Advanced Virgo: a 2nd generation interferometric gravitational wave detector

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Abstract.

Advanced Virgo is the project to upgrade the Virgo interferometric detector of gravitational waves, with the aim of increasing the number of observable galaxies (and thus the detection rate) by three orders of magnitude. The project is now in advanced phase of realization and the assembly and integration will be completed by 2015. Advanced Virgo will be part of a network with the two Advanced LIGO detectors in the US and GEO HF in Germany, with the goal of contributing to the early detections of gravitational waves and to opening a new observation window on the universe. In this paper we describe the main features of the Advanced Virgo detector and outline the status of the construction.

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1. Introduction: scope of the Advanced Virgo upgrade

Advanced Virgo (AdV) is the project to upgrade the Virgo detector [1] to a second generation instrument. It is designed to achieve a sensitivity about one order of magnitude better than the Virgo’s one, which corresponds to an increase of the detection rate by about three orders of magnitude. Therefore, most of the detector subsystems have to deliver a largely improved performance to be compatible with the design sensitivity. The choices of the AdV design were made on the basis of the outcome of the different R&D investigations carried out within the community of gravitational waves and the experience gained with Virgo, but also taking into account the budget and schedule constraints. The AdV upgrade has been funded in December 2009 and it is currently in advanced phase of installation. In March 2014 a Memorandum of Understanding for full data exchange, joint data analysis and publication policy has been signed with the LIGO Scientific Collaboration, thus establishing a world wide network of second generation detectors (including Advanced Virgo, the two Advanced LIGO [3], GEO HF[4]).

In the following we shortly describe the main upgrades foreseen in the AdV design. Comprehensive and more detailed descriptions can be found in the next sections and in the Technical Design Report [2].

Interferometer optical configuration AdV will be a dual recycled interferometer. Beside the standard power recycling, a signal recycling cavity will be present. The tuning of the signal recycling parameter allows changing the shape of the sensitivity curve and optimizing the detector for different astrophysical sources. To reduce the impact of the coating thermal noise in the mid-frequency range the spot size on the test masses has been enlarged. Therefore, unlike Virgo, the beam waist will be placed close to the center of the 3 km Fabry-Perot cavities, resulting in beam radii of 48.7 mm and 58 mm for the input and end mirrors, respectively. The cavity finesse will be higher with respect to Virgo: a reference value of 443 has been chosen. Having a larger beam requires installation of larger vacuum links in the central area and new mode matching telescopes at the interferometer input/output. To ease the lock of the full interferometer an auxiliary green laser which sees the cavity as low finesse ones will be installed.

Increased laser power Improving the sensitivity at high frequency requires high power. The AdV reference sensitivity is computed assuming 125 W entering the interferometer (after the input mode cleaner). Therefore, considering the losses of the injection system, the laser must provide a power of at least 175 W. A 200W laser based on fiber amplifiers will be installed after 2018, while in the first years of operation (at a lower power) AdV will use the Virgo laser, capable of providing up to 60 W. The input optics for AdV must be compliant with the 10 times increased optical power. Proper electro-optic modulators and Faraday isolators able to withstand high power have been developed and a DC readout scheme will be used, requiring a new design of the output mode cleaner. To cope with the increased impact of radiation pressure fluctuations the AdV test masses will be twice heavier than the Virgo’s ones (42 kg). A sophisticated thermal compensation system has been designed to cope

‡ Though squeezing is not part of the AdV baseline the infrastructure has been prepared to host a squeezer in the next years.
with thermally induced aberrations. The sensing is based on Hartmann sensors and phase cameras. The actuators are: ring heaters around several suspended optics, allowing to change the radius of curvature; CO$_2$ laser projectors shined on dedicated compensation plates through a double-axicon system. A a scanning laser systems to cope with non-axisymmetric defects.

**Stray light control** Scattered light could be a relevant limitation to the detector sensitivity. In order to limit the phase noise due to part of light being back-scattered into the interferometer, new diaphragm baffles will be installed either suspended around the mirrors, or ground connected inside the vacuum links. To fulfill the system requirement that all photodiodes to be used in science mode be seismically isolated and in vacuum, a compact vibration isolation system with its vacuum chamber has been realized. Five of such *minitowers* will be installed. State of the art polishing technology is used to reach a flatness better than 0.5 nm rms in the central area of the test masses, thus reducing the losses due to scattering.

**Payloads and vibration isolation** A new design of the payloads has been done mainly triggered by the need of suspending heavier mirrors, baffles and compensation plates. The controllability and the mechanical losses have been improved as well. The Virgo super attenuators provide a seismic isolation compliant with the AdV requirements. However, some upgrades are planned to match the new payload design and to further improve the robustness in high seismicity conditions: the possibility of actively control the ground tilt will be implemented.

**General detector infrastructure** Important modifications have been done in the central hall to host the minitowers and upgrade the laser lab and the detection lab, turning them into acoustically isolated clean rooms. The vacuum has been upgraded by installing large cryotrap at the ends of the 3 km pipes, in order to improve the residual pressure by a factor of about 100. Several upgrades of the data acquisition and general purpose electronics are foreseen for AdV, to keep up with the increasing number of channels and the more demanding control system for the signal recycling configuration, and to cope with the obsolescence of several boards.

### 2. Sensitivity goals

#### 2.1. Target sensitivity for AdV

In the Advanced Virgo Technical Design Report [2] approved by the funding agencies in 2012 a target sensitivity curve for the detector is defined, based on the detector design and noise modeling at that time (solid black line in fig. 1). The curve corresponds to a detector configuration with 125 W at the interferometer input and SR parameters chosen in order to maximize the sight distance for coalescing binary neutron stars (BNS). The corresponding inspiral ranges are $\sim 140$ Mpc for BNS and $\sim 1$ Gpc for $30 M_\odot$ coalescing binary black holes (BBH).

Some basic assumptions are done in the sensitivity computation that are to be considered as system requirements. Some design choices of different subsystems were made to comply with such requirements:

- **input power**: it is assumed that a laser power of 125 W be available in the TEM$_{00}$ mode after the input mode cleaner;
• **round trip losses:** the power lost in a round trip inside a Fabry-Perot cavity must not exceed 75 ppm;

• **technical noises:** all technical noises must be kept reduced at a level such that the corresponding strain noise is $<0.1$ of the design sensitivity over the whole frequency range.

However, The AdV detector is tunable in three ways: by changing the laser power, by changing the transmissivity of the SR mirror or by tuning the position of the SR mirror. The SR mirror transmittance influences the detector bandwidth, while the position of the SR mirror at a microscopic scale changes the frequency of the maximal sensitivity. Thus, the presence of the SR cavity allows to think of AdV as a tunable detector (see section 3): the sensitivity curve can be shaped in order to perform runs optimized for targeting different astrophysical sources. For the sake of simplicity, we refer to three different operation modes:

• **power recycled, 25 W;**

• **dual recycled, 125 W, tuned signal recycling;**

• **dual recycled, 125 W, detuned signal recycling** (SR tuning chosen to optimize BNS inspiral range).

AdV will not be operated in the final configuration since the beginning. The new features will put new problems forward, which must be faced with a step by step approach. The above-mentioned modes of operation corresponds to commissioning steps of increasing complexity. They should be considered as *benchmark configurations*. The commissioning will progress through many intermediate steps. Periods of commissioning will be alternated with periods of data taking and such plans will need to be coordinated with Advanced LIGO in order to maximize the network capabilities.

Fig. 1 compares the target sensitivity curves for the reference scenarios described, as defined in the TDR.

### 2.2. Further progress

Since the TDR release some progress has been done both on the design of the detector and the modeling of the noise:

• The design of the payload has been finalized: the recoil mass, present in the Virgo payload has been removed. Moreover, experimental tests have shown that the mechanical dissipation at the level of the marionette is smaller than previously assumed. This has lead to a new modeling of the suspension thermal noise which would not limit anymore the sensitivity at low frequency (see sec. 5);

• The model of the gravity gradient noise has also evolved. Now it uses as input the typical seismic noise spectrum measured on the Virgo site.

• We have started to add, in the noise budget, some technical noises that we know how to model.

In Fig. 2 we show the result of this work (which must be considered as work in progress).

‡ The sensitivity curves shown in this section have been plotted using *GWINC*, a MATLAB code developed within the LSC [?] and adapted to AdV [?]. A document on the AdV sensitivity curve and all the contributing noises is available [?].
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3. Optical design

The optical configuration of Advanced Virgo was designed to maximize the detector sensitivity while inducing only minor changes to the infrastructure. The very same vacuum envelop which housed the Virgo interferometer constraints the cavity lengths for Advanced Virgo. As a result for Advanced Virgo, the arm cavity length is 3 km while the recycling cavities are \( \sim 12 \) m long.

A sketch of the optical configuration is presented in figure 3. The core of Advanced Virgo is constituted of a dual recycled Michelson interferometer with Fabry-Perot arm cavities.

3.1. Design of the arm cavities

The arm cavities have a bi-concave geometry, with each test mass mirror having a concave radius of curvature of slightly larger than half the arm cavity length. Such a near-concentric resonator configuration is chosen for two principle reasons: (1) to increase the beam size at the mirrors, thus averaging over a larger area of the mirror’s surface and reducing the relative contribution of mirror coating thermal noise and thermal gradient in the substrate and (2) to limit the effect of radiation-pressure...
induced alignment instabilities.

This type of topology means that the cavity waist is near the middle of the arm cavity. Having different Radii of Curvature (RoC) for the two cavity mirrors displaces the waist toward the mirror with the smaller radius of curvature, and the beam size on that mirror is also reduced. This can actually cause an increase in detector sensitivity, as the input mirror will have fewer coating layers and so its coating thermal noise contribution is actually slightly smaller for identical beam sizes on the two mirrors. We thus choose to have the End Mirror (EM) with a larger radius, and thus larger beam size, than the Input Mirror (IM).

Regarding the choice of the arm mirrors radii of curvature, several competing factors must enter the decision. These include mirror thermal noise, cavity stability, clipping losses as beams become larger, and tolerance to manufacturer errors in mirror production, which can limit the cavity stability in the cold (uncorrected) state. The RoC should also be chosen in such a way as to minimize the accidental degeneracy of higher-order-modes in the arm cavities. After careful simulations, taking into account mirror thermal noise and clipping losses. We choose an average radius of 1551 m, which means the cavity mode is situated directly between higher-order-mode degeneracies of order 8 and 9. Next, as described above, we reduce the IM RoC and increase the EM RoC to minimize the impact of mirror thermal noise while also keeping the clipping losses low by limiting the final beam size on the EM. This procedure yields mirror radii of 1420 m for the IM and 1683 m for the EM.
Since Advanced Virgo will use the signal recycling technique, the detector response will vary with the arm cavity input mirror transmissivity, the signal recycling mirror transmissivity, the signal recycling cavity length, and the circulating power. This combination of factors means that the detector bandwidth depends only weakly on the specific choice of arm cavity finesse, since changes in the arm cavity input mirror transmissivity can be compensated by changing one of the other parameters.

Factors other than the ideal sensitivity curves thus drive the choice of arm cavity finesse. These factors include thermal loading in the central interferometer, length noise coupling from auxiliary degrees of freedom, and the relative impact of losses in the arm and signal recycling cavities.

As a trade off, we choose a value of finesse around 450. This value is chosen because sufficient investigation of the resulting increased thermal load in the central interferometer has already been done, lending confidence that this value is still safe. The resulting arm input mirror transmission is set to 1.4% while the EM is almost perfectly reflective (transmission of few ppm).

3.2. Choice of the recycling cavities

The recycling cavities have a geometry referred to as marginally stable. The cavities are formed by the input test masses having a radius of curvature of 1420 m and the power and signal recycling mirrors having a radius of curvature of 1430 m. The recycling cavity length is of 11.952 m. This yields a beam diameter of about 5 cm (the beam size is constant in the cavity as there is no focusing element). In such a configuration some
high-order modes can resonate at the same time as the fundamental mode, since the Gouy phase accumulated during the free space propagation inside the recycling cavity is not sufficient to move all high-order modes out of resonance. This configuration is conceptually similar to that used in initial Virgo. However, in Advanced Virgo the increase in beam size from 2 to 5 cm further reduces the round-trip Gouy phase and hence increases the degeneracy. This degeneracy results in this type of recycling cavity being extremely sensitive to optical aberrations that may arise during fabrication of the mirrors or through thermal effects in the working interferometer. The carrier field is largely unaffected by these effects as it is stabilized by the arm cavities. The Radio Frequency (RF) sidebands, however, do not resonate in the arm cavities and therefore excessive aberrations in the recycling cavities may result in noisy and unstable control signals.

The recycling cavity design differs to that of other Advanced GW interferometers, such as LIGO, which have opted for non-degenerate cavities that will be less sensitive to aberrations. The choice to use marginally stable cavities was mainly driven by the construction schedule, budget and the increased suspension complexity that would be required for a non-degenerate cavity solution. However, a thermal compensation system in initial Virgo was successfully used to reduce aberrations in the recycling cavity and this work will continue with an upgraded system in Advanced Virgo. Optical simulations have indicated that an acceptable RF sideband signal may be obtained if the total round-trip recycling cavity aberrations are reduced to less than 2 nm.

The choice of power recycling (PR) mirror transmission was a trade-off between maximizing the circulating power in the arms and reducing the sensitivity of the power recycling cavity to aberrations. The former requires matching the reflectivity of the power recycling mirror with the effective reflectivity of the arm cavities (PR transmission of 2.8%). The latter requires reducing the PR cavity finesse to a minimum. A PR transmission of 5% was chosen as the best compromise. The choice of signal recycling (SR) mirror transmission was a trade-off between optimizing the sensitivity to BNS inspirals, to BBH inspirals and in a broadband (zero detuning) configuration. A SR transmission of 20% was chosen as the best compromise.

4. Mirror technology

4.1. Introduction

The mirrors play a crucial role in the sensitivity of AdV. On one side the mechanical losses in the coating determine the quality factor of the mirror and as a consequence the displacement of the mirror surface due to its thermal vibration. On the other side the optical losses in the coatings determine the amount of power which is lost in the Fabry-Perot cavity and as a consequence the power that is stored in the recycling cavity. This quantity determines the quantum noise which is expected to limit the sensitivity at the higher frequencies.

