Stable Recycling cavities for AdV+:

Conceptual design studies

Virgo collaboration

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1 Introduction

This document summarizes the status of the works done by the Virgo collaboration to study the possibility to implement stable cavities in Virgo before joining the run O5. At the time of writing the run O5 is planned to start at the beginning of 2027.

1.1 Motivations

The commissioning of Advanced Virgo and Advanced Virgo Plus has shown the limitations that come from using marginally stable recycling cavities. The difficulties originate from two main issues.

The modulation sidebands are degenerate in the power recycling and signal recycling cavities. This situation makes them very sensitive to small wave-front deformation originating from mirror defects or thermal effects. The wave-front deformation is amplified by the fact that high order modes are resonant in the recycling cavities. It is not just a matter of scalar losses affecting the recycling gains of the sidebands and so the signal-to-noise ratio of the locking & alignment signals. The field's wave-fronts are deformed in a way that it is difficult to predict depending on the exact shape of the mirror's surface or thermal deformations. The consequence is that many of the locking and alignment error signals that are carried by interference between the modulation sidebands and the carrier field are not reliable. In particular their zero cannot be trusted since they are affected by offsets that can change during the commissioning and operation of the interferometer. As a consequence several mechanical modulations of the mirror longitudinal and angular positions, in the observation band, are necessary to identify the good operation points. In some cases even the detection of the mechanical modulations in the photodiodes output is not sufficient and the only solution is to adjust the locking & alignment position by minimizing the coupling of laser noise at some specific frequencies in the detection band. Those mechanical modulations have the effect of deteriorating the sensitivity in a wide frequency band.

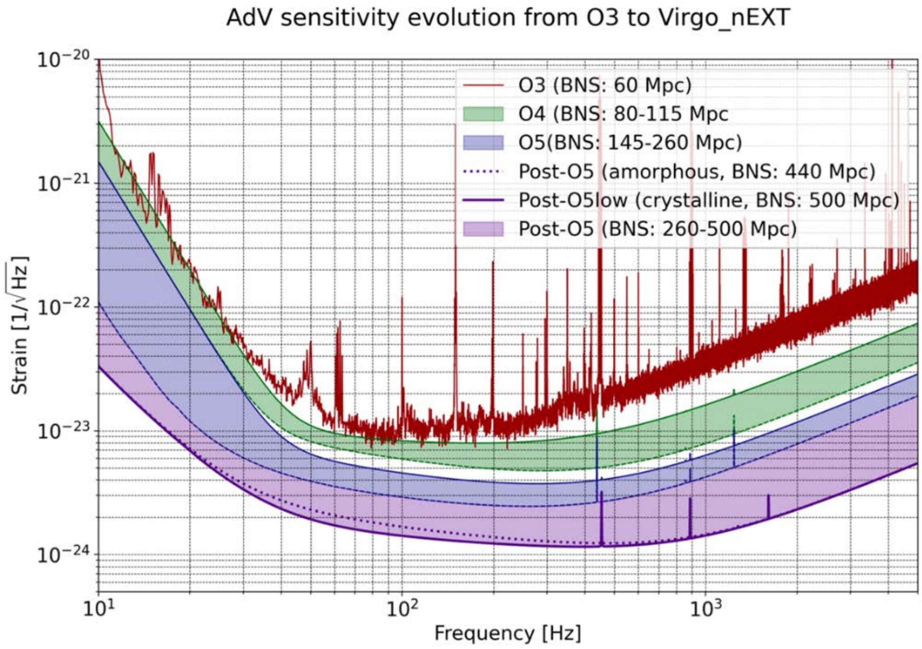
The use of resonant sidebands extraction with the signal recycling mirror requires the carrier to be anti-resonant in the signal recycling cavity. As a consequence, the high order modes of the carrier are all resonant in this cavity. Since the field exiting the interferometer from the beam-splitter is mainly constituted of high order modes originating from the imperfect interference between the two interferometer arm cavities, these imperfections get amplified by the signal recycling cavity and degrades the interferometer contrast. This favors the transmission of input beam noises to the output port. Moreover, the losses originating from the signal recycling cavity degeneracy also affect the squeezing performances since the latter are very sensitive to losses. It has indeed not been possible to obtain a significant improvement of the sensitivity by injecting a squeezed beam in the interferometer.

Other issues related to marginally stable cavities, e.g. the risks related to the extraction of spurious beams originating from secondary faces of input test masses, beam splitter and compensation plates, are described in the document "The need for stable recycling cavities in Virgo-nEXT" (VIR-0047B-23).

The issues above get worse as the power is increased and for this reason it has not been possible to operate the interferometer with more than 33 W of input power. This has to be compared with the Advanced Virgo goal of 125 W. So far, the best sensitivity in terms of binary neutron range has been 60 Mpc. It was achieved during the run O3 in the power recycling configuration with about 25 W of input power. The successive operation of the dual recycled interferometer did not allow to improve the detector range, which remains far from the Advanced Virgo and Advanced Virgo+ design sensitivities. This situation motivates the choice to adopt stable recycling cavities and to try implementing them by the time of O5.

1.2 Sensitivity goals

While planning for the installation of stable recycling cavities, it is important to keep in mind that their design should be compatible with the sensitivity of Virgo_nEXT. While the change of optical devices is expected in any case during the Virgo_nEXT upgrade, we would like to avoid changes in infrastructure, vacuum systems and seismic isolation installed at the time of the stable recycling cavities implementation. The figure below shows the sensitivity goals of Advanced Virgo Plus and the range of sensitivities reachable within the post-O5 upgrades.



1.3 Optical requirements

Stable recycling cavities for Virgo were studied quite deeply already at the time of the Advanced Virgo design. A short summary of those studies can be found at VIR-1060A-22 and at VIR-0570A-23. Since then stable recycling cavities have been designed and implemented both in LIGO (https://dcc.ligo.org/LIGO-T0900043) and in KAGRA (https://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0009/T1200913/006/MIF_Design.pdf).

The stability of the cavities is defined by the value of their Gouy phases (which is close to zero for marginally stable cavities). Given the present signal recycling cavity finesse, if one wants the n+m=2 modes to have gain below unity the Gouy phase has to be larger than 10 degrees. On the other hand it has been shown that for Gouy phases larger the 19 degrees the n+m<10 modes can be resonant in the signal recycling cavity (SRC). This is to be avoided since these modes can still have non negligible gain in the arm cavities. This gives a reasonable range of Gouy phases for the signal recycling cavity. Similar considerations can be made for the stability of the modulation sidebands fields in the power recycling cavity (PRC). Moreover, studies done in LIGO have shown that having the same Gouy phase in the power and signal recycling cavities can give rise to difficulties with the alignment signal extraction. Based on these considerations, the LIGO SRC and PRC Gouy phases are respectively 19 degrees and 25 degrees. KAGRA has instead chosen 16.4 degrees for the PRC and 13 degrees for the SRC. In the studies done for the Virgo stable recycling cavities we have adopted 19 degrees and 25 degrees for the SRC and PRC respectively. However, it is important to note that by changing the radius of curvature (RoC) of the recycling mirrors it is possible to choose the most appropriate Gouy phase. This optimization hasn't been done yet.

Other aspects to be considered for a given optical configuration are:

- The effect of astigmatism
- The feasibility of the required mirrors radius of curvature
- The needed remote control over the mirrors radius of curvature
- The losses in the signal recycling cavity
- The ability to safely extract the auxiliary beams avoiding scattered light effects
- The sensitivity to thermal lenses in the input mirrors
- The beam intensity on the mirrors
- The effect of radiation pressure on the alignment control
- The modulation frequencies needed for the interferometer sensing and control
- The interferometer length and alignment sensing and control scheme

1.4 Displacement noise requirements

Vibrations of the signal and power recycling mirrors can convert into noise at the interferometer output. This depends on the coupling between the signal/power recycling cavity length variations and the interferometer output signal. It turns out that the coupling of the power recycling mirrors is much smaller than the coupling of the signal recycling mirrors. As a consequence a suspension system satisfying the requirements for the signal recycling mirrors will also satisfy the requirements for the power recycling mirrors.

In the case of the signal recycling mirrors, the coupling to the output signal is mediated by radiation pressure on the arm cavity mirrors. Indeed the small local oscillator field impinging on the signal recycling mirrors is reflected back towards the interferometer and, if the signal recycling mirrors moves, produces a differential variation in the radiation pressure applied on the arm cavity mirrors. This effect increases with the power stored in the arms and the differential arm length difference used to create the local oscillator. Instead it decreases with the square of the frequency and the mirror mass because of the mirror's inertia resisting the radiation pressure fluctuations.

