The seismic isolation system of AdVirgo+ Phase II

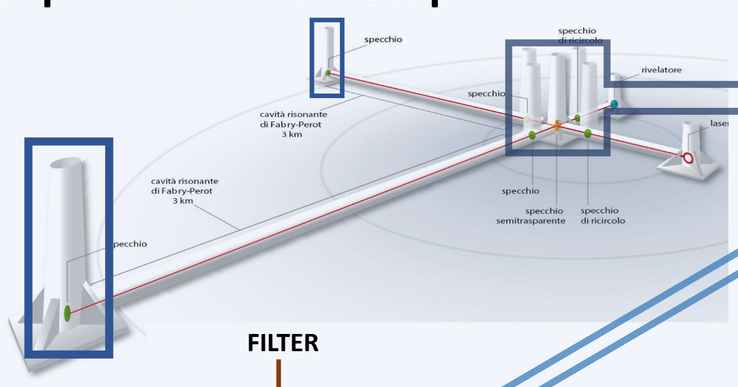
A. Basti, V. Boschi, P. Chessa,
V. Dattilo, R. Passaquieti, P. Ruggi

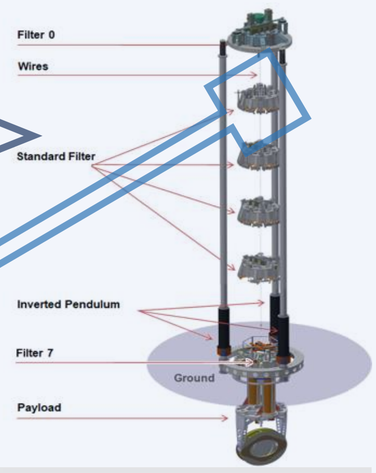
1 Istituto Nazionale di Fisica Nucleare (INFN)
2 Università di Pisa
3 European Gravitational Observatory

By the end of 2024, the Advanced Virgo+ gravitational wave interferometer (AdVirgo+) will undergo a major upgrade, called Phase II and aimed at a reduction of thermal noise and an extension of the observing horizon to more than 150 Mpc.
The laser beam size will be enlarged on end test masses and better coatings will be implemented on mirrors to lower mechanical losses. In particular, end mirrors will be larger (55 cm in diameter) and heavier (104 kg) to deal with the larger beam size.
The seismic isolation of AdVirgo+ mirrors and suspended benches will be provided by an upgraded version of the SuperAttenuator (SA), a passive attenuation system capable of reducing the seismic noise by more than 10 orders of magnitude in all six degrees of freedom above a few Hz.

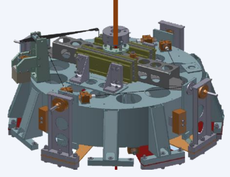
The new end mirrors will require a re-scaling of the payload and, consequently, a re-design of all the elastic elements of the end SAs (blade springs, suspension wires, magnetic AntiSprings and Inverted Pendulum flex joints), in order to sustain the new loads without significant changes of the resonant frequencies. Several studies are being performed in order to design and validate the required mechanical updates.
Such studies are also providing useful insights on the design of seismic isolation systems for the third generation detectors.

SuperAttenuator recap





FILTER



6 DOF Seismic isolator
=
Horizontal Isolator: pendulum
(~ mass independent)
+
Vertical Isolator: Spring-AntiSpring device
(mass dependent)

WORKING PRINCIPLE

If we neglect the cross coupling between the DOFs, the *i*-th DOF has a transfer function:

$$T_i(f) = \frac{f_i^2}{f_i^2 - f^2 + 4\pi^2 \mathrm{j} \frac{f_i f}{Q_i}}$$

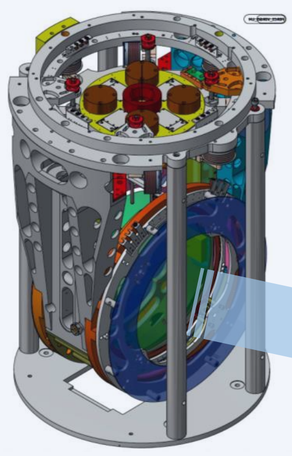
where the resonant frequencies f_i and quality factors Q_i are typically set to 0.5 Hz and 50, respectively.
Seismic waves with frequency $f >> f_i$ are transmitted by the filter with gain