4.2. Substrates

A new type of fused silica with smaller absorption (Suprasil 3001/3002) is available today and has been chosen for the AdV mirrors. The bulk absorption for this material is 3 times smaller than the one used for Virgo (measurements made at LMA,
0.2 ppm/cm at 1064 nm \cite{10}, the other relevant parameters (quality factor, index homogeneity, residual strain, birefringence) are still the same or even better. Reducing the absorption in the substrates is certainly of interest as the power absorbed causes thermal lensing in all transmissive optics. This is more relevant in 2nd generation detectors since the power stored in the interferometer is larger and the test masses are thicker. On the other hand one should remind that so far thermal effects are dominated by coating absorption, and this will be enhanced by the very high circulating power in AdV. From this point of view it is more important to improve the absorption of the coatings than to improve the absorption of the silica.

List of the AdV substrates

- **Input test masses (IM)** - The tAdV test masses will have the same diameter of the Virgo mirrors (35 cm) but will be twice as thick (20 cm) and heavy (42 kg). A high quality fused silica (Suprasil 3002) having a very low bulk absorption (0.2 ppm/cm) has been used, as these optics transmit a relatively large amount of power (of the order of 2 kW).

- **End test masses (EM)** - Suprasil 312, a fused silica grade of lower optical quality (and cost) has been used for the end mirrors as in this case the mirrors are reflecting most of the light. The only constraint in this case is the substrate mechanical quality factor that has to be sufficiently high to avoid increasing the thermal noise above the level determined by the mechanical losses in the coating and this is the case for chosen grade \cite{11}.

- **Beam Splitter (BS)** - The BS will be 55 cm in diameter and 6.5 cm thick. A high quality fused silica grade (Suprasil 3001) was chosen. This particular type of Suprasil is particularly suitable for the BS because it is an optically isotropic 3D-material. It is highly homogeneous and has no striations in all three directions.

- **Compensation Plates (CP), Pick Off Plate (POP)** - These components have been machined from the Virgo+ input mirrors, made of Suprasil 312 SV. The absorption measured on this silica blanks was lower than 1 ppm/cm.

- **Power/Signal Recycling mirrors (PR/SR)** of the recycling cavities - The PR/SR are 35 cm in diameter and 10 cm thick and are made of Suprasil 312.

All the substrates needed for the interferometer as well as the spare parts were produced and delivered by HERAEUS at the end of 2012 (fig. \textbf{4}).

4.3. Polishing

The polishing quality is characterized by two different parameters: the flatness and the micro-roughness. The first parameter gives the RMS of the difference between the perfect surface (typically a sphere for spherical mirrors) and the actual surface as measured by phase map interferometer (for Virgo a flatness of a few nm was achieved \cite{7,8}). The second parameter gives a measurement of the mirror surface roughness at small scale lengths, from a few microns, up to about 1 mm (of the order of 0.05 nm in Virgo).

Both effects contribute to scatter the light from the fundamental mode to higher order modes. They generate losses and extra noise. These polishing losses will play an even more important role in AdV due to the higher finesse of the cavities. Depending on the difference in the losses between the two cavities they could be the source
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Figure 4. LEFT: Power recycling substrate (35 cm in diameter, left) beside the large Beam Splitter of 55 cm. RIGHT: a test mass.

of finesse asymmetry and contrast defect thus modifying the constraints on other subsystems.

The losses in Virgo+ were about 500 ppm per round trip. To meet the round trip losses requirement in the AdV cavities (75 ppm) a flatness requirement of 0.5 nm RMS on 150 mm diameter for the arm cavity mirrors (IM, EM) was set [13].

Moreover, the shape of the Power Spectral Density (PSD) of the surfaces is important too, as different PSD shapes gives different losses in a FP cavity for an equal flatness. Thus, it was required that the RMS in the frequency range $50 \text{ m}^{-1}$ - $1000 \text{ m}^{-1}$ must not exceed 0.15 nm [13].

The flatness specifications for all the other optics were set to be lower than 2 nm RMS on 150 mm diameter.

The first polished substrates were delivered by ZYGO at the beginning of 2014. In order to characterize the large substrates before and after coating, some upgrades of the existing metrology benches were made (new sample holder for the scatterometer CASI, new stronger motors for the absorption bench). To be able to measure the flatness of the AdV substrates and mirrors at the level required (RMS flatness of 0.5 nm), a new interferometer at 1064 nm coupled to a 18” beam expander was purchased to ZYGO (fig. 5).

This interferometer uses a new technique to realize the phase shifting: the wavelength shifting. The main advantage of this technique is to be able to characterize substrates having parallel surfaces as the IM substrates getting rid of the backside interferences.

The first flat substrates (CP, POP, BS) were characterized with this new tool and a flatness of $\sim$0.5 nm RMS on the central 150 mm part was measured, much better than the specifications asked for these optics ($< 2$ nm RMS). At the time of writing we also know that the polishing of the first Input Mirror ( cavity mirror) achieved a flatness of 0.17 nm RMS on 150 mm diameter (power, astigmatism removed - fig. 6), versus a requirement of 0.5 nm RMS.

4.4. Coating

The coatings of the mirrors determine both the total mechanical losses of the mirrors and their optical losses.
Mechanical losses  At present, the lowest mechanical losses measured for Ta₂O₅ coating are those obtained with Ti doped Ta₂O₅. The losses value is within the AdV requirement of 2.3 10⁻⁴ [5]. An option to further reduce the mechanical losses consists in optimizing the thickness of the layers of Ta₂O₅ and SiO₂ (we will refer to this as optimized coating). Since the Ta₂O₅ is the more lossy material, it is possible to reduce the mechanical losses of the multi-layer by reducing the amount of Ta₂O₅ and increasing the amount of SiO₂. For a given required reflectivity it is possible to find an optimum combination. Tests done at LMA have shown that the coating machine is able to produce such optimized multilayers with a quite good accuracy. Thanks to this result, the optimized coatings for the IM and EM will be used for AdV.

Absorption losses  The absorption losses of the coatings play also an important role as they determine the power absorbed in the test mass and thus the thermal lensing effect. The lower are the losses in the coating the lower is the burden for the thermal compensation. An absorption level between 0.3 ppm and 0.4 ppm at 1064 nm is done currently on high reflectivity mirrors (EM, IM) thanks to the use of Ti doped Ta₂O₅.
Coating uniformity  In order to maintain after coating the substrate flatness, a very good coating uniformity is needed. The goal is to coat two parts (IM or EM) in a coating run to have the same optical performances. In this configuration, the transmission of the two mirrors will be equal and consequently, the AdV cavities will be identical. Otherwise, the asymmetry in finesse and power on the dark fringe might be too large. The finesse asymmetry is dominated by the transmission mismatch between the two IM rather than the losses induced by the flatness of the cavity mirrors (as in AdV, the mirror RMS flatness is very low). The only possible solution to get the uniformity on two large substrates at the same time is to use a planetary motion coupled to a masking technique. A new planetary system was manufactured and installed in the LMA large Virgo coater (fig. 7).

Optical simulations have been done to prove that we are able to reach an RMS flatness of 0.5 nm with this configuration.

5. Mirror suspensions

In Advanced Virgo the payload must not only suspend and control the mirrors but also additional components that need seismic isolation of control: the baffles, the compensation plates, the ring heaters. This need has triggered a deep re-thinking of the payload structure: the recoil mass (see description in [10]) has been removed and both the mirror and the marionette are actuated from the body of the first seismic filter above it (called Filter 7 or steering filter, see next section). In this way, we can support easily large pieces very near to the mirror, and have the additional advantage to take out some low frequency resonances of the suspended recoil mass (e.g. the bouncing frequency of the wires of the recoil mass suspension) that were difficult to control. Of course, this new scheme has also some disadvantages: the control of the Filter 7 must be improved, because now also the positioning of the coils facing the magnets on the mirror depends on it. Moreover, the metal wall that in Virgo separated the upper vacuum of the tower from the lower one, where the mirror is located, must be moved over the Filter 7. This change requires also that the Filter 7 must now meet the strict requirements of cleanliness and UHV compatibility of all other parts of the payload. These constraints imply a thorough redesign of the Filter 7 and of some elements of the vacuum chamber of the suspension. Moreover, we chose to take into
account an additional constraint in the design of the new payloads: the overall load of each suspension element of the Super Attenuator had to remain the same as in the previous configurations of Virgo: this allowed us to minimize the work necessary to retune the Super Attenuators for the Advanced Virgo configuration.

5.1. Tests on the new beam splitter payload

We used the design of the beam splitter (BS) mirror suspension for AdV as a test bench for the new scheme. After a first assembly for mechanical tests, the BS payload was suspended to the North End Super Attenuator, and an extensive series of tests was performed:

- **Controllability**: using optical levers, controllability studies were done, including tests of hierarchical actuation. Those tests demonstrated that the new design is controllable;

- **Pendulum Q**: we were also able to optimize the setup of the pendulum of the upper stage of the mirror suspension, the marionette, so to minimize its dissipations. We obtained in the end Q values of $2 \times 10^4$, larger by almost two orders of magnitude than the value of $Q = 300$ had used to compute in the official sensitivity curve for AdV. Assuming that the same Q will be achieved on the test mass payloads, the expected contribution of the suspension thermal noise at low frequency is that shown in fig. 2

- **Coupling with e.m. stray fields**: we are developing detailed electromagnetic finite element models of each payload to study and eventually mitigate the force acting on mirror magnets due to eddy currents induced in the conductive parts of the payload by local variable magnetic fields. The model for the BS payload has been tested implementing a facility to measure the response of the payload to a variable magnetic field produced by a large coil in its proximity. The shape
of the magnetic field, due to the presence of the payload, is measured in several relevant points of the space with a magnetic probe, and the results are compared with those of a simulation where the finite element magnetic model of the BS payload is subjected to the same field. The magnetic model of the BS has been refined according to the results of the tests, and it has been used to predict the influence of measured environmental magnetic noise on the BS. It was found that no relevant contribution to the sensitivity curve due to effects of magnetic noise on the BS is present. Similar electromagnetic models and tests are being implemented for all payloads.

5.2. Parts on the new input mirror payload

The mechanics of the new payloads will be more complex for the presence of large additional elements. In the following, we describe the solutions for each one of these elements for the most complex case, which is the suspension of the mirror at the input of the Fabry-Perot arms. All other payloads (the end mirror payloads, the power recycling payload, the signal recycling payload) are composed by a different arrangement of these same parts.

5.2.1. The Compensation Plate Support

A Compensation Plate (CP) must be suspended in front of each input mirror, in the recycling cavity (see fig. 3). The CP is a fused silica disk having a diameter of 350 mm and a thickness of 35 mm. The plate is placed on the back side of the input test masses at a distance of 20 cm from their back surface and it is attached to the cage of the payload by means of fused silica ears, silicate bonded to the plate (fig. 9). This kind of suspension is designed in order to have a level of stress on the CP comparable to that of a standard mirror, so to limit birefringence effects. Two stainless steel clamps hold the other side of the ears and are rigidly connected to an external aluminum ring, which is fixed on the supporting frame, bolted to the Filter 7 (the cage). The CP suspension has been designed so to
have frequencies inside the detection bandwidth, in order to avoid any coupling with the pendulum modes of the mirror. In this way, the CP behaves like any other part of the cage. A detailed study of the possible noise contributions to the sensitivity coming from the thermal motion of the CP and from possible excitation due to the thermal compensations system has been carried out. The results are described in [25].

5.2.2. The ring heater and large baffles supports

A Ring Heater (RH, see sec. 7) must surround the mirror. Centering of the RH with respect to the mirror could be critical: as a consequence we have implemented a system of remote adjustment of the RH position along the vertical and horizontal axes. Moreover, a manual system is used to put the RH in rest position, outside of the mirror. This manual adjustment allows us to put in operation the RH only when the mirror is fully suspended and in its working position.

The large baffles are clamped at the end of the payload (see sec. 12). The supports are designed so to have resonance frequencies of the clamped baffle as high as possible, taking into account also the necessity to limit the total weight of the structure. For this reason, the baffle holders usually have also other functions: for instance, in the BS payload they are used also as mirror coil holders in the BS payload, while in the input payload they act also as a counterweight to balance the load of the CP support.

5.3. The Monolithic Suspensions

One of the main noise sources limiting the sensitivity of gravitational wave interferometers is the thermal motion of the mirror pendulum (the mirror and its suspension) and of the bulk of the mirror itself (both substrate and coating)([26], [27], [28]). Moreover, an important contribution is also given by the friction on the clamping points of the suspension ([29], [30], [31]). Thanks to the pioneering work of the Glasgow, GEO and Perugia groups ([32], [33], [34]), the best way devised so far to reduce these sources of noise, has been to use fused silica wires, attached to the mirror by welding or using silica bonding, which can reproduce the connection between materials at the molecular level ([22, 23, 24]). We refer to this design as monolithic suspensions.

In Advanced Virgo we have developed a suspension design where the ends of each fiber are welded to two T-shaped fused silica blocks (the anchors, see fig. ??) which are then connected to the marionette on one side and to the mirror on the other side. On the mirror side, the anchor is glued with a silica bonding technique to a section of fused silica protruding from the mirror (the ear). Machining the ear out of the mirror is rather difficult, so the ear itself is silica bonded to the mirror before the fiber is assembled. If silica bonding is correctly applied, fiber, anchor, ear and mirror are a continuous body, and we have a monolithic suspension. The other end of the fiber, welded to another anchor, is connected to the marionette with a stainless steel interface (the upper clamp assembly).