A quantitative evaluation shows that the acceptable signal recycling mirrors displacement noise at 10 Hz is 10-17 m/√Hz. This requirement allows keeping the signal recycling cavity displacement noise ten times below the sensitivity planned for AdV+ Phase II at 10 Hz. Since the effect decreases with the frequency, the requirement at 100 Hz is less stringent even if the design sensitivity at this frequency decreases to 3 10-24 /√Hz. A displacement noise of 3 10-17 m/√Hz at 100 Hz is sufficient.

The situation for Virgo_nEXT is different for several reasons. The power in the arms increases by a factor of four (from 400 kW to 1.5 MW) but the mirror mass increases by a factor of two and a half (from 42 kg to 105 kg). This would increase the coupling of signal recycling mirror displacement to the interferometer signal by 4/2.5. But the most important difference comes from the use of the balanced homodyne technique. This technique avoids using the differential arm cavity length to produce the local oscillator impinging on the signal recycling mirrors. The residual coupling is then due to remaining TEM00 mode from the imperfect interferometer contrast defect. This field being in a different quadrature, its coupling to the interferometer signal is via phase fluctuations instead of radiation pressure fluctuations and so it does not increase at low frequency. Numerical simulations allows to establish that the requirements on the signal recycling mirror displacement noise becomes 6 10-16 m/√Hz at 10 Hz and 3 10-17 m/√Hz at 100 Hz which is less stringent than for O5.

Given the requirements above it has been shown that a seismic isolator consisting of three vertical stages of attenuation (so similar to what is currently used for the input mode-cleaner curved mirror) provides the required seismic isolation with some additional margin.

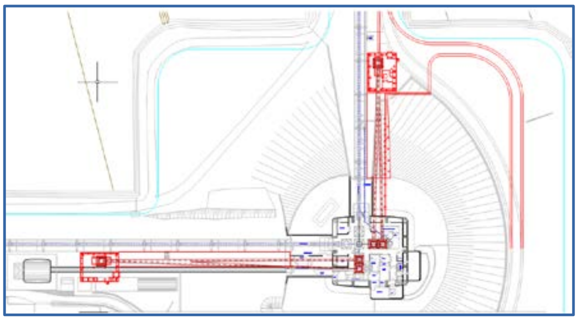
1.5 Options

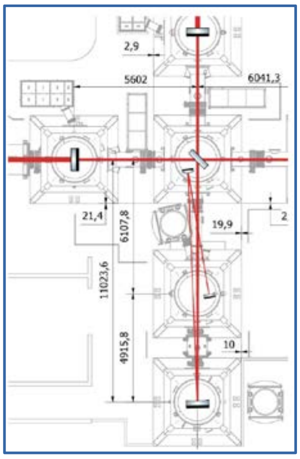
Two main options have been considered during this study.

The first is based on 160 m long recycling cavities. The detailed description of this solution is given in section 2. This solution requires the construction of two new buildings located at 80 m from the central building along the interferometer arms to host two of the required six additional mirrors. In addition two tunnels connecting these two new buildings with the central building are needed to host the vacuum tubes in which the laser beam propagates back and forth. This is called the external or long solution.

The second solution is based on a 36 m long recycling cavities hosted in the central building. The detailed description of this solution is given in section 3. Since three mirrors are needed for each recycling cavity, this solution requires changing part of the existing vacuum systems. This is called the internal or short solution.

The two solutions are sketched in the picture here below.



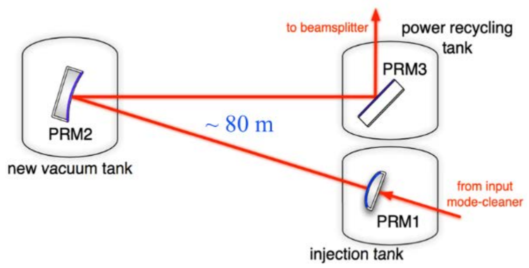


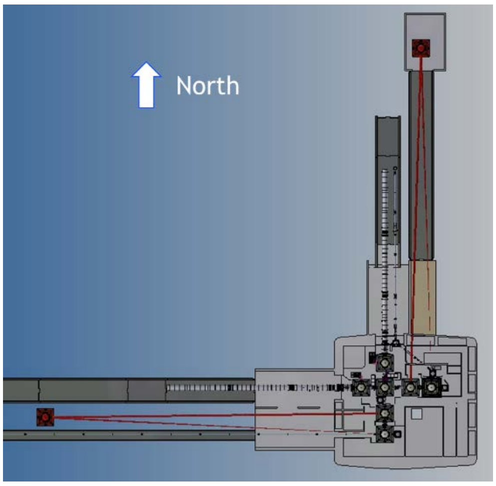
In the following two sections, for each solution, we first describe the layout, the optical configuration, the needed mirrors and suspensions, the modifications to be made to the injection and detection systems and finally the vacuum and infrastructure works. We end each section with the expected schedule and the needed budget.

2 Long recycling cavities

2.1 Layout

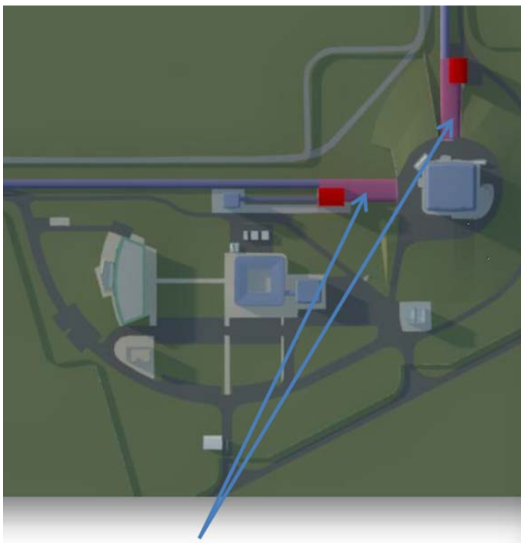
The layout of the proposed long cavity solution is shown in the figure below. A small power recycling mirror (PR1) is suspended on the top of the input bench inside the injection tower. From there the beam is sent toward a curved mirror (PR2) placed about 80 m in the west arm direction. Along this path the beam expands and acquires the required Gouy phase. The PR2 mirror collimates the beam and reflects it toward the present power recycling tower in the central building. There a large flat mirror (PR3) suspended to the present power recycling super-attenuator reflects it toward the beam splitter and the rest of the interferometer.





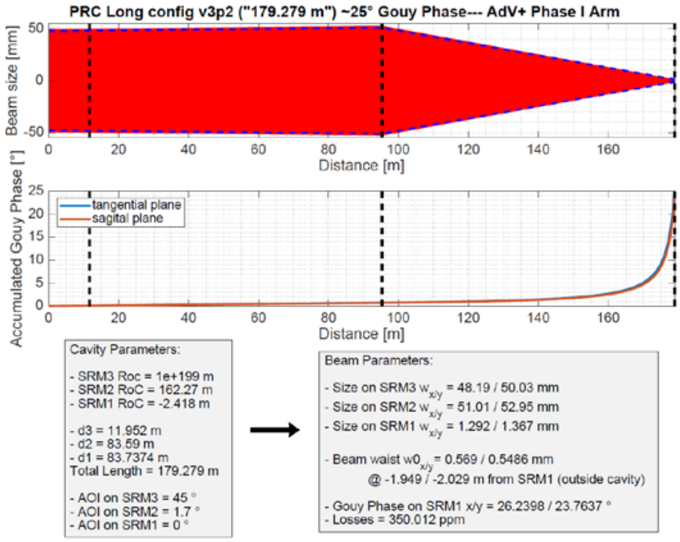
The signal recycling cavity uses a symmetrical solution along the north arm with a nearly identical arrangement (to be confirmed depending on the final modulation's frequency choice).

