The Advanced Virgo+ status

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Abstract.

The gravitational wave detector Advanced Virgo+ is currently in the commissioning phase in view of the fourth Observing Run (O4).

The major upgrades with respect to the Advanced Virgo configuration are the implementation of an additional recycling cavity, the Signal Recycling cavity (SRC), at the output of the interferometer to broaden the sensitivity band and the Frequency Dependent Squeezing (FDS) to reduce quantum noise at all frequencies.

The main difference of the Advanced Virgo + detector with respect to the LIGO detectors is the presence of marginally stable recycling cavities, with respect to the stable recycling cavities present in the LIGO detectors, which increases the difficulties in controlling the interferometer in presence of defects (both thermal and cold defects).

This work will focus on the interferometer commissioning, highlighting the control challenges to maintain the detector in the working point which maximizes the sensitivity and the duty cycle for scientific data taking.

1. Introduction

The Advanced Virgo detector is a long scale enhanced Michelson interferometer located in Italy, close to Pisa, with the aim of detecting gravitational waves from astronomical sources. The Advanced Virgo interferometer has detected, together with the LIGO interferometers located in the USA [1], an impressive collection of gravitational wave emissions 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 gravitational wave network, the first triple coincidence was observed (GW170817,[2]). 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 detected.

After the O3 observation run the Advanced Virgo detector has been upgraded to the Advanced Virgo+ configuration to further improve the sensitivity and join the foreseen O4 run, together

with the LIGO and Kagra detectors, which will start in March 2023.

The major upgrades with respect to the Advanced Virgo detector are:

- Increase of the input power

- Implementation of the Frequency Dependent Squeezing (FDS)

- Addition of the Signal Recycling cavity (SRC).

All the aforementioned upgrades are meant to improve the detector sensitivity, but lead to an increase of complexity in the commissioning of the detector.

The increase of input power will improve the quantum noise at high frequency (shot-noise), but it will also lead to an increase of thermal aberration and radiation pressure effects. The implementation of the FDS will improve the broad-band sensitivity but it requires the installation and commissioning of a completely new hardware system [3]. The addition of the SRC will enhance the detector response to the gravitational wave signal. However it will require to control an additional degree of freedom (both in the longitudinal and angular directions) forcing to completely re-design the lock acquisition scheme and the steady state control scheme. The paper will focus on the commissioning of the Advanced Virgo+ detector upgrades, while the status of the FDS will be detailed in [4].
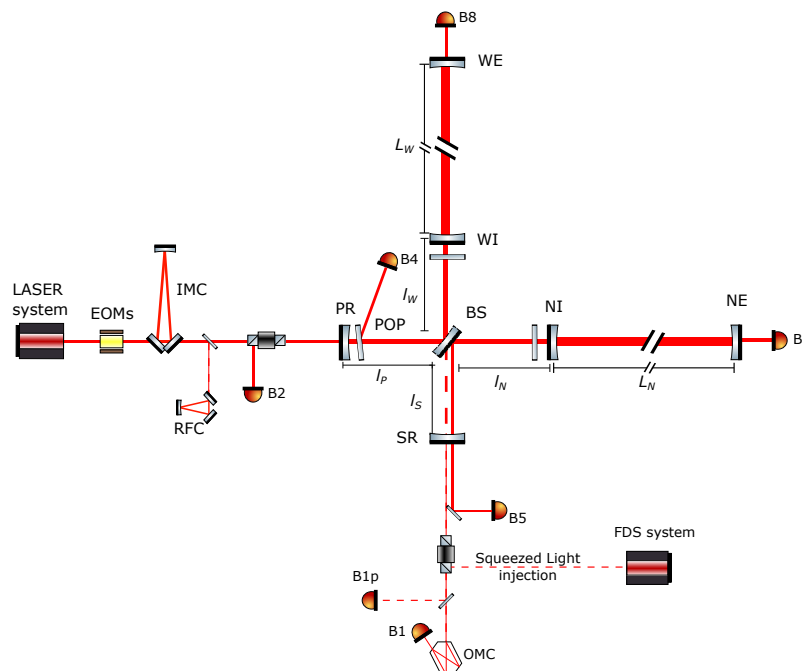
2. Advanced Virgo+ upgrades

Figure 1. Optical scheme of Advanced Virgo+ in which the main optical components are shown and the main output ports are detailed (B_{XX}). Moreover the Injection system, including the Input Mode Cleaner cavity (IMC) is shown, as well as the Detection system, including the Output Mode Cleaner cavity (OMC). Moreover the FDS system injection point is shown.