In 2009, a solution similar to the one we have described was implemented in the configuration of our interferometer called Virgo+ ([?]). It was the first time that such a technology was used on a large gravitational wave detector: the four mirrors of the 3 km Fabry-Perot arms were in operation for about two years, suspended to glass fibers 0.3 mm in diameter, before being disassembled to start the upgrade of Virgo to the Advanced state. While this new set up was a success as a technical achievement, the actual values of Q measured for violin modes were in general a factor 10 lower.
Figure 10. Comparison of the $\phi$ values of the violin modes measured in Virgo+ (white circles) and in the Perugia facility where the new configuration for AdV has been tested (black squares). At low frequency and at 8 kHz are two dissipation peaks due to recoils of the structure supporting the fiber.

than expected. We identified the probable cause of these extra dissipations in the design of the upper clamp of the fibers ([?). This design has been revised in order to implement monolithic suspension in Advanced Virgo, guided by an extensive FEM simulations model that have been used to optimize the dissipation paths of the new suspension, and by a series of tests performed in a dedicated facility in the Perugia Virgo Laboratory. In the new design, we tried both to implement a reliable way of connecting the fused silica parts to the metal ones, and to limit as much as possible the losses due to the friction between metal and fused silica surfaces. The solution that we have finally selected consists in a $\simeq 1$ kg fused silica block which is silica bonded to a plate of stainless steel coated with fused silica. The tests showed that in this way an improved behavior of the dissipations of the violin modes of the fibers with respect to what observed in Virgo+ could be found at all frequencies, but for two intervals where dissipation peaks due to the recoil of the structure could be observed (fig. [10]). Currently, the last details of this configuration are being tested to be implemented in the AdV payloads.

5.4. Fiber production and test

Fiber length, fiber stiffness and position of bending points are constrained by the available space and the choice of resonant frequency of the various modes of the suspension, driven strongly by control issues. For instance, the vertical bouncing frequency of the last stage represents the lower limit of the detection band because, although the vertical to horizontal coupling is small (a value of $10^{-3}$ is assumed), the vertical oscillation does not have any dilution factor ([37]). So, in order not to spoil the sensitivity, this frequency must be kept below the low frequency limit of the detection bandwidth (i.e. 10 Hz). This can be achieved with a careful choice of the dimensions and shape of the fiber. Also, in order to have the detection band with the smallest possible number of resonant modes, the first violin mode should be as high as possible. On the other hand, the frequency of the first violin mode and of its harmonics depends on the fiber cross section and then ultimately on its breaking
stress. As a further constraint, we must take into account also the thermoelastic dissipations \([38]\), whose contribution to thermal noise can be made negligible with a suitable choice of the diameter of the fiber.

In AdV mirrors will be suspended to a 400 \(\mu m\) diameter fiber, having a load stress of 780 MPa, about the same of the fibers used for Virgo+ and well below 4-5 GPa, that is the breaking stress estimated by the tests we have carried out before Virgo+ fibers production. With this diameter, bouncing frequency is about 6 Hz, and the first violin mode frequency is at about 430 Hz. However, this is not the optimal value to limit thermoelastic dissipations. So, the fiber is also dumbbell-shaped, as it is shown in fig. 11. In this scheme, most of the fiber length has a diameter of 400 \(\mu m\), while at both fiber ends are two short heads, with a diameter of 800 \(\mu m\). In this way, since most of the bending energy is stored close to the bending points that are inside the 800 \(\mu m\) regions (heads), the cancellation mechanism can minimize the thermal noise due to the thermo elastic effect. Moreover, the two 3 mm thick ends (bars), can be used to weld the fiber to the rest of the suspension and, also, to set the bending point on the right position with respect to the mirror and the marionette. In any case these regions must not be longer than a few millimeters, to limit the bending energy stored there and to make the bending point position independent of the welding shape. A finite element model, implemented by a specifically developed code \([39]\) was used to simulate the elastic behavior and to estimate the thermal noise, for fibers with a diameter variable along their length.

Each fused silica fiber is produced starting from high purity fused silica cylindrical bars, commercially available (suitable materials are Herasil or Suprasil), 10 cm long and 1.5 mm thick. This small cylindrical bar is clamped at both ends and heated in the central region using a 200 W \(CO_2\) commercial laser with 10.6 \(\mu m\) wavelength. Subsequently the two ends are pulled apart, extending the fiber at the desired length and shape. In fact, once melted, the fused silica material becomes highly viscous and it can be plastically deformed. This process is performed by a dedicated machine developed at the University of Glasgow for GEO gravitational interferometer and duplicated in Virgo in a dedicated lab.

After being produced, the fibers are tested to a load at least double the operation load. Then, if the fiber survives, its bending length is measured. The bending length \(\lambda\) of the suspension is the distance of the fiber bending point from the clamped end. This is an important information, because tells us where is the point where the fiber bends during the pendulum motion of the mirror. That is also the point that must be contained in the plane passing by the suspension point of the marionette and the actuation axis of the coil-magnet actuators. Positioning the bending point on the center of mass plane of both the marionette and the mirror allows minimum coupling between the different degrees of freedom; it is also possible, through a simple model of the fiber based on the knowledge of \(\lambda\), to study its dynamical behavior.
profiles of the fibers near the heads require this quantity to be directly measured. For doing this a specific instrument was realized.

After being produced and validated, the fibers are then placed in position, clamping the upper part to the marionette and inserting the lower anchor below the lateral supports bonded to the mirror. In the end the anchor and the supports are bonded together with silicate bonding.

5.5. Payload assembly and integration

As soon as the silica bonding as cured, the monolithic suspensions are integrated with the rest of the mechanical elements described above, and the complex procedure to integrate the mirror and its last stage suspension with the Super Attenuator starts. The complete payload is inserted in a container with controlled humidity and cleanliness and transported into the clean room under the vacuum chamber surrounding the Super Attenuator chain (the tower, with a continuous monitor of many physical parameters during transport (acceleration, temperature, humidity). The actual suspension of the mirror at the end of the super attenuator chain requires several hours of stressful work. After that, the weeks long procedure to activate the local control begins.

6. Mirror isolation and control

The seismic isolation of AdV mirrors will be provided by the Superattenuator (SA), a mostly passive attenuation system capable of reducing the seismic noise by more than 10 orders of magnitude in all six degrees of freedom (DOFs) above a few Hz. A detailed description of the SA and its performance are given in [40, 41, 42].

6.1. Mechanics

Since the performance of the SA is already compliant with the AdV requirements no major changes in the mechanical design are introduced.

The AdV SA mechanical structure, shown in fig. 12, consists of three fundamental parts:

- the inverted pendulum (IP);
- the chain of seismic filters;
- the mirror suspension.

The IP [43] is constituted by three 6 m-long hollow legs, each one connected to ground through a flexible joint and supporting an interconnecting structure (the top ring) on its top. The top ring, which is a mechanical support for an additional seismic filter, called filter 0, similar to those used in the chain, is equipped with a set of sensors and actuators, placed in a pinwheel configuration, that are used to actively damp the IP resonance modes. Two kinds of sensors, LVDTs with $10^{-8}$m/$\sqrt{\text{Hz}}$ noise and accelerometers with $3 \cdot 10^{-10}$m/s$^2$//$\sqrt{\text{Hz}}$ sensitivity, specifically designed for Virgo/Virgo+ [], are used. Two sets of actuators, coil-magnets and motor-springs, are also installed on the top ring.

The chain of seismic filters is suspended from the filter 0 and is constituted by an 8 m-long set of five cylindrical passive filters, each one designed to reduce the seismic noise by 40 dB, starting from a few Hz, in both horizontal and vertical directions.
Figure 12. View from top of the AdV superattenuator. We can distinguish, from top to bottom, the three legs of the inverted pendulum, the filter 0, the top ring, the passive filters 1 to 4, and the mirror suspension. This last stage, constituted by the steering filter, the marionetta and the actuation cage, is dedicated to the control of the mirror position for frequencies $f > 10$ mHz.

The mirror suspension is supported by the last seismic filter of the chain called filter 7 or steering filter. Since in AdV, as described in sec. 5, the last stage of the SA has been completely redesigned, several changes have been introduced in the mechanics of the filter 7. In order to keep the same total weight for the payload-filter 7 assembly, the steering filters supporting the Fabry-Perot and Signal Recycling test masses are now 55 kg lighter than in Virgo/Virgo+. The mass reduction is obtained by using a shorter drum steel structure for the filter body and a lighter support, called crossbar, for the matrix of permanent magnets used to lower the vertical resonance frequency of the standard filters. Moreover six LVDTs and six coil-magnet actuators are now installed in pinwheel configuration on the ring surrounding the filter 7, in order to control its motion in all DOFs.

6.2. SA Control System

Since, between 200 mHz and 2 Hz, the seismic noise is amplified by the resonance modes of the isolation stages, an active control of the SA is needed. As in Virgo/Virgo+, the system has been designed using a hierarchical strategy regulated by the dynamic range of the actuators. In the ultra-low frequency band ($f < 10$ mHz), the actuation will be done on the IP top stage along $z$, $x$, and $\theta_y$ DOFs (as customary we consider $z$ aligned with the suspended mirror optical axis) using 3 coils, disposed
In pinwheel configuration on the top ring. In the $10 \, \text{mHz} < f < 1 \, \text{Hz}$ band, the control will act both on the filter 7 along six DOFs using 6 actuators and on the marionetta along 4 DOFs ($z, \theta_x, \theta_y, \theta_z$) using 8 coils. For frequencies higher than a few Hz, the force will be applied directly to the mirror along $z$, using 4 coils screwed on the actuation cage that allow also tiny corrections along $\theta_x$ and $\theta_y$.

In Virgo/Virgo+ the controllers have been designed using classical Nyquist-like techniques, diagonalizing the sensor-actuator space with static matrices in order to obtain a set of single-input single-output (SISO) systems \cite{44}. In AdV, a multivariable design approach, based on optimal predictive regulators \cite{45}, will be instead used in order to have a user-independent and completely automatic design process and to optimize the feedback performance for both the mixed and diagonal term elements of the sensor/actuator transfer function matrix.

As in Virgo/Virgo+, the regulators will be implemented in a digital hard real-time control system based on Digital Signal Processors (DSPs). The hardware has been completely redesigned for AdV and is constituted by MicroTCA boards, using the RapidIO bus, that integrate front-end electronics, data conversion and data processing in a single unit. The processor chosen is the Texas Instruments TMS320C6678, a high-performance multicore fixed and floating point DSP with a total computing power of 160 GFLOPs in single precision at 1.25 GHz. Data conversion is based on the Texas Instruments ADS1675, a 24-bit $\Sigma - \Delta$ analog to digital converter with a maximum throughput of 4 MSPS, and on the Analog Devices AD1955, a 24-bit $\Sigma - \Delta$ digital to analog converter (DAC) that can process both PCM and DSD data formats. The maximum sampling frequency that can be implemented on the control system is 640 kHz. A series of multi-channel low noise power amplifiers, simply called coil drivers, are used to drive the coil-magnet pairs installed on the SA. Every coil driver has an on-board DSP and two distinct sections, each driven by an independent DAC channel: one high power section used for lock acquisition of the ITF optical cavities, and one low noise section for linear regime. In this latter mode, the coil drivers can supply up to 0.5 A with a few of $\mu \text{A}/\sqrt{\text{Hz}}$ of noise. Since each suspension will be typically connected to 20 boards, each one hosting a TMS320C6678, a DSP farm with 3.2 TFLOPs computing power, in single precision, will be available for the control of the SA and the processing of its signals.

### 6.3. Tilt Control

We know experimentally that, due to earthquakes or bad weather conditions, seismic noise grows up to 2 or 3 orders of magnitude in $100 \, \text{mHz} - 1 \, \text{Hz}$ band with its maximum between 400 and 500 mHz (micro-seismic peak). Since the ground tilt is transmitted without any attenuation to the SA top stage, we estimate that, in those conditions, the angular component of the seismic noise can reach levels high enough to compromise the duty cycle of the interferometer. A tilt control of the SA will be therefore implemented in AdV.

For this reason a set piezo-electric actuators (Physik Instrumente P-239.30), capable of providing a force of 4500 N with a dynamic range of 40 $\mu \text{m}$, are installed on the ring supporting the IP flex joints. Three LVDTs, that monitor the vertical displacement of the ring, are used in closed loop with the piezos in order to increase the linearity of the actuators.

At the same time, a sensor capable to provide tilt measurements uncontaminated by translational components is mandatory to implement a tilt control of the suspension
because the SA accelerometers produce a signal proportional to a linear combination of both acceleration and angle. While several studies on mechanical gyroscopes with high sensitivity at low frequencies have been done [46, 47], the most promising angular sensor candidate in terms of angle/acceleration cross-coupling is the Hemispherical Resonator Gyroscope (HRG) [48, 49].

An HRG custom-made by the Russian firm MEDICON for AdV is currently being tested. The results of this study will be the subject of a forthcoming paper.

7. Managing thermal aberrations and optical defects

7.1. Introduction

The amount of allowable circulating probe power in an interferometric GW detector is limited by the nonzero optical absorption in the substrate and coatings of the test masses. The dependence from temperature of the refraction index and the thermal expansion coefficient of optical materials ensure that temperature gradients, induced by the absorption of the Gaussian-profiled probe light, will result in nonuniform optical path length distortion, the so called thermal lensing, in the optics crossed by the probe beam (ITMs, PR mirror and BS), and in a change of the profile of the high reflective surface in both input and end test masses.

Thermal lensing was already observed in Virgo [51] and LIGO [52] and required the installation of Thermal Compensation Systems (TCS). Advanced detectors [54, 55] will be characterized by a higher circulating power (from 20 kW in the initial interferometers to 700 kW in the second generation detectors) and thermal effects will become even more relevant.

Besides thermal aberrations, there are sources of optical defects arising from imperfections in the production and polishing of the glass used for the various substrates in the recycling cavity. Surface figure errors on reflective and transmissive surfaces do contribute to the aberrations as well as spatial variations in the index of refraction of the substrates.

Thermal lensing and fabrication errors change the cavity mode, thus the input laser no longer matches the PRC and the coupling coefficient between the laser TEM\(_{00}\) and the cavity TEM\(_{00}\) becomes less than one. This leads to a decrease of the recycling cavity gain and thus in the sidebands power. Since sidebands are used to keep the interferometer locked, thermal lensing affects the possibility to operate the detector at high input powers. The ultimate consequence is a loss of signal-to-noise ratio at high frequencies due to the increase of shot noise. This will be especially true in the case of Advanced Virgo, due to the marginal stability of the power recycling cavity (PRC).