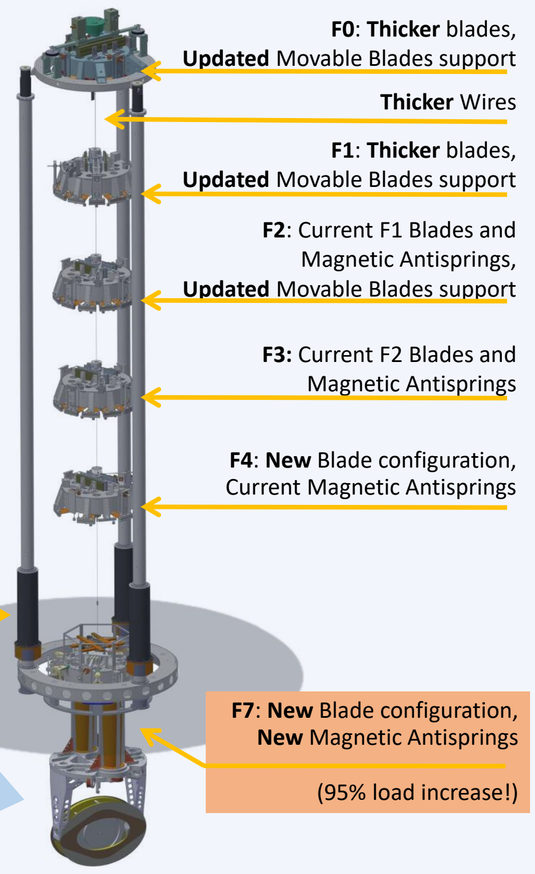
$$(f_i / f)^2$$

New large mass end mirrors

Physical quantity (SI units)	Phase I	Phase II
Mirror mass	42	**104.4**
Marionette mass	103.7	**180.6**
F7 mass (total) • Body+interface • **Actuation cage**	315 120 195	**345** 120 **225**
Total mass below F7 blades	145.7	**285**
Total mass below F4 blades	460.7	**630**

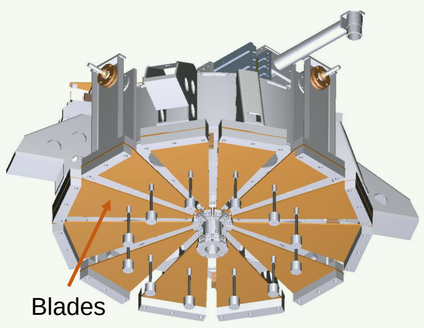
LARGE MASS PAYLOAD



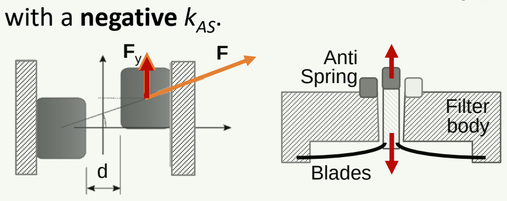


Filters: vertical resonant frequency

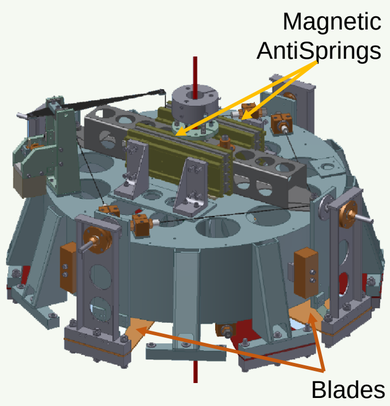
Each filter supports the weight of the subsequent chain of filters by means of pre-bended **elastic maraging blades**. The blades must be stiff enough to support load. Such stiff **springs** have a high vertical resonant frequency (~ 1.5 Hz).



The springs are coupled with **magnetic AntiSprings**, exerting an force $F = -k_{AS} \cdot y$ with a **negative** k_{AS}.



The total elastic force $F = -(k_{blades} + k_{AS}) \cdot y$ is set to give a vertical frequency f_v = 0.3 Hz.



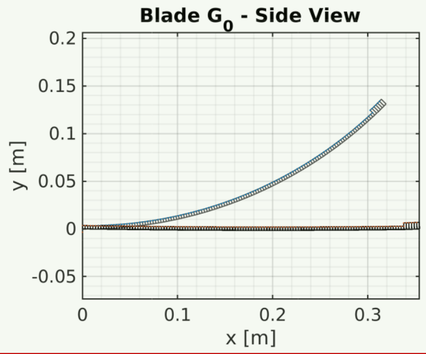
Current **blades** must be changed with **stiffer** blades, to support the increased load. Resonant frequency must be kept to reference (1.5 Hz) while keeping **stress** within 0.5 UTS (0.92 GPa).