The Advanced Virgo+ detector scheme is shown in Figure 1. The input beam is generated by a system of master/slave lasers with a current output power of 33 W after having passed through a 144 m long triangular cavity (Input Mode cleaner, IMC). The main beam is split at the beam splitter mirror (BS) into two beams which are injected into the two orthogonal
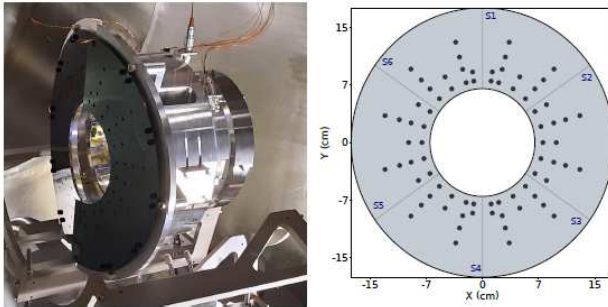
Figure 2. *left* Picture of the instrumented baffle installed in front of MC mirror. *right* Scheme of the embedded diodes on the baffle.

Figure 3. View of the filter cavity for the Frequency Dependent Squeezing.

Fabry-Perot arm cavities (North and West arms), to enhance the phase shift produced by the optical path length variation of the beam caused by a gravitational wave.

The power circulating is enhanced by the Power Recycling, while the SR cavity enhances the response of the detector versus the gravitational wave signal (detected on the dark port B1, see Figure 1). The installation of Advanced Virgo+ has been successfully completed in December 2020.

The major upgrades are the improvement of the injection system, the installation of the Frequency Dependent Squeezing (FDS) and the installation of the SR mirror at the output of the interferometer.

The injection system has been upgraded in order to allow an injected power to the interferometer of 40 W maximum (as a reference the injected power in O3 was 23 W). Moreover the MC mirror payload mechanics has been modified in order to fix controllability issues in the pitch direction, and stray light monitoring has been implemented using a baffle with embedded sensors, see Figure 2 [5].

The baseline design of AdV + involves injecting a Frequency-Dependent Squeezed vacuum field (FDS) in the interferometer (ITF) anti-symmetric port. This should lead to a decrease in the quantum noise contribution over the entire detection bandwidth. The selected method to realize FDS [6] is by exploiting the dispersion in reflection of a frequency independent squeezed (FIS) beam [7] by a detuned 285 meters long filter cavity (FC). The installation of the filter cavity including the 5 additional optical benches (two of which are suspended and operating in vacuum) used for the FC control and FDS injection [8] was completed in March 2021. Afterwards the commissioning phase of the FDS source started. Currently the rotation of the squeezing ellipse at about 20 Hz has been demonstrated with a FC lock accuracy down to 1 Hz and a level of round trip losses lower than 31 ppm in the best condition. These values together with the estimate of the optical propagation losses of 5-6 % and the squeezing ellipse angular jitter of 20 mrad are compliant with the first phase of the project. The second phase of the project, the injection of FDS into the interferometer, has just begun. The FDS cavity external view is shown in Figure 3.