Thermal expansion will change the profile of the high reflectivity surface: a bump will raise in the center of the test mass faces, making their surface profile non-spherical and the Radius of Curvature (RoC) will increase in Advanced Virgo by about 44 m. The cavity will become less concentric, and the spot sizes at the mirrors will shrink. To maintain the arm cavity mode structure, it will be then necessary to control the radii of curvature of all test masses within ±2 m from the initial RoC.

In Advanced Virgo, TCS will need to compensate for optical aberrations in the PRC and to tune the RoCs of the test masses, acting on both ITMs and ETMs.

A useful way to picture the effect of optical distortions is the fractional power scattered out from the TEM\(_{00}\) mode [56, 57], termed ”coupling losses”, and the
Gaussian weighted Root-Mean-Squared (RMS) of the optical path length increase $58$. In Advanced Virgo, the sideband fields coupling losses, due to all aberrations, would amount to approximately $5 \cdot 10^5$ ppm, corresponding to an RMS of about 125 nm. The Advanced Virgo TCS needs to reduce the coupling losses at least by a factor of $10^3$ (corresponding, roughly speaking, to a maximum RMS of about 2 nm $59, 60$) to allow the correct operation of the detector at design sensitivity.

7.2. Thermal compensation actuators

The conceptual actuation scheme of the Advanced Virgo compensation system $61, 62, 63$ is shown in figure 13. The wavefront distortions in the recycling cavities will be corrected with an appropriate heating pattern generated by a CO$_2$ laser, whose wavelength is almost completely absorbed by fused silica. For the control of the radii of curvature of all the test masses, ring-shaped resistive heaters (RH) will be used. In Advanced Virgo, due to the sensitivity improvement, it will be no more possible to shine the input test masses directly with the CO$_2$ laser, as it was done in initial detectors $53$. The displacement noise introduced by the intensity fluctuations of the CO$_2$ laser would spoil the detector sensitivity in the frequency band 50 Hz - 100 Hz. To make TCS compliant with Advanced Virgo noise requirement, the relative intensity noise of the CO$_2$ laser should be reduced to the level of $10^{-8} / \sqrt{\text{Hz}}$ at 50 Hz, one order of magnitude below what it is possible to achieve with the present technology. This implies the need of an additional transmissive optic, named Compensation Plate (CP) to act on with the compensating beam. The CPs are placed in the recycling cavity, where the noise requirements are less stringent by a factor of $\pi/2F$ than in the Fabry-Perot cavity.

This scheme also allows to reduce the coupling between the two degrees of freedom (lensing and RoC), so to have a control matrix as diagonal as possible.

The thickness of the CP has been optimized by minimizing the heat escaping from its barrel and taking into account the need to accumulate enough optical path length. The distance between CP and ITM is 20 cm, this allows to minimize the radiative coupling between the two optics. In fact, the heated CP radiates heat towards the test mass. The heating of the TM is uniform, but since the barrel of the input mirror radiates away a part of the heat, a radial temperature gradient is established. This gives rise to an increase of optical path length that adds to the thermal lensing.

The position of the RH along the barrel of the TM is such as to maximize its efficiency.

To optimize the heating pattern to be applied to the CP, the aberrations have been classified according to their symmetry properties, regardless of their origin:

- aberrations with cylindrical symmetry;
- non-symmetric defects.

The studies on the optimization of the heating pattern have been carried out with Finite Element Model (FEM). For those aberrations with cylindrical symmetry, the modeling has shown that the optimum heating pattern $63$ would reduce the residual coupling losses to about 6 ppm (about 0.1 nm RMS), thus leading to a reduction factor of about $10^5$, with about 18 W of CO$_2$ power shined on the compensation plate.

For the non-symmetric optical defects, full 3D modeling is required, making this kind of simulations rather computationally expensive (few days of CPU time). The results of the optimization procedure show that, by depositing heat in the right CP
positions, the residual optical path length RMS can be reduced by a factor of 20 for spatial frequencies below 40 m$^{-1}$ and amounts to 0.35 nm, well within the requirements. The method selected to generate this heating pattern is based on a CO$_2$ laser scanning system. This technique, developed at MIT [64], comprises a pair of galvanometer mirrors, to move the laser beam on the surface of the CP, and an acousto-optic modulator to modify the power content of the beam.

**Figure 13.** Left: Actuation scheme of the Advanced Virgo TCS: blue rectangles represent the CPs (heated by the CO$_2$ lasers) while the green dots around the test masses are the ring heaters. Right: Conceptual layout of the HWS probe beams in the recycling cavity. For the sake of clarity the beams have different colors, but the wavelength is the same.

7.3. Sensing for thermal compensation

The aberrations in the recycling cavity optics will be sensed by several complementary techniques. The amplitude of the optical path length increase will appear in some ITF channels, such as the power stored in the radio frequency sidebands. These are scalar quantities that can only give a measurement of the amount of power scattered into higher order modes. Moreover, phase cameras [65, 66] will sense the intensity distribution and phase of the fields in the recycling cavity (carrier and sidebands).

Each optic with a significant thermal load will be independently monitored. The HR face of each test mass will be monitored in reflection off-axis for deformation. The input test mass/compensation plate phase profile will be monitored on reflection on-axis from the recycling cavity side. The TCS control loop will then use a blend of all the signals from the different channels.

The TCS sensors, dedicated to the measurement of thermally induced distortions, consist of a Hartmann Wavefront Sensor (HWS), and a probe beam (at a different wavelength than the ITF beam) whose wavefront contains the thermal aberration information to be sensed.

The Hartmann sensor selected for Advanced Virgo is that already developed and characterized on test bench experiments and in the Gingin High Optical Power Test Facility for the measurement of wavefront distortion [67]. This sensor has been demonstrated to have a shot-to-shot reproducibility of $\lambda/1450$ at 820 nm, which can be improved to $\lambda/15500$ with averaging, and with an overall accuracy of $\lambda/6800$ [68].
The conceptual layout of the HWS beams in the recycling cavity is shown in figure 13. In the picture, the beams have different colors for the sake of clarity, indeed the wavelength is the same for both beams. The beams will be injected/extracted from the injection and detection suspended benches, superposed to the main ITF beam with a dichroic mirror at the level of the mode matching telescopes. This scheme allows for on-axis double pass wavefront measurement (that increases the signal-to-noise ratio by a factor of two) and for probing of all the optics in the recycling cavity.

Additional optics are necessary to fulfill the main optical requirements for HWS beams: to image a plane around the ITM HR surface on the Hartmann plate, to illuminate the ITM with a Gaussian beam 10 cm in size and to match the optimal beam size on the sensor. The two sensing beams separated by the BS HR coating. Beam from the detection bench will also sense the BS thermal lensing, thus allowing its correction on the NI CP.

8. Laser

8.1. Overview

The laser source of AdV is a high power (HP) continuous wave laser, which is stabilized in frequency, in intensity and in beam pointing. The high power requirement is necessary to overcome the shot noise limit, while the stabilizations bring the technical noises of the laser down to a level where they don’t mask the tiny signal of gravitational waves. A laser power of at least 175 W in TEM$_{00}$ mode is required to meet the sensitivity goal. In absence of a perfect symmetry in the cavities, the interference between the two arms of the Michelson reflects all the frequency and power fluctuations of the laser. In order to detect such a small GW signal as $10^{-23}$ in relative strain, the relative frequency and power fluctuations of the laser have to stick to the same order of magnitude. Then for a laser light emitting at 1 $\mu$m wavelength, we end up with a few $\mu$Hz/$\sqrt{\text{Hz}}$ for the laser frequency fluctuations, while in free-running conditions a quiet laser produces a noise of a few kHz/$\sqrt{\text{Hz}}$. This makes a stabilization factor of 9 orders of magnitude which is quite hard to get with a single stage of servo-loop: then a multi-stage servo-loop is used for the frequency stabilization, with different references ranging from a rigid Fabry-Perot cavity to the arms differential of the Michelson itself. To minimize the laser power fluctuations, the Michelson operates on the dark fringe, but the DC readout method used in advanced detectors requires a small deviation from the dark fringe. Combined to the fluctuating radiation pressure noise suffered by the mirrors, the laser power fluctuations have to be in the range of $10^{-9}$/$\sqrt{\text{Hz}}$ while the beam pointing has to be below $10^{-11}$ $\text{rd}/\sqrt{\text{Hz}}$.

8.2. HP Laser for AdV

Getting such high power output with a highly stable laser is a serious challenge that is managed by separating the two functions of HP output and stabilization: a low power stable laser is used to transfer its stability to a HP oscillator by either injection-locking and/or amplifying it through an internal laser process helped by a slow servo-loop to prevent drifts. While in the first case the stable output of the low power laser is automatically transferred to the HP laser, the amplifier case contains no filtering cavity and transfer of stability is achieved only in saturation regimes. HP oscillator used so far in initial Virgo and Virgo+ phases is bulk lasers based on Nd:YV04 (Neodymium
doped Yttrium Orthovanadate) crystals, which are the best choice for the 100W class lasers. The first phase of the AdV project requires a medium power laser of around 35-40W at the input of the Injection sub-system and the final phase will need about 200W output such that at least 175W in TEM\textsubscript{00} mode can be delivered as requested. The medium power laser is today an Nd:YVO\textsubscript{4} oscillator amplifying a 20W injection locked laser to deliver around 60W. The free-running frequency noise of this amplifier copies the one of the master laser, which is a monolithic commercial non-planar ring oscillator of 1W (Innolight NPRO). Though intrinsically stable in short term, it will be nevertheless frequency stabilized to the Michelson arms.

To reach the ultimate power we plan to use amplifiers based on fiber technology. A R&D work is in progress with the goal of delivering the final laser for installation in 2018.

8.3. Stabilizations of the HP laser

8.3.1. Frequency stabilizations

The frequency stabilizations act on the piezo-transducer of the Master laser, the error signal is a combination resulting from a multi-stage servo-loop having as references, the rigid reference cavity (RC), the input mode cleaner (IMC) and the differential arms of the Michelson.

8.3.2. Power stabilization of the laser

Comparing the light power fluctuations to a stable voltage gives the error signal, which is fed back to the pumping diodes current of the HP amplifier for the power stabilization. The principle sounds simple, but a voltage fluctuation measured out of a photodiode contains not only, the light fluctuations but also any other fluctuation due to surface inhomogeneity (e.g. air pressure fluctuations, dust crossing the beam). Then a careful selection of photodiodes has to be made, and they have to stay in a quiet environment such as under vacuum. Furthermore we know that resonant cavities beams act as low pass 1st order filters for amplitude and beam jitters noise of the laser. For amplitude noise the corner frequency of this filtering is equal to half the line width of the cavity. Then placing the power stabilization photodiode under vacuum after the IMC will relax the constraints of the servo loop in the MHz range and in our case amplitude and beam jitter noise start to be attenuated by the IMC above 800 \(-\) 900 Hz. Nevertheless a power stabilization servo-loop is still necessary inside the detection range mostly below 500 Hz. The photodiodes have been designed to fulfill the specifications set in the table above i.e. a RIN of \(1.2 \times 10^{-9}/\sqrt{\text{Hz}}\) at the frequency of 30 Hz, which is the most stringent frequency part. To reach that level of stabilization, the required shot noise limit on the photodiodes has to be lower than \(10^{-9}/\sqrt{\text{Hz}}\) that requires an equivalent of about 400 mA. Due to the limited standing power of fast photodiodes, the light sensor is composed by 2 sets of 2 photodiodes sharing a total amount of 400 mA of photocurrent. A box of 4 photodiodes has been realized and delivered on site where it has been clamped on the bottom face of the suspended injection bench SIB1 to receive 400 mW of the light transmitted by the IMC. Two photodiodes have been coherently combined and give a measured the noise floor limit of \(1.3 \times 10^{-9}/\sqrt{\text{Hz}}\) with a 400 mA photocurrent. The two others will be used for out-of-loop check out.

8.3.3. Beam shape and beam jitter controls of the laser

The last control of the laser beam concerns the beam shape and the beam pointing noise, which requirements are quite stringent inside the interferometer (see requirements table). To lower the beam
noise at the entrance of the injection bench and to filter out the high order modes inherent to HP lasers, a pre-mode-cleaner (PMC) is positioned on the laser bench. A compromise has been found for its specifications between the finesse and the high level of stored light in a small beam waist. To avoid direct feedback to the laser the PMC is a triangular cavity non monolithic as it carries a piezo transducer to control its length relative to the laser frequency. This PMC has been already used for Virgo+ phase and could stand the 50W laser with a finesse of 500 in a beam of 500 µm. Let’s recall that the PMC is lying on a horizontal plane and favors then the horizontal beam jitter. Final HP amplifiers have to be exhaustively characterized in noises as well as beam pointing in both horizontal and vertical directions in order to figure out whether one PMC on horizontal plane is enough to tackle for the noises in both directions.

9. Light injection

9.1. Overview

Figure 14 shows an overview of the input optics set between the laser and the interferometer and designed to provide a beam with the required power, geometrical shape, frequency and angular stability. The main requirements for the input optics are:

- Transmission to the ITF > 70% TEM\textsubscript{00}
- Non-TEM\textsubscript{00} power < 5%
- Intensity noise $2 \times 10^{-9}/\sqrt{Hz}$ at 10 Hz
- Beam Jitter < $10^{-10}$ rad/$\sqrt{Hz}$ ($f > 10$ Hz)
- Frequency noise (for lock acquisition) < 1 Hz r.m.s

An Electro-Optic Modulation (EOM) system is providing the RF phase modulations needed for the interferometer (ITF) cavities control. A system based
on piezo actuators and DC quadrant photodiodes has been developped to reduce as much as possible the low frequency beam jitter before entering into the vacuum system (Beam pointing control system). Another system (EIB–SAS) reduces the beam jitter induced by structural resonances of optical benches legs. Then, a power adjustment system (Input Power Control), consisting of a half waveplate and a few polarizers is being used to tune the ITF input power. Some matching and steering optics in air are required to properly couple the beam into the in-vacuum suspended input mode cleaner cavity (IMC). The IMC is geometrically cleaning the beam and reducing its amplitude and beam pointing fluctuations before the ITF. The resonant IMC for which the length is locked on the reference cavity (RFC) is serving as a first stage of frequency stabilization of the main laser. After the IMC, an intensity stabilization section will provide the signal for stabilizing the laser RIN (Relative Intensity Noise) and reach the requirements. Then, an in-vacuum Faraday isolator is preventing interaction of the ITF rejected light with the IMC and the laser system. Finally, a mode matching telescope (ITF mode matching telescope) is there to match the laser beam on the interferometer.

