New Generation Super Attenuator for Einstein Telescope-NGSA: status of the project

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Outline

- Introduction
- NGSA: Scientific goals
- NGSA: organization and the present status of the project
- Next steps and perspective

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- **Introduction**
- NGSA: Scientific goals
- NGSA: organization and the present status of the project
- Next steps and perspective

NGSA: New Generation of Super-Attenuator

- NGSA is an R&D project started at the beginning of 2022, approved and funded by INFN commission 5.

- The project was expected to last 3 years

  - ✓ Requested one-year extension for NGSA (2025)

- The research group includes 3 INFN research units: (INFN-Pisa, INFN-Napoli, INFN-CA/UniSS) and a participation by EGO.

- It is strictly connected to Einstein Telescope (ET): it is devoted to the study of a seismic isolation system for 3rd generation GW antennas.

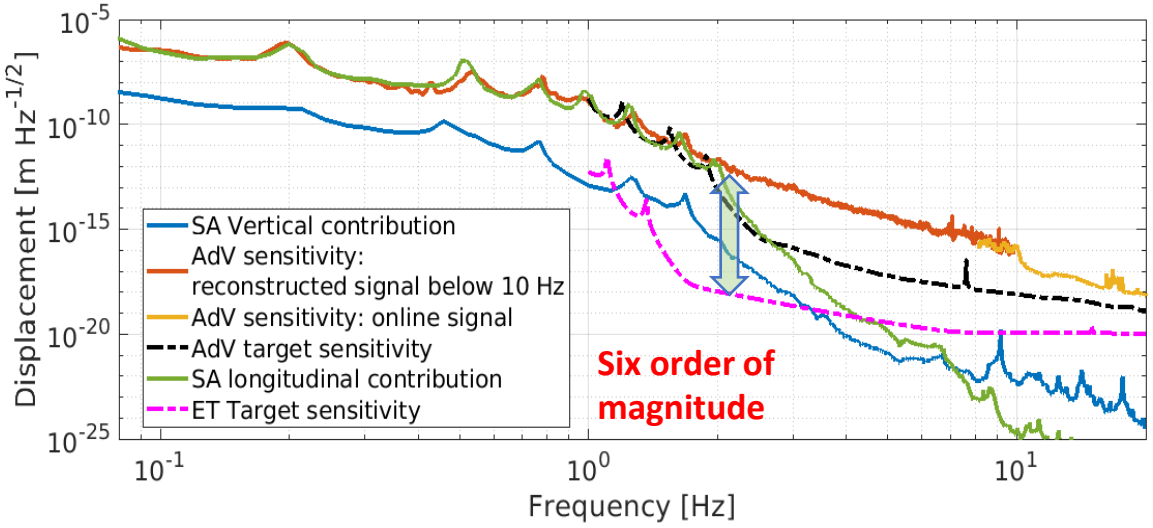
Introduction

✓ Subject of NGSA project is the development of a new vibration isolation system (Superattenuator) for the mirrors of the ET gravitational Wave antenna

➢ ET goal is to improve the sensitivity by more than one order of magnitude extending the detection band to the low frequency, down to 2-3 Hz, with respect to the 2nd generation detectors

✓ Reaching the ET design sensitivity is an ambitious task requiring enormous technological development on all the aspect of the detector

➢ Seismic vibration is one of the most relevant noise limiting the low frequency ET sensitivity ➔ to reduce this noise, underground operation and an improved seismic isolation system will be required.



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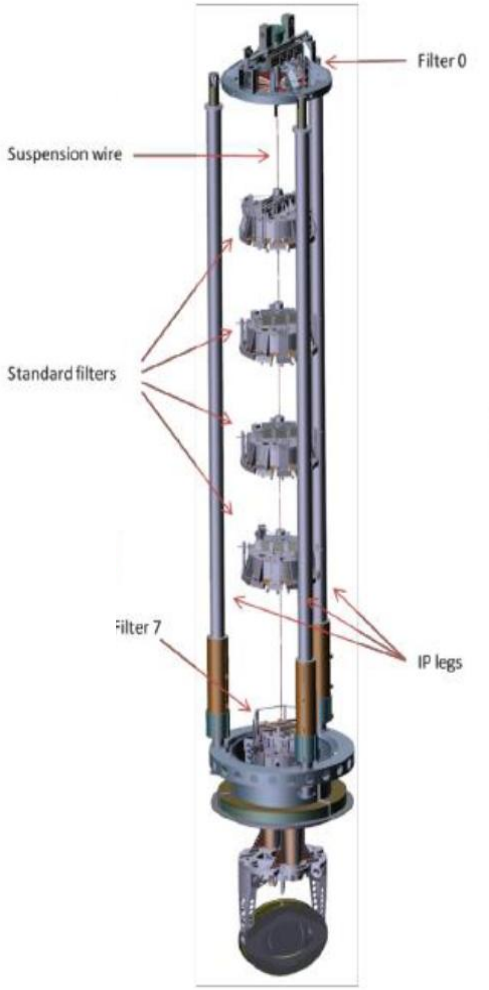
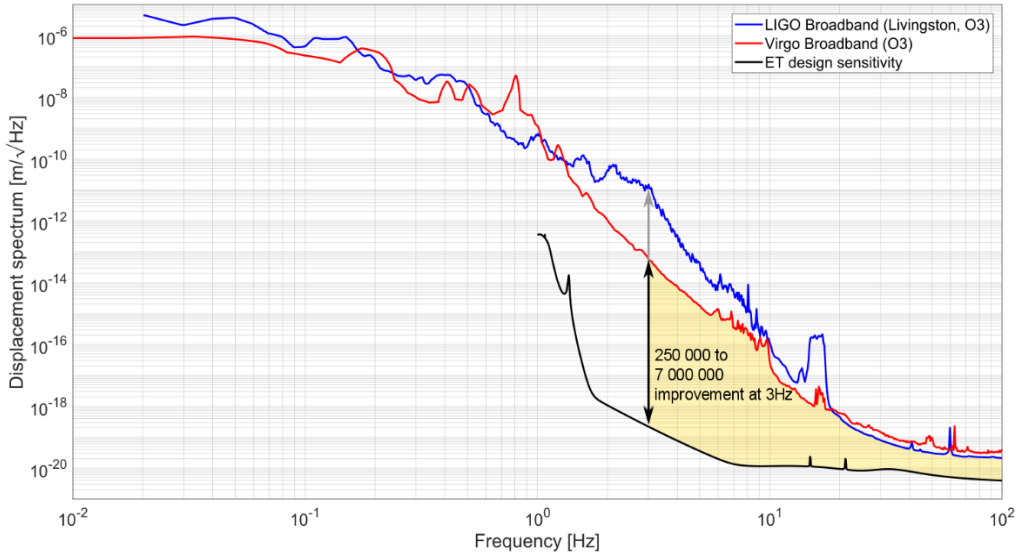
- **NGSA: Scientific goals**
- NGSA: organization and the present status of the project
- Next steps and perspective

From Virgo to ET



We will focus on seismic isolation, starting from the Virgo heritage

The Virgo Super-Attenuator is the best seismic isolator in the world. It is the result of years of R&D in INFN and was crucial to allow the extension of the antenna detection band down to 10 Hz.
The SA is made by a pre-isolator (inverted-pendulum), a passive filter chain and a Payload (mirror and control elements). The total length is about 9 m.

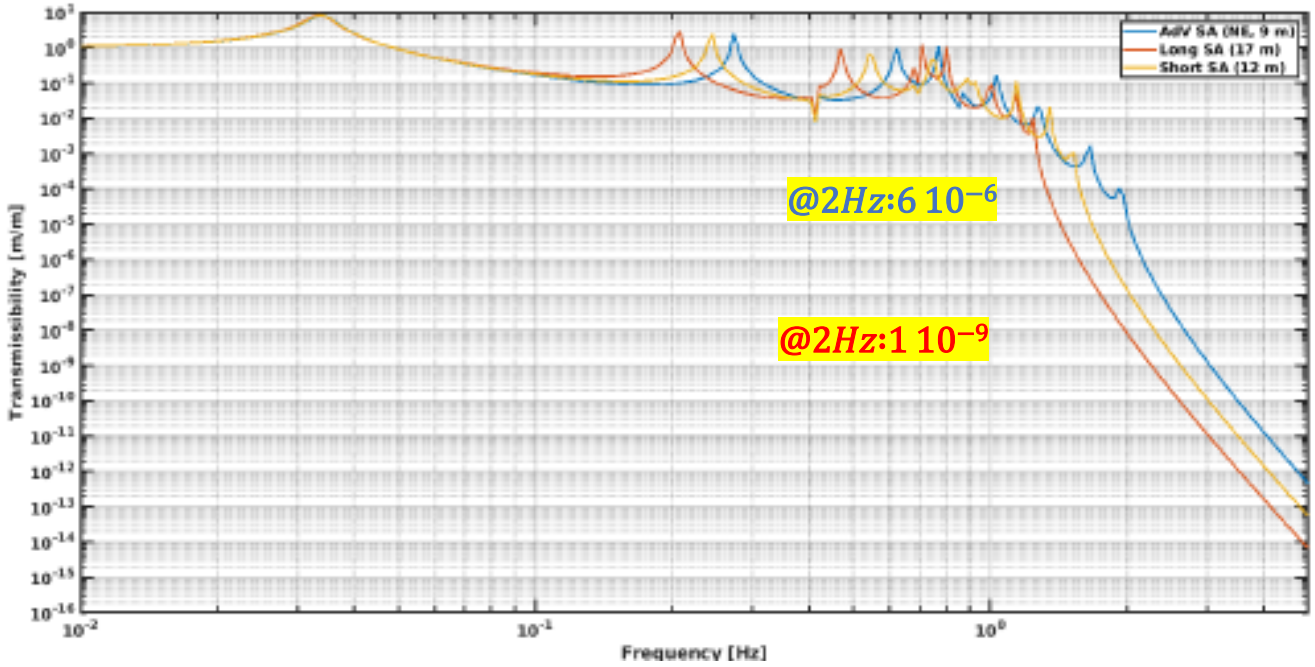


INFN holds a consolidated leadership on this subject

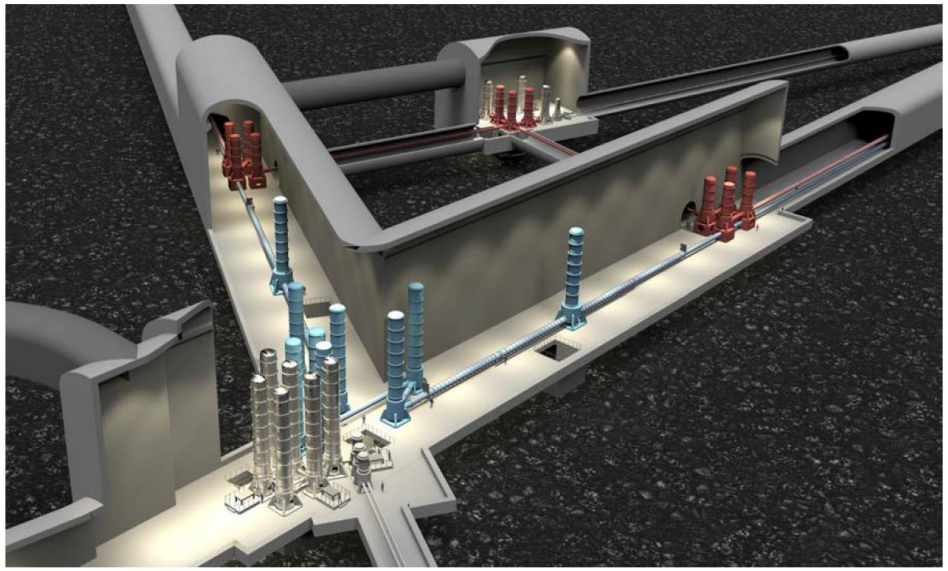
Keeping and improving this expertise will be essential for the development of ET.

