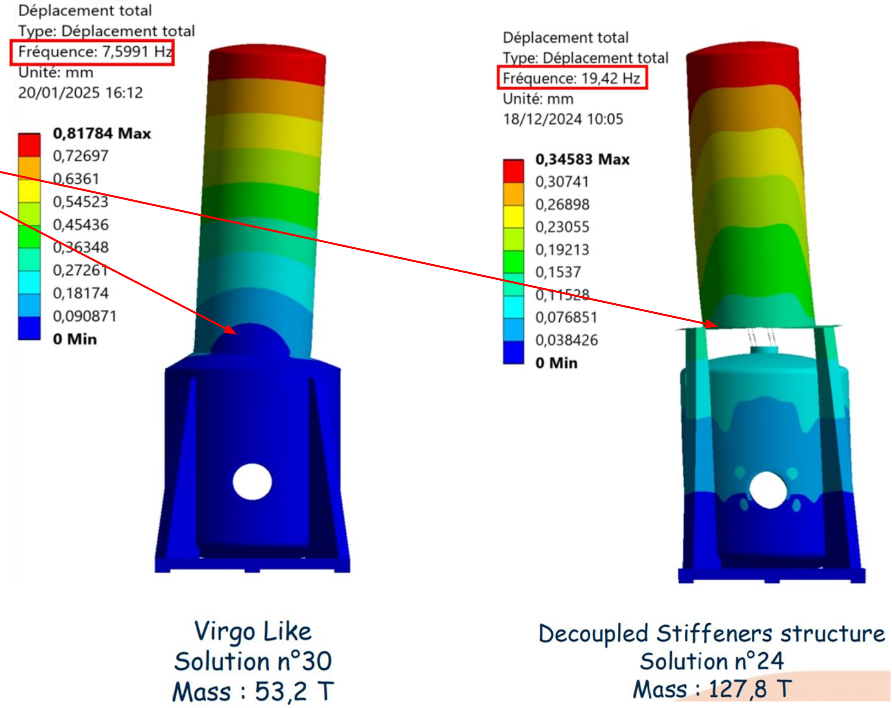
Given a specific geometry of the installed hardware (sensing and driving matrices), it is possible to **propagate the correspondent noise** towards the controlled degrees of freedom.

Seismic background effect through the structure* and impact on the design

Case of study: Baseline 12m Suspension and Cryo-PAY model

Baseline solution** for the single cavern option + Cryo-PAY have been taken as case of study.



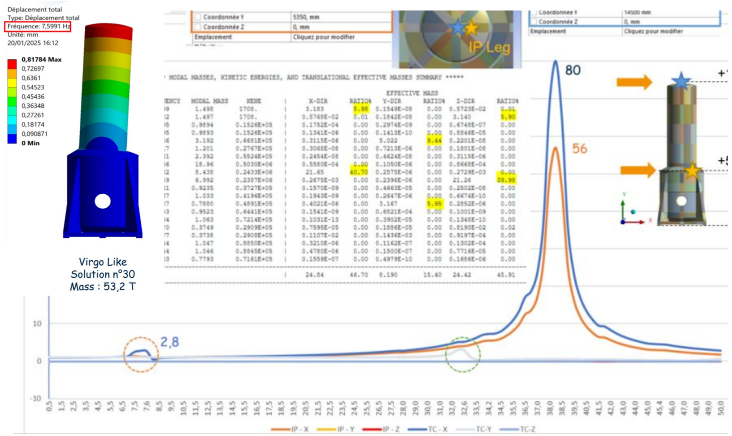


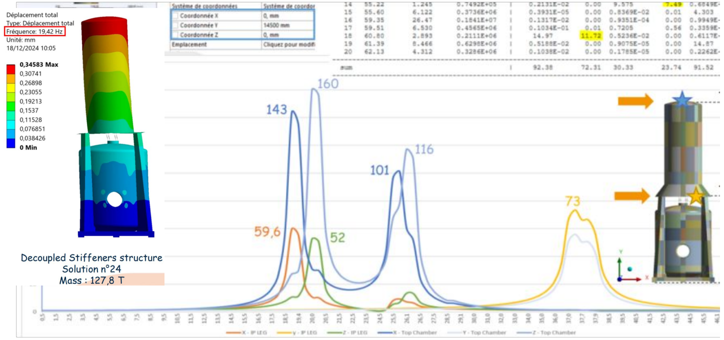
- ** Trozzo, Spada, Ruggi, Pinto, Lucchesi, Losurdo - *A Superattenuator for the ET-LF Test Masses*. <u>II. Workshop on ET-LF TM Tower Integration March 25 – 27, 2025</u>.
- ** Spada, Losurdo, Lucchesi, Pinto, Ruggi, Trozzo - *Feasibility and Compliance Study for the Seismic Isolator of Low-Frequency Einstein Telescope Test Masses*. <u>GR24/Amaldi16 Conference Proceedings</u>.

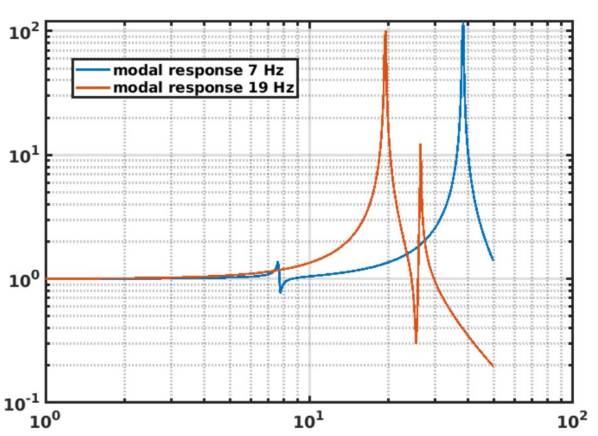
* Credits: G. Iaquaniello - *Cryostat Simulations*. ET-ISB susp meeting. 24-01-2025.