9.2. Electro-optic modulator

In Advanced Virgo, five different modulation frequencies are required. To create them, we use three custom modulators, located between the laser system and the vacuum vessel on the external injection bench (EIB). Because of the high input laser power, we have selected a low absorption electro-optic material: the RTP (Rubidium Tantanyle Phosphate RbTiOPO$_4$) from Raicol Crystals Ltd. Indeed, this material offers a very low absorption level (<50ppm/cm @ 1064nm) and this allowed us to reduce the thermal lensing effect. In fact, a thermal focal length $\sim 10$m for 200W input optical power has been measured for each modulator. Each crystal surface is wedged and has a trapezoidal shape. An horizontal wedged of one degree on the both sides allows the separation of the linear polarizations by walk-off. We can also avoid the cavity effect and reduce the residual amplitude modulation (RAM) \cite{69} that could be a source of noise (RAM < $10^{-6}$ required). These modulators have been tested in the laboratory and a modulation depth higher than 0.1 has been obtained. They are currently being installed on the detector. Figure \ref{fig:modulator} shows a view of one modulator and the spectrum of the laser beam after passing through the modulator.

9.3. Beam pointing control system

The beam pointing fluctuations can be a relevant source of noise. Indeed, in case of geometrical asymmetries between the arms of the ITF, created by spurious misalignments of ITF optics, the input beam jitter creates a phase noise directly affecting detector sensitivity \cite{70,71}.

In Advanced Virgo a very simple but effective system to mitigate, below 10 Hz, and to monitor, in the detection frequency band 10 Hz - 10 kHz, the beam pointing noise at the input of the IMC has been developed and tested. It is the so called ‘Beam Pointing Control system’ (BPC) \cite{72,73,74}.

The control system is composed by two quadrant diodes to sense the input beam displacement and two tip/tilt piezoelectric actuators to compensated it. The sensing has been designed placing the two quadrant diodes in the focal and in the image plane of the input of the IMC to sense respectively the tilt and the shift of the beam.
The BPC system has shown unprecedented performance in terms of control accuracy and sensing noise, achieving a control accuracy of $\sim 10^{-8}$ rad for the tilt and $\sim 10^{-7}$ m for the shift, and a sensing noise of less than 1 nrad making it compliant with the requirements.

9.4. EIB–SAS

The excess motion of the External Injection Bench, due to the seismic excitation of its rigid body modes can be a major source of angular and lateral beam jitter in the injection system and limit the detector sensitivity. A new actively controlled bench support system, called EIB–SAS (EIB Seismic Attenuation System), has been realized following the requirement of having a neutral behavior with respect to the ground motion in a broad frequency range (DC to several hundreds of Hz). The EIB-SAS (see an impression in Fig. 16) is a single stage six degrees of freedom vibration isolator, the design of which is derived from the Advanced LIGO HAM–SAS prototype [88], more recently upgraded and adapted at the AEI Hannover, in order to be incorporated in their 10–m prototype interferometer [89].

Passive seismic attenuation, from 20 to 70 dB in vertical and from 30 to 70 dB in horizontal between 2 and 400 Hz [91], is achieved by means of a combination of a short (0.5 m long legs) inverted pendulum (IP) and three set of cantilever blades in geometric anti-spring (GAS) configuration [90]. All six fundamental rigid body modes have natural frequencies tuned between 0.2 and 0.5 Hz. The EIB–SAS is instrumented with position (LVDT) and inertial (geophones) sensors and voice coil actuators to actively damp the low frequency eigenmodes and to stabilize position and orientation of the supported bench. Higher frequency modes, originating from the GAS spring lateral compliance and from the vertical compliance of the inverted pendulum structure, are treated with tuned dampers placed on the spring-box. The internal modes of the IP legs are cured with eddy current dampers. Stepper motor driven correction springs are used for initial (and periodical on the long term) coarse alignment of the bench.
9.5. IMC cavity

The input mode cleaner (IMC) cavity is an in-vacuum triangular cavity comprising suspended optics which has a length of 143.424 m and a finesse of 1200 (corresponding to an input/output coupler reflectivity of 2500 ppm, and total round trip losses lower than 100 ppm). The finesse and length of the cavity are unchanged with respect to Virgo, as they are still thought to be a good compromise when considering the high spatial filtering effect of the cavity and issues linked to the high finesse and length, such as radiation pressure, thermal effects and the small angle backscattering from the end mirror. On the other hand stricter polishing requirements have been set to improve the cavity performance in terms of throughput losses and backscattering. At the time of writing the mirrors have been polished, coated and installed. Simulation using measured mirror maps yielded an estimated throughput loss and effective “reflectivity” of 2 % and 300 ppm respectively.

9.6. Faraday isolator

Light back reflected from the ITF may scatter inside the IMC and interfere with the input beam [75, 76] . This issue may be tackled by adding an in-vacuum Faraday isolator on the SIB between the PR mirror and the IMC. With the high input power of AdV, a standard Faraday Isolator (FI) would exhibit loss of optical isolation due to thermally induced birefringence [77, 78] and modification of mean angle rotation due to heating of the TGG crystal under laser radiation. This last effect is particularly problematic under-vacuum where thermal dissipation is mainly insured by radiation [79] . Indeed, a standard device would also exhibit very high thermal lensing that is mandatory to correct inside the Faraday itself to avoid large power dependent mismatching inside the system.

A dedicated FI allowing for compensation of all these effects was developed
for AdV \[80\] in collaboration with the Institute of Applied Physics (Russia) and is described in Fig. 17.

![Figure 17. Left: Scheme of the high power compatible Faraday isolator. Right: View of the assembled device.](image)

It consists of an input polarizer, a half waveplate, two Terbium Gallium Garnet (TGG) crystals rotating the polarization by 22.5° and separated by a -67.5° quartz rotator (QR), an end polarizer and a DKDP plate. By using two TGG crystals separated by a quartz rotator, it is possible to limit the effects of thermal depolarization by compensating with the second crystal the depolarization created in the first one \[81\]. The variation of mean angle rotation of the two TGG crystals can be compensated by slightly turning the half wave plate, which can be done remotely \[82\]. This also enables to compensate for the modification of isolation observed with the whole setup when it is tuned in air and then placed in vacuum where thermal dissipation process is different. Finally, a DKDP (Deuterated Potassium Dihydrogen Phosphate, KD$_2$PO$_4$) plate is used to compensate for thermal lensing created inside the TGG crystals, thanks to its large negative thermo-optic coefficient \[83\]. Using this device we can insure an isolation ratio of 40dB at 150W, a residual thermal lens as low as 100 m at full power and a total transmission of about 98 % which fully complies with AdV needs.

9.7. Mode matching telescope

The design of the mode-matching telescopes (MMT) has been driven by the space constraints on the suspended injection bench (SIB) and in order to limit as much as possible the aberrations of the beam \[84\]. The telescope is made by an afocal 2 mirrors off-axis parabolic telescope which increases the beam size from 2.6 mm (size of the beam inside the Faraday), to 22 mm. Then the beam is expanded by a meniscus lens, and it is finally re-collimated by the power recycling mirror, whose anti-reflecting (AR) coated surface is curved, to the Fabry-Perot cavities. The meniscus lens is needed to compensate for the spherical aberrations of the power recycling mirror. This design allows to reach a theoretical matching of the input beam with the ITF higher than 99.9 %. The two parabolic mirrors and the meniscus lens, including the opto-mechanical mounts, hold in an area of 76 cm x 30 cm, satisfying the space constraints.

In order to set requirements on the actuator ranges needed for the telescope mounts, a tolerancing study was performed using a Monte Carlo simulation method, taking in consideration possible errors on the surface of the optics, on their alignment and on the beam parameters \[85\].
In order to limit the scattered light by the optics, requirements on the surface quality of the parabolic mirrors (roughness < 1 nm) and on the AR coating of the meniscus lens (<100 ppm) have been set. In addition, the optical mounts have been designed in order to limit the presence of low frequency resonances. Moreover, the telescope is suspended from a Virgo seismic superattenuator, limiting the modulation of the scattered light in the AdV detection band by the seismic noise.

The telescope has been installed on the suspended injection bench 1 (SIB1) and pre-aligned at the beginning of 2014. The fine tuning will be done when the ITF will be available.

![Figure 18. Catadioptric telescope of the Suspended Injection Bench 1 (SIB1) layout (left); MMT installed on SIB1 (right) in February 2014.](image)

10. Light detection

10.1. Overview

The detection system extracts the ITF signals from the anti-symmetric port and from the auxiliary beams. It is made of several optical benches hosting photodetectors as well as motorized alignment optics and mode-matching telescopes. The beam from the anti-symmetric port, that will be referred to as dark fringe beam, carries information about a change in the differential arm length (DARM) and is thus sensitive to gravitational waves (GW). The detection system must comply with the DC detection scheme which has been selected for AdV. Auxiliary beams are sensitive to other degrees of freedom of the ITF, such as cavity lengths and laser frequency variations, providing signals needed for the ITF control systems. The optical benches designed for the extraction of the main ITF beams are sketched in Fig. 19.a and described below.

A first detection bench, denoted as SDB1, is placed along the path of the dark fringe beam. An optical layout of SDB1 is presented in Fig. 19.b. This bench hosts an output mode cleaner (OMC) whose goal is to improve the contrast defect by filtering out spurious components of the light induced by interferometer imperfections. In the DC detection scheme the OMC must also filter out the RF side bands. The OMC designed for AdV is described in section 10.3. In order to adapt the beam waist to the OMC, a mode matching telescope is placed at the input of the SDB1 bench. This telescope is presented in section 10.4. The SDB1 bench is followed by a second suspended detection bench, denoted as SDB2, which hosts sensors for the detection of the dark
fringe beam and secondary beams involved in the ITF control. The sensors involved in the detection system are described in section 10.5. Both SDB1 and SDB2 benches are suspended and placed under vacuum to isolate sensitive optics and photodetectors. An external detection bench, denoted as EDB, hosts less sensitive equipments, such as a phase camera \[65\] and a Hartmann wavefront sensor which, as explained in section 7, will be used to monitor the thermal aberrations and optical defects in the ITF. A suspended bench denoted as SPRB is used to extract a pick-off beam from the power recycling cavity. It hosts a telescope to adapt the beam size and Gouy phase to the photodetectors. Similarly a suspended bench equipped with a telescope at the end of each ITF arm (denoted as SNEB for the north arm and SWEB for the west arm) allows the extraction of the beam transmitted by the Fabry-Perot cavity. Another suspended bench denoted as SIB2 extracts the beam reflected by the ITF.

One of the design criteria of the detection system has been the minimization of the impact of stray light and scattered light, which was one of the noise sources limiting the sensitivity of the first generation interferometers. In order to limit the amount of back-scattered light stringent requirements have been set on the micro-roughness (typically \( \leq 0.3 \text{ nm RMS}\) for spherical and flat optics, and \( \leq 1 \text{ nm RMS}\) for the parabolic mirrors of the telescope discussed in section 10.4) and the anti-reflective coating (\( \approx 100 \text{ ppm}\) targeted) of the optics placed along the path of the dark fringe beam. Moreover scattered light noise couples through the displacement of the optics which is amplified at the resonance frequencies of the mounts. Therefore the absence of resonances at low frequency with high quality factors has been one of the criteria for designing and selecting optical mounts. Furthermore, the main optical benches are seismically and acoustically isolated as discussed in section 10.2.

![Figure 19.](image-url) (a) Scheme of the optical benches foreseen for AdV. (b) Optical layout of the first suspended detection bench SDB1. YAG beams (\(\lambda = 1064 \text{ nm}\)) are displayed in red. A Hartmann beam (\(\lambda = 800 \text{ nm}\)) is displayed in green.
10.2. Suspended detection benches

In addition to SDB1 which is suspended to a short version of the Virgo Superattenuator (cf. section 6), five new benches are going to be installed in new vacuum chambers and suspended at complex isolation systems. The main motivation for isolating these benches is to mitigate scattered light noise which couples through seismic and acoustic vibrations. As shown in section 13, the designed vacuum chambers are very compact, which is necessary to comply with the stringent space constraints regarding the implementation of these chambers within the existing infrastructure. Accordingly a compact isolation system (cf. section 13) and a new suspended bench body fitting in these vacuum chambers have been designed. A 3D drawing of the bench is shown in Fig. 20a. The bench body is made of aluminium and incorporates a sealed air container hosting, in particular, electronic boards used for the readout and the control of the sensors located on the bench. This strategy minimizes the number of cables running along the suspension, which helps keeping the isolation system compact while avoiding mechanical short-circuiting. As a consequence of having the sensing electronics integrated within the bench body, a significant amount of heat has to be dissipated in the vacuum chambers. The heat will be evacuated from the electronic components to the bench body through conduction using heat links, and from the bench body to the vacuum chamber walls through radiation. To this purpose, the suspended bench will be anodized in order to maximize its thermal emissivity.

10.3. Output Mode Cleaner

The AdV OMC is made of two identical cavities placed in series (cf. Fig. 19b). Each cavity is made of a monolithic block of fused silica (cf. Fig. 20b) with four polished surfaces, which together form a four mirrors bow-tie cavity. The choice of a compact monolithic cavity has been made to minimize the cavity length noise and to keep mechanical resonances above the detector bandwidth, namely above 10 kHz. The round-trip length \(L_{rt} = 248 \text{ mm}\) and the nominal finesse \(F = 143\) of the cavity have been chosen to meet the AdV requirements on the filtering of the RF side bands for DC detection. Having two cavities in series offers the asset of keeping a moderate finesse.