From Virgo to ET

Reference solution, carried out in the framework of the 2011 ET Conceptual Design is a SA with a total length of 17 m



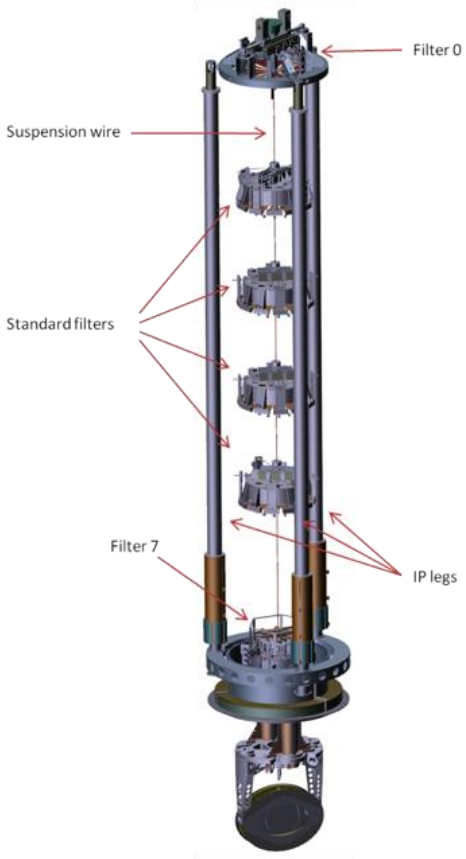
- This has an important impact on the cost of the excavation and its complexity



- ✓ In order to fulfill the ET requirements, while keeping the total SA length around 12 m, a dedicated R&D program is needed.

From SA to NGSA

How can we improve seismic isolation keeping a SA within a reasonable height?



1) Improving pre-isolation

- Active pre-isolation
- Two-fold inverted pendulum (NGSA)

2) Improving passive filter chain

- Optimization of filter chain masses and length distribution (NGSA) [1]
- Improved Magnetic Anti-Spring for vertical isolation (NGSA)

Constrains..

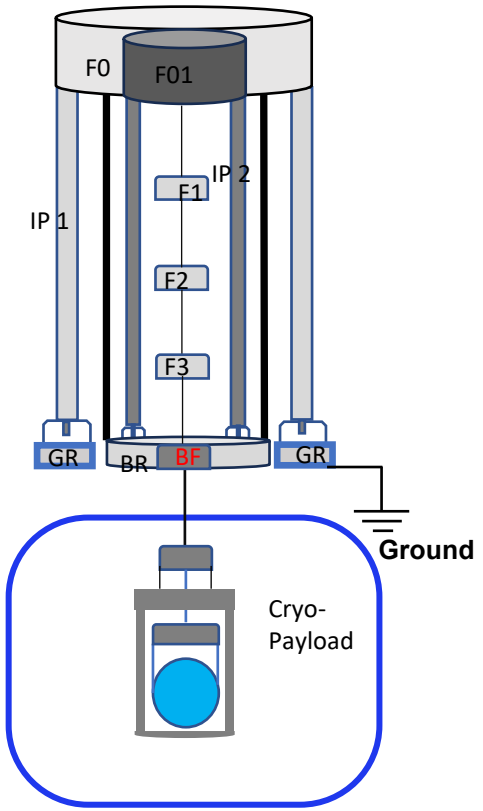
- Complex, heavy cryogenic payload (~ 800 kg) will be surrounded by a big cryostat
- The legs of the inverted pendulums must start above the cryostat

IPs legs (~ 5.7 m) **Larger SA total mass**

To keep in mind:

- Tilt and vertical to longitudinal Cross talk
- Control noise

Schematic view of a suspension adopting a double nested inverted pendulum (NIP-SA)



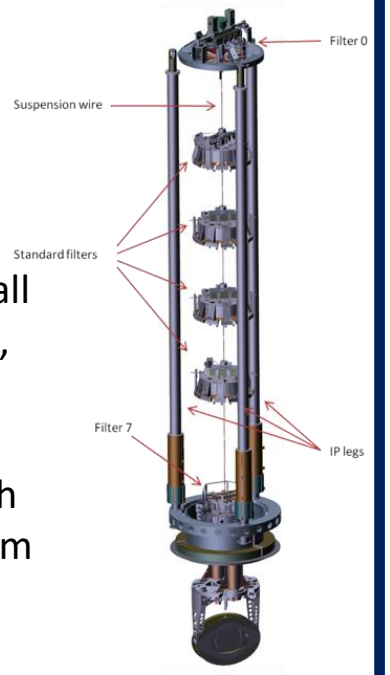
NGSA research lines

✓ Goal is to keep the total SA length around 10-12 m

The project is organized in two parallel experimental lines:

1) Traditional solution (SA)

Based on the **AdV mechanical structure** (Inverted Pendulum, Filters chain, heavy/cryogenic payload) with the intent to better distribute the mass all along the suspension chain, improving vertical attenuation performance and keeping the total length of the structure around 12 m

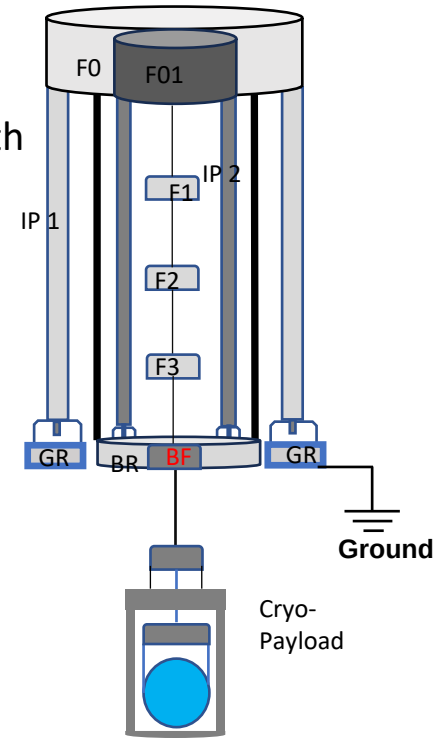


2) Innovative solution (NIP-SA)

Based on the use of a **two-stage Nested Inverted Pendulum (NIP)**: evident advantages from the point of view of the horizontal pre-isolation stages but never put in operation with many open questions (stability, automatic control, cross coupling of different d.o.f., vertical and tilt noise at ground level, …)

- A dedicate NIP prototype (in 1:2 scale) will be realized to experimentally validate this configuration. The prototype will be installed and tested in the new PLaNET Laboratory in Naples. Assembling and integration will start in the next weeks.

Schematic view of a suspension adopting a double nested inverted pendulum (NIP-SA)



- **Final goal, after comparison of the two alternatives, will be the definition of a Conceptual Design of the SA for the ET Antenna.**

The PlaNET laboratory

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- **NGSA: organization and the present status of the project**
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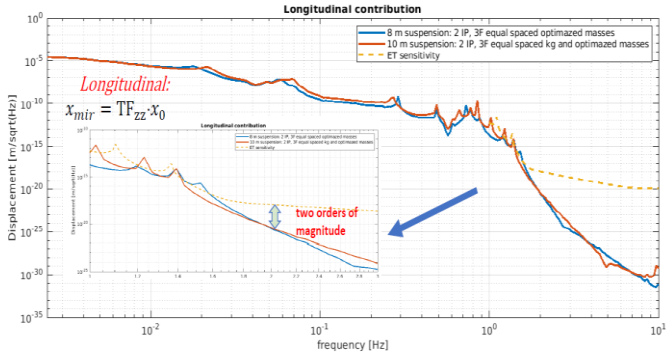
NGSA organization

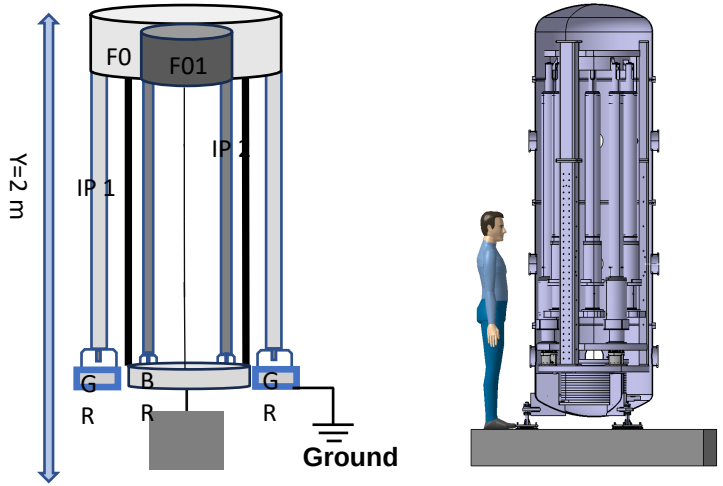
PI of project: L. Di Fiore (INFN-NA)

The project is organized in 4 WPs:

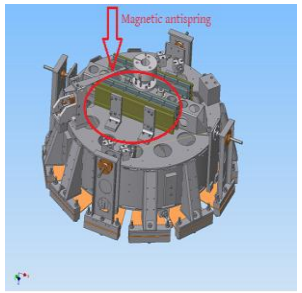
WP1 – Simulation and optimization of the Superattenuator in different configurations
Coordinator: L. Trozzo (INFN-NA)



WP3 – Development and test of a Nested Inverted Pendulum (NIP) prototype in the PlanET laboratory
Coordinator: R. De Rosa (INFN-NA)



WP2-Development and design of new Magnetic Anti-Spring (MAS) for passive attenuation of seismic noise
-Design and optimization of mechanical filter based on new MAS with rare-earth magnets
Coordinator: F. Frasconi (INFN-PI)



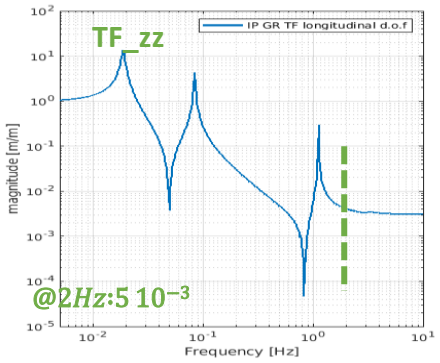
WP4 –Devices selection and procurement of a test station for feedback control application (LabView based)
-Preliminary set-up/configuration test in view of feedback control system to be used on NIP
Coordinator: A. Gennai (INFN PI)

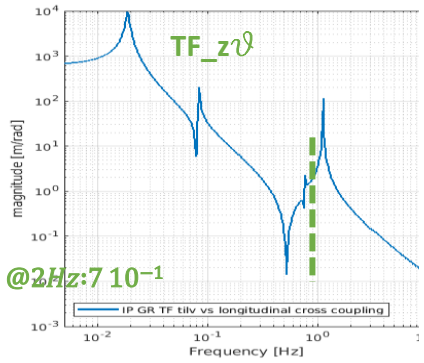
WP1 – Simulation and optimization of the Superattenuator (I)

Simulation tools are crucial to evaluate the effect of mechanical design choices on system performance:

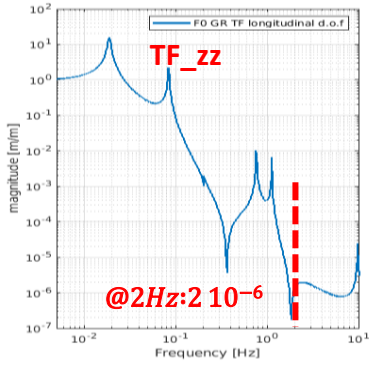
- Masses, flex-joints, legs, etc. have been defined
- This was the starting point for the mechanical design of the NIP prototype.