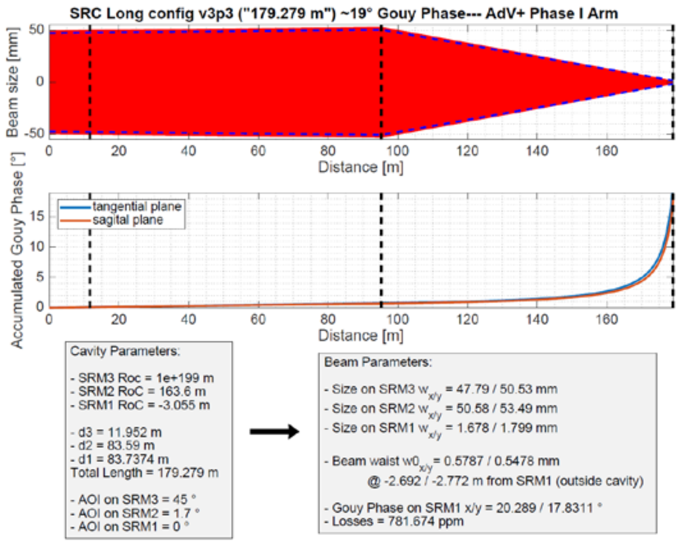
To host this power recycling cavity a new building has to be built at 80 m from the present central building and connected to the latter through a tunnel (see picture below). The building should host a vacuum chamber itself hosting the suspension for the PR2 mirror. The tunnel should host a V-shaped tube connecting the new vacuum chamber in the PR2 building with the injection and power recycling tanks in the central building.



2.2 Optical configuration

The parameters of the power recycling cavity (PRC) and of signal recycling cavity (SRC) are given in the two figures below. This configuration uses the same lengths for the two cavities as it is done in KAGRA. Depending on the final choice on the modulation frequencies for the alignment control the SRC could be 2.6 m longer (or shorter).





A peculiarity of this solution is that only two of the three mirrors composing the recycling cavities are curved (this is different compared to the LIGO and KAGRA designs). As a consequence only the curvatures of these two mirrors and their distance can be used to adjust the Gouy phase and the matching with the arm cavity. Once the distance is given, the RoC of PR2 defines uniquely the Gouy phase. The consequence is that the larger is the required Gouy phase, the smaller will be the beam size on PR1. This does not seem to be a showstopper but clearly one cannot state that this design has already been tested elsewhere.

As shown in the data above, the 1.7 degrees of angle of incidence on PR2 generates some astigmatism which gives rise to different Gouy phases in the sagittal and tangential plane. This can be a source of complications since all high order modes in the recycling cavities are split in several peaks. It is possible to compensate for this residual astigmatism by heating the PR3 with a Central Heating Radius Of Curvature Correction (CHROCC) to obtain a convex 90 km long radius of curvature.

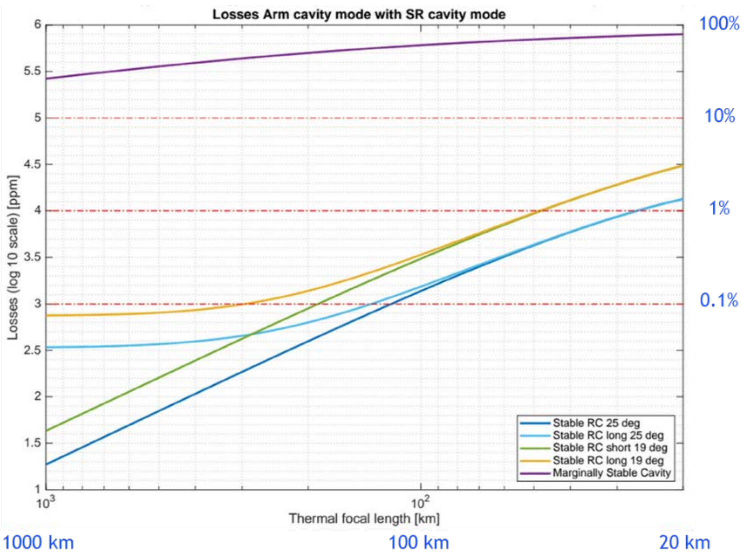
This implies that this solution needs a thermal actuator switched on and properly tuned also at low input power.

Errors of 1% in the radius of curvature (RoC) of PR1 can be compensated by slightly changing the distance between PR2 and PR1. Realizing a PR1 mirror with a RoC accuracy of 1% is no problem. Errors of 1% in the RoC of PR2 can be compensated with a thermal actuator. A 1% accuracy on PR2 needs a good polishing but it is feasible. The input mode cleaner mirror has a similar RoC (185m). An accuracy of 1% was achieved for the input mode-cleaner mirror at least once.

The losses in the SRC have been simulated with the ABCD formalism and give 750 ppm in the absence of the thermal correction on PR3. The same formalism says that the losses can be made negligible with the thermal correction. An evaluation has been made with OSCAR but with a slightly larger Gouy phase (average of 21.3 degrees instead of 19 degrees). In this case the losses are estimated to 200 ppm assuming the field is resonant both in the SRC and in the arms (this is actually the case of the carrier in the PRC). When instead the field is resonant in the recycling cavity but not in the arms (case of the carrier in the SRC at high frequency i.e. the most relevant for the squeezing) the OSCAR result is compatible with the ABCD formalism.

The auxiliary beams originating from the compensation plates and the secondary face of the beam splitter have been traced. No showstoppers have been found provided the PR3/SR3 mirrors diameter is 55 cm and the SR2/PR2 mirrors diameter is 35 cm. The beams are well separated at the level of PR1/SR1 thanks to the stable cavities magnifying optics.

The sensitivity of the recycling cavities to thermal lenses in the input mirrors have only been studied with the ABCD matrix formalisms. The result is shown in the figure below. The result is that for a given thermal lens the losses in the stable cavities are orders of magnitude smaller than in a marginally stable cavity. The plot shows that a long stable cavity and a short stable cavity having the same Gouy phase, have the same losses for thermal lenses shorter than 100 km. For longer thermal lenses the difference comes from the uncompensated astigmatism in the long cavity case. The bottom line is that the Gouy phase matters more than the length.



The question was raised whether at the time of Virgo_nEXT, when the power on PR1 can reach up to 10 kW, the intensity on the mirror can damage the mirror. From the values available in the literature, it turns out that for beam sizes larger than 1 mm the intensity remains well below the laser damage threshold. Given the short curvature of PR1, the change of RoC due to the thermal lens induced by the 10 kW is negligible.

It is possible to adjust the cavity lengths to use exactly the same modulation frequencies for the interferometer locking as the one used today (6.27 MHz and 56.4 MHz).

The investigations about interferometer sensing and control have been focused on the locking error signals. No showstoppers have been found so far. The matrix relating the photodiode error signals and the interferometer lengths is identical to the present one given their very weak dependence on the recycling cavities length and their independence on the Gouy phase. Only the modulation frequencies and their resonance conditions in the recycling cavities matter. The latter can be chosen by properly choosing the exact cavity lengths. The study of the alignment control signals remains to be done.

2.3 Mirrors

The required mirrors and their main characteristics are given in the table below.

PR3/SR3 mirrors are flat 550 mm diameter mirrors (so like the Virgo beam-splitter). Their diameter is dictated by the need to catch the beams coming from the beam splitter. Moreover in the case of PR3 its transmission should be made available for picking-off the beam inside the power recycling cavity and directing it toward SPRB.

PR2/SR2 mirrors are curved concave mirrors, 350 mm in diameter (so like the Virgo recycling mirrors). Their diameters are dictated by catching the beams coming from the beam splitter without cutting them too much. Their radii of curvature are dictated by the required Gouy phase and the distance from PR1. In case the two recycling cavities have to have different lengths the SR2 and PR2 will have to have slightly different RoC's. This can be important when counting the minimum number of needed spares.

PR1/SR1 mirrors are curved convex mirrors 100 mm in diameter, so 1.3 kg in mass. Given the beam size on these mirrors (~1.5 mm), these mirrors can be very small. The proposed size/mass is chosen to ease their suspension on the injection and detection benches (see section about suspensions).

Mirror	Diameter	Thickness	Mass	RoC	deltaRoC
PR1	100 mm	75 mm	1.3 kg	see Sec 2.2	1%
PR2	350 mm	100 mm	21 kg	see Sec 2.2	1%
PR3	550 mm	65 mm	34 kg	Flat	NA

Is it worth noticing that the production of these mirrors takes several years (see section 2.9). After an internal inspection on the available substrates, it turns out that we have enough substrates for producing the PR2/SR2 and PRS1/SR1 mirrors. Instead for PR3/SR3 the substrates will have to be procured.

2.4 Suspensions

This section describes briefly the suspension envisaged to suspend PR1/SR1, PR2/SR2 and PR3/SR3. It is important to remember that a vibration isolation system based on three vertical stages of SAT filters or of GAS filters will be sufficient to satisfy the requirements.