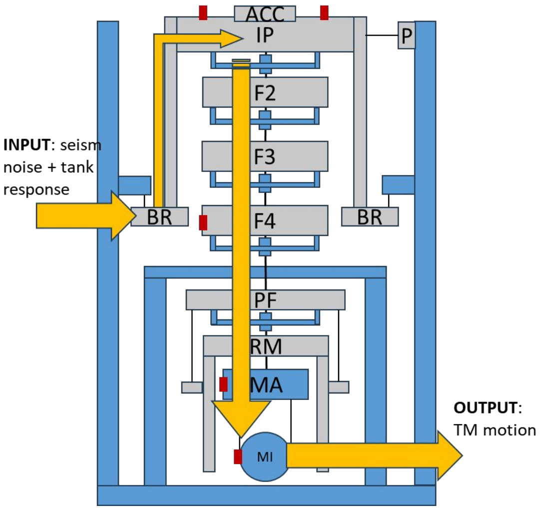
An update might be elaborated soon by G. Iaquaniello

Tower modal analysis - seismic transfer on TM









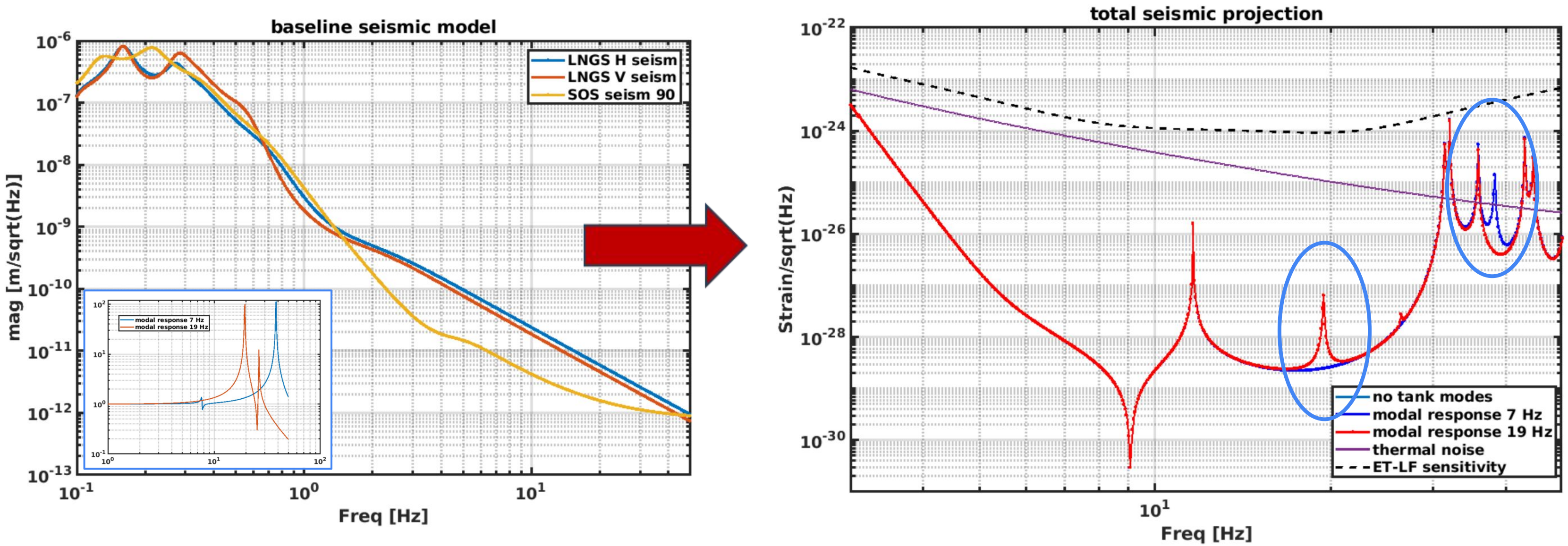
Modal analysis on several tower 3D design have been carried out*. Two solutions have been considered for now.

1) Virgo-like solution (53.2 T; 7.6Hz mode);
2) Decoupled Cryo-Tower solution (127.8 T; 19.42 Hz mode).

Input displacement at the height of the base of the suspension (BR) has been applied; displacement response of the BR has been taken as output. Results have been fitted (with pessimistic higher Q) and inserted in the seismic model in order to evaluate the overall noise propagation along the suspension chain down to the TM.

❑ Credits: G. Iaquaniello - *Cryostat's Simulations*. ET-ISB susp meeting. 24-01-2025.