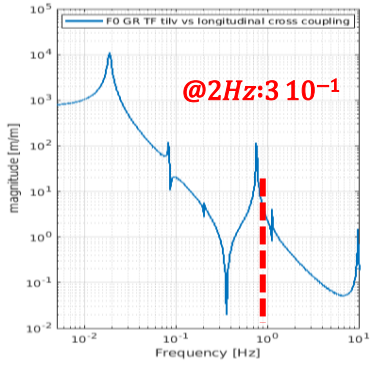
NIP TF: ground to IP



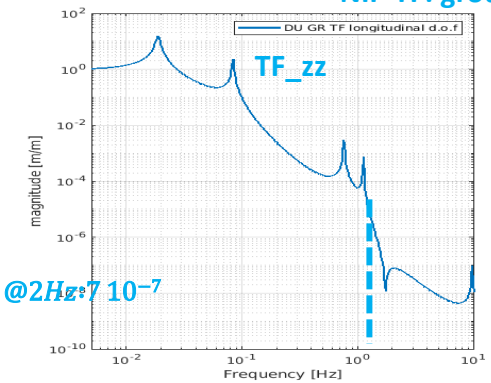


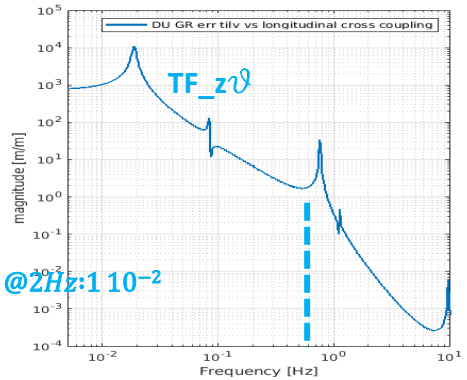
NIP TF: ground to F0





NIP TF: ground to MA





Simulation's tool

A MATLAB code (**OCTOPUS**), based on the impedance matrix approach, has been developed and applied for studying and upgrading the VIRGO seismic attenuators [2,3,4].

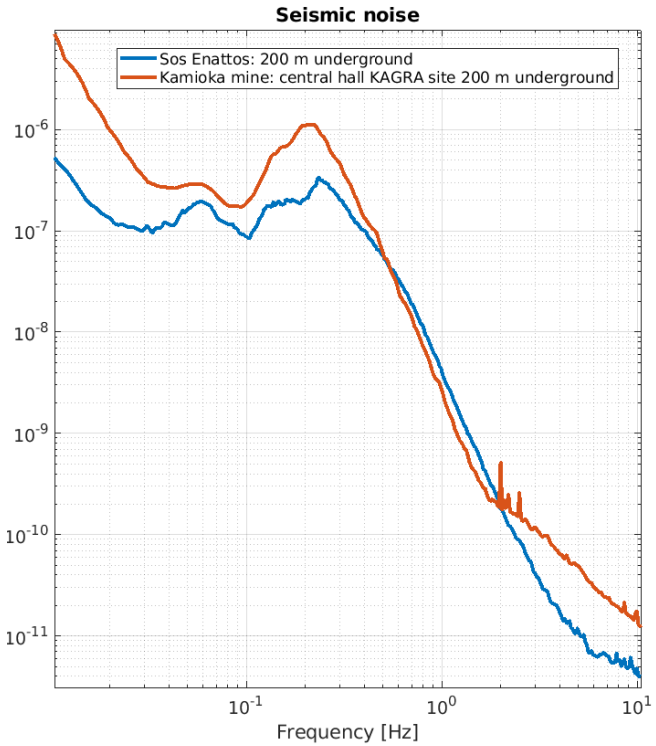
In ref [5,6] are reported the preliminary studies about a NIP-SA performance virtually installed at Sos-Enattos mine and the studies of the expected performance of a 2 m tall NIP prototype which will be installed at the PlaNET laboratory in Naples

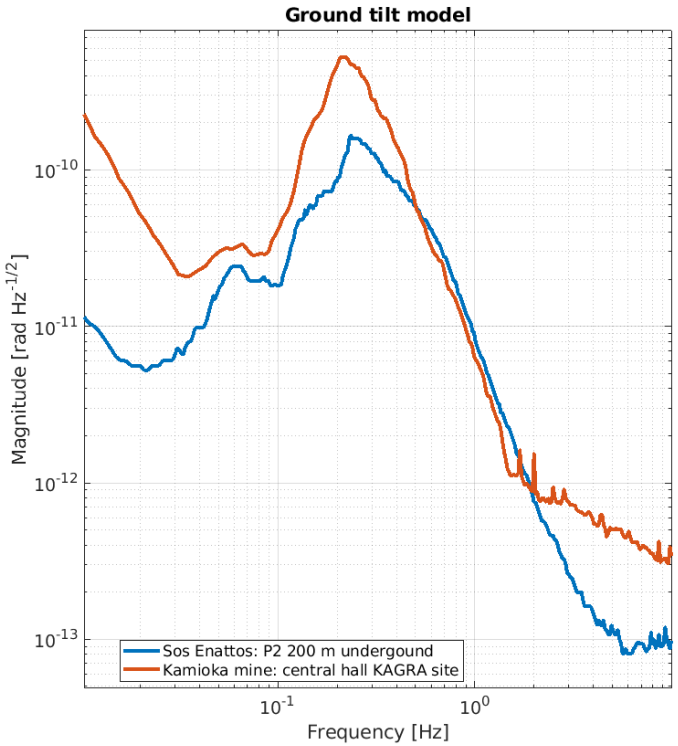
WP1 – Simulation and optimization of the Superattenuator (II)

[6] Matteo Di Giovanni et al., A seismological study of the Sos Enattos Area the Sardina candidate site for the Einstein Telescope, Seismological Research Letters, 2020.

➢ Input noise:

✓ **90-th percentile of the seismic noise measured at KAGRA* site and Sos-Enattos site in Sardina [6]**





✓ **Ground tilt noise calculated by using the empirical formula**

$$\alpha_0 = \frac{\omega}{v} \cdot x_0$$

Where the values of **v** (seismic wave speed) and x_0 are assumed to be about 3000 m/s and the vertical ground motion respectively for both sites.

	Long. (2 Hz) $[\mathrm{m} \cdot Hz^{-1/2}]$	Tilt (2 Hz) $[\boldsymbol{rad} \cdot Hz^{-1/2}]$	Long. (3 Hz) $[\mathrm{m} \cdot Hz^{-1/2}]$	Long. (3 Hz) $[\boldsymbol{rad} \cdot Hz^{-1/2}]$
Kamioka	$1.8 \cdot 10^{-10}$	$7.5 \cdot 10^{-13}$	$1.2 \cdot 10^{-10}$	$7.2 \cdot 10^{-13}$
Sos-Enattos	$1.4 \cdot 10^{-10}$	$6.5 \cdot 10^{-13}$	$4.2 \cdot 10^{-11}$	$2.8 \cdot 10^{-13}$

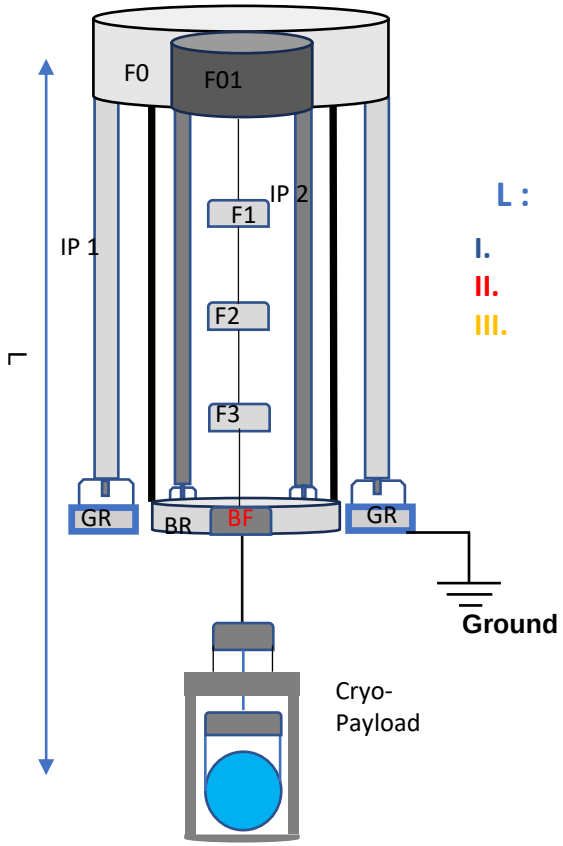
* the seismic noise data at KAGRA site are provided by T. Yokozawa from Kagra collaboration

WP1 – NIP-SA solution

NIP-SA equipped with 5 standard filters Virgo like (F01,F1,F2,F3, BF)

Total mass: 3650 Kg

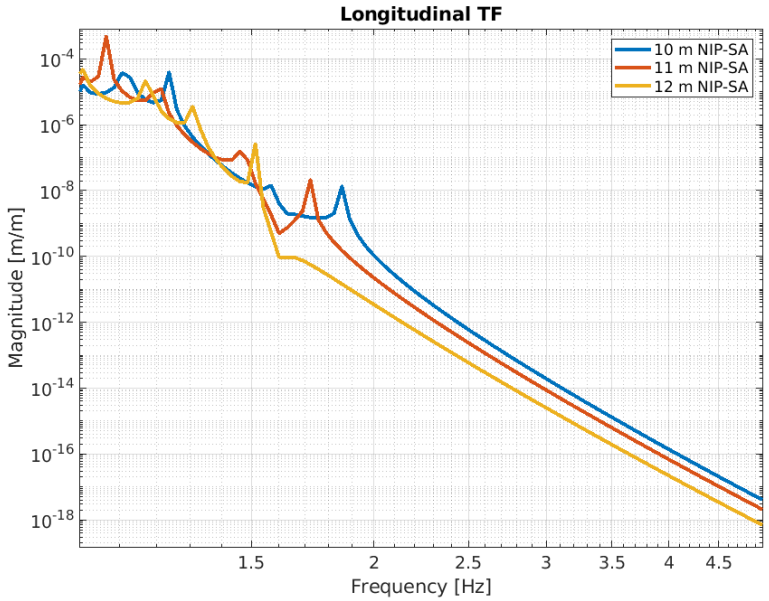
X1= Suspension point (F0)