As already anticipated PR1 and SR1 are suspended on the top of the injection and detection benches. The proposal is to suspend them with double pendulums similar to the ones developed for the filter cavity. In order to satisfy the displacement noise requirements given in 1.4 the last pendulum length is 400 mm and the marionette suspension wire length is 250 mm. Clearly the development of this system requires developing a prototype. Overall, the total double pendulum height measured from the bench plane is 850 mm. This is more than the distance between the benches and their marionette. For this reason the injection and detection bench super-attenuators have to be upgraded so as to be able to raise the bench marionette.

For PR2 and SR2 two super-attenuator similar to the one built for the curved mirror of the input mode-cleaner appears to be the most straightforward solution. The three stages of vertical attenuation allows meeting the requirements with some margin. The payload (filter 7 + marionette + mirror) can be identical to the ones currently used for the signal and power recycling mirrors.

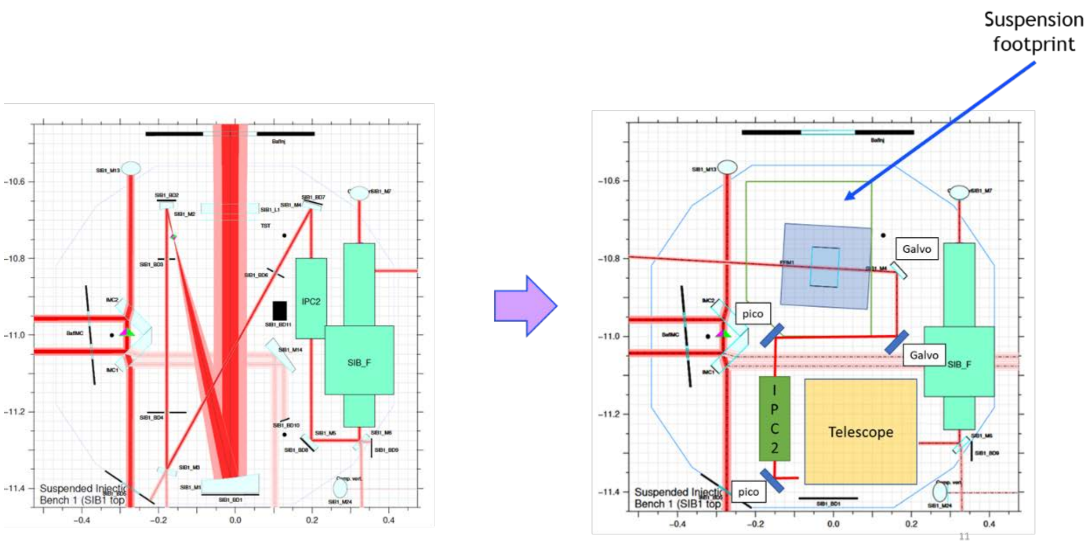
For PR3 and SR3 it is possible to use the super-attenuators currently used for signal and power recycling mirrors. No changes are needed. The payload instead has to be changed to allow suspending a payload identical to the current Virgo beam splitter.

2.5 Injection

The suspended input bench has to be modified in order to:

- Send the beam towards PR2 in the west direction instead of the north direction as it is done now
- Host the PR1 double pendulum
- Change the large telescope currently used with a smaller one to adapt the beam exiting from the input mode cleaner to the 1.3 mm beam radius on PR1

A preliminary implementation is shown in the figure below. On the left it is shown the bench layout as it is today. On the right a possible rearrangement to host the suspended PR1 mirror.



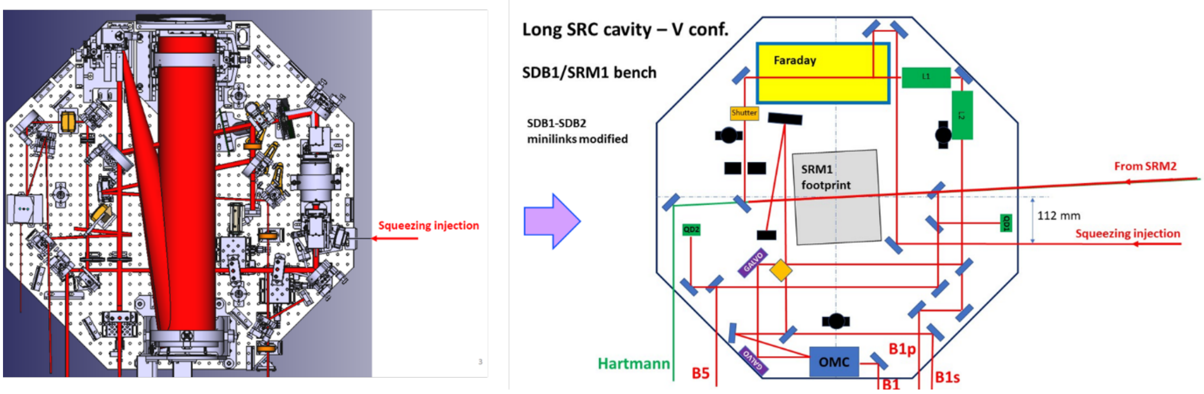
The main challenge is the control of PR1 and of the bench which also host the flat mirrors of the input mode-cleaner (the dihedron). To simplify this task two folding mirrors equipped with galvos will be implemented between the exit of the input mode-cleaner and PR1. Nevertheless if, in the future, the need will appear to suspend the input mode-cleaner mirrors the space available and the related control may represent a risk.

2.6 Detection

The suspended detection bench has to be modified in order to:

- Receive the beam from SR2 in the north direction instead of receiving it directly from the beam splitter from the west direction
- Host the SR1 double pendulum
- Change the large telescope currently used with a smaller one to adapt the beam exiting from SR1 mirror to the output mode-cleaner

A preliminary implementation is shown in the figure below.

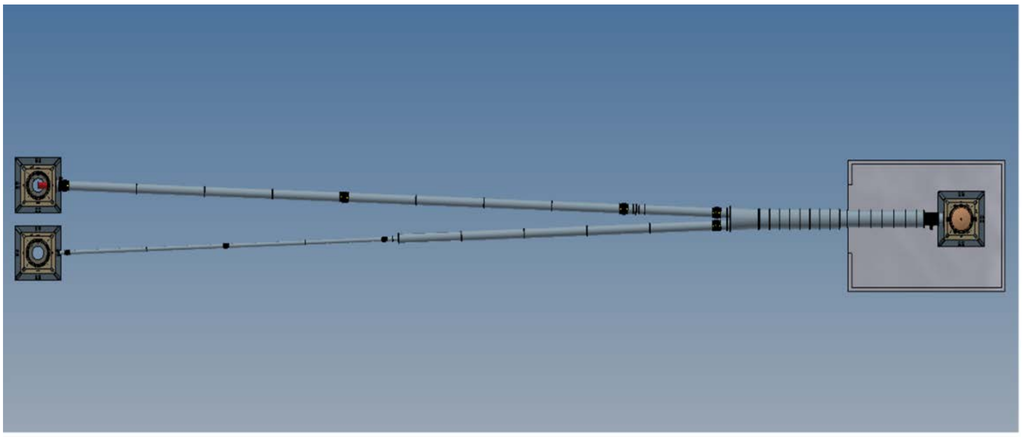


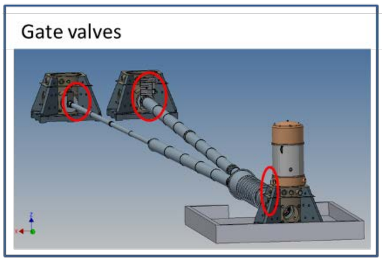
The main challenge is the control of SR1 and of the bench which also hosts the output mode-cleaner. To simplify this task two folding mirrors equipped with galvos will be implemented between the output of the SR1 and the output mode-cleaner. Nevertheless if, in the future, the need will appear to suspend the output mode-cleaner as it is done e.g. in LIGO and KAGRA the space available and the related control may represent a risk.

It is clear that the space remaining will not allow the implementation of the balanced homodyne as foreseen for Virgo_nEXT. Such a change will require the installation of an additional vacuum chamber equipped with another suspended optical bench at the south of the present detection tower. This new equipment could be similar to the one used for SDB2 but the vacuum will have to communicate directly with the detection tower as it will not be possible to put windows along the beam paths between the detection tower and the new chamber.

2.7 Vacuum

A sketch of the vacuum system required to host the signal recycling cavity is shown in the figure below. A similar equipment is required for the power recycling cavity.