Seismic transfer down to TM - including tower modal response

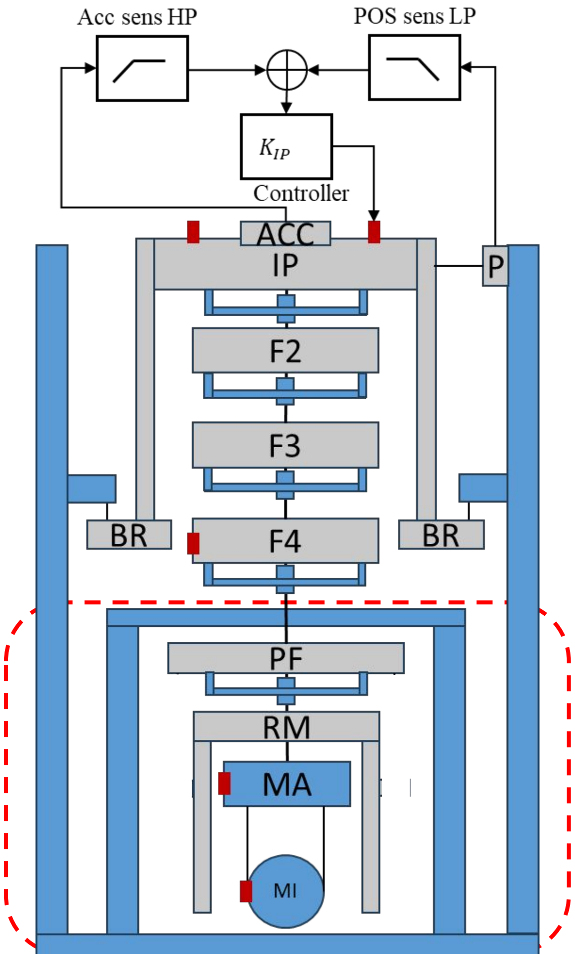


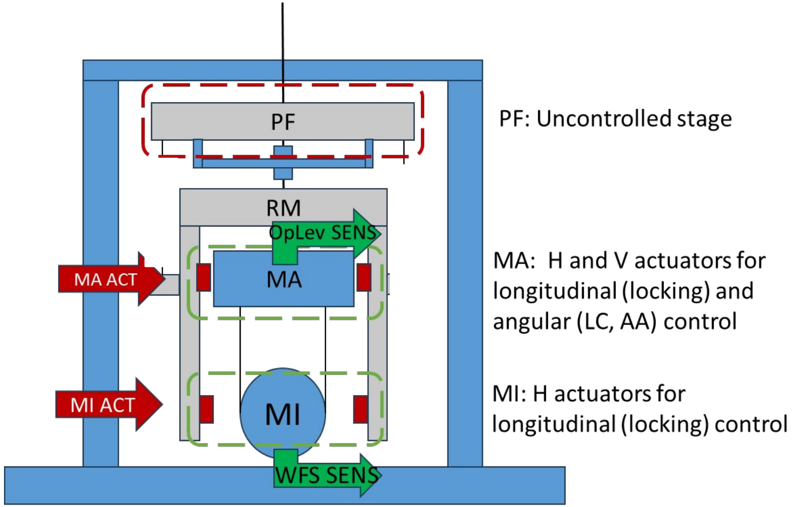
Total transmission of ground noise (H and V) to the test mass. The dominant part is the vertical component, which allows to transmit the horizontal modes of the tower, given an arbitrary additional coupling mechanism.

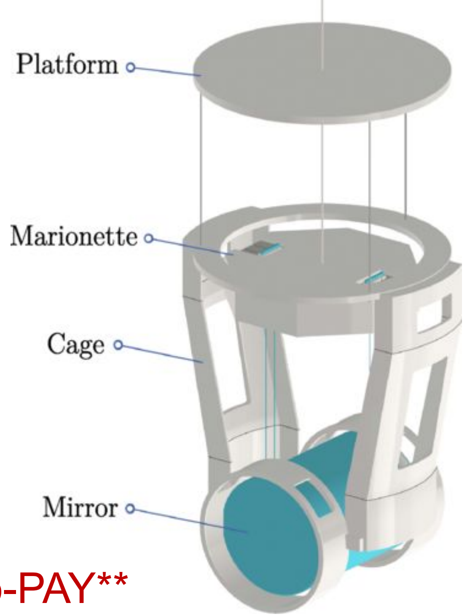
- ➔ **At LF (3 Hz) the nominal Thermal noise dominates** and there is no reason to further constrain the system design to evade structural mode effects.
- ➔ **De facto a mode at 7 Hz is not harmful (not even visible in the projection)**, but the 2nd mode @ 38 Hz of the 1st solution may approach the sensitivity, but arises anyhow in the middle of vertical mechanical modes (crossbars…).
- ➔ **Iterative process**, we have the tool to properly design the tower base and make the effect negligible
- ➔ Too massive (deployment issues) is 53 and 128 T are to high? Can we optimize adopting smaller values (eg **40-50 T** Tower + Cryostat) ?

Angular control of the Cryo-Payload

Case of study: Baseline 12m Suspension and Cryo-PAY model



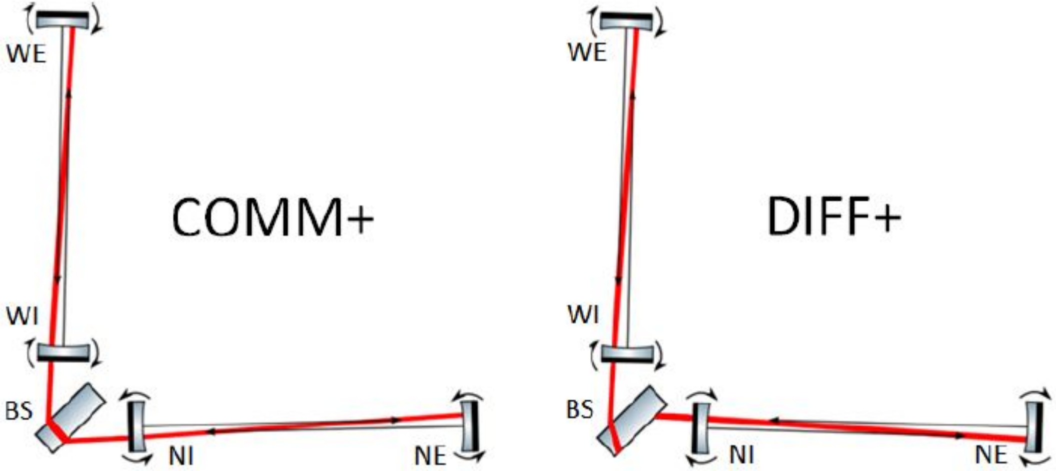




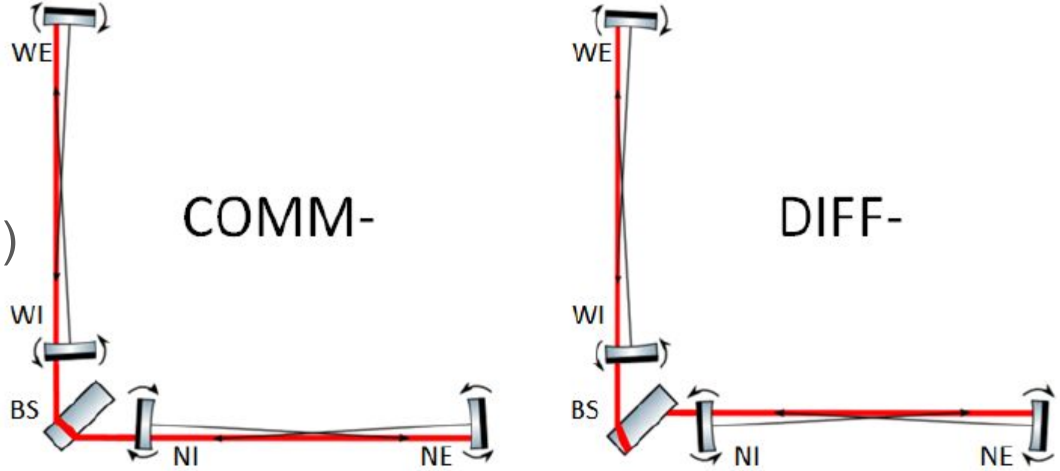
- Case of study: baseline solution + Cryo-PAY**
- **Basic ID control** strategy.
- Angular control using **OpLev** and **WFS** ("soft" mode on OpLevs)
- **No actuation neither on the PF, nor on the RM(cage), relevant not to add further components into the cryostat**