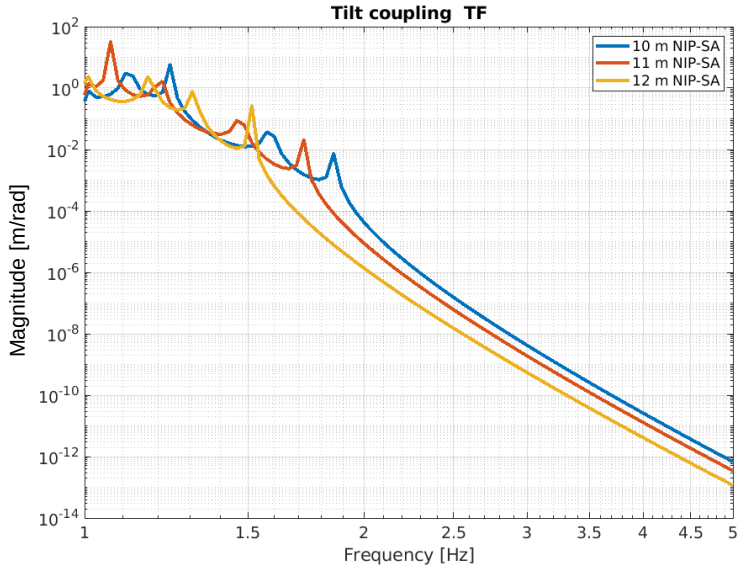


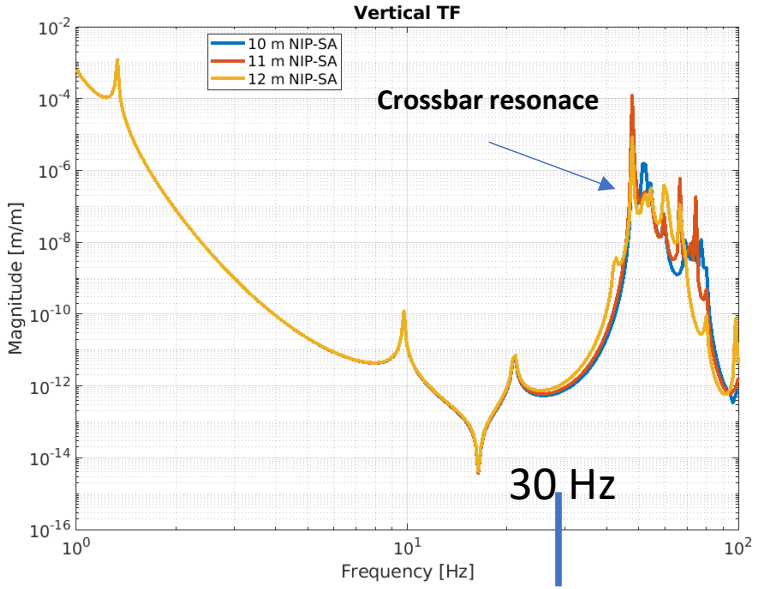
X2= Center of the mirror

L :

- I. **10 m**
- II. **11 m**
- III. **12 m**

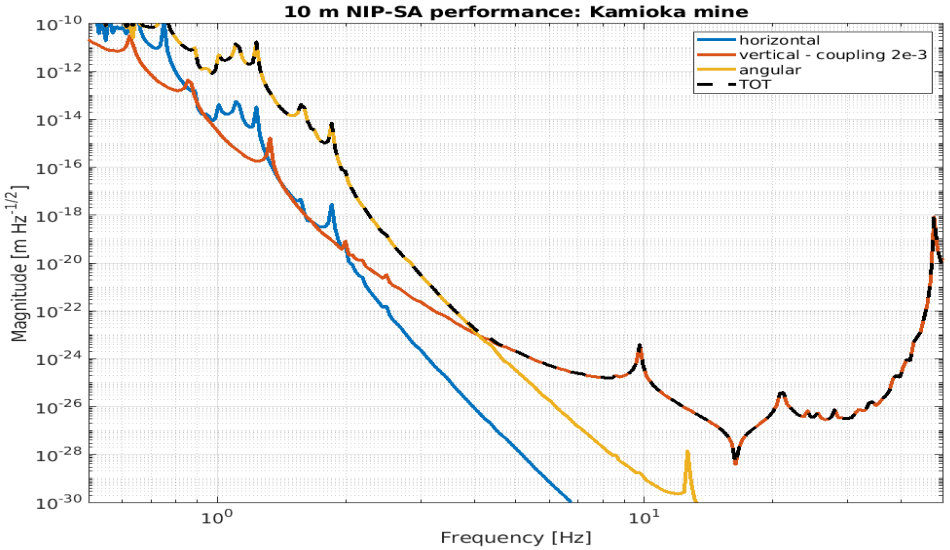


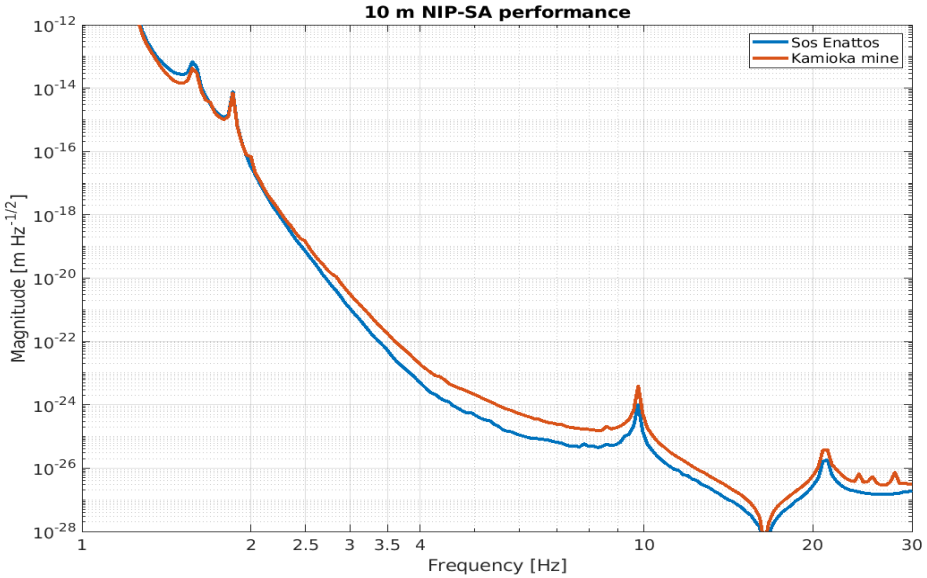


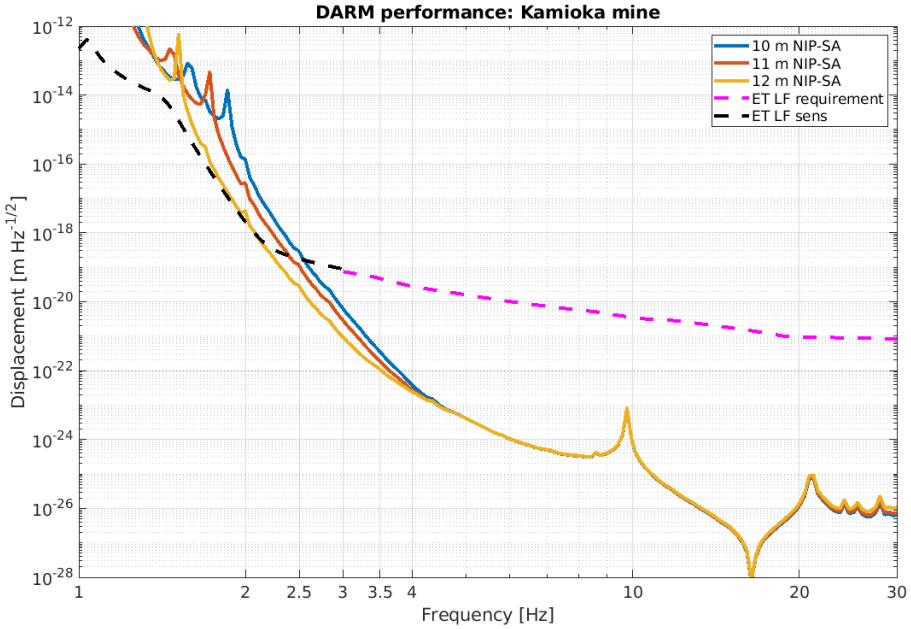


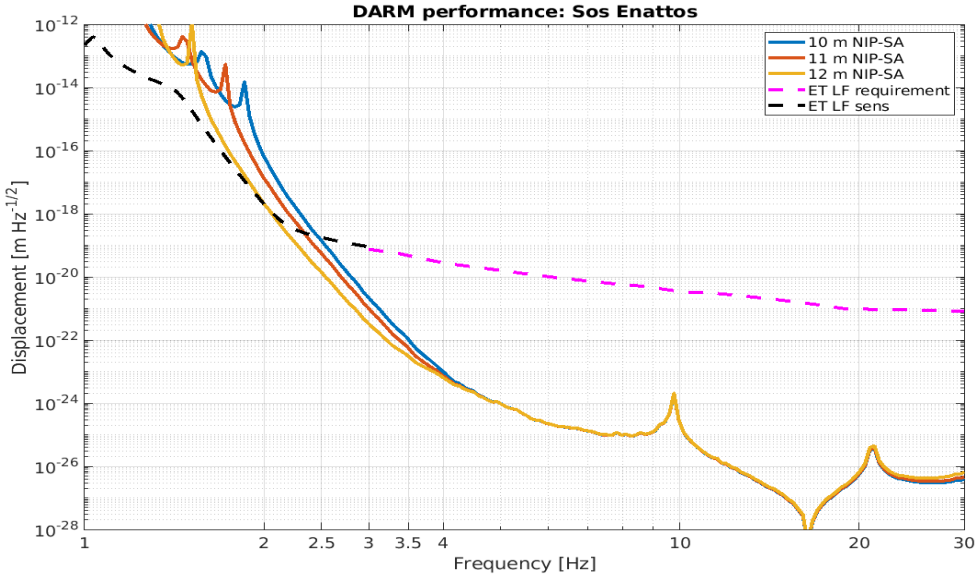
NIP-SA	Long. TF (2 Hz)	Tilt coup. TF (2 Hz)	Long. TF (3 Hz)	Tilt coup. TF (3 Hz)
10 m	$1.1 \cdot 10^{-10}$	$4.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-14}$	$4.2 \cdot 10^{-9}$
11 m	$2.3 \cdot 10^{-11}$	$9.2 \cdot 10^{-6}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-9}$
12 m	$3.5 \cdot 10^{-12}$	$1.4 \cdot 10^{-6}$	$2.5 \cdot 10^{-15}$	$5.5 \cdot 10^{-10}$

WP1 – NIP-SA results (I)