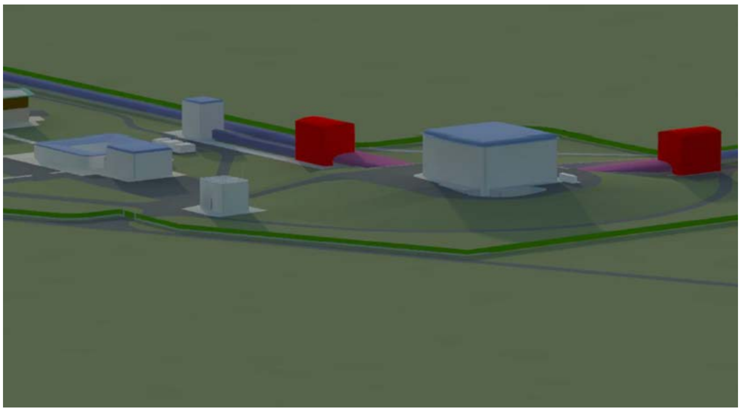


The main parts are:

- Two vacuum chambers to host the PR2 and SR2 mirrors and their suspensions;
- Beam pipe: Ø700 mm x 180 m + Ø300 mm x 60 m, with a reduced number of bellows, lip joints at extremities, to be assembled by welding;
- Two special cylindrical components to realize the V connections between the beam pipe and the towers;
- Four large gate valves diameter 650 mm to isolate each tower;
- One main pumping group per tube to be installed near the V point. One full pumping set per tower with two compartments based on a turbo-molecular pump and an ion pump.

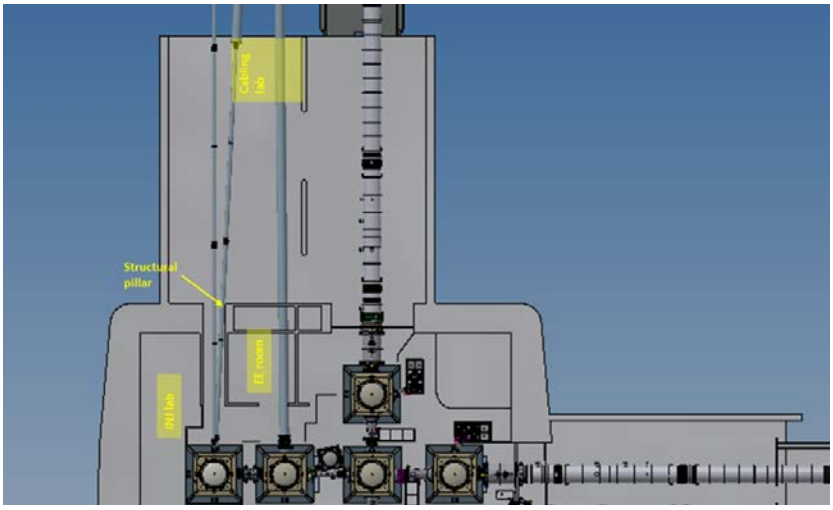
2.8 Infrastructure

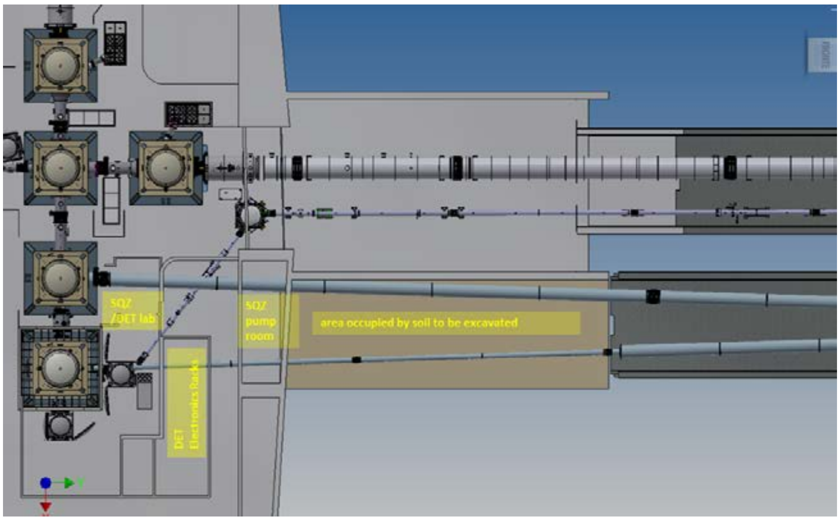
A drawing representing the required infrastructure is shown in the figure below.



Two buildings have to be built 80 m from the central building. Each building hosts a vacuum chamber itself containing the PR2 and SR2 mirror and their suspensions. A crane at a height of 6 m is needed to open/close the vacuum chambers and support the installation of the equipment. At the side of the vacuum chambers there has to be a clean room from which the vacuum chambers can be accessed and that allows installing the mirrors in clean conditions. Two tunnels 80 m long have to be realized to connect the PR2 and SR2 buildings with the central building. The tunnels host the vacuum beam pipes.

The four vacuum tubes coming from the PR2 and SR2 building need to enter the central building and reach the injection tower, the power recycling tower, the signal recycling tower and the detection tower. In order to do so they have to cross several concrete walls including structural ones. Two pictures representing the works to be done in the central building are shown below. On the injection side one of the tubes intersect with one of the structural pillars of the building. On the same side two laboratories will have to be relocated to allow the passage of the tube. On the detection side the tubes pass through the detection/squeezing clean room, the detection electronics room and the squeezing pump room. Right at the exit of the building, in the north direction, the soil has to be excavated over a distance of about 20 m to allow building the tunnel towards the SR2 building.



