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Advanced Virgo Plus: Future Perspectives

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Advanced Virgo Plus: Future Perspectives

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Abstract. While completing the commissioning phase to prepare the Virgo interferometer for the next joint Observation Run (O4), the Virgo collaboration is also finalizing the design of the next upgrades to the detector to be employed in the following Observation Run (O5). The major upgrade will concern decreasing the thermal noise limit, which will imply using very large test masses and increased laser beam size. But this will not be the only upgrade to be implemented in the break between the O4 and O5 observation runs to increase the Virgo detector strain sensitivity. The paper will cover the challenges linked to this upgrade and implications on the detector's reach and observational potential, reflecting the talk given at 12th Cosmic Ray International Seminar - CRIS 2022 held in September 2022 in Napoli.

1. Introduction

The Advanced Virgo Gravitational Wave Antenna is a kilometer-scale, Fabry-Perot-enhanced, dual recycled Michelson interferometer located in Italy, close to Pisa [1]. The Advanced Virgo interferometer has detected, together with the two LIGO interferometers located in the USA [2], an impressive collection of Gravitational Wave (GW) emissions from Astronomical sources in the last observation runs O2 and O3. Indeed, during the O2 observation run, just after the joining of the Advanced Virgo detector to the GW-antenna network, a triple coincidence signal was observed by the three detectors. Such a signal triggered the observations of an Electromagnetic counterpart which was the first Multi-messenger event (GW170817,[3]). Furthermore, during the last observation run (O3), which lasted about one year of data taking from April 2019 to March 2020, about 80 gravitational waves were also detected by the joint GW detector network LIGO-Virgo.

Even an ideal interferometer will encounter limits to its strain sensitivity which are dictated by Physics laws or by the fact that it is ground-based. For instance, even with ideal isolation from seismic noise, the low-frequency region of the strain sensitivity will be limited by the displacement noise of the mass distribution around the interferometer test-masses: the Newtonian Noise [4]. At some frequencies (around 40 Hz for current technologies and configuration) the Newtonian

Noise is overcome by another fundamental noise: the thermal vibration noise of the test-mass mirror surfaces. This noise is due to the coating mechanical friction and is sensed by the laser beam wave front reflected off the test masses [5]. At higher frequencies, it is the Quantum nature of the light which eventually sets a limit to the faintest possible signal an interferometer is able to detect [6].

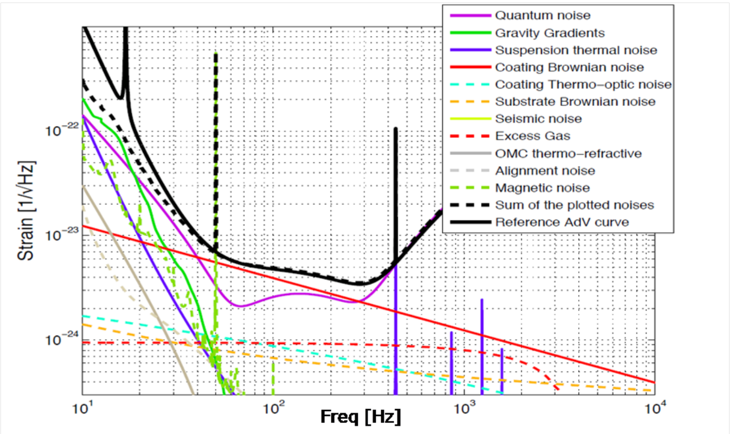

Figure 1. An example of the limiting noises in a dual recycled GW interferometer. The cumulative power spectral density for the residual strain noise is plotted against frequency for the detection bandwidth. The breakdown of the noise budget is computed via GWINC. From the Advanced Virgo Technical Design Report [7]

After the O3 observation run, the Advanced Virgo detector started its upgrade to the Advanced Virgo Plus (AdV+) configuration to further improve the sensitivity [8]. These improvements concerned both the residual technical noises and the impact of fundamental noises. It is staged in two phases: the phase 1 aims to reduce the quantum noise affecting the interferometer and make the thermal noise the ultimate limit of the Virgo sensitivity. This phase will be completed before the foreseen O4 run, together with the LIGO and Kagra detectors, which is currently due to start in March 2023 [9].
A second phase will then start after the completion of the Observation Run 4 (O4) and will be aimed to reduce the impact of the thermal noise on the AdV+ strain sensitivity. It will be completed by the beginning of the Observation Run 5 (O5), currently foreseen at the beginning of 2026.