![Figure 20](image-url)
value, which eases the lock of the cavity and, for a given locking accuracy, limits the coupling of cavity length noises, proportional to the square of the finesse. The finesse has also been chosen sufficiently low to keep the internal losses per cavity, expected to be dominated by scattering losses, lower than 1%. One of the cavity surface is spherical, which makes the cavity stable. The radius of curvature, equal to 1.7 m, has been chosen to avoid degeneracies between the carrier fundamental mode and the high order modes of the carrier and side bands, as well as to minimize the cavity thermo-refractive noise which is inversely proportional to the square of the cavity waist \[94\] (the nominal waist is equal to 321 \(\mu m\)). The carrier fundamental mode must be kept resonant in the two OMC cavities, which is achieved by controlling each cavity optical length with two types of actuators: Peltier cells and a PZT. The PZT actuator is also used to modulate the cavity length. The error signal used to control the cavity length is extracted by demodulating the signal provided by the photodetectors placed in transmission of the OMC at the PZT modulation frequency. This control system is designed to satisfy the requirements of a locking accuracy lower than \(1.2 \times 10^{-12}\) m.

10.4. Telescopes

As discussed in section 10.1 two types of telescopes are needed: an output mode cleaner mode matching telescope (OMC_MMT) on the SDB1 bench (cf. Fig. 19b), and a telescope used to adapt the beam parameters to the photodetectors placed on the end benches (SNEB and SWEB) and pick-off bench (SPRB).

The design of the OMC_MMT is very similar to the injection mode matching telescope described in section 9.7. This design has been driven by the space constraints on the SDB1 bench and the requirements on the beam quality to limit aberrations. This telescope consists of a diverging meniscus lens used in combination with a curved surface of the signal recycling mirror (SR) to reduce the size of the beam from 49 mm to 22 mm and compensate the spherical aberrations induced by the SR. Then, an afocal off axis telescope made of two mirrors is used to decrease the beam size by a factor 17. Finally, two lenses are used to match the beam on the OMC. Thanks to this design, the theoretical matching of the ITF beam on the OMC is higher than 99.9%. The telescopes of SNEB, SWEB and SPRB are very similar to the ones used in Virgo, with a doublet as a main focusing element and a second lens used to tune the Gouy phase on two quadrants photodiodes.

10.5. Sensors and front-end electronics

Three main types of sensors are used as part of the detection system:

- “Longitudinal” photodiodes provide signals which are sensitive to length variations in the ITF and, in the case of the photodiodes placed at the dark port, to gravitational wave signals.
- Quadrant photodiodes provide signals sensitive to the alignment of the ITF mirrors.
- Phase cameras are used to monitor the surface defects of the ITF mirrors.

The main longitudinal and quadrants photodiodes are hosted on the suspended benches listed in section 10.1. Each photodiode is placed inside a sealed air box, whose analog outputs are connected to the suspended bench electronic container (cf.
section 10.2) through in-vacuum cables and feedthroughs.

**Longitudinal photodiodes:**
Longitudinal photodiodes are high quantum efficiency InGaAs PIN photodiodes, with clear apertures of 2 mm and 3 mm. The photodiode electronics chain is made of three main parts. First a preamplifier converts the photodiode current to voltage and provides channels for different bandwidths: a large dynamics DC channel to be used up to a few hertz, a highly sensitive audio channel high-pass filtered above 5 Hz, and a RF channel with a high frequency bandwidth. The RF signal is then digitized by a demodulation board, which, as explained in section 15, performs the digital demodulation at the frequencies of the modulation side bands (ranging from 6 MHz to 132 MHz) and their double frequencies. The audio and DC signals are digitized by a "service" board which also provides the bias voltage and monitors the photodiode air box.

With the DC detection scheme the audio signals of the photodiodes placed at the anti-symmetric port are used to search for gravitational waves, and hence must satisfy stringent noise requirements. Demodulated signals are used as error signals to control the ITF longitudinal degrees of freedom and thus their noise can also have an impact on the ITF sensitivity. Accordingly both RF and audio channels are designed to have their electronics noise lower than the photodiodes shot noise, by up to a factor 10 for the audio channel of the dark fringe.

**Quadrant photodiodes:**
Quadrant photodiodes are Si-PIN diodes, with a 5 mm diameter total aperture, divided in four sections. By design, these sensors are sensitive to beam misalignments. Two types of electronic configurations are foreseen. Quadrants placed at the terminal benches SNEB and SWEB are optimized for a DC sensing: their DC channels, which are designed to be shot-noise limited, provide error signals involved in the alignment of the Fabry-Perot arm cavities. Quadrants placed on other suspended benches are equipped with a RF channel which, after being demodulated at the side band frequencies, provide error signals for the alignment of the other ITF degrees of freedom.

**Phase cameras:**
Phase cameras provide wavefront sensing capabilities to measure the spatial profiles of each frequency component of the laser field (carrier and side bands). These spatial profiles contain information about the mirror surface defects and can thus be used to determine corrections to be applied to the mirrors. The AdV phase cameras are based on an optical heterodyne measurement: A reference beam, extracted from the AdV laser bench, is frequency shifted at 80 MHz by an acousto-optic modulator, and travels up to the phase camera benches through optical fibers. The reference and test beams are combined onto a beam splitter and co-propagate towards a detection port of the phase camera. The detection port is made of a pinhole photodiode and a scanning system allowing to scan the wavefront over the pinhole diode. Information on the wavefront amplitude and phase are then obtained by demodulating the photodiode output at the beat frequency between the reference beam and the frequency components of the tested beam.
11. Interferometer control

11.1. Steady state

To be able to detect gravitational waves, the various cavities of the interferometer must all be kept on resonance with picometer accuracy. To stay at this working point in spite of external disturbances, a highly performing feedback system is therefore needed. This is achieved with a real-time, digital control system (see section 14), which uses the output of various photodiodes (see section 10) as errors signals and actuates on the mirror position using voice-coils (see section 5). This control system acts on the interferometer as a whole, e.g. a signal from the dark fringe photodiode in the central building is used to actuate on the end-test-masses located 3 km away.

For the control of the interferometer, it is common to define 5 longitudinal degrees of freedom (DOF), which roughly correspond to signals available on the various photodiodes:

- The differential length of the two 3 km long arm-cavities (DARM). This is the most important DOF, since it contains the gravitational wave signal. The most sensitive photodiode for controlling this DOF is the DC power of the dark-fringe (B1). A slight offset away from the ideal dark-fringe is needed to generate this error signal. To filter out the demodulation sidebands, this beam is first passed through the output mode cleaner. This DOF is controlled by actuating differentially on the two end-test-masses.

- The common length of the two arm-cavities (CARM). A demodulated signal in reflection of the interferometer (B2) is used as an error signal. Instead of actuating mechanically on some mirrors, this DOF is controlled by actuating with high bandwidth on the frequency of the main laser. At very low frequencies, this frequency is stabilized on a monolithic reference cavity, by actuating in a common way on the end-test-masses.

- The differential length of the short Michelson interferometer formed between the beam-splitter and the two input-test-masses (MICH). As an error signal, a demodulated signal from the pickoff beam (B4) is used. Actuation is performed on a combination of various mirrors.

- The length of the power-recycling cavity (PRCL), which is the cavity between the power-recycling mirror and the two input-test-masses. As error signal, a demodulated signal in reflection of the interferometer (B2) is used, while the actuation is performed on the power-recycling mirror only.

- The length of the signal-recycling cavity (SRCL), which is the cavity formed between the signal-recycling mirror and the two input-test-masses. As error signal, a demodulated signal from the pickoff beam (B4) is used, while the actuation is performed on the signal-recycling mirror only.

The first four of these DOFs were also used before in Virgo+, in a configuration which is known as a power-recycled interferometer. Initially, Advanced Virgo will be run in the same configuration. Only in a second step, the signal-recycling mirror will be added, which adds the new SRCL degree of freedom. This configuration is known as a dual-recycled interferometer.

Slightly different photodiodes, demodulation sidebands and demodulation phases are used in the power-recycled and double-recycled configuration. To chose the optimal photodiodes for controlling the various DOFs, the optical response of the
interferometer is first simulated in the frequency domain using Optickle [115]. For each DOF, the photodiode and demodulation phase is chosen, in which a particular DOF is visible with the highest SNR. Since most photodiodes are sensitive to multiple DOFs, the effect of the control system must be taken into account. This whole design is therefore an iterative procedure, in which the various feedback loops are optimized until the various requirements on the accuracy are fulfilled [97].

11.1.1. Noise subtraction

The optical response of the interferometer to the various degrees of freedom is unfortunately not a diagonal system, meaning that main photodiode is not sensitive to DARM only, but also to a lesser degree to signals from the other degrees of freedom (mainly MICH and SRCL). For this reason, also the sensing noise of these auxiliary degrees of freedom will end up in the gravitational wave signal. To reduce this effect, a noise subtraction technique is used, in which the appropriately filtered actuation signal of the auxiliary DOFs is added to the actuators used for DARM. A subtraction of a factor 500 was achieved in the past [98]. A similar subtraction factor will be need for Advanced Virgo to not spoil the sensitivity at low frequencies.

11.2. Lock acquisition

When all cavities are on resonance, the optical response of the interferometer acts like a linear system. It is therefore not too hard to design a robust control system, which can keep the interferometer locked for many hours, failing only in case of large external disturbances like earthquakes. Arriving at this working point is however non-trivial, since the uncontrolled mirrors are initially swinging with a large amplitude, causing complex non-linear transient signals. The procedure to get from this uncontrolled state to the final working point, ready to collect science data, is called the lock acquisition. Developing this procedure is done with the help of time-domain simulation tools like E2E [101]. A typical lock acquisition consists of many steps, in which the control of the various DOFs is handed off from one photodiode to another.

In the past, with the Virgo+ interferometer, this was achieved with a deterministic procedure called the variable finesse technique [99]. Since Advanced Virgo will initially start without a signal-recycling mirror, the optical scheme is very similar, so we will use the same procedure. The main difference is that at the end, the lock of DARM will change from a demodulated to a DC signal.

Only in a second stage, the signal recycling mirror will installed, which adds a 5th DOF that needs to be controlled: SRCL. This makes the conventional methods to lock a complete interferometer very complicated. To solve this issue, an auxiliary laser system operating at a wavelength of 532 nm was developed at LIGO, which can measure the arm-cavity lengths independent of any other degrees of freedom [100]. For Advanced Virgo, we plan to implement a similar system. This system is still being developed, but the coatings of the main mirrors have already been designed to take the extra wavelength into account. Meanwhile, we will keep searching for alternative methods that do not require an auxiliary laser in simulations.

11.3. Angular control

Apart from the longitudinal degrees of freedom, also the two angular degrees of freedom of each mirror must be controlled with nano-radian accuracy [73]. For
this reason a global angular control system, which uses the signals coming from the interferometer itself called Automatic Alignment (AA), system has to be implemented. The implementation of the angular control for Advanced Virgo will have to face with a more complex configuration with respect to what has been done for Virgo \cite{102, 103}. The main differences between the Advanced Virgo and the Virgo interferometer configurations are indeed the higher circulating power and the presence of the signal recycling cavity. These modifications produce an improvement in the interferometer sensitivity, but an increase of complexity for the development of the AA control system. The high circulating power produces strong radiation pressure effects which modify the opto-mechanical transfer function and it has to be taken into account in the control scheme design, while the presence of the Signal recycling cavity which increases the number of degrees of freedom to control the off-diagonal couplings in the AA error signals.

The control scheme, based on a wave-front sensing scheme which uses the modulation-demodulation technique, has been modeled with the frequency domain simulation tools Optickle \cite{115} and Finesse \cite{104} obtaining a simulated control noise below the design sensitivity safety factor (a factor 10 below the design) \cite{73}.

12. Scattered light mitigation: baffling

12.1. Introduction

The problem related to stray light was put in evidence, as early as in 1979, with the first prototypes of interferometric gravitational antennae \cite{105}. Since then, all this kind of detectors had to deal with stray light, and have been limited by it to some extent \cite{107, 106}.

We term \textit{stray light} the laser light in the interferometric antenna that does not follow the designed path. This light can recombine with the main beam after probing the position of different structures out of the intended path, so bringing spurious information to the detection port. Possible origins of stray light are, for instance, scattering off surface with residual roughness, secondary beams/spurious reflections due to non-ideal anti-reflective coating, scattering off from point-like defects (like dust, ditch or scratch on a mirror), diffraction due to limited aperture of the optical components.

12.2. Noise from stray-light

Stray light will carry a phase information which depends on the length of the scattering path before recombination with the fundamental mode. Such a path lenght is, in turn, modulated by the longitudinal motion of the scattering element $z_s(t)$ with respect to the test-mass position, so that the phase of the scattered field reads:

$$\phi_s(t) = \phi_0 + \frac{4\pi}{\lambda} z_s(t) \quad (1)$$

It can be shown \cite{108} that the sum $E_0$ of the fundamental field $E_{in}$ and the scattered field $E_s$ at some reference plane inside the interferometer can be recast as:

$$E_0 = E_{in} + E_s = E_{in} \exp \left[ \sqrt{f_{sc} \frac{P_{out}}{P_{in}}} \left( \cos (\phi_s(t)) + i \sin (\phi_s(t)) \right) \right] \quad (2)$$
where $P_{in}$ and $P_{out}$ assume the general meaning of the power in the fundamental field at the reference plane and the power impinging onto the scatterer being considered, respectively, while $f_{sc}$ is the fraction of the power impinging onto the scatterer that manages to recombine with the fundamental field.

Equation 2 shows that the effect of the phase modulation carried by the stray-light field affects both the amplitude and the phase of the total fundamental field. Furthermore, it is inherently non-linear with respect to the scatterer displacement noise $z_s(t)$, and might be described by linearized equations only when $z_s(t) \ll \lambda/4\pi$.