** Koroveshi, Busch, Majorana, Puppo, Rapagnani, Ricci, Ruggi, Grohmann - *Cryogenic payloads for the Einstein Telescope: Baseline design with heat extraction, suspension thermal noise modeling, and sensitivity analyses.* Phys. Rev. D 108, 123009

HARD modes
(tilt of the beam)

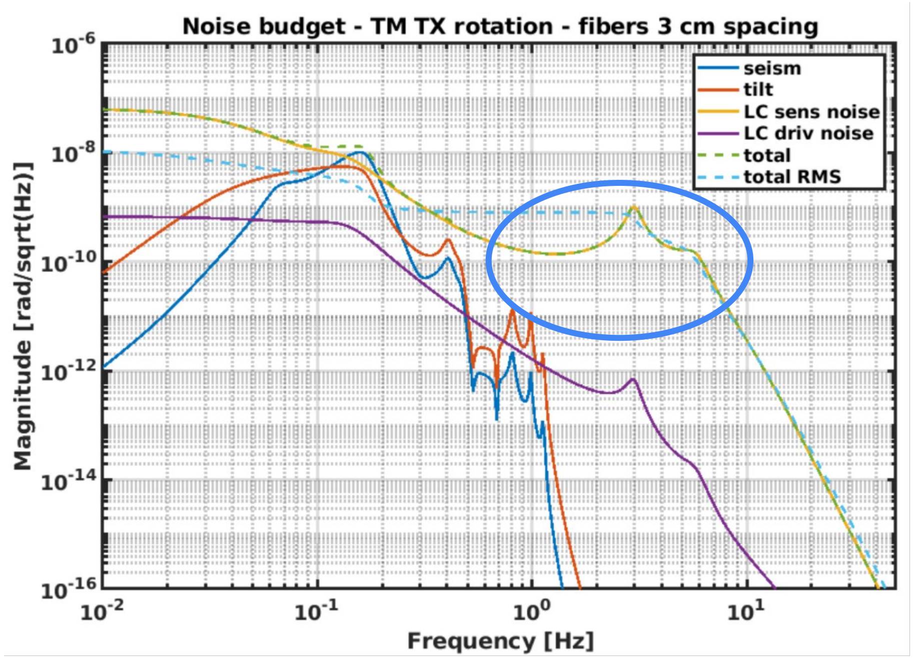


SOFT modes
(shift of the beam)

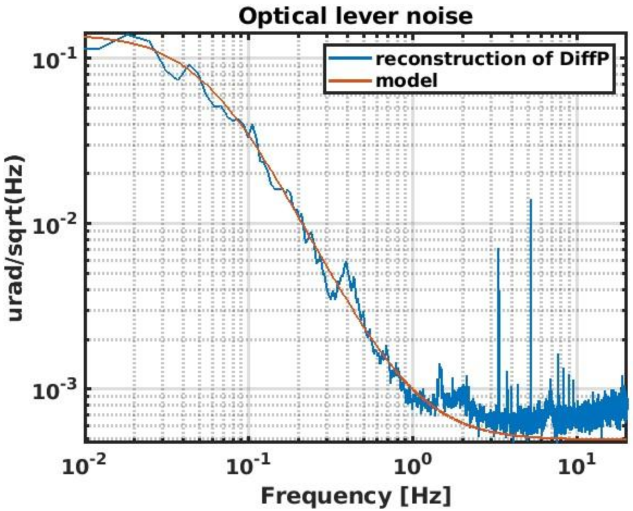


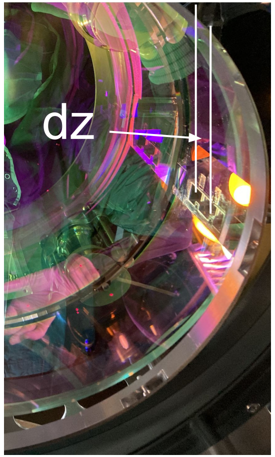
Angular control noise SOFT tx control - Payload baseline design (dz = 3 cm)

Baseline: 3Hz diff mode critical for the angular budget. Residual rotation dominated by the sensing of the OpLev sensors (current known noise model used as a first step).



Control based on OpLev sensing at Marionette level.



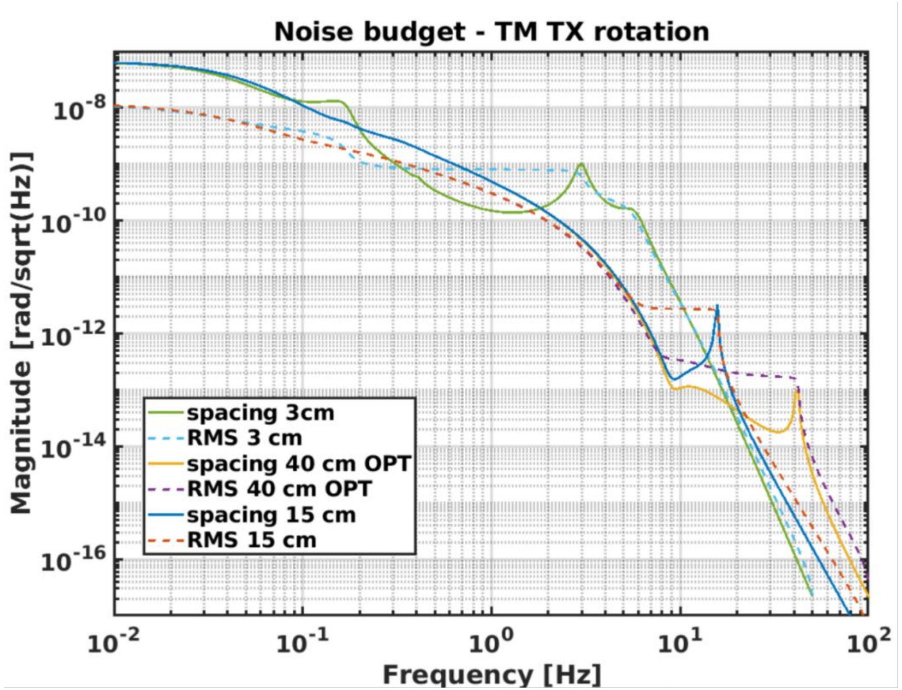


Residual motion 6e-10 rad @ 3 Hz. Assuming a coupling ang2length of 1e-5 (miscentering), we reach around 6e-15 VS ~10^-19 m/sqrt(Hz) of the sensitivity requirements.