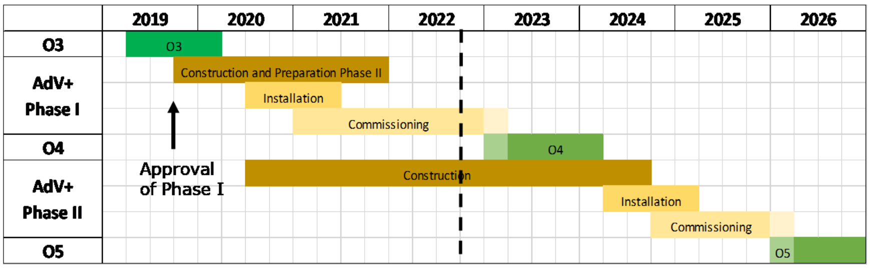

Figure 2. The schedule for the two-staged Advanced Virgo Plus project. In the first phase the aim is to reduce the quantum noise and hit the thermal noise wall, while in the second phase the thermal noise impact on the interferometers gets reduced.

2. The second phase of the Advanced Virgo Plus Project

In order to push down the limit imposed by the thermal noise to the sensitivity, a combination of approaches can be used: 1) reduce the thermal noise source by a) going to cryogenic temperatures, b) reducing the mechanical friction inside the coating; and 2) improve the optical design so that the interferometer is less sensitive to the thermal noise, as described in [5]:

$$S_x(f) \propto \frac{Td}{w^2}\left(\frac{Y_C}{Y_S}+\frac{Y_S}{Y_C}\right)\phi_C \tag{1}$$

where $S_x(f)$ is the power spectral density of the strain noise due to the displacement noise of the mirror surface, T the equilibrium temperature, d the coating thickness, w the Gaussian beam radius on the mirror, Y_S and Y_C the Young moduli of the substrate and coating materials, and ϕ_C the mechanical loss angle of the coating stack. While the solution 1a) is enticing, its deployment means a very invasive hardware change and it is not mature enough in terms of technology for the GW interferometers. The chosen approach for AdV+ phase II is then to improve the coating loss angle ϕ_C and enlarge the beam size. The beam size will be significantly enlarged only on the end test masses (ETMs) where the reflectivity requirements imply a large number of coating layers [10].

2.1. Implication of a larger beam: a tighter control for less stable resonators

The design of a larger beam on the ETMs has a large impact on the whole detector. The most obvious is that also the diameters of the ETM mirrors have to be proportionally enlarged. In the design of the arm Fabry-Perot resonator to obtain the large beam on the ETMs, the proven substrate production capabilities, the vacuum link apertures and the interferometer sensing and control were into account. The size of the ETMs was decided to be 55 cm diameter (from the current 35 cm), equal in size as the currently used beam-splitter mirror in Advanced Virgo, while keeping the current thickness of 20 cm, so resulting in a mass of roughly 100 Kg from the current 42 Kg. The size of the beam which can be allocated on the new ETMs was therefore increased to 96 mm from the current 58 mm.

The radii of curvature (RoC) for both the ETMs and the Input Test Mass (ITM) mirrors were adjusted to provide such an eigenmode for the arm Fabry-Perot: the ETM RoC is 1683 m for AdV+ phase I and will be 1969 m for phase II, while the ITM RoC will change from the current 1420 m to a shorter 1067 m. Also the RoC of the recycling mirrors will have to adapt to these values, and in turn all the mode-matching telescopes at the ports of the interferometers will have to be modified. A consequence of this revised design is that arm Fabry-Perot resonator will have a cavity g-factor closer to the 1 [11], so closer to optical instability region, requiring not only more stringent control of the optical aberrations and figure errors of the core optics, but also a more demanding angular control during the interferometer operations.

The Thermal Compensation System (TCS) will also play a major role in controlling the aberrations induced by the high power circulating in the interferometer [12]. Indeed the foreseen injected power will be of the order of 80 W, a factor two larger than what expected for phase I. In order to cope with the more delicate inteferometer, a large upgrade of the TCS is foreseen both in terms of actuators (thermal projectors, CO_2 lasers, ring heater for correcting core-optics RoC) and sensors (Phase cameras and Hartman Wavefront sensors).