The calculation of the effects of stray-light can be broken down to the following steps:

(a) compute the coupling efficiency $f_{sc} \frac{P_{out}}{P_{in}}$ of the scatterer to the interferometer fundamental mode;

(b) estimate the expected residual displacement noise $z_s(t)$ for the scatterer;

(c) compute the transfer function from the scatterer motion to the strain $h$;

(d) use the above quantities to get the noise projection to the strain sensitivity $h_s$.

Step (a) can be done with different tools according to the kind of scattering conditions. FFT propagation simulations are able to reliably estimate the scattered field if the involved angle is small, and provided that the description of the roughness of the scatterer is accurate [109, 110]. On the contrary, when a wide angle scattering is considered, then either semi-analytical estimates with Bidirectional Reflectance Distribution Functions (BRDF) [111, 112] or Monte-Carlo analysis can be employed [113].

Step (b) is given directly from measurement campaigns, while for step (c) a suitable transfer function has to be derived from the scatterer displacement noise to the measured strain. This can be done either analytically [114] or by means of some simulation package [115, 116, 104]. The problem arises when equation 2 cannot be treated linearly with $z_s(t)$ [117]. In this case, an effective motion can be used to reproduce the effect of the noise generated by the scatterer [111].

12.3. Advanced Virgo solution

In order to mitigate the effect of the stray light on the strain sensitivity of the interferometer, complementary approaches can be pursued: either the displacement noise $z_s(t)$ of a potential scatterer can be controlled (emphasis on seismic isolation) or the fraction of recombined light $f_{sc}$ can be minimized (emphasis on optical quality of the surface). A trade-off between those two approaches is considered on case-by-case basis.

In AdV, baffles and diaphragms are placed at suitable locations inside the interferometer vacuum environment, mainly to shade rough surfaces and sudden discontinuities form the core optics line-of-sight. They are designed to intercept and absorb as much as possible the stray light. Furthermore, they must feature low scattering and low reflectivity as well. When this is difficult to achieve, because of requirements on the roughness being too stringent, the baffles are also required to be suspended so that their effect on the strain sensitivity is kept negligible. Requirements on the residual displacement noise of the baffles and their BRDF are derived with the procedure depicted above.

We used FOG [118] and figure error maps for the mirrors provided by Laboratoire des Materiaux Avancés (LMA) to compute the intensity distribution around the
mirror. Indeed, given the optical design of Advanced Virgo [2], the input power is mainly lost in the arm cavities. Most of the losses from the scattering off the core optics are accounted for by low spatial frequency figure error of the mirrors (below $10^3 m^{-1}$). So, a large amount of the light will be lost at very small angles, just around the coating diameter of the arm cavity mirrors. Furthermore, spurious phase information generated inside the arm cavities compare directly with the gravitational signal, so the baffling around the test masses is the most delicate to be accomplished. Because of that, baffles are integrated in the test-mass payloads so exploiting the seismic isolation provided by the super-attenuators. Figure 21 shows a layout of the baffles suspended to the core optics super-attenuators. Unfortunately, the large cryogenic traps in the arms cannot be shielded by suspended baffles, although they are interested by small-angle scattering off the test masses. So additional baffles connected to the vacuum pipes are foreseen to prevent the inner structure of the cryotrap from being seen from the mirrors. Figure 22 shows the first of these baffles installed in the West-End cryotrap. In [119] details are given for the expected overall noise due to backscattering off the cryotrap baffles. The noise projection curves are reported here in fig. 24 according to the current design, the noise contribution to the sensitivity is negligible even for severe micro-seismic activity.

The rest of the light will be scattered off at a larger angle and lost in the 3km vacuum tube, where 160 baffles per arm, installed for the first generation of Virgo, have been shown to be compliant also for AdV sensitivity after a measurement campaign by S. Braccini, I. Fiori, C. Bradaschia, and F. Paoletti performed in 2008. More baffles will be installed in the central interferometer links (fig. 25) and in the vacuum tanks housing the suspensions [112].

![Figure 21. Schematics of the baffles suspended to the core optic super-attenuators. Inside the long arm pipes there are 320 baffles soldered to the pipes, not shown here.](image)

### 12.4. Material characterization

After a survey of the materials used in Virgo+, in KAGRA and in LIGO/aLIGO, we narrowed the choice basically among two candidates for the construction of the baffles,
Figure 22. The large cryogenic traps separate the tanks housing the test-masses from the long vacuum pipes of the arms. Inner structures need to be shielded from the test-mass view, so dedicated baffles are installed there. The West End cryotrap was the first to be equipped with such baffles, shown in right panel.

Figure 23. Statistical property of the spectral amplitude of the microseismic displacement noise measured in the Virgo Central Building (CB). For each frequency bin, it is reconstructed the probability to find a seismic amplitude below the threshold indicated by each curve.

namely Silicon Carbide (SiC), and a coating of Diamond-Like Carbon (DLC) on stainless-steel substrate. While SiC stood up as the best choice from the point of view of laser induced damage threshold ($\sim 30kW/cm^2$) and Total Integrated Scattering (TIS) that could be made as low as 50ppm [120], the realization of large baffles in SiC resulted too expensive. DLC, on the other hand, features a very good absorption for $\lambda = 1064nm$, and an acceptable damage threshold, although much smaller than SiC’s ($\sim 0.5kW/cm^2$) [121]. The chemical vapor deposition (CVD) technique makes it possible to have conformal coating, i.e. DLC films replicating the roughness of the substrate, so the TIS value is determined by the choice of the substrate. As for SiC, the mismatch of the refractive index requires an AR-coating on top of the DLC layer to reduce the direct reflection (reflectivity of about $\sim 15\%$ at $0^\circ$ angle of incidence). DLC on mirror-finish stainless steel, topped with AR coating was compliant with SLC requirements and with budget needs, so it is so far the reference choice for the baffle construction when expected laser intensity are well below $\sim 0.5kW/cm^2$. 

Figure 24. Projection of the displacement noise affecting the major contributors of the cryotraps baffles. The overall noise projection is estimated as the incoherent sum of the displacement noise coming from various surfaces of the baffles, times a factor 2 to account for the four cryotraps of the arm cavities (incoherent sum). Solid line is for high microseismic activity (95th percentile upper limit), dashed line for usual microseismic activity (50th percentile upper limit), as reported in fig. 23.

Figure 25. Schematics of the baffles positions inside the central area. Baffles connected to the vacuum links are depicted in blue, while the green baffles are suspended to the core optic super-attenuator. In top-left panel a 3D section view of the baffles foreseen in the link WI-BS is shown, where clearance for the CO2 laser for the TCS is given with a special shape of a baffle. Bottom-left panel shows a 3D rendering of the baffle integrated in the Beam-Splitter payload. Also depicted: beams impinging onto the beam-splitter mirror have clearance through the baffles.
13. Scattered light mitigation: photodiode seismic and acoustic isolation

The five optical benches, SNEB, SWEB, SIB2, SPRB, SDB2, are suspended in vacuum in order to have all the relevant photodiodes for longitudinal and angular control better isolated from in-band seismic and acoustic noise. Moreover suspending the benches allows to implement global control strategies in which low frequency relative motion between the interferometer optics and pick-off telescopes (and related QPDs) is suppressed, making the detector less vulnerable to upconversion of large amplitude motion of scattering sources around the microseismic peak \cite{122}. An integrated system called Minitower (see Fig. [26]), consisting of a multistage vibration isolator named MultiSAS and vacuum chamber, is provided for each bench.

![Figure 26. Impression of the Minitower for the end benches.](image)

The MultiSAS is a compact (1200 mm high, 1070 mm in diameter) multi-stage seismic attenuation system designed to provide the best possible vibration isolation for the suspended benches, matching the limited space available in the facility. The MultiSAS design has been driven by the requirements of the end benches, the most demanding in terms of seismic isolation. The end benches carry telescopes and DC quadrant photodiodes for the interferometer automatic alignment, for which shot noise limited controls require QPD residual linear (horizontal and vertical) and angular (pitch, roll and yaw) motion at 10 Hz of $2.1 \cdot 10^{-12}$ m/$\sqrt{\text{Hz}}$ and $3.3 \cdot 10^{-15}$ rad/$\sqrt{\text{Hz}}$ respectively.

MultiSAS, following the philosophy of the Super-attenuator, is a hybrid seismic isolator in which bulk attenuation is provided passively by means of a chain of low natural frequency mechanical oscillators (filters). Filters are realized with simple pendulums in horizontal and GAS springs in vertical \cite{123}. Feedback is used only to damp the rigid body eigenmodes of the system and to maintain, on the long term, position and orientation of the optical bench. High frequency internal modes are handled, whether necessary, by means of passive resonant dampers. The main
components of the MultiSAS chain are illustrated in Fig. 27.

- A horizontal pre-isolation stage, realized with a short (about 0.5-m) inverted pendulum (IP) tuned to a natural frequency around 100 mHz, attenuates the bench motion in the microseismic peak band and it allows its precise positioning at very low frequencies. The IP also provides an inertial platform on which to detect the recoil and actively damp the rigid body modes of the suspended chain. Passive attenuation between the IP itself and the optical bench is exploited to apply controls without re-injecting noise. The IP is instrumented with LVDT position sensors, geophones (L4–C from Sercel) and voice-coil actuators for dynamic controls. Stepper motor driven correction springs are foreseen for static positioning with micrometer accuracy.

- A vertical pre-isolation stage, called top filter, consisting of a GAS spring supported by the IP platform and tuned to 200 mHz. The top filter is equipped with a stepper motor driven static positioning spring, so called fishing rod, and with a collocated LVDT/voice coil pair for feedback control.

- A 100 kg mass intermediate stage, called intermediate filter, consisting of a GAS spring tuned to 400 mHz suspended from the pre-isolation stage via a 694-mm long wire. The filter is instrumented with a fishing rod and a LVDT/voice coil actuator for monitoring and test purposes.

- The 320–kg mass optical bench suspended from the intermediate filter, via a 760–mm long wire. By adjusting the position of the bending point of the suspension wire with respect to the bench center of mass, the tilt modes of the payload will be tuned around 200 mHz for better decoupling from the horizontal pendulum modes of the chain. The bench is equipped (not shown in this document) with two motorized counterweights for remote fine balancing and with a set of collocated LVDT coil-magnet actuators, referred to ground, for the local control of the angular degrees of freedom.
More details of the MultiSAS control system are presented in [124]. The MultiSAS seismic attenuation performance has been characterized by measuring its transfer function (see Fig. 28, left panel). The vertical isolation ratio exceeds 100 dB at all frequencies above 10 Hz. In horizontal, thank to the three stages design, a residual transmissibility around $-180$ dB has been measured. Transfer functions have been convoluted with the ground motion spectra measured at the Virgo site to make estimates of the seismic motion of the benches. The projections in Fig. 28, right panel show that the requirements for the translational degrees of freedom are met with a considerable safety margin, despite the effect of the vertical–to–horizontal coupling. Requirements for pitch and roll are also met since, above a few Hz, the tilt residual motion is expected to be dominated by the horizontal–to–tilt geometric coupling.

\[ \frac{h}{R^2}, \text{ where } h \text{ is the distance between the bench center of gravity and the bending point of the wire, and } R \text{ is the radius of gyration of the bench. For the AdV benches the coupling is about } 0.16 \text{ rad/m.} \]
14. Data acquisition

14.1. Real-time interferometer synchronization and control

The interferometer is a complex apparatus composed by a lot of sub-systems that have to work altogether in order to reach and keep the detector working point, with the optimal sensitivity to GW. Of the order of hundred active feedback systems are necessary to tune and control the whole detector. As an example, the positions of the suspended mirrors and benches have to be controlled both individually, with local sensors when the interferometer is not locked, and as a whole, depending mostly on the signals seen by photodiodes monitoring different beams in the ITF during the lock acquisition and when the detector is kept at its working point.

The AdV detector control scheme goes towards less analog and more digital feedback loops than in Virgo. Having more digital loops adds more flexibility to the design and configuration of the loop filters, and improves the loop stability. It also helps to monitor the detector by making it is easier to extract intermediate information from digital processes rather than adding probes into analog electronics boards.

14.1.1. Centralized timing distribution

In order to perform real-time control loops, all the detector devices must be synchronized: the ADC channels that digitize the sensor outputs, the digital cameras that acquire images used for the controls, the DAC channels that generate actuator signals and the real-time processing units (PC or DSPs) where the digital filtering of the loops are processed. The centralized timing distribution system is based on the GPS timestamp in order to be also synchronized with other experiments, and particularly LIGO experiment. The IRIG-B signal generated by a GPS receiver is distributed through the whole interferometer with optical fibers and finally to the front-end digital electronics. It is used to lock the local oscillators of the devices and to timestamp the sampled data with GPS time. The propagation delays in the distribution system are fine-tuned such that the timing signal is the same down to all digital devices, within better than 50 ns. In this way, all the data sampling clocks are synchronous. The timing jitter between the clocks of different devices in the setup is lower than $0.1 \text{ns}/\sqrt{\text{Hz}}$ above 1 Hz [125].

14.1.2. Fast online data network and real-time processing

A custom fast data network has been built in order to exchange and process in real-time the data from the sensing electronics to the driving electronics, and to provide them to the data collection system.

The global longitudinal and angular controls of the interferometer are performed through synchronous fast digital loops, running at $\sim 20 \text{kHz}$ and $\sim 2 \text{kHz}$ respectively. The signals are collected by the sensing electronics in different locations of the detector. They are sent through optical fibers to real-time processing units that run the digital servo-loops and send the data to other processing units or to the driving channels of the different interferometer suspensions. A set of multiplexer/demultiplexer boards is used to route the data packets in the network. The data can be delivered from any ITF device to any other ITF device with latencies usually dominated by the optical fiber propagation time. New devices, called DAQ-boxes, will be installed in AdV: they are digital mother boards that can host specific mezzanines (for ADC, DAC, digital demodulation channels, camera triggers, ...) and manage the interface with the timing and fast data networks. The same interface is setup in the electronics used to control
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the suspensions. Some controls are made locally: they are implemented sending the
data directly on-board from the sensing part to the driving part where the needed
filtering is performed by the associated DSP.