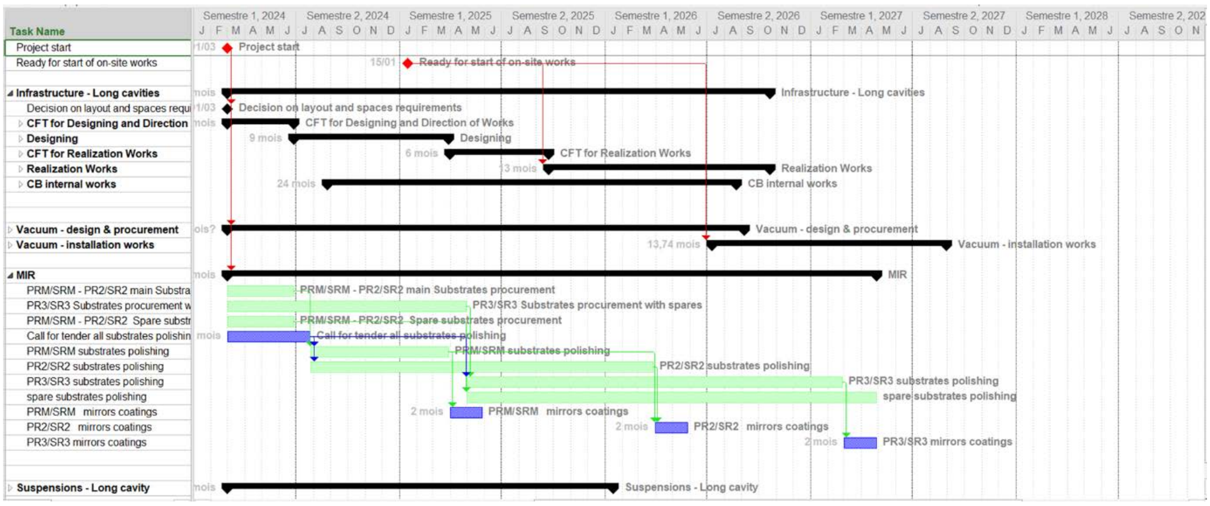


2.9 Modification of the quantum noise reduction system

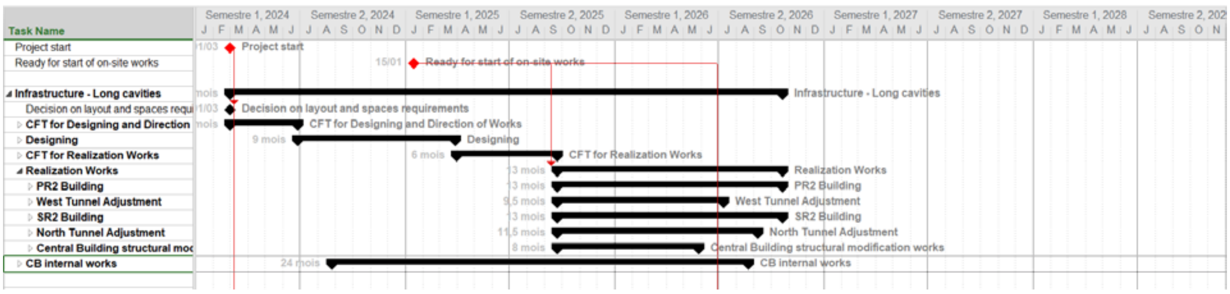
As it is well visible in the picture above, the deployment of the tubes for the signal recycling cavity interfere with the tube of the quantum noise reduction (QNR) system i.e. the system built for AdV+ Phase I to inject frequency dependent squeezing. The main problem is that the two vacuum levels are different (10-8 mBar in the main interferometer vs 5 10-7 mBar in the QNR system). For this reason a window separates the quantum noise reduction system vacuum envelope from the detection tower. Moreover the signal recycling cavity beam path crosses one of the vacuum chambers (called SQB1) used to inject the vacuum squeezed beam into the interferometer. The proposed solution consists in changing both the SQB1 vacuum chamber and the bench contained in the chamber to allow the signal recycling cavity beam to pass through. Moreover the window separating the two vacuum levels is moved downhill towards the filter cavity. In conclusion, the solution of this issue requires building a new vacuum chamber and displaced the position of the window separating the two vacuum levels. Moreover a new bench with a new optical layout has to be built.

2.10 Schedule

A preliminary schedule is shown in the planning below. The planning covers the period until the completion of the vacuum system installation and includes the works necessary to build the suspensions and the mirrors. The suspension and mirrors installation, their pre-commissioning and the commissioning of the interferometer are not included. The detail of this part of the plan has to be worked out but it is plausible to imagine two more years of work before starting observation around summer 2029.



It is worth noticing that the critical path passes through the realization of the infrastructure. The detailed planning of this work is shown in the figure below. A preparatory phase of 19 months including the design and the calls for tender is followed by the construction works themselves which are scheduled to last 13 months. This is achieved by having five construction sites pursued in parallel: the two buildings, the two tunnels and the works in the central building. This appears to be the biggest risk of this solution.



2.11 Budget

The estimate of the budget required to build the long cavities is given in the table below. This estimate includes VAT. It does not include the cost for suspensions, control electronics, additional data acquisition channels and environmental sensors to be located in the new buildings. On the other hand, it includes 20% of contingency.

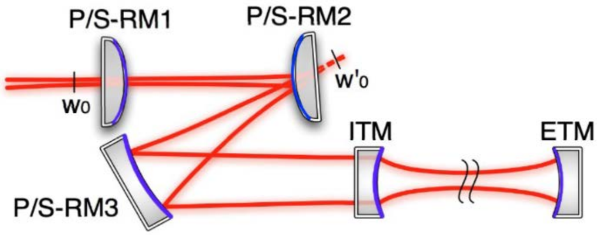
	2024 (k€)	2025 (k€)	2026 (k€)	TOTAL (k€)
INFRASTRUCTURE	1000	7200		**8200**
VACUUM	1600	2000	400	**4000**
MIRRORS	1500	1200		**2700**
SUSPENSIONS	500	1000	400	**1900**
INJECTION/DETECTION	0	100	0	**100**
QNR MODIFICATIONS	0	300	0	**300**
Contingency	920	2360	160	**3440**
TOTAL	**5520**	**14160**	**960**	**20640**

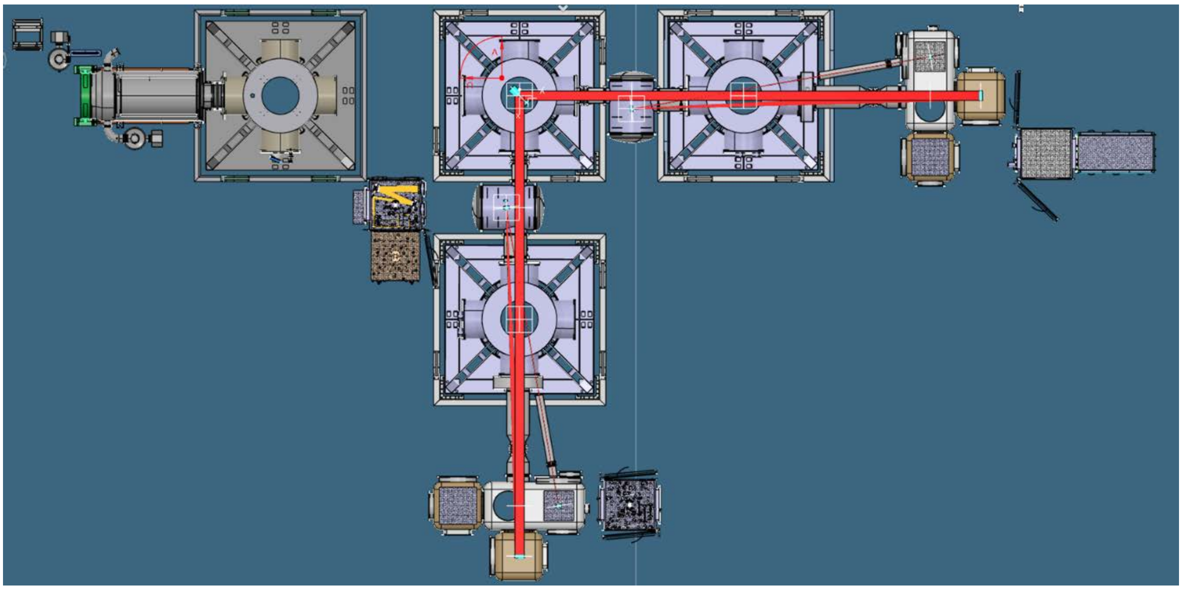
The table also shows the commitment profile. Please note that some of the works last for more than a year (e.g. mirrors and infrastructure) so the spending profile will be distributed over a slightly longer period.

3 Short recycling cavities

3.1 Layout

The sketch of the optical layout of the short stable recycling cavities and the actual implementation in the central building are shown in the two figures below.





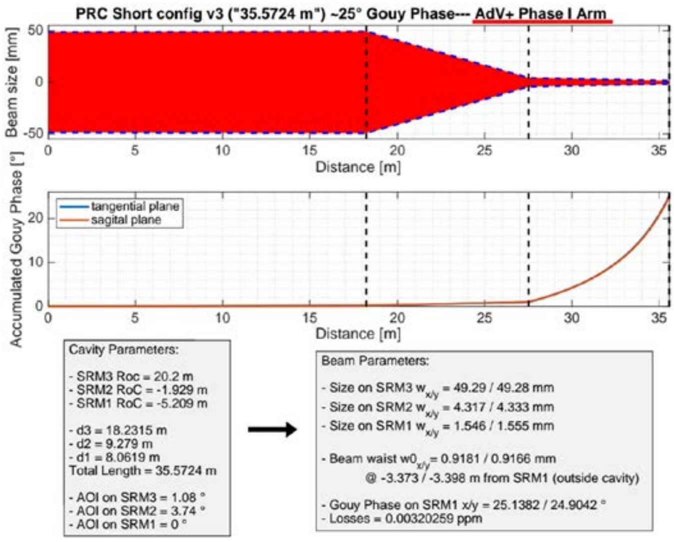
In this scheme the present suspended input bench is split into two separate benches. The first (SIB1) hosts the flat mirrors of the input mode-cleaner and the reference cavity as it is the case now. The second one (PR bench) hosts the input Faraday isolator and the power recycling mirror suspended via a double pendulum on the top of this bench. The laser beam reaches SIB1 first and, after being filtered by the input mode-cleaner, is sent toward the PR bench. From this point on the stable power recycling cavity is realized by means of three curved mirrors as in the scheme adopted by LIGO and KAGRA: PR1, PR2 and PR3. After transmission through PR1 the laser beam expands and reaches PR2 a convex curved mirror suspended inside a new vacuum chamber placed between the current power recycling and beam splitter towers. The Gouy phase is mainly acquired in this part of the cavity. PR2 expands further the beam and reflects it toward the PR3 mirror suspended inside another vacuum chamber placed in part of the central building currently occupied by the injection tower. The PR3 mirror is a concave curved mirror that collimates the beam and sends it towards the beam splitter and the interferometer.