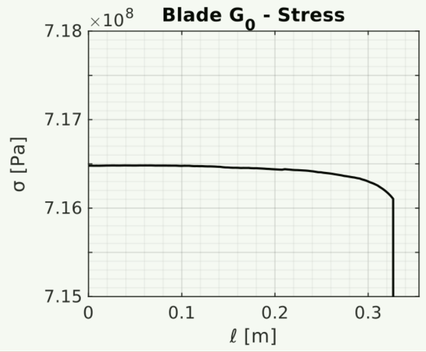
Magnetic AntiSprings must be re-tuned or re-designed to increase the antielastic constant k_{AS}.

Simulations have been developed to check new blades and develop new AntiSprings.

Blades

Simulation of new Filter 7





Overall filter tuning

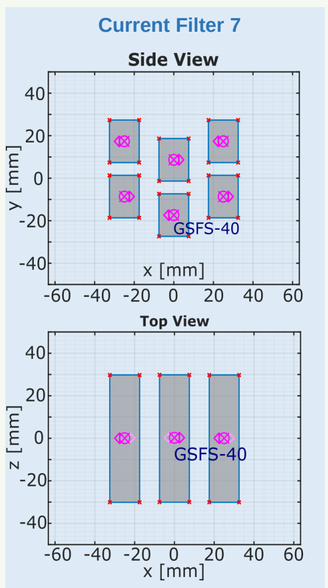
FILTER SUMMARY
Total stiffness: (20000 ± 1000) N/m
Frequency: (1.34 ± 0.03) Hz

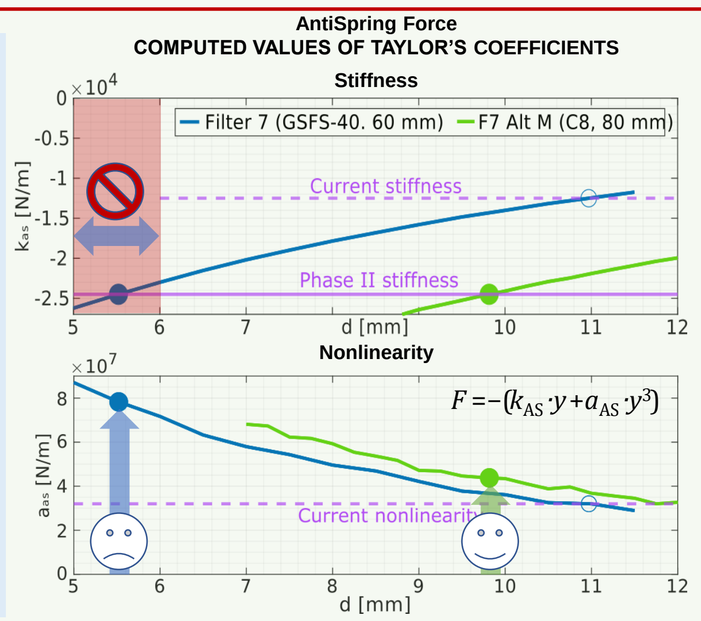
FIXED BLADES
Load: (470 ± 30) N
Stiffness: (3400 ± 200) N/m
Stress: (0.75 ± 0.04) GPa

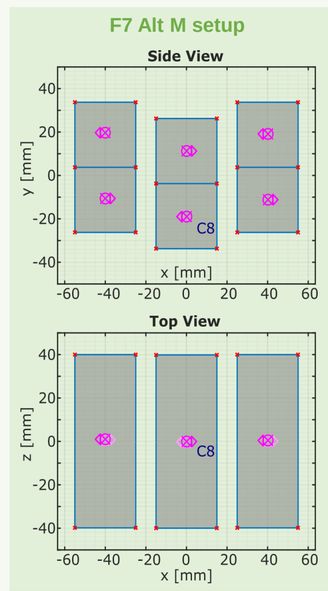
MOVABLE BLADES
Angle: (-1 ± 6) deg
Load: (500 ± 100) N
Stiffness: (3400 ± 200) N/m
Stress: (0.7 ± 0.2) GPa

Magnetic AntiSpring

Setup and simnulation of new Filter 7





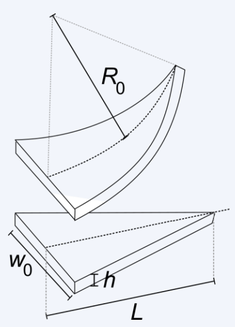


New blade equipments

Filter 0 and **Filter 1** have filled out blade slots (with the stiffest preset blades available)
⇒ Stiffer blades have to be designed.