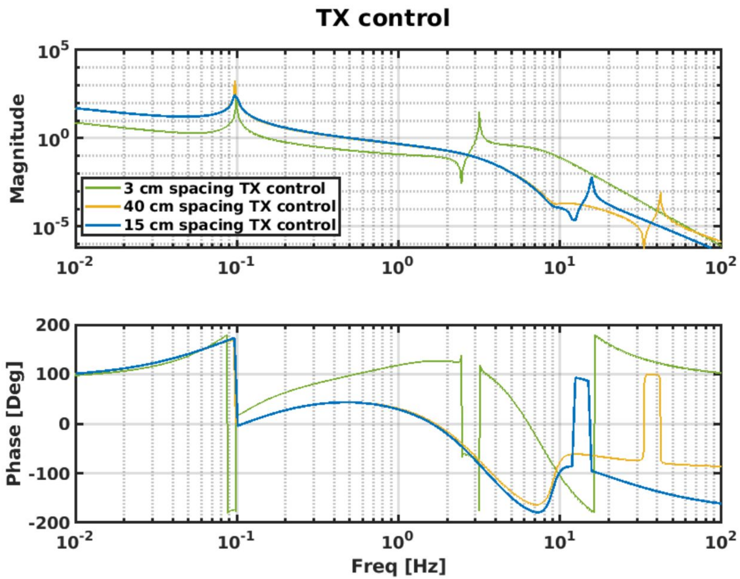
Proposal:

modification of a payload mechanics parameter (dz).

SOFT tx - Modified mechanics: different spacing comparison



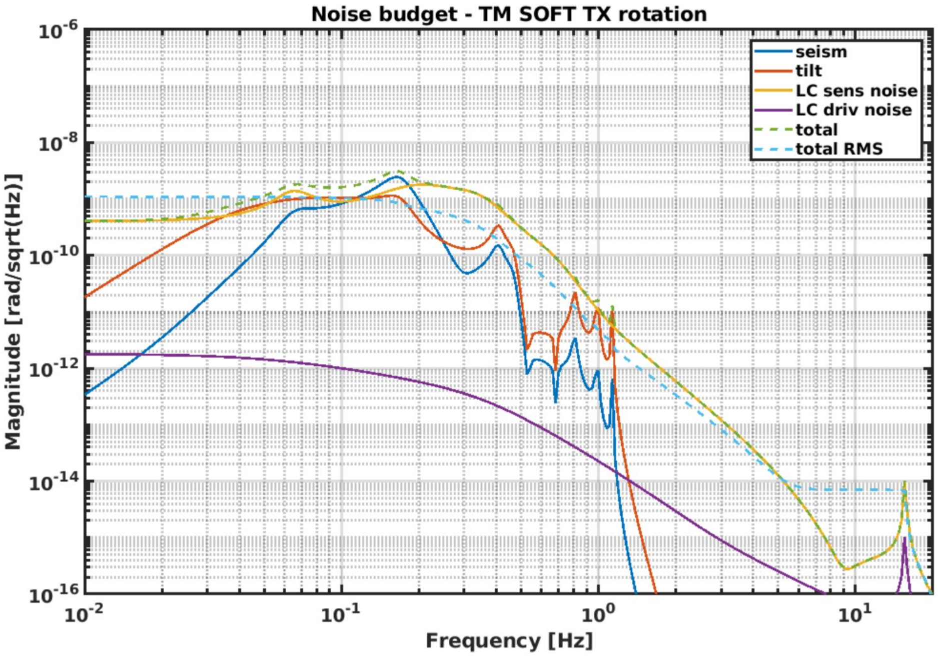
Parameter: **MIR fibers separation (dz)**. From 3 cm we increased up to 15 cm, and potentially 40 cm, in order to move ahead the diff mode. This allows to use a low bandwidth control of the only comm mode.



Improvement of 1 order of mag: 3e-11 rad @ 3Hz -> projection of 3e-16 m/sqrt(Hz) in sensitivity. **Not yet enough**.

Hypothesis: assume the value for a plausible **sensing noise of OpLev sensors: flat 10^-12 rad/sqrt(Hz)** (2 order of mag less).

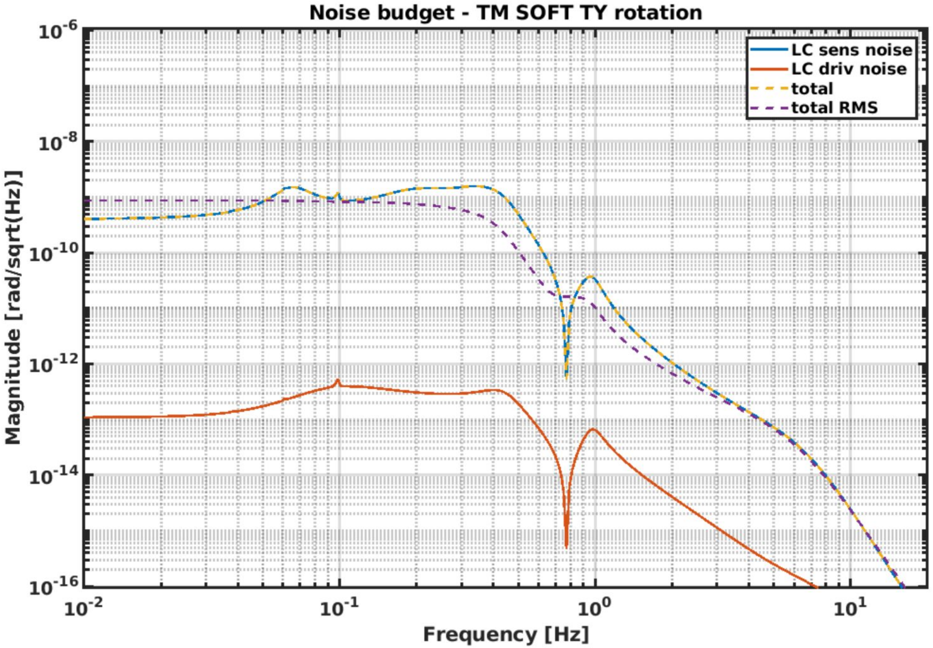
SOFT tx control - Optimistic OpLev sensing noise model