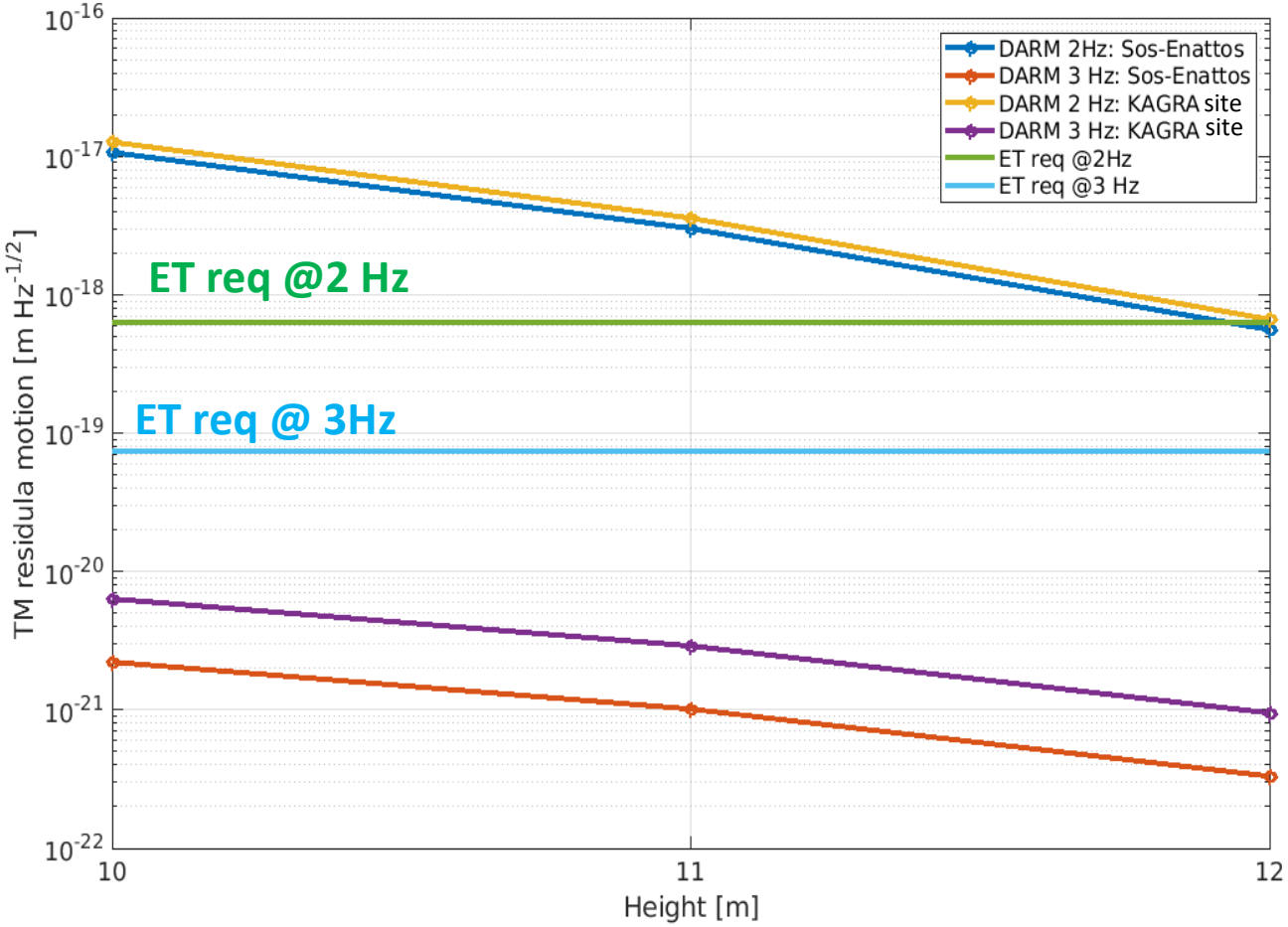






Tilt is the dominant contribution

WP1 – NIP-SA results (II)



NIP-SA	Kamioka(2 Hz)	Sos-Enattos (2 Hz)	Kamioka(3 Hz)	Sos Enattos (3 Hz)
10 m	N.C	N.C	11.7	33.4
11 m	N.C	N.C	25.6	73.0
12 m	1.1	1	78.0	223.2

- ✓ **@ 2Hz: Tilt is the dominant contribution**

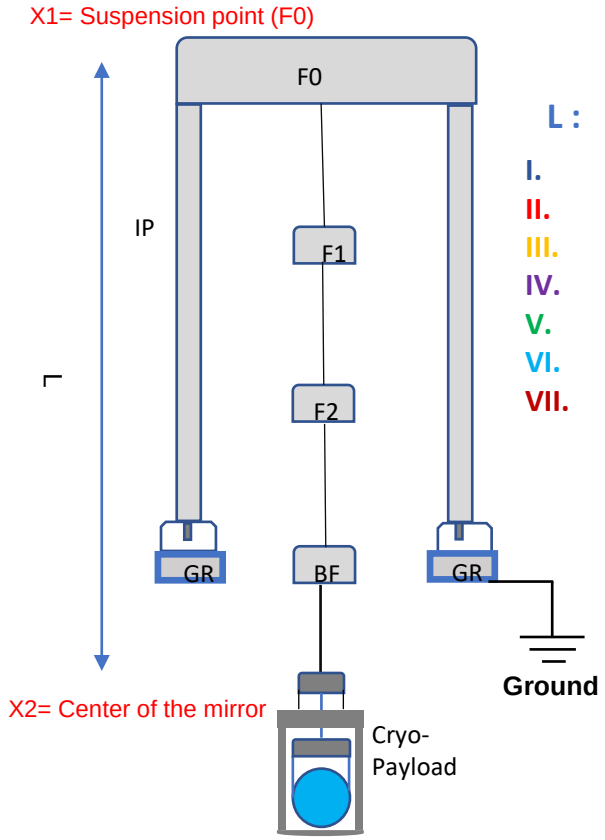
  10 m NIP-SA and 11 NIP-SA: are not compliant with the ET requirement . To suppress this excess of noise a TILT control is required

- ➢ **Next: include into the simulations the control loops**

WP1 – SA results

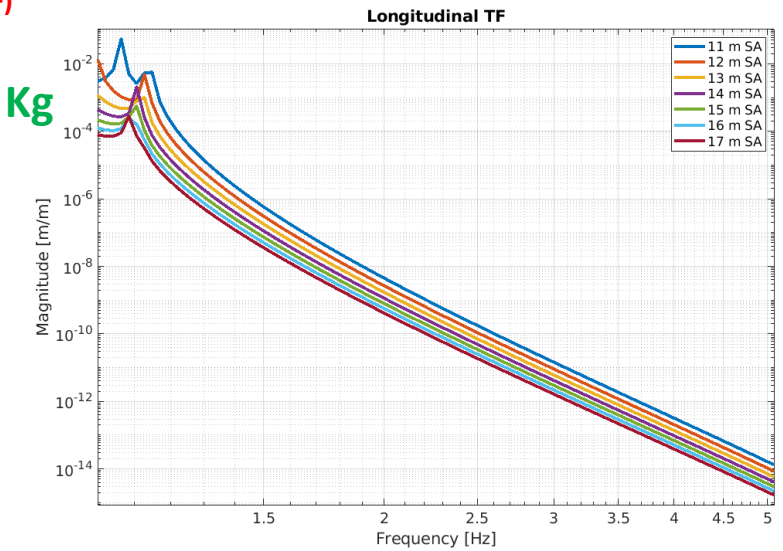
NIP-SA equipped with 4 standard filters Virgo like (F0,F1,F2, BF)

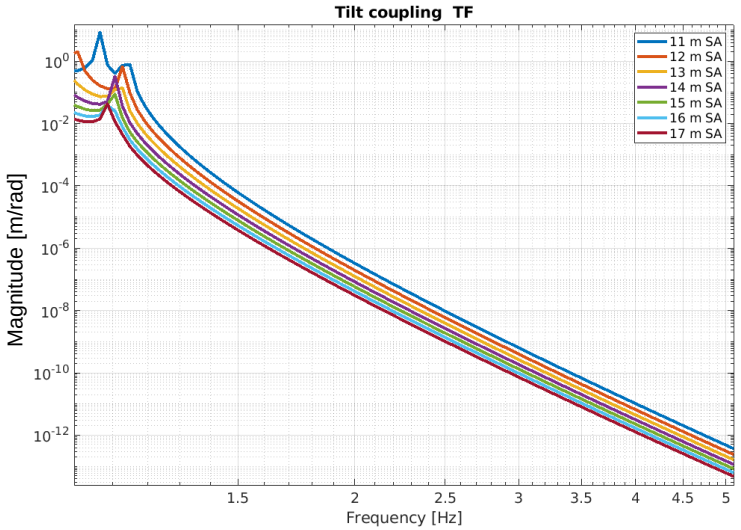
Total mass: 3650 Kg

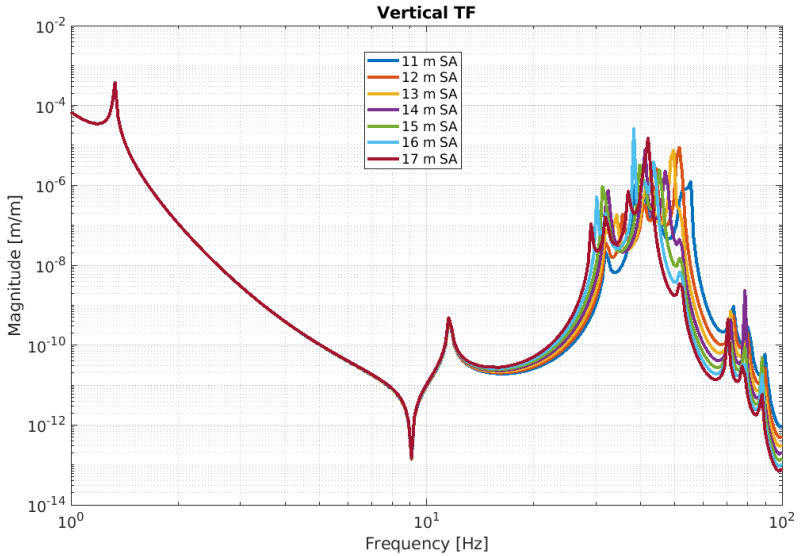


L :