2.2. Mirrors and coatings

The larger beam will be accommodated on larger ETMs. The substrates for producing such mirrors have already been procured and the polishing started in December 2021. This is a very delicate and long process to ensure that the surface error is within the tight requirements. Several upgrades at the Laboratoire des Matériaux Avancés are then needed to properly coat these substrates, including the tools for handling the substrates, the upgrades of the Grand Coater machine, the improvements for the cleaning tools. Also the metrology needs to be largely upgraded, in order to provide increased accuracy for the scattering, absorption, and geometry measurements.

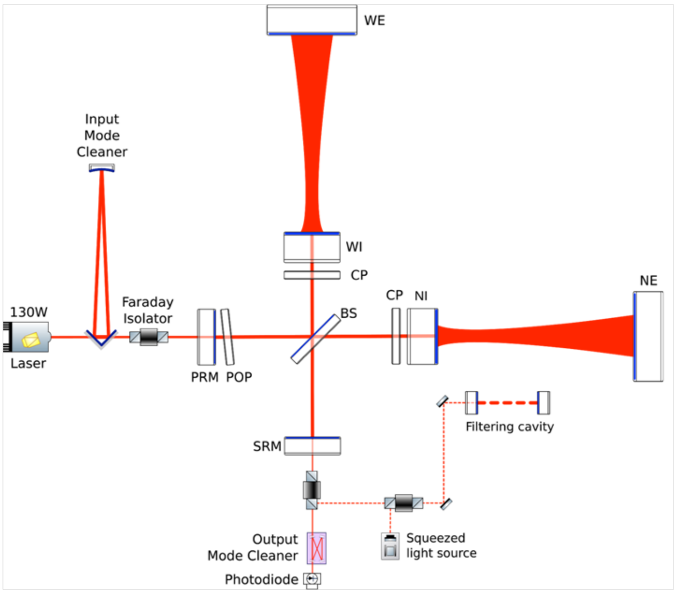

Figure 3. Simplified optical scheme for the second phase of AdV+. With respect to the first phase of the project, the main modification will be the enlargement of the End Mirrors of the Fabry-Perot resonators and the related implications [9, 8].

The coating material development is one of the other pillar activity to reduce the thermal noise impact on the interferometer sensitivity. Indeed the research and development for the coating has eventually become a joint activity between LIGO and Virgo collaborations, in the common interest of reaching a better sensitivity for the whole network. Promising results in terms of optical and mechanical properties have been achieved by studying $TiO_2 : GeO_2/SiO_2$ stacks: first monolayer and multi-layers coating were produced at the LMA Grand Coater and the final choice of the coating design will be taken jointly by LIGO and Virgo collaborations in a few months.

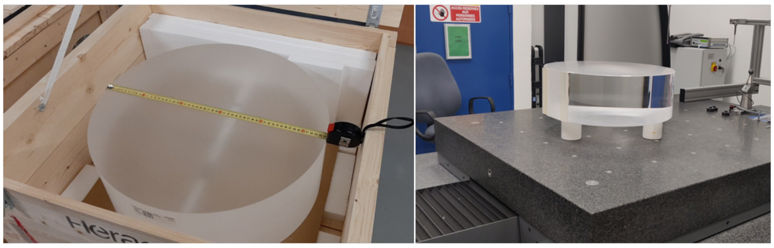

Figure 4. The large substrates for the phase II test masses. The Fused Silica substrates will be used to made the 55cm-large End Mirrors needed in the phase two.