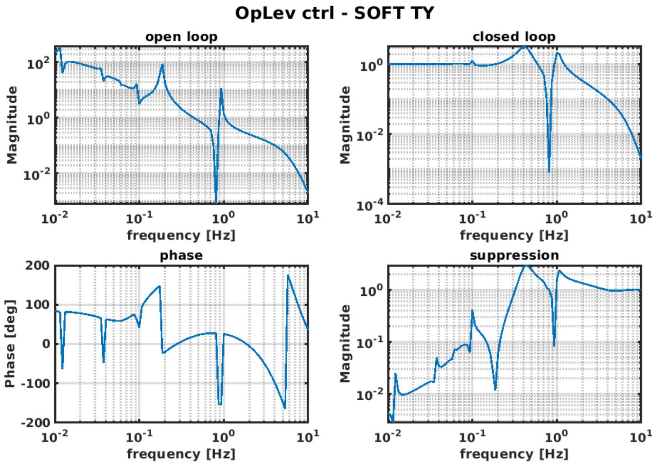


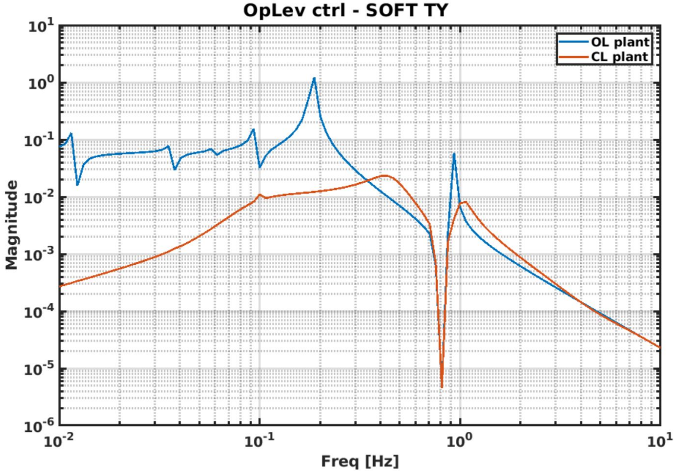
- the original sensing noise model was not compatible with a chosen miscentering of 1e-5m;
- This value would require (roughly) a level of SOFT angular accuracy of 1 nrad;
- **A sufficient sensing noise for this angular requirement is 1e-12 rad/sqrt(hz)**.

Assuming a more optimistic value for the OpLev sensing noise, we reduce the projected reintroduction of control noise.
10^-13 rad @ 3 Hz -> 10^-18 m on the sensitivity.
Room for control filter improvement (steeper roll-off).

SOFT ty control - TM residual rotation



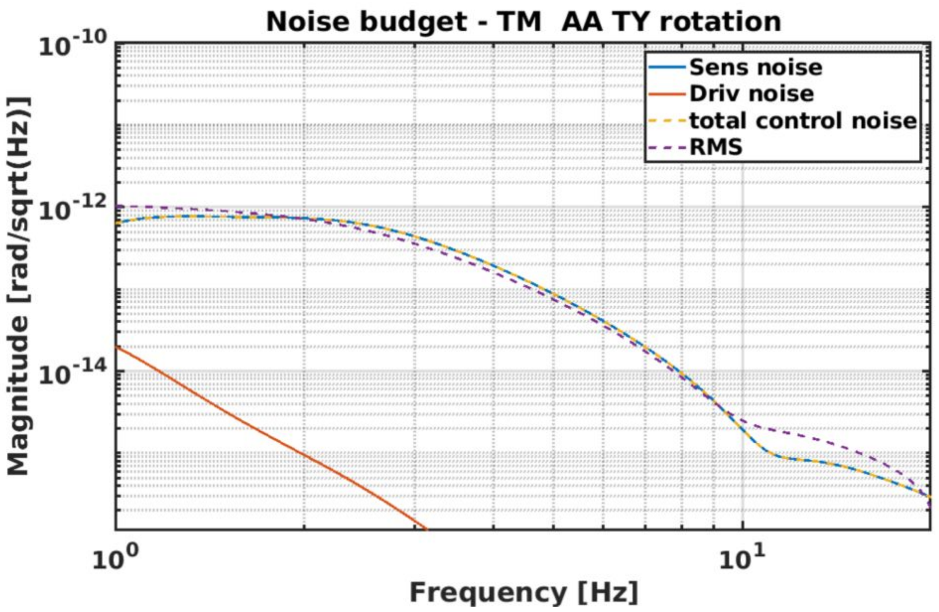


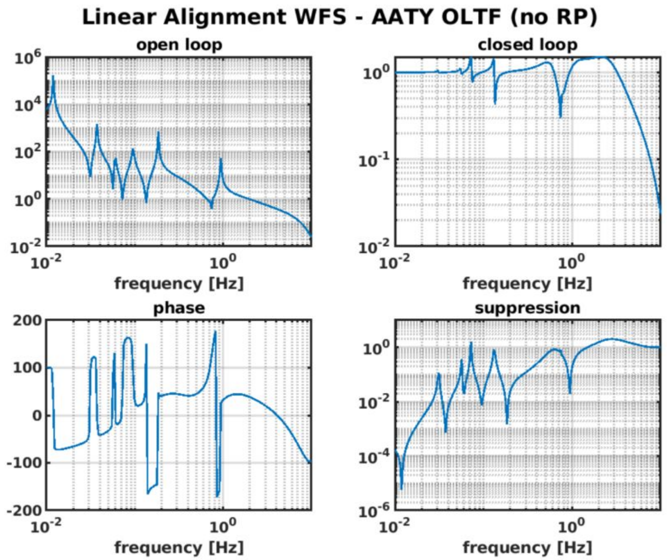


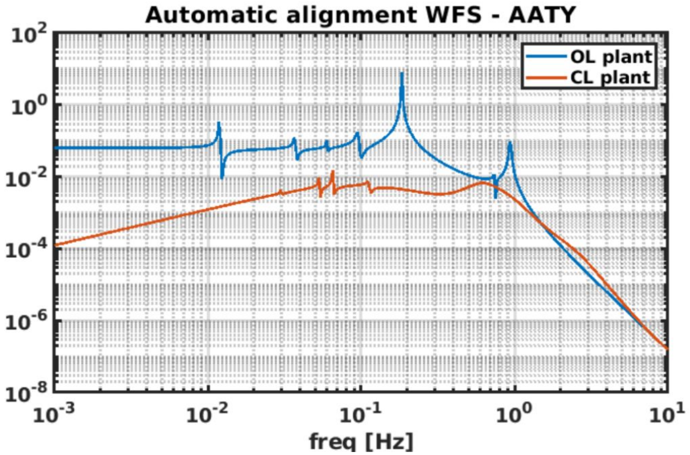
Same limitation for the Yaw ty: 3e-13 rad @ 3 Hz. -> 3e-18m in sensitivity.
In this case, concerning mechanics, we have less margin of modification since 0.9 Hz (Mario/Mirr diff mode) can't be easily moved.