Simple laws apply to the **flattening load** of pre-bended triangular blades and the **stress** of the loaded blades:

$$L = E \frac{h^3 w_0}{12\, L\, R_C}\ ,\ \sigma = E \frac{h}{2\, R_C}$$ (E = Young modulus).



Thickness ***h* is increased** from 3.5 mm to 3.7 mm => { **Load increased** / **Stress ≈ constant**

UPGRADED BLADE SERIES
10 kinds of **preset blades**: A_0, B_0, ..., G_0 (h = 3.5 mm) + **A_1**, **B_1**, **C_1** (h = 3.7 mm)

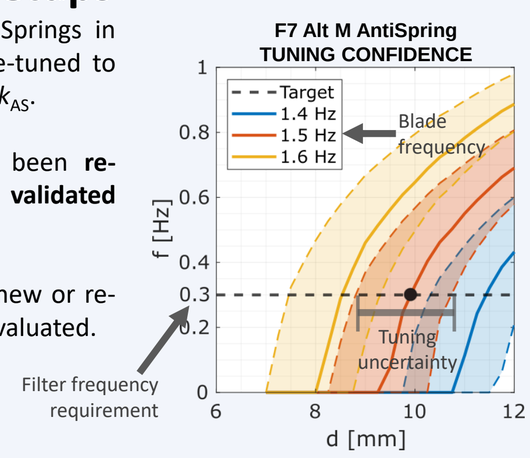
Filter #	Load [kg]	Blades	Nominal Load [kg]	Load Mismatch [kg]	Total Stiffness [N/m]	Res. Freq. [Hz]
0	1223	8·**A_1** + 4·**B_1**	1275	52	**108644**	**1.53**
1	1050	8·**C_1** + 4·**B_1**	1113	63	**93277**	**1.54**
2	885	8.C_0 + 4·B_0	942	57	**78620**	**1.55**
3	745	6·D_0 + 4·B_0	771	26	**66185**	**1.53**
4	630	4·D_0 + 4·B_0	625	-2	**55703**	**1.50**
7	285	**6**·G_0	290	3	**25493**	**1.51**

New AntiSpring setups

Simulations indicate that AntiSprings in filters 0 to 4 can be simply re-tuned to the required negative stiffness k_{AS}.

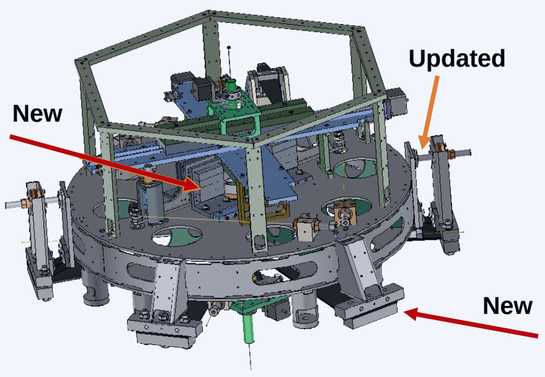
AntiSprings of Filter 7 have been **re-designed** and **experimentally validated** at INFN Pisa.

The tuning confidence of the new or re-tuned AntiSprings have been evaluated.



Filter #	Load [kg]	Blades stiffness [N/m]	AntiSpring stiffness [N/m]	AntiSpring tuning [mm]	Compared nonlinearity [Phase II / I]
0	1223	108644	- 104298	**9.5**	**1.07**
1	1050	93277	- 89546	**7.5**	**1.03**
2	885	78620	- 75475	**8.5**	**1.03**
3	745	66185	- 63537	**10**	**1.00**
4	630	55703	- 53475	**11.5**	**0.72**
7	285	25493	- 24473	**9.8**	**0.67**

Filter 7 design upgraded



Perspectives

Phase II upgade is designed and a prototype of new Filter 7 is being assembled and studied.
AdVirgo+ will run with the new configuration in the fifth observation period O5 expected to start in Dec 2024.

Based also on these results, new generation attenuators are currently being studied.