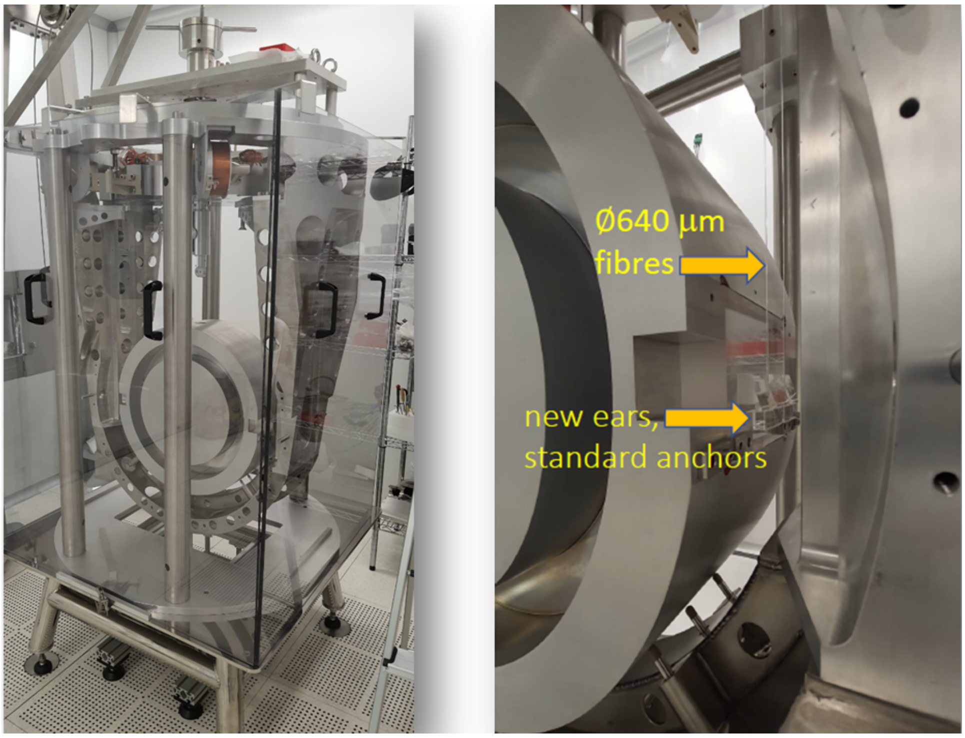

Figure 5. The prototype payload for phase II large masses has been assembled and it is under the test phase, including the 640 μm thick fused silica fibers which will hold the real mirror.

2.3. Large mirrors, large payloads, large super-attenuators

These mirrors will have anyway to be suspended and isolated from the external environment, so requiring a largely modified payload and super-attenuator [13] to host them. The payload for the ETMs has beam strongly modified with the goal of suspending a 100 kg mirror. The first prototype already demonstrated to be able to carry this kind of mirror, including the development and installation of prototype fused silica fibers of 640 μm diameter holding a dummy 100 kg cylinder. Also the super-attenuator design is roughly completed, and a prototype with revised elastic elements is under construction and validation.

3. Conclusions

While completing the commissioning to join the O4 run together with LIGO, the Virgo Collaboration is preparing the upgrade for the next observation run O5. This upgrade is designed to bring an increase of the inteferometer reach by almost a factor three with respect to the phase I (almost an order magnitude more in terms of explored volume). For this purpose, the main throttle will be to push down the thermal noise limiting the strain sensitivity at mid-band, where the detector has its peak sensitivity. This will be achieved with a two-fold approach: reduce the source of the thermal noise via engineering of the coating material and technique and with a new optical design, which will be less sensitive to this kind of noise.

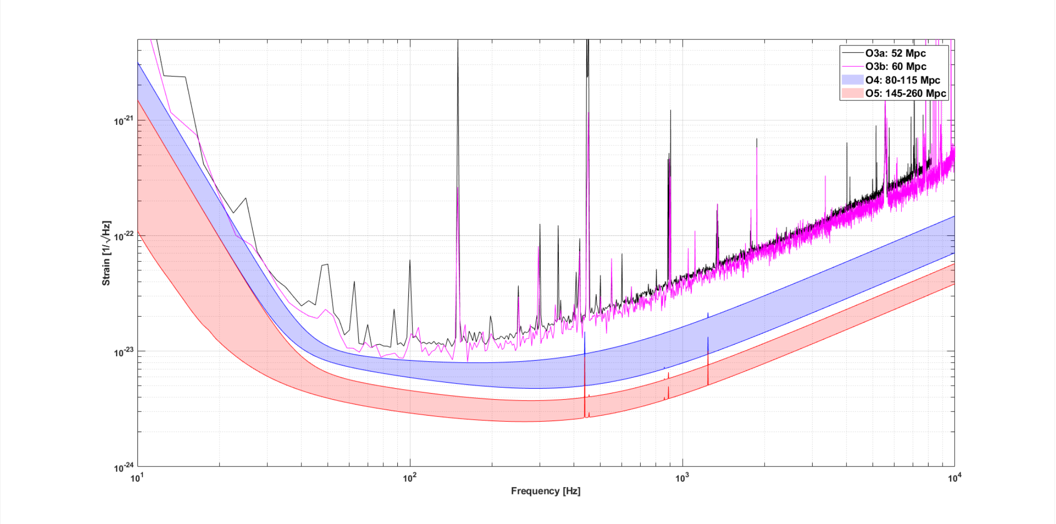

Figure 6. Expected evolution of Advanced Virgo sensitivity. The solid lines are the measured strain residual noise for O3 (range of 60Mpc) while the two bands identify the target for O4 (blue area, range 80-115Mpc), and O5 (pink area, range 145-260Mpc).

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