AA TY (no RP) noise budget

Wavefront sensing alignment loops: No radiation pressure effect included at this stage. In this case we project only control noise focusing on the noise within detection/control band.

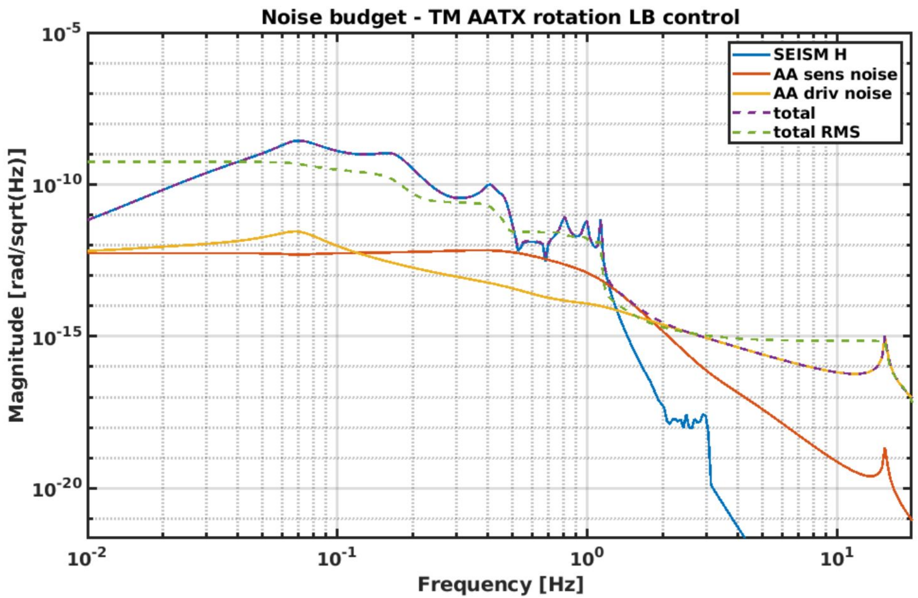


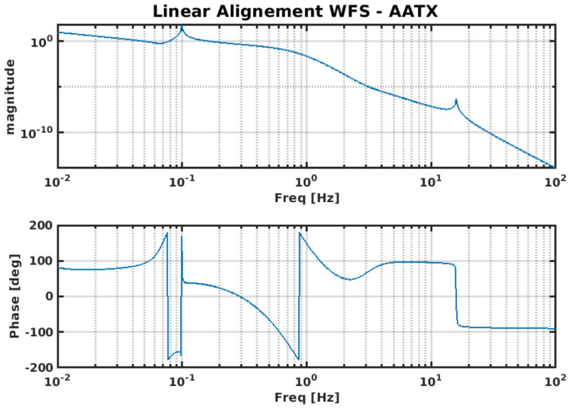


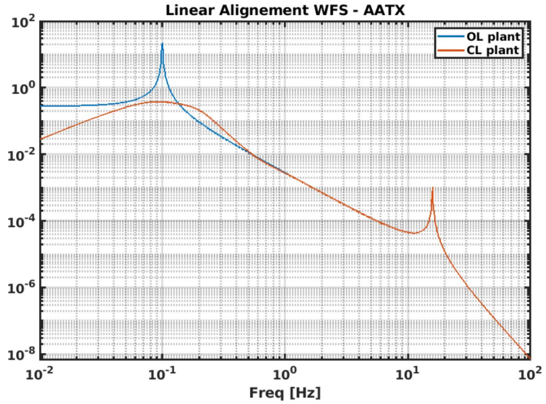


Assuming a value for the WFS sensing noise with floor at 1e-14 rad, we obtain a residual motion of 3e-13 rad/sqrt(Hz) @3 Hz -> 3e-18 m/sqrt(Hz) in sensitivity.

AA TX noise budget (low bandwidth control)

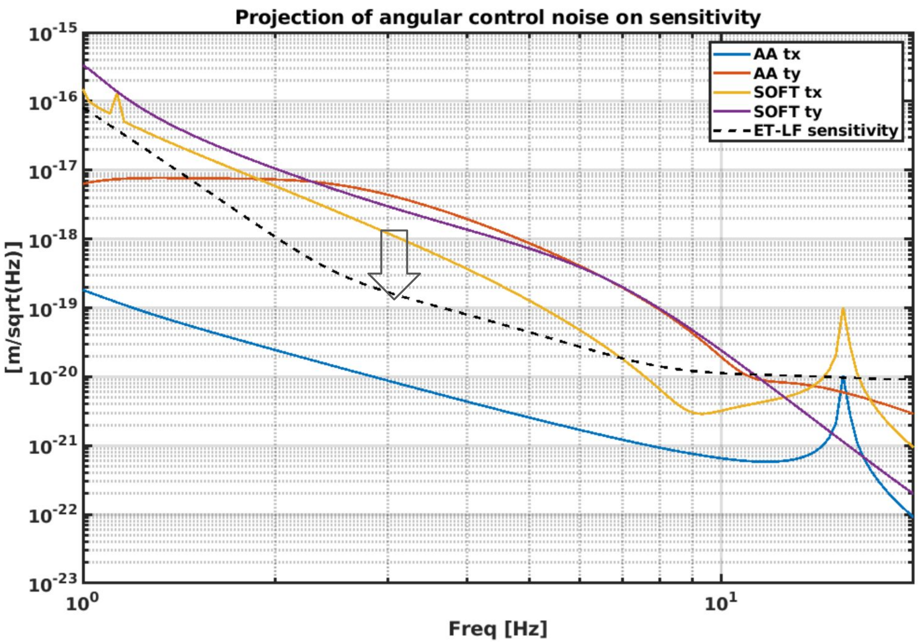






Using a low-bandwidth control (200 mHz), we reduced the contribution of noise coming from the sensing, reaching 1e-15rad @3 Hz -> 1e-20 m in sensitivity.