Last but not least, the SR mirror has been added at the dark port of the interferometer. This upgrade is the one that improves the most the target sensitivity but also the one that requires the largest commissioning time since it strongly modifies the optomechanical response of the detector.
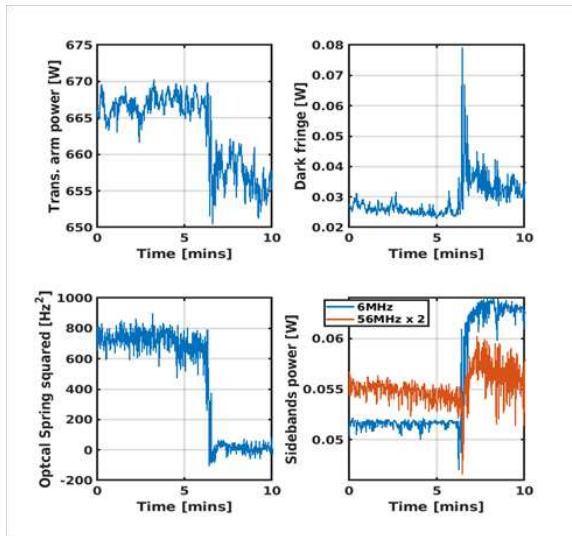
Figure 4. Example of sudden change of state in the detector working point. The change of state is visible in the powers detected in the various ports of the detectors.
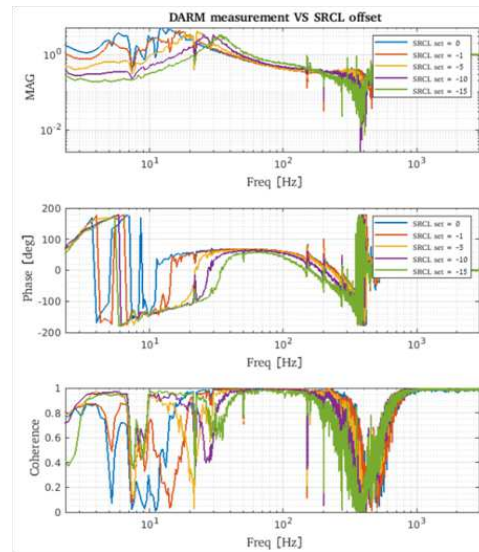

Figure 5. Example of detector response with respect to the SRC working point. It is visible that the structure at low frequency is largely changing the frequency of the peak from 15 Hz to 40 Hz, creating control instabilities.

3. Advanced Virgo+ commissioning phase

After the installation phase, the commissioning of the detector has started in January 2020. As already mentioned, the main part of the commissioning has been devoted to the control of the new optical configuration, including the process which brings the main optical components from the un-controlled state to the precise microscopic positions, called lock acquisition. The set of precise microscopic positions, called working point, is chosen in order to fulfill the resonance conditions of the optical cavities to provide the best sensitivity of the detector.

The control is done based on the Pound-Drever-Hall technique [9], for longitudinal control, and on the Ward technique [10], for the angular control, by adding phase modulations to the main beam (carrier). The phase modulations at 6.27 MHz, 56.44 MHz and 8.36 MHz are realized using Electro-Optic Modulators (EOMs, see Figure 1). The resonance conditions for the modulation sidebands and the Carrier fields, which define the longitudinal working point, are:

- Carrier resonant in the long arm cavities and in the PRC
- 8 MHz sidebands not resonant in any cavity
- 6 MHz sidebands resonant in the PR cavity
- 56 MHz sidebands resonant in the PR and SR cavities

Moreover the differential short Michelson degree of freedom (called MICH, equivalent to $l_n - l_w$) has to be kept in destructive interference.

Due to the addition of the SRC the lock acquisition has been strongly changed with respect to the one developed and implemented for the Advanced Virgo detector [11]. The lock acquisition strategy is generally based on the principle of controlling at first simple configurations and then increase the complexity of the system in semi-adiabatic steps. The lock acquisition developed
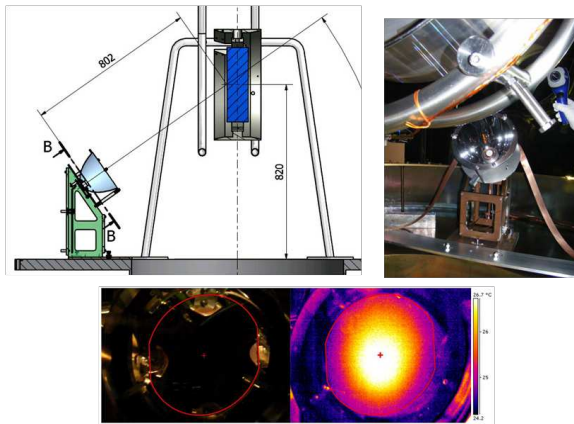
Figure 6. **top left** Technical drawing of the CHRoCC installation. **top right** Picture of the CHRoCC installed in the PR tower **bottom** Picture of the heating profile using, on the right, a thermal camera.
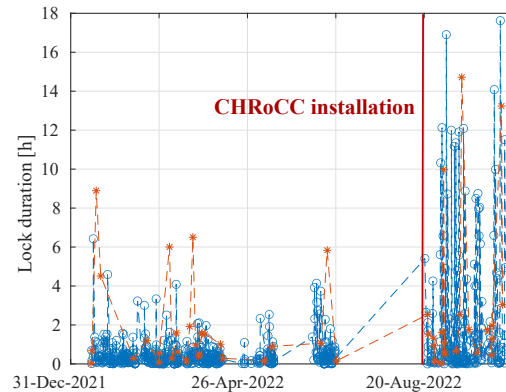