- I. 11 m
- II. 12 m
- III. 13 m
- IV. 14 m
- V. 15 m
- VI. 16 m
- VII. 17 m

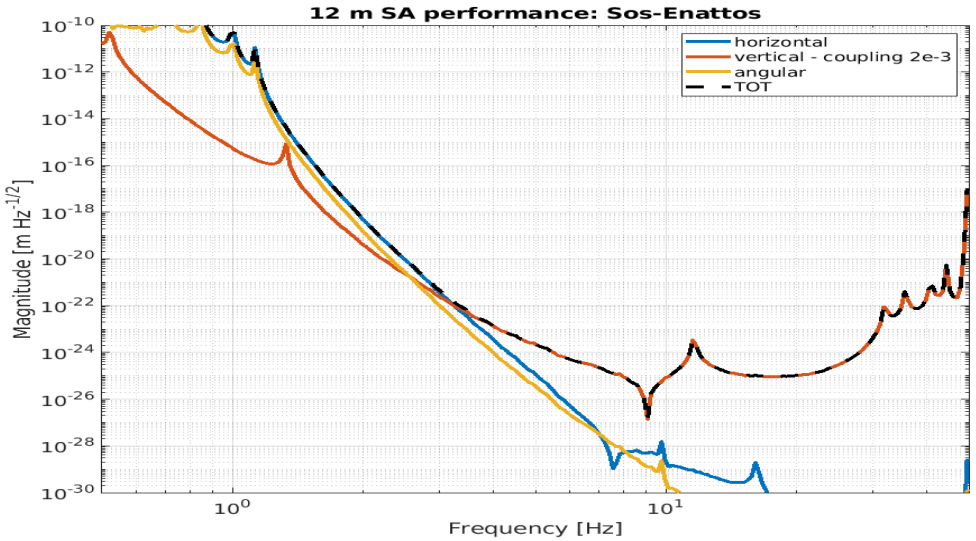


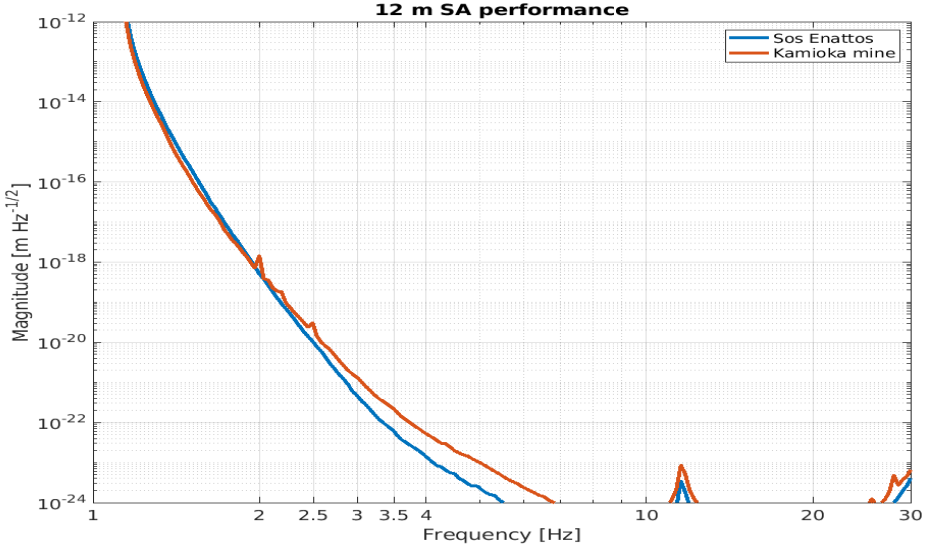


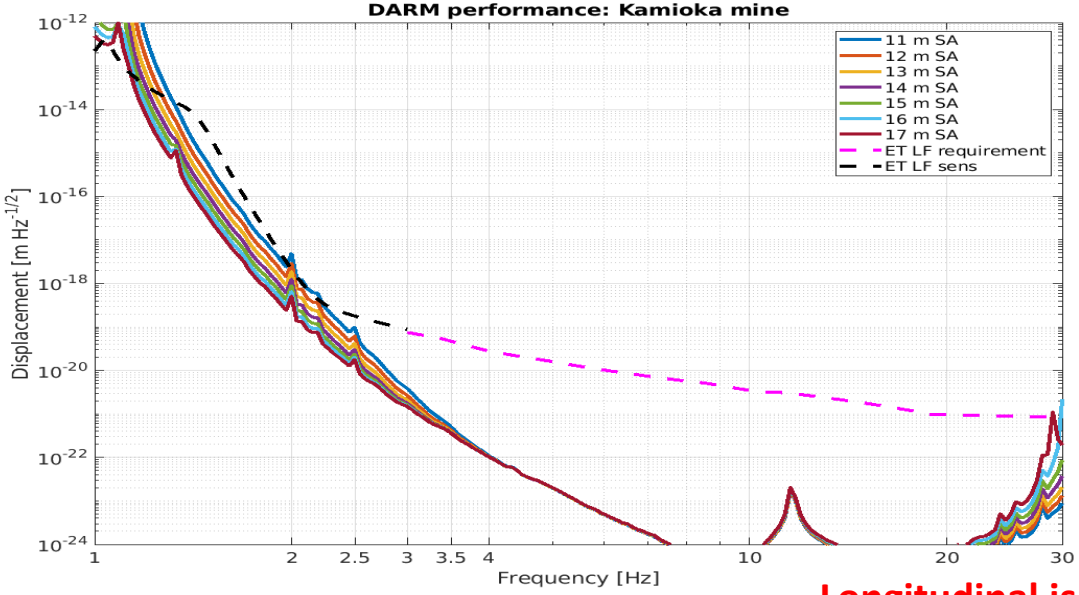


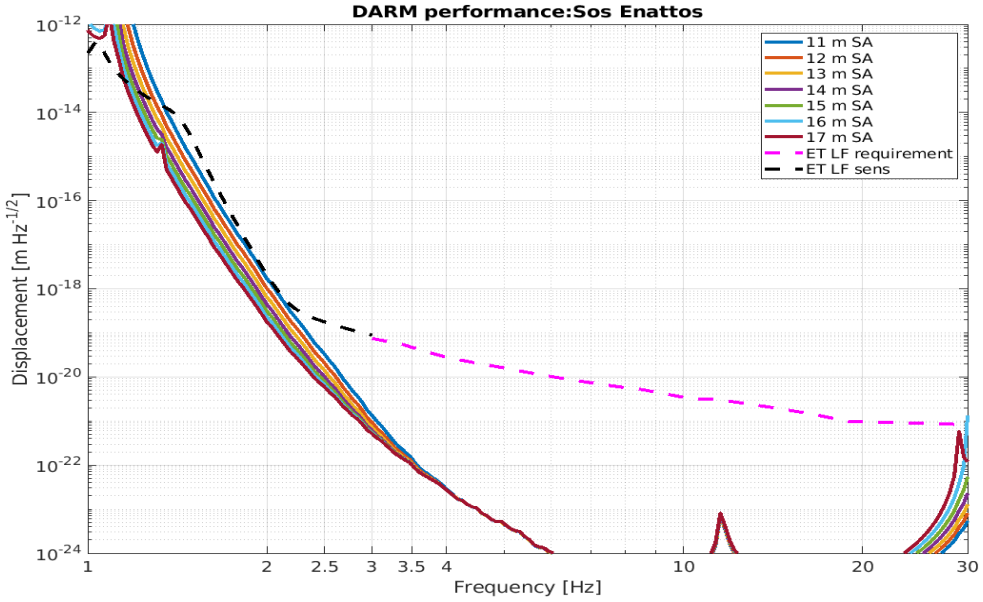
SA	Long. TF (2 Hz)	Tilt coup. TF (2 Hz)	Long. TF (3 Hz)	Tilt coup. TF (3 Hz)
11m	$4.5 \cdot 10^{-9}$	$3.5 \cdot 10^{-7}$	$1.5 \cdot 10^{-11}$	$6.3 \cdot 10^{-10}$
12m	$2.7 \cdot 10^{-9}$	$2.0 \cdot 10^{-7}$	$9.2 \cdot 10^{-12}$	$4.0 \cdot 10^{-10}$
13m	$1.7 \cdot 10^{-9}$	$1.2 \cdot 10^{-7}$	$6.0 \cdot 10^{-12}$	$2.7 \cdot 10^{-10}$
14m	$1.2 \cdot 10^{-9}$	$8.5 \cdot 10^{-8}$	$4.2 \cdot 10^{-12}$	$1.8 \cdot 10^{-10}$
15m	$7.9 \cdot 10^{-10}$	$6.0 \cdot 10^{-8}$	$3.0 \cdot 10^{-12}$	$1.3 \cdot 10^{-10}$
16m	$5.7 \cdot 10^{-10}$	$4.2 \cdot 10^{-8}$	$2.2 \cdot 10^{-12}$	$9.6 \cdot 10^{-11}$
17m	$4.2 \cdot 10^{-10}$	$3.1 \cdot 10^{-8}$	$1.5 \cdot 10^{-12}$	$7.3 \cdot 10^{-11}$

WP1 – SA results (I)



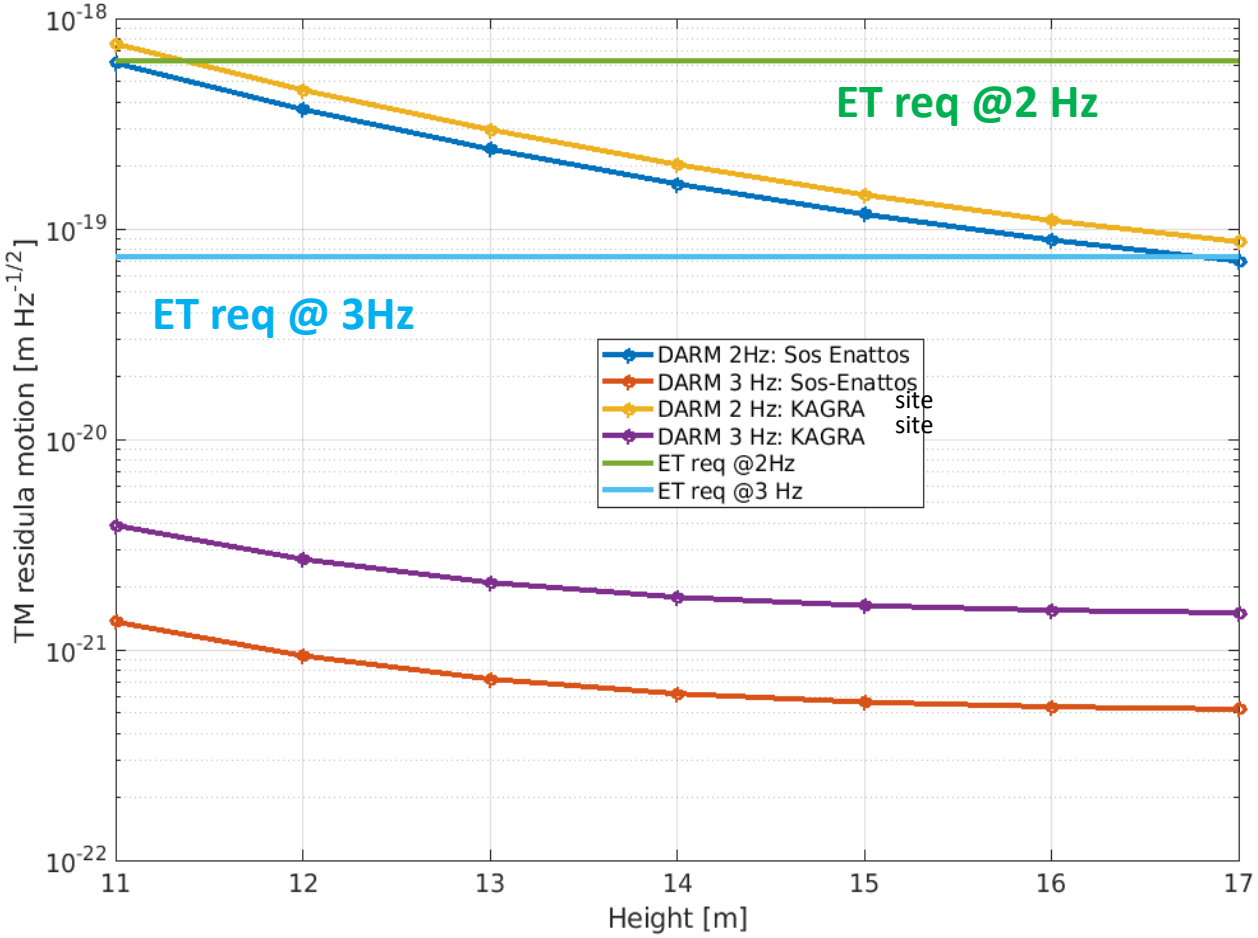






Longitudinal is the dominant contribution

WP1 – SA results (II)



SA	Kamioka (2 Hz)	Sos-Enattos (2 Hz)	Kamioka(3 Hz)	Sos Enattos (3 Hz)
11 m	N.C	1.0	19	54.6
12 m	1.5	1.7	27.5	79.0
13 m	2.2	2.6	35.5	102.0
14 m	3.2	3.8	41.6	119.7
15 m	4.3	5.4	45.6	131.3
16 m	5.6	7.1	48.0	138.0
17 m	7.3	8.9	49.4	141.9