Most of the sensor signals are digitized by ADCs at $\sim 1$ MHz and digitally low-
pass filtered and decimated on-board down to frequencies between a few kHz and a
few tens of kHz. The data are then sent to the fast data network. Some are then
used as error signals for feedback loops and others are used to monitor the different
sub-systems and the detector environment.

14.1.3. Digital demodulation

Demodulation will be used for many applications where
error signals are needed. For example, LVDTs will be used to control locally the
positions of some suspended benches. Instead of acquiring the error signal in the
low frequency band (below a few hertz), where the $1/f$ noise of the ADC might not
be negligible, the probe signal which is modulated at typically 10 kHz is acquired
at $\sim 40$ kHz, and then demodulated in a real-time PC or in the on-board DSPs in
order to extract the error signal in a band where the ADC noise is lower than at low
frequencies. Implementing such demodulation digitally adds flexibility in the choice
and number of modulation frequencies, as well as in the possibility to modify them
online to study cross talk between LVDTs for instance.

Special cases are the signals measured by the photodiodes. As explained in
sections [10] and [11] most of the photodiode signals are demodulated at frequencies
between 6 MHz and 132 MHz. In Virgo, the output signals of analog demodulation
boards were digitized by standard ADCs. For AdV, digital demodulation will be used
instead. The RF signals of the photodiode are digitized in dedicated fast ADCs at
$\sim 500$ MHz and the demodulation processing is computed on-board by a FPGA. The
in-phase and in-quadrature output channels are then low-pass filtered and decimated
in the FPGA and in DSPs such that the frequencies of the final output channels,
sent to the fast data network, are $\sim 20$ kHz. In this digital scheme, even in the case
of demodulation at multiple frequencies, the RF output of a photodiode is acquired
only once in a fast ADC and then different digital computations are processed for the
different frequencies. Compared to the analog solution, this reduces the number of
cables and electronics boards. Another important advantage is that it is not needed to
distribute the local oscillator clocks from the laser modulator to all the demodulation
deVICES. The reference is the distributed timing signal used to lock the local clocks of
the boards. The on-board timing distribution adds some low frequency phase noise
that can be subtracted online since it is common to all demodulation channels: the
phase noise can be monitored using either the demodulated photodiode signal at twice
the main frequency which provides also some side-band amplitude noise, or a 10 MHz
clock that is distributed through the timing network.

14.1.4. Expected digital channels

The estimated numbers of front-end channels to
be acquired or driven through the fast data network of AdV are of the order of
2200 ADCs with sampling frequencies higher than a kilohertz, 1400 DACs, 100 digital
demodulation inputs and 40 cameras synchronized on the timing system.

14.2. Data collection

The goal of the data collection is to build different data streams and provide them both
for long term storage on disk and online for commissioning, noise studies, data quality
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definitions and $h(t)$ reconstruction before data analysis. Digital data generated all over the detector are acquired through the fast data network ($\sim 400$ MBytes/s) and merged in different streams at the front-end of the data collection pipeline. Data are then reduced (decimation, compression, image processing, ...) in order to limit the flow on the Ethernet network and to request reasonable storage disk space. Data are then provided to several online processes (detector automation and monitoring, data quality tools, $h(t)$ reconstruction) that enrich the streams with additional computed channels that can be shared with other online processes. The data sharing is performed via shared memories or TCP/IP protocol. The data available in shared memories can be reached by a data display tool to study the detector behavior online, with a latency of the order of a second for the front-end data.

At the end of the data collection tree, different data streams are stored on disk using the data format of gravitational wave experiments [127]. The raw data stream (2 TB/day) contains all the channels at their nominal sampling frequency, including the channels generated by the front-end electronics and the channels generated by the online processes along the data collection tree. Other streams are generated: a fast stream, with the channels stored at their maximum frequency, before any decimation of the data collection pipeline, in order to monitor and debug the front-end electronics; a RDS (30 GB/day), with the channels decimated at lower frequencies than nominal (typically $\sim 100$ Hz) for commissioning and noise studies at low frequencies; trend data streams, with statistical information computed over 1 s (4 GB/day) and few tenths of seconds over all the channels; the $h(t)$ data stream (7 GB/day), which contains the reconstructed GW strain channel and data quality flags, and that can be directly used by the data analysis pipelines. The data are kept on circular buffers at the Virgo site, with a depth of $\sim 6$ months for the raw data. During science runs all the data are transferred to computing centers for permanent storage and offline data analysis.

14.3. Calibration and $h(t)$ reconstruction

The main output of the calibration and reconstruction procedures is the $h(t)$ time series that describes the reconstructed GW strain signal. It is the main input for the GW searches. For AdV, the requirements from the different data analysis groups, searching for CBC, bursts, continuous waves and stochastic sources, call for uncertainties below 9% in amplitude, 90 mrad in phase, 24 $\mu$s in timing. These are $1\sigma$ uncertainties given in the range 10 Hz to 2 kHz.

During Virgo [129], the systematic uncertainties of the reconstructed $h(t)$ time series already met these requirements. They were estimated to be 8% in amplitude and $h(t)$ was 50 mrad in phase at 10 Hz with a frequency dependence following a delay of 8 $\mu$s at high frequency.

Consequently, the same calibration methods [128] will still be used for AdV. Similarly, the same method will be used for the $h(t)$ reconstruction, in particular at the start of AdV, in the power-recycled configuration. Developments will be needed to adapt the reconstruction to the dual-recycled configuration when the SR mirror is added.

In parallel to the standard calibration methods, a photon calibrator has been used in Virgo [129] to validate, with independent measurements, the reconstructed $h(t)$ time series. An improved design of the photon calibrator is being defined for AdV. Two such devices will be installed, one on each end test-mass.
15. Vacuum upgrades

The vacuum enclosure is one single volume consisting of several parts [2], [1]:

- two 3 km long straight tubes, 1.2 m in diameter;
- several vertical cylinders, called towers, 2 m in diameter, up to 11 m high, containing the superattenuators;
- one 142 m long tube, 30 cm in diameter, containing the Mode Cleaner optical cavity;
- several valves, with up to 1 m aperture;
- several pumping groups, including many types of pumps and vacuum gauges;
- a few large cryostats.

The Advanced Virgo design sensitivity of $3 \times 10^{-24} \text{Hz}^{-1/2}$ at 200–400 Hz, requires a residual gas pressure inside the 3 km long arm tubes of about $10^{-9} \text{mbar}$.

In order to cope with the vacuum and cleanliness prescriptions, a careful material selection has been performed for all the in vacuum components, and suitable vacuum/thermal treatments have been developed and performed before installation:

1) Bake-out Baked vacuum systems have been considered, since it is mandatory to eliminate the layers of water molecule sticking on the inner wall of the enclosure, otherwise prevalent in the residual gas. The chosen bake-out process consists in heating the pipes, once under vacuum, at 150°C for about 1 week. Contrary to the initial design choice, it has been decided not to bake the towers, to avoid risk of damage to the suspended payloads. To prevent migration of water molecules from the unbaked towers to the 3 km pipes we have installed cryogenic traps (cryotrap) at each end of the pipes.

2) Firing Looking forward to the Advanced Virgo operating pressure, all the constituents of the UHV enclosure (pipe modules and tower lower chambers) have been fired in air at 400°C in order to reduce by at least a factor of 100 the outgassing of hydrogen from stainless steel walls. This allows to meet the base pressure requirements with only one pumping station every 600 m of pipe.

3) Cleanliness The residual gas must be free of condensable organic molecules (hydrocarbons), in order to keep the optical surfaces clean. A conservative hydrocarbon partial pressure of $10^{-13} \text{mbar}$ has been prescribed for the mirror vacuum chambers; the adjacent cryotrap contribute to approach such values condensing hydrocarbon vapors. The seven mirror towers are divided in a lower mirror chamber and an upper chamber containing all the mechanics and cables of the antiseismic suspensions; the separating roof has a low conductance passage in the center for the wire supporting the suspended pay-load. This low conductance (1.6 l/s or 0.4 l/s when differentially pumped) allows to tolerate in the upper tower chamber a pressure of up to $10^{-6} \text{mbar}$ dominated by water. Similar conditions are allowed also in the injection and detection bench towers and in the Mode Cleaner tower; they are separated from the mirror towers by two additional cryotrap. Finally the evacuated volume has to be kept free of dust, in order to avoid optics contamination. This request holds, in particular, for the tower lower part, where optical components are located. Figure 29 shows a rendering of the central part of the system.
15.1. Pumping system

Most of the Virgo pumps are still used in Advanced Virgo. Upper and lower chamber of each tower are separately pumped by a turbo-molecular group consisting of a 1500 l/s turbo backed by a dry scroll pump, used also for roughing. In order to reduce vibration level and maintenance times, the turbo pumps are of the hybrid type with magnetic suspensions. To further reduce the mechanical vibrations, scroll pumps have been moved to a far and acoustically isolated room and turbos are clamped to ground and connected to the towers with soft bellows. In a second phase and if proven necessary during commissioning tests, turbos will be progressively replaced with Ion pumps, in order to further reduce the noise emissions (seismic, acoustic and magnetics). A downtime for turbo-pumping will be anyway necessary after in-towers interventions and ventings to recover the appropriate vacuum level and to deplete the residual traces of air otherwise diffusing in the system. In the arm tubes, roughing and intermediate phases are achieved with a large dry mechanical pumping group. Evacuation continues with a turbo-molecular group similar to those of the towers every 600 m. Final vacuum will be reached after baking and maintained by Titanium sublimation pumps most suited to pump hydrogen (3000 l/s) and smaller Ion pumps (70 l/s) to handle inert gases. Periodical regeneration of Ti evaporated layer will slightly lower the pumping duty cycle; normally 5 out of 7 groups will be in operation along each arm.

15.2. Cryogenics

In Advanced Virgo water migrating from the towers to the 3 km pipes will be stopped with four large cryotraps, one at each end of the arm pipes and with two smaller ones between the bench towers and the recycling towers. The large cryotraps are installed between the input (end) towers and the corresponding Large Valve. They consist (fig. 30) of a vacuum pipe about 3 m long and 1.4 m in diameter, containing a 2 m long tank with the shape of a sleeve, filled with about 300 l of liquid nitrogen. The sleeve has been built in aluminum for a more uniform temperature distribution; with an inner diameter of 0.95 m it has a 6 m² cold surface to capture water and other condensable gases. The outer wall of the cold tank is centered out of the beam axis in order to
maximize the liquid/gaseous nitrogen open surface, to allow a smooth evaporation and reducing the bubbling noise. The cold tank is thermally shielded by a twofold aluminum foil screen, while the free aperture for the laser beam is limited to 600 mm diameter by suitable thermal and optical baffles.

The escaping fraction of water molecules is estimated about 3%; the thermal loss, verified on the first built trap is 250 W, corresponding to a consumption of 5.61 l/h of liquid nitrogen and 1 l/s of gas at 80 K. Consumption depends also on the thickness of ice deposit, growing progressively by about 1 micron per year (Fig. 30) and causing a slow increase of infrared emissivity. Regenerations are not envisaged more than once per year, the process will take about 1 week or slightly more.

The cryogenic liquid is continuously supplied by a distribution plant equipped with three standard reservoirs (1 x 30,000 l + 2 x 15,000 l) laying horizontal, in order to reduce the hydraulic head and the wind grip. The overall site consumption is estimated as 1000 l/d (including the reservoirs auto-consumption) and the refilling of each tank is planned once per month, by truck coming on site during the maintenance breaks. Transfer lines have been installed with slopes studied to avoid sections subject to gas accumulation and risk of noisy intermittent flow.

The cooling effect on the test masses due to the cryotraps has been evaluated as negligible (the induced change of radius of curvature is estimated as 2 m with respect to its original value of about 1500 m) and, anyway, opposite to the warming effect of the laser beam.

The two smaller cryotraps, 0.9 long and with an aperture of 350 mm, play the same role. They can be operated also in batch mode (without the seismic noise due to the moving dosing valve) and feature a relatively large volume of liquid nitrogen (100 l) to reach 4 days of autonomy.

15.3. New vacuum components

The vacuum system for the new signal recycling superattenuator is being built. All the link pipes connecting the tower bases in the central building are being replaced with larger aperture ones, to cope with larger laser beams. The new link pipes have also
different lengths due to the displacement of several towers. They have been designed to have mechanical resonant frequencies above 30 Hz, to avoid strong coupling with seismic noise. Each new link pipe is made of 3-4 parts, including expansion bellows and gate valves with diameters up to 650 mm. They also house the extraction or introduction ports for different auxiliary beams used for the interferometer control (‘Thermal compensation’, ‘pickoff’, ‘Local Controls’).

15.4. Control System

The Control System comprehends 33 main stations, one per each separable vacuum volume. The stations allow operating the equipment (pumps, gauges, valves) in local or remote mode, insuring interlocks and loops actively protecting the system against wrong maneuvers or failures. Low level interlocks are hard-wired while higher level controls are implemented at software level by PLC, that also provide the versatility to include future devices and pumps.

16. Timeline

One of the main goals of the AdV project is to start taking data in 2016. AdV will be operated in two main phases:

- Early operation: the interferometer configuration will be a power-recycled Fary-Perot Michelson and the power injected will not exceed 40 W. Such a configuration is, for many aspects, similar to the Virgo+ one. Thus, we expect a faster commissioning time and progress in the sensitivity improvement. The achievable BNS inspiral range is larger than 100 Mpc.

- Late operation: the interferometer will be then upgraded installing the signal recycling mirror and the high power laser, fulfilling the full specifications. The tentative date for such upgrade is 2018, though this will depend on the joint plans for science runs agreed with the partners in the network.

The installation and integration of the upgrades needed for the first phase and their acceptance are scheduled to be completed in fall 2015. Before that date, the commissioning of parts of the detector will start:

- the commissioning of the input mode cleaner cavity has started in June 2014, after the lock;
- in spring 2015 the beam will be available at the dark port, allowing to commission the detection system;
- a single 3 km arm will be available shortly after.

Such commissioning activities will be very useful to debug important parts of the apparatus, train students who will later be part of the commissioning team and, in general, speed up the process.

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