Figure 7. Distribution of the lock duration in hours since the beginning of the commissioning of the detector in the final working point (the red starred locks are the one manually ended). The red line show the start of the locking activities after the installation and pre-commissioning of the CHRoCC.

in Advanced Virgo+ is based on the lock procedure implemented in LIGO which implies the use of auxiliary lasers to disentangle the long arm degrees of freedom from the central area ones, [12] [13] [14] [15].

The first lock at the final working point, described above, with an input power of 33 W has been achieved on December 2021, but the lock showed strong instabilities and un-expected modifications in the detector response. An example of instability is shown in Figure 4, where is visible a sudden change of state in the longitudinal working point which causes lock loss, the so called *jumps*. The other un-expected effect is the strong modification in the opto-mechanical response of the detector. Figure 5 shows an example of the detector response versus the longitudinal position of the SR cavity (SRC set point).

These observations led to strong efforts in simulation studies to understand the origin of the instabilities. The outcomes of the studies proved that a possible cause of the issues was linked to aberrations in the optical configurations. It has to be noted that similar effects have been observed also in LIGO, but with a much lower impact [16]. This can be linked to the fact that Advanced Virgo+, in contrast to the LIGO design, has marginally stable recycling cavities.

The stability of a cavity is a very important characteristic, which depends only on the cavity geometry, and it determines the capability of a cavity to clean and suppress the transverse modes (High Order Modes [17]) generated by optical aberrations. This means that the Advanced Virgo+ detector is much more affected by cold and thermal aberrations with respect to the LIGO detector.

The most affecting parameter has been found to be the PR mirror radius of curvature (RoC) [18], and indeed in the initial optical configuration we had a PR RoC mistuned by 40m (it was pre-tuned to be compliant the thermal configuration of the PRC in case of 125 W of input power) making the PRC unstable. Unfortunately the actuator that was meant to tune the RoC could not be used due to installation problems. This issue has been overcome by adding an additional thermal actuator, called CHRoCC (Central Heating Radius of Curvature Correction, developed in 2013 for initial Virgo [19]). This actuator, visible in Figure 6, has been installed in July 2022

and its working principle is to shine black body radiation to the pick-off plate (POP) placed in front of the PR mirror, see Figure 1, to create a converging lens and to stabilize the PR cavity [20]. After the installation and the pre-commissioning of the actuator the lock stability has been strongly improved.

Figure 7 shows the lock duration distribution from the start of the final working point commissioning (after the complete lock acquisition has been implemented). Moreover it has to be noted that the lock duration distribution is dominated by un-attended operations during nights, since during day time the commissioning activities affect the locking stability.

After the lock losses issue has been mitigated, currently the detector is in the phase of optimizing of the global working point, which includes the tuning of the angular loops and the thermal actuators, to optimize the detector response and achieve good sensitivity for scientific data taking. This phase consists also in the noise hunting campaign to mitigate the technical noise sources and their couplings to the sensitivity.

4. Conclusions

The Advanced Virgo+ detector has successfully concluded the installation phase in 2021 and it is currently in the commissioning phase. The lock acquisition has been completed in December 2021 and a better lock robustness has been achieved after the installation of the CHRoCC actuator. The Advanced Virgo+ commissioning is now entering in the phase of fine tuning of the global working point and in the sensitivity improvement, through a campaign of reduction of technical noise and their coupling to the gravitational wave signal which is called *noise hunting phase.*

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