✓ @ 2Hz: the safety factor is less than 10

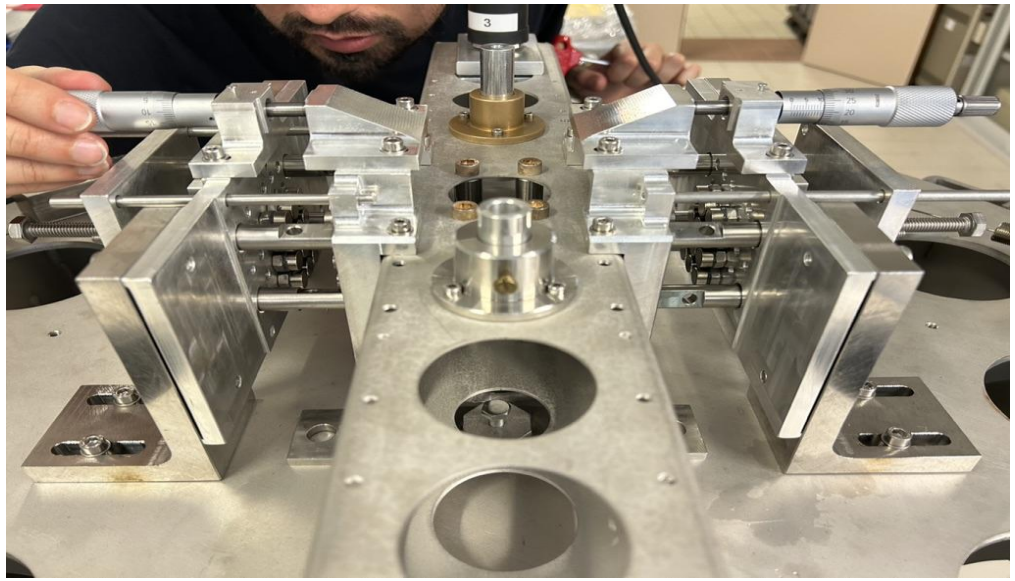
It can be improved introducing the control loops into the simulations….

➢ Next: include into the simulations the control loops

WP2 – Mechanical filter with improved Magnetic Anti-Spring (MAS)

Goals:

- Studies and development of new **Magnetic Anti-Spring (nMAS**) enhancing passive attenuation performance of seismic noise for VERTICAL d.o.f.;
- Design and optimization of mechanical filter based on nMAS with rare-earth magnets.

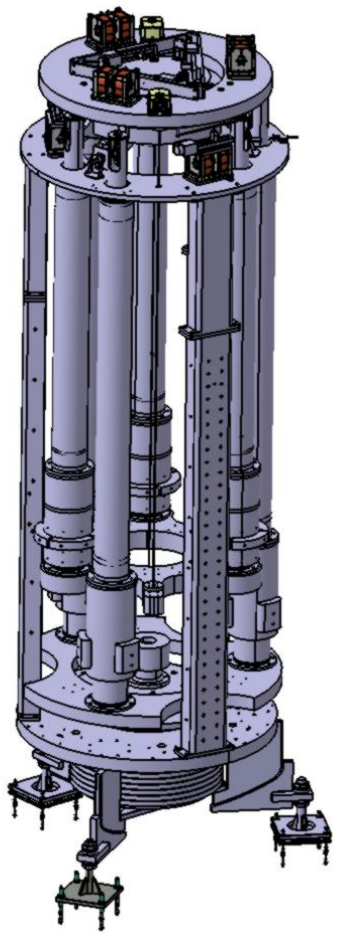


After a detailed study on **SmCo** permanent magnets (Nickel coated) and their compatibility with UHV environment, the nMAS matrices were assembled and characterized on a mechanical filter: the goal was the improvement of the performance in filtering seismic noise in VERTICAL direction.

A new cross-bar, based on nMAS has been designed and a first prototype is under preparation to be used in a long Superattenuator (about 14 m high) for CAOS facility (at Perugia University).

WP3 – Development and test of a Nested Inverted Pendulum (NIP)

➢ **Building a prototipe of NIP in 1:2 scale, in the PlaNET Laboratory at INFN-Napoli**



✓ In this context, **all the Groups involved in NGSA Project** contributed to the final design of the Superattenuator with NIP;

➢ The INFN Pisa Group has a fundamental role in defining many details of the mechanical structure, like suspension wires, IP mechanical structures, IP bottom ring and the three feet for the Active Platform, etc.;

✓ **The design is based on preliminary studies with OCTOPUS**

- Total mass 1200 kg
- Legs of about 1.7 and 1.4 m (excluding flex joints)
- Dummy mass = 600 kg

✓ **The mechanical design is supported by Octopus and FEM simulations**

The design is quite advanced:

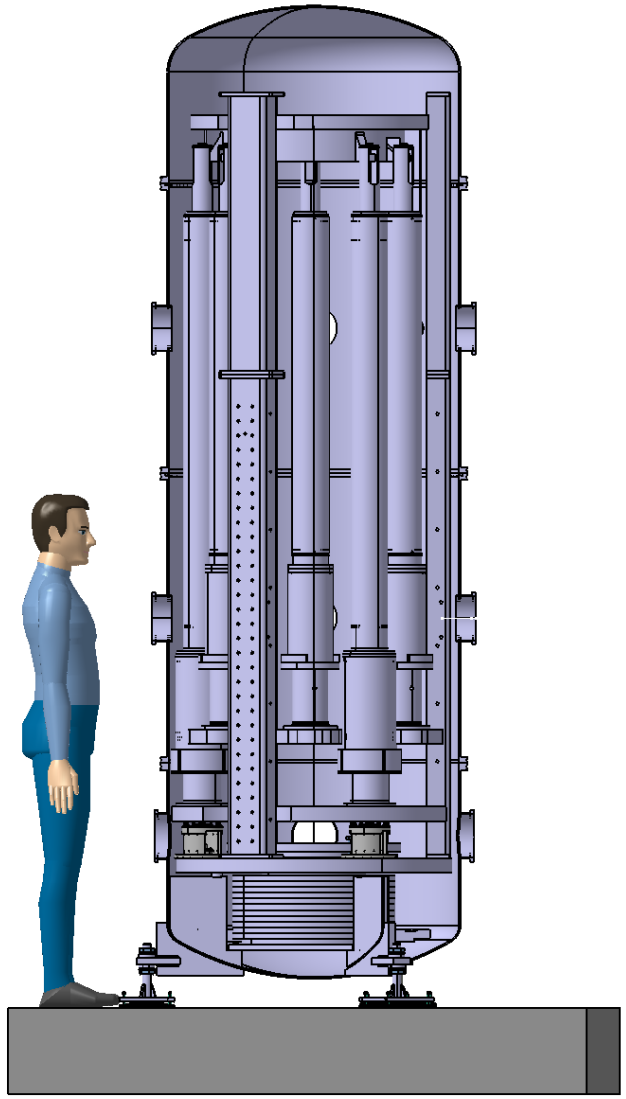
✓ Vacuum chamber base and feet (installation)
✓ Base ring, flex joints and legs (ready for the installation)
✓ Platform, dummy test mass and safety structure (ready for the installation)
✓ IP top stage and F0 (in the process of being manufactured)
✓ Sensors supports and interfaces, wire supports and junctions (defined and ready for the manufacturing process)

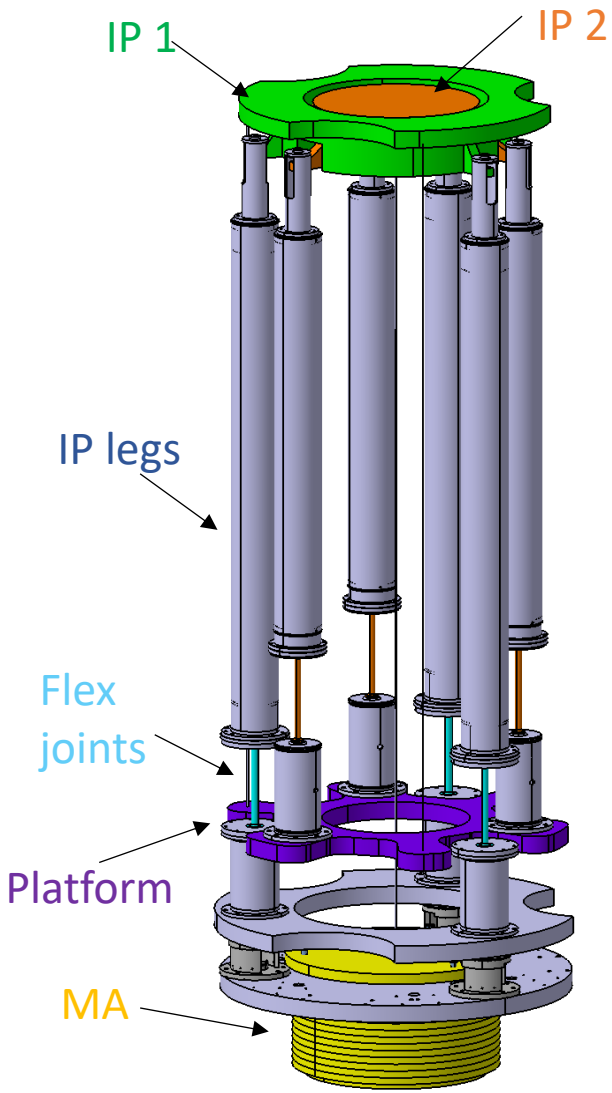
We plan to:

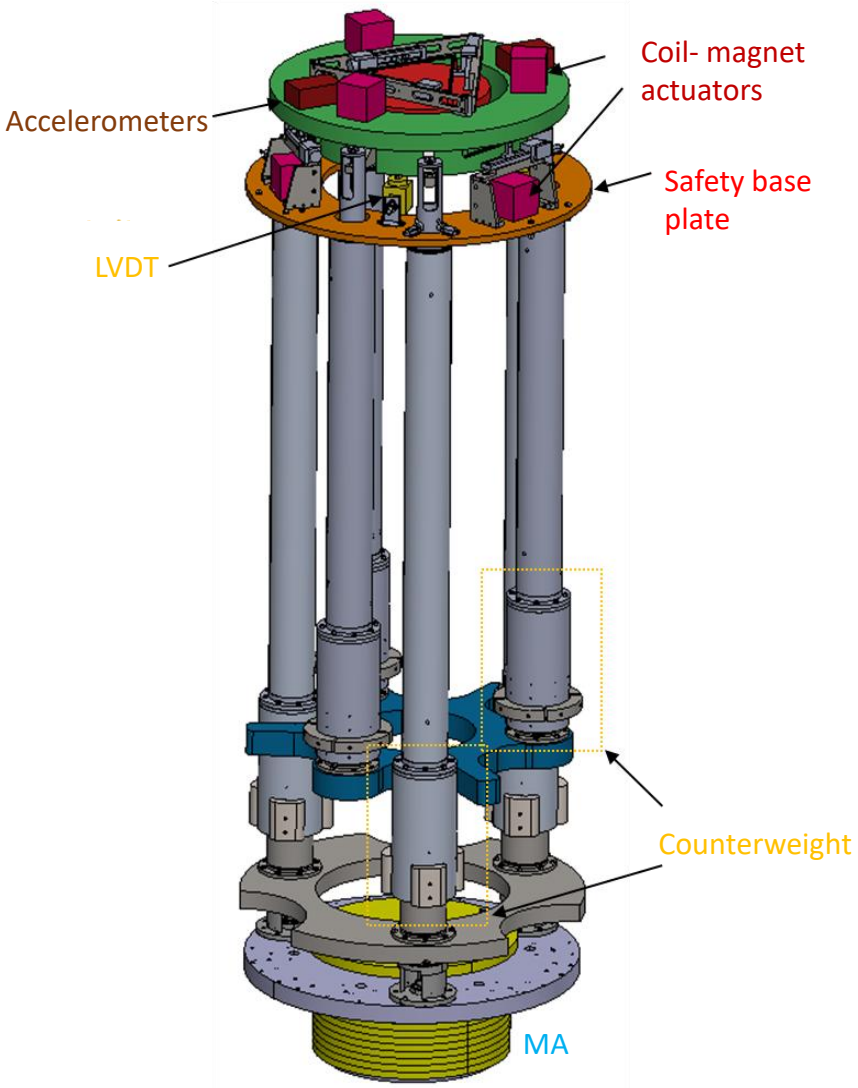
➢ Cleaning and Installation of the first components is started in the past weeks