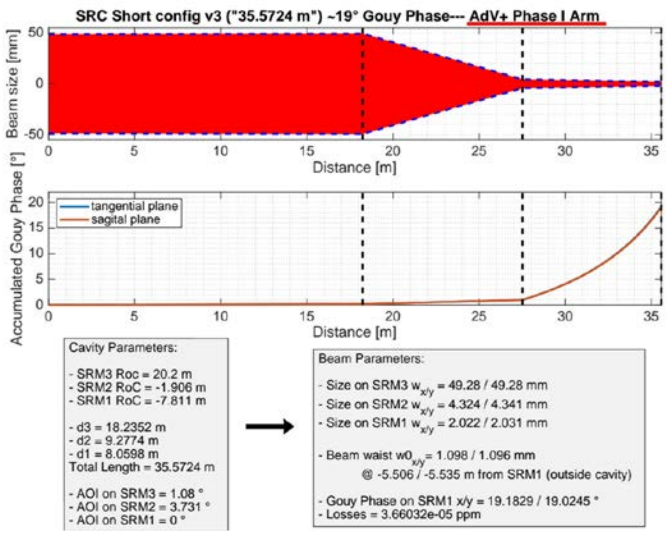
In order to fit the SIB1 bench, the PR bench and the PR3 mirror in the building the large injection vacuum tower (2 m in diameter) is dismantled thus freeing a surface of 4mx4m. This space is used to place three vacuum chambers each containing a separate suspension. In this manner each critical mirror (PR3, PR1 and the input mode-cleaner dihedron) has its own suspension.

The signal recycling cavity follows a symmetrical scheme at the output of the interferometer (see figure above). In this case the detection tower is dismantled to make the needed space available.

3.2 Optical configuration

The parameters of the power recycling cavity (PRC) and signal recycling cavity (SRC) are given in the two figures below. This configuration uses the same lengths for the two cavities as it is done in KAGRA. Depending on the final choice on the modulation frequencies for the alignment control the SRC should be 2.6 m longer (or shorter). The space available in the central building allows for it.





As in the case of LIGO and KAGRA this solution uses three curved mirrors. So, compared to the long solution there is an extra degree of freedom to adjust the Gouy phase and the matching with the arm cavity.

As shown in the data above in this solution the astigmatism is negligible and so the Gouy phases in the sagittal and tangential planes are very close. This is achieved by having two different angles of incidence on PR3 and PR2 and taking advantage of the fact that these two mirrors have opposite curvatures.

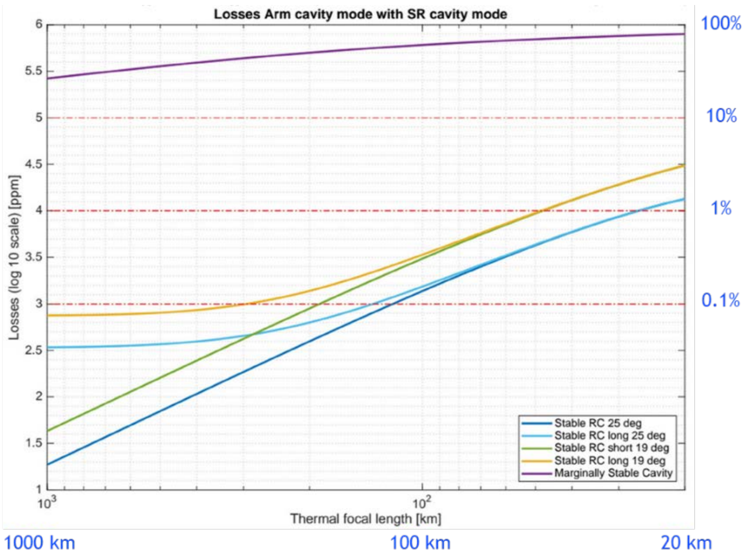
Errors of 1% in the radii of curvature (RoC) of PR1/SR1 and PR2/SR2 can be compensated by slightly changing their relative distance. Realizing these mirrors with a RoC accuracy of 1% is no problem. Errors of 0.2% in the RoC of PR3 can be compensated with a thermal actuator. A 0.5% accuracy on

PR3 needs a good polishing. In the context of the LIGO project, polishers have already accepted this level of accuracy and were able to achieve accuracies of the order of 0.2% or better. The mirror focusing the beam into the filter cavity has a RoC similar to PR3/SR3. An accuracy of the order of 0.1% was achieved in that case. If the PR3/SR3 mirror RoC's were wrong by 0.5%, the distance between PR3/SR3 and PR2/SR2 would have to be changed by about 5 cm and the one between PR2/SR2 and PR1/SR1 by 10 cm. If deemed necessary, these type of adjustments can be foreseen at the time of the construction of vacuum chambers and suspensions

The losses in the SRC have been simulated with the ABCD formalism and give a negligible result. An evaluation has been made with an FFT propagation code (OSCAR) in the case of the PRC and gives 50 ppm. The calculation of the losses in the SRC with FFT propagation code is in progress

The auxiliary beams originating from the compensation plates and the secondary face of the beam splitter have been traced. Using PR3/SR3 mirrors diameter equal to 26.5 cm the losses on the main beam are negligible. The losses on the B5 beam are 900 ppm (see Section 3.3). The beams are all well reflected by the PR2/SR2 mirrors and are well separated at the level of PR1/SR1 thanks to the stable cavities magnifying optics.

The sensitivity of the recycling cavities to thermal lenses in the input mirrors have only been studied with the ABCD matrix formalisms. The result is shown in the figure below. The result is that for a given thermal lens the losses in the stable cavities are orders of magnitude smaller than in a marginally stable cavity. The plot shows that a long stable cavity and a short stable cavity having the same Gouy phase, have the same losses for thermal lenses shorter than 100 km. For longer thermal lenses the difference comes from the uncompensated astigmatism in the long cavity case. The bottom line is that the Gouy phase matters more than the length.



The question was raised whether at the time of Virgo_nEXT, when the power on PR1 can reach up to 10 kW, the intensity on the mirror can damage the mirror. From the values available in the literature, it turns out that for beam sizes larger than 1 mm the intensity remains well below the laser damage threshold. Given the short curvature of PR1, the change of RoC due to the thermal lens induced by the 10 kW is negligible.

Given the chosen length for the PRC, the first modulation frequency (6.27 MHz) has to be changed by 50 kHz and the second modulation (56.4 MHz) frequency by 9 x 50kHz. This requires to shorten the input mode-cleaner length by 1.13 m. Given that in this solution the input mode-cleaner flat mirrors (so called dihedron) are moved in the west direction by 1.30 m, the input mode-cleaner end mirror will have to be moved in the east direction by 17 cm. These types of mode-cleaner tower displacement have already been done in the past.

The investigations about interferometer sensing and control have been focused on the locking error signals. No showstoppers have been found so far. The matrix relating the photodiode error signals and the interferometer lengths are very close to the present one given their very weak dependence on the recycling cavities length/modulation frequencies and their independence on the Gouy phase. Only the modulation frequencies and their resonance conditions in the recycling cavities matter. The latter can be chosen by properly choosing the exact cavity lengths and modulation frequencies. The study of the alignment control signals remains to be done.

3.3 Mirrors

The required mirrors and their main characteristics are given in the table below.

PR3/SR3 mirrors are curved concave 265 mm diameter mirrors (so like the LIGO PR3/SR3 mirrors). Having a thickness of 100 mm their weight is 12 kg. Their diameter is dictated by the need to catch the beams coming from the beam splitter. Their radii of curvature is dictated by the distance between PR3/SR3 and PR2/SR2. If the 900 ppm losses on B5 are considered excessive the diameter of this mirror can be increased to e.g. 300 mm. Alternatively, the known issue with beam splitter vertical wedge can be solved and the new wedge chosen to be horizontal and appropriate to superpose B5 and B1 on the SR3 mirror (as it was done in initial Virgo where the wedge was chosen so to have B1 and B5 superposed at the entrance of the detection bench).

PR2/SR2 mirrors are curved concave mirrors, 150 mm in diameter (so like the Virgo filter cavity mirrors and the LIGO PR2/SR2 mirrors). Their radii of curvature are dictated by the required Gouy phase and the distance from PR1/SR1.

PR1/SR1 mirrors are curved convex mirrors 100 mm in diameter, so 1.3 kg in mass. Given the beam size on these mirrors (~1.5 mm and 2 mm on PR1 and SR1 respectively), these mirrors can be very small. The proposed size/mass is chosen to ease their suspension on the injection and detection benches (see section about suspensions).

In case the two recycling cavities have to have different lengths the SR2 and PR2 will have slightly different RoC's. This can be important when counting the minimum number of needed spares.