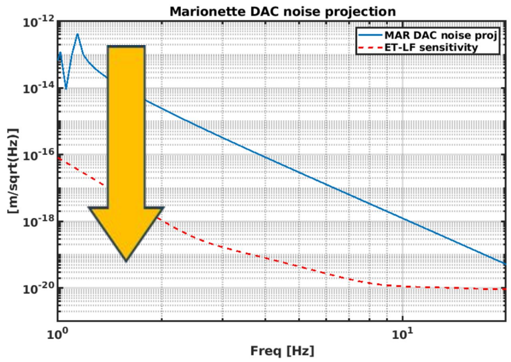
Recap of angular noise budget and Concluding Remarks



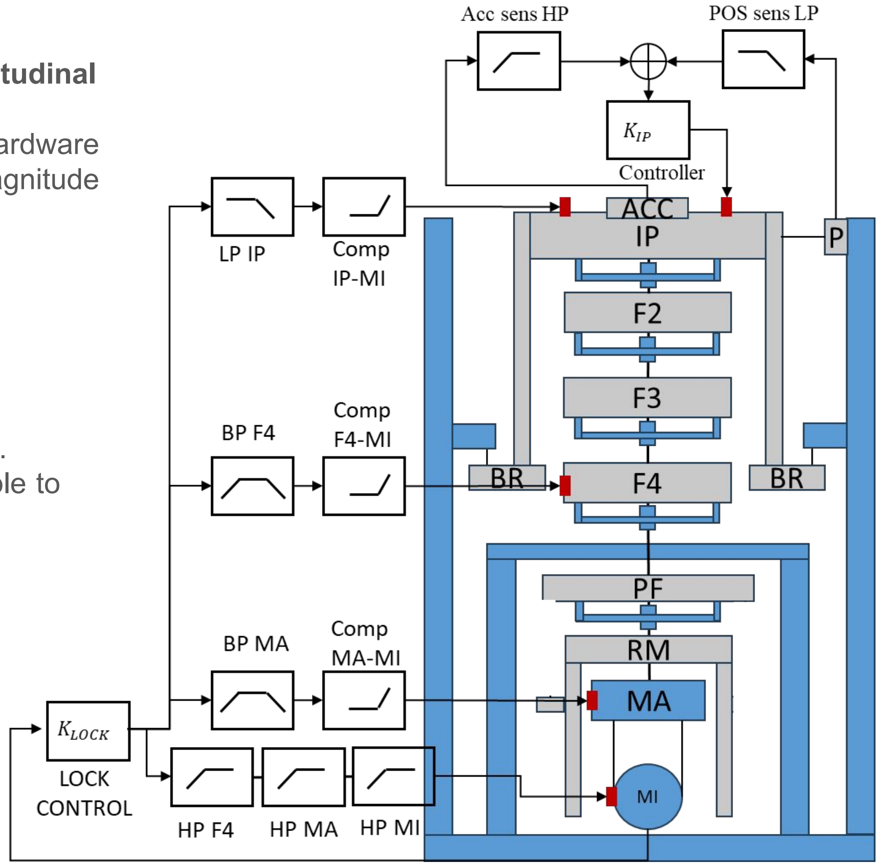
- ❏ YAW AND PITCH TFs are significantly different due to the intrinsically different structure

- ❏ Results reported here enhance the plausible **limitations coming from the angular control noise**;
- ❏ Results are preliminary, we are interested in the ‘order of magnitude’ gap WRT the sensitivity requirements.
- ❏ The methodology enlightens the **‘knobs’ on which the design effort be focused:** hardware noise, control strategy, control design…
- ❏ This can be used as a tool in order to **derive requirements** on the performance of the hardware (sensors and actuators) in order to reach the sensitivity goals.
- ❏ Additionally this could also drive the **optimal choice for the mechanical design** of the suspension elements (SA & Cryo-PAY) and their control strategy.
- ❏ At 3 Hz the OpLevs must be improved by 10

Next steps: 4-stages longitudinal Hierarchical control



- ❑ Need to tackle the **longitudinal actuation noise budget**;
- ❑ With the current DAC hardware we are few orders of magnitude far from the requirements;



- ❑ Low-noise actuation strategy is needed: (**Hierarchical control***);
- ❑ Strategy already proven to be effective and stable on Virgo ITF**.
- ❑ Updated measurement of ground TILT*** noise at LNGS available to test the strategy.

- ❖ * Ruggi, Pinto, Majorana, Losurdo - *Considerations on the control strategy for the ET-LF superattenuator:* ET-0527A-24*;*
- ❖ ** Ruggi, Pinto, Majorana, Losurdo - *Modelling further advancement of Virgo-like seismic isolation system towards ET-LF design:* 3rd ET annual meeting, Warsaw Nov,13th 2024 ET-0637A-24*;*
- ❖ *** Naticchioni, Trozzo, Ricci M., Pirro, Majorana, Di Giovanni - *Low frequency noise measurements at LNGS & tilt estimation* - ET-0434A-25

Concluding remarks

Structural Tower
Needed effort to feature the tower base structure. Notice that a 7 Hz peak is not harmful. The effect is smaller or comparable to that of other parts that need improvements on the superattenuator. There should be an easy margin to tune properly the design.

Angular noise
By separating more the two suspension units located on the side of the Mirror, differential mode is shifted at higher frequency and left out of loop ⇒ the angular noise contamination is reduced. The OpLev sensing noise should be FURTHER reduced (~10 at least at 3 Hz, this is neither trivial nor a show stopper).

Applying the same technique to ty (yaw) is not easy ⇒ however, some smart design might diminish the noise impact

Global noise
For the overall design the **complete control strategy** and global signals must be considered. Several noise sources preventing the reaching of the sensitivity. Issues: electronics, seismic background, tilt at the ground. TRUE FOR BOTH LOCK AND ANGULAR CASES

NEXT STEPS (timeline ….)
Improving the quality of the assumptions (more reasonable tilt noise model associated to the environment). Distribute the lock force passing from HyerarchicalControl-3 to HC-4 (another point of the chain, possibly a room temperature stage above the cryostat (tested for Virgo using F7).

Given the latter, an iterative process of mechanical optimization will be pursued…………