The apparatus should be in operation by the end of 2025

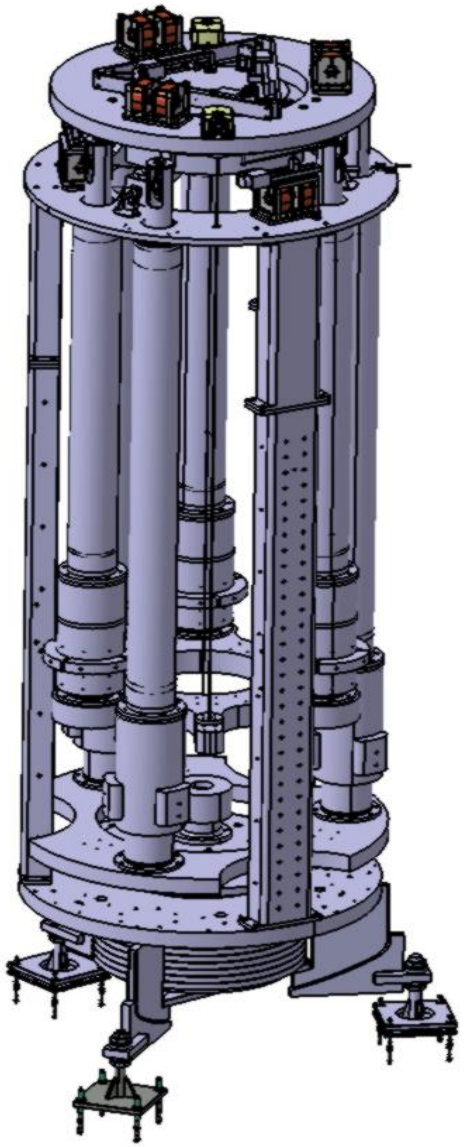
WP3 – Development and test of a Nested Inverted Pendulum (NIP)

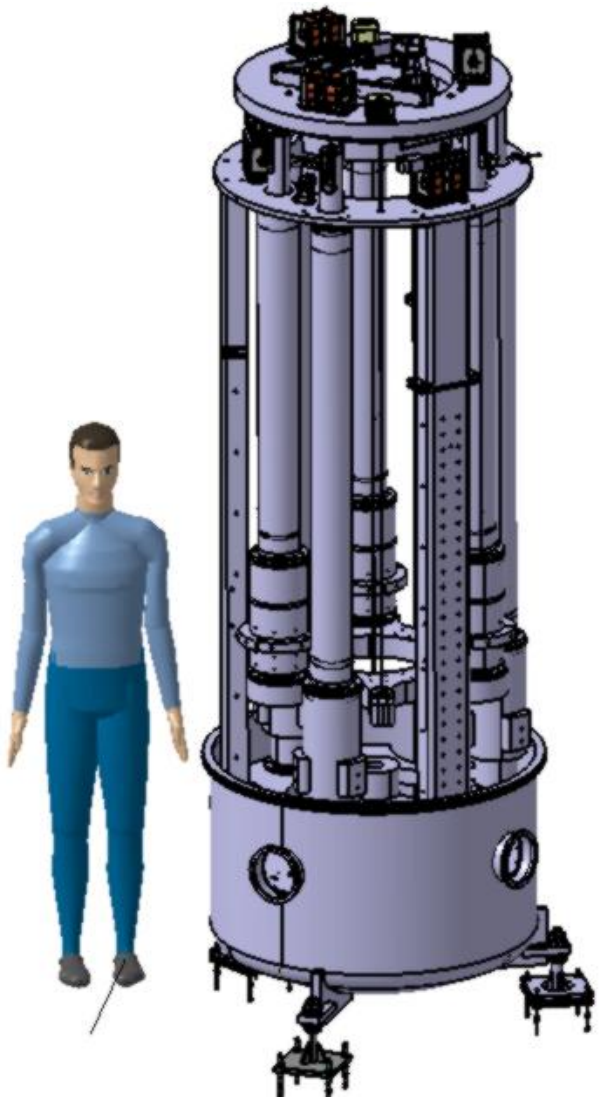


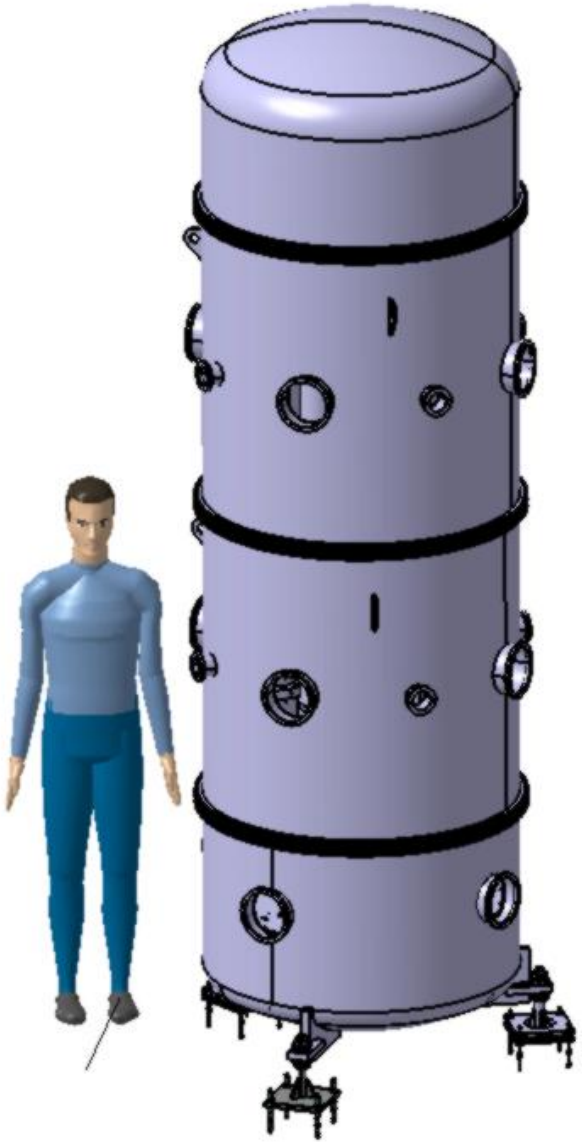




WP3 – Development and test of a Nested Inverted Pendulum (NIP)







WP3 – assembling dummy mass (collage)

WP4 – Sensing and Control (S&C)

A first list of type of sensors, actuators, motors, ADC, and DAC channels is available

Stadio	LVDT	Accelerometri	ORO	ADC	DAC-A	DAC-B	Bobine/ magneti	Motori
IP	3	3 (monoassiali)	-		3	3	3	3 (per le molle)
BR	-	-	3	9-12	3 (6 ?)	-	3 (6)	6 per ORO
F0	-	-	3	9-12	3 (6 ?)	-	3 (6)	6 per ORO
TM	-	1 (triassiale)	-	3	3			

These components were defined, procured and ordered.

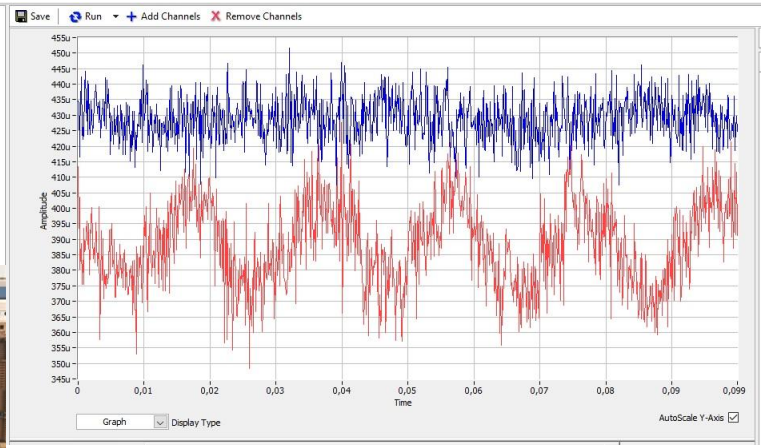
DAC_A 24 bit, 2 channels per card - DAC_B 16 bit, 6 channels per card

National instrument input/output hardware based on LabView software has been identified for the data acquisition and control and ordered:

- Crate, CPU DAC and most relevant components/boards arrived @ INFN Pisa
- Preliminary configuration and arrangement in progress
- In the process of defining custom-made coil-magnet actuators to control both IP of NIP-SA (work in progress)

ELECTRONIC SETTINGUP

- Acquisition and control electronics are available, tests are ongoing



- Controller NI PXIe-880 Xeon 8-Core – LabVIEW RT
- Module AI 6 channels 24-bit PXIe-4480 1.25 MS/s
- Module AO (Analog Output), 2 channels 24-bit, PXIe 4463

- **Development of feedback control system based on commercial electronics and LabView software**
  - **We expect to have everything ready to start operations after the prototype assembly (first half of 2025).**

Outline

- Introduction
- NGSA: Scientific goals
- NGSA: organization and the present status of the project
- **Next steps and perspective**

Conclusions

- ✓ The NGSA is devoted to the development of a new generation seismic isolation system with the goal to improve the attenuation performance of the system with the possibility to reduce the total height of the system SA with respect to the present reference solution

- ✓ The project is organized in two research lines:
  - ➢ Optimized SA with the AdV architecture and improved nMAS
  - ➢ New architecture SA with a two stage NIP (+ optimized chain and improved nMAS)

- ✓ A NIP prototype (in 1:2 scale) is under development and will be tested for checking reliability and performance

- ✓ The final outcome will be a conceptual design of the Seismic isolation system for the Einstein Telescope (ET)

- ✓ First results are expected by the end of 2025

References

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[2] P. Ruggi, *L'attenuazione del rumore sismico nel rilevatore di onde gravitazionali Virgo*, thesis (2003). https://tds.virgo-gw.eu/ql/?c=16268

[3] L. Trozzo, Low Frequency Optimization and Performance of Advanced Virgo Seismic Isolation System , PhD thesis (2018). https://tds.virgo-gw.eu/ql/?c=13271

[4] P. Ruggi, M. Pinto, L. Trozzo et al OCTOPUS: a mechanical simulation tool based on impedence matrices. (accepted for pubblication to PRD)

[5] Bertocco et al, New Generation of Superattenuator for Einstein Telescope: preliminary studies", A, *Class. Quantum Grav.* 41 (2024) 117004 (14pp) *ET TDS link: https://apps.et-gw.eu/tds/ql/?c=17333

[6] L. Trozzo, at al., A Nested Inverted Pendulum as a possible pre-isolator for the ET-LF Seismic Isolation System , Galaxies, 2025,13 (2),21. https://www.mdpi.com/2075-4434/13/2/21

Thanks for your attention!