Mirror	Diameter	Thickness	Mass	RoC	deltaRoC
PR1	100 mm	75 mm	1.3 kg	see Sec 3.2	1%
PR2	150 mm	100 mm	2.9 kg	see Sec 3.2	1%
PR3	265 mm	100 mm	12 kg	See Sec 3.2	0.5% (goal 0.2%)

Is it worth noticing that the production of these mirrors takes several years (see section 3.9). After an internal inspection on the available substrate it turns out that we have enough substrates for producing the four required PR3/SR3 mirrors (1 mirror + 1 spare of each), at least three of the four PR2/SR2 mirrors and three of the four PRS1/SR1 mirrors.

3.4 Suspensions

This section describes briefly the suspension envisaged to suspend PR1/SR1, PR2/SR2 and PR3/SR3. It is important to remember that a vibration isolation system based on three vertical stages of SAT filters or of GAS filters will be sufficient to satisfy the requirements.

As already anticipated PR1 and SR1 are suspended on the top of two new benches called PR! And SR1 benches. The proposal is to suspend them with double pendulums similar to the ones developed for the filter cavity. In order to satisfy the displacement noise requirements given in 1.4 the last pendulum length is 400 mm and the marionette suspension wire length is 250 mm. Clearly the development of this system requires developing a prototype. The PR1/SR1 benches will be suspended to a marionette similar to the one used for the injection and the detection benches itself suspended to a MSAS composed of three GAS filters in cascade and an inverted pendulum. Thus the seismic isolator would be similar to the one used for the suspended benches but with one additional GAS filter, while the bench payload would be similar to the present injection and detection payloads.

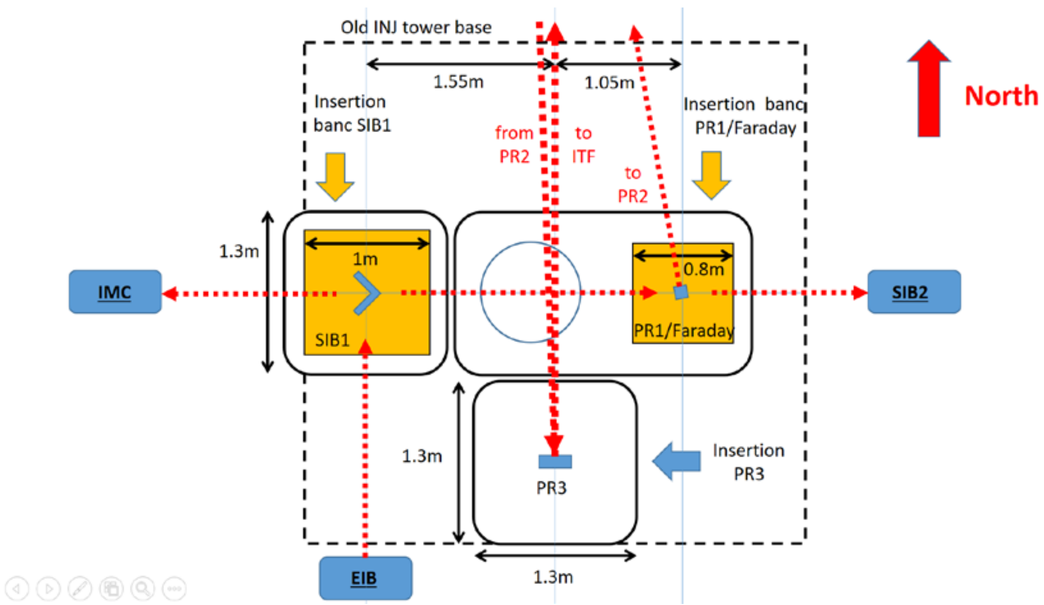
For PR2 and SR2 two MSAS based on three GAS filters in cascade and an inverted pendulum appears to be the most straightforward solution. Thus the seismic isolator would be similar to the one currently used for the suspended benches but with one additional GAS filter. The payload instead would be similar to the standard Virgo payloads but reduced in size given the smaller mirror (150 mm diameter and 2.9 kg).

A similar solution can be used for PR3 and SR3. They could be suspended to an MSAS based on three GAS filters in cascade and an inverted pendulum. The payload instead would be similar to the standard Virgo payloads but adapted to the mirror size.

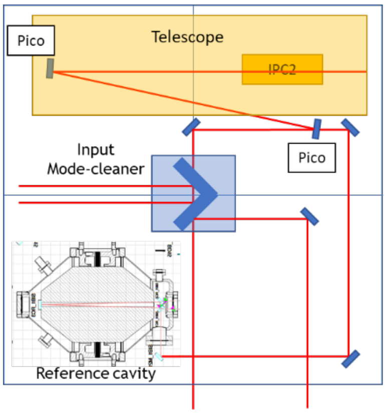
Finally two additional suspensions will be needed to suspend the injection and detection benches. In this case the seismic isolation could be provided by an MSAS made of two or three GAS filters and an inverted pendulum. The payload instead would be similar to the present injection and detection benches payloads (or alternatively to the present SDB2/SIB2 benches if a central wire suspension is preferred).

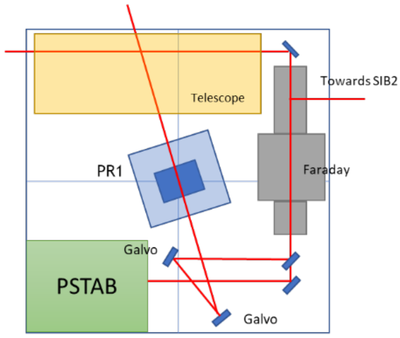
3.5 Injection

As explained in section 3.1 the hardware currently hosted on the injection bench will be split on two benches: the new input bench (SIB1, 1mx1m) and the PR1 bench (0.8mx0.8m) i.e. the bench hosting the suspended power recycling mirror. For comparison, at present the entire hardware is mounted on a 0.9 m dodecagonal bench: as a consequence the total bench area is increased from 0.65 m2 to 1.64 m2. The overall corresponding layout is shown in the figure below.



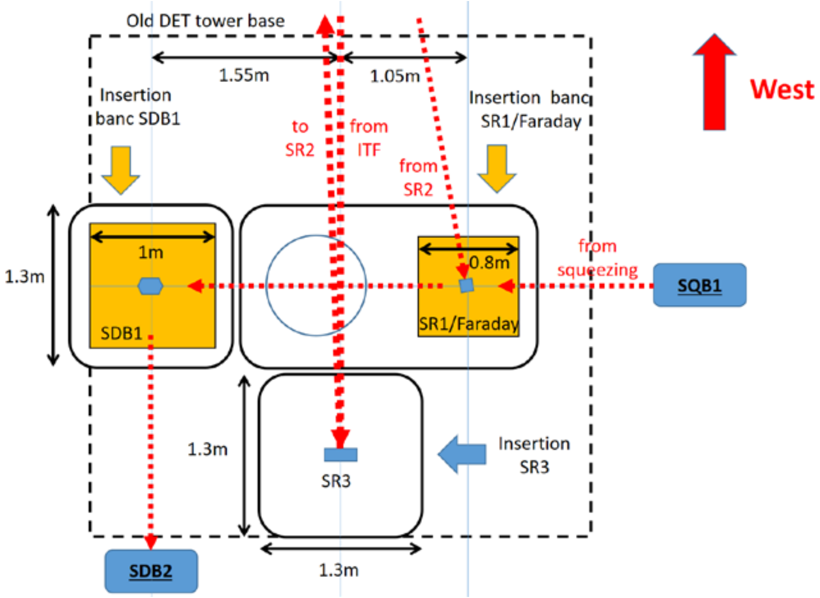
A more detailed representation of the implementation of the hardware on the two benches is shown below. The input mode-cleaner and the reference cavity will be sitting on a new injection bench while the Faraday isolator and the beam power stabilization detectors will be sitting on the PR1 bench. Two telescopes will allow sending the beam from the injection bench to the PR1 bench.





3.6 Detection

Similarly to what is proposed for the injection also in the case of the detection the hardware currently hosted on the injection bench will be split on two benches: the new detection bench (SDB1, 1mx1m) and the SR1 bench (0.8mx0.8m) i.e. the bench hosting the suspended signal recycling mirror. For comparison, at present the entire hardware is mounted on a 0.88 m octagonal bench: as a consequence the total bench area is increased from 0.6 m2 to 1.64 m2. The overall corresponding layout is shown in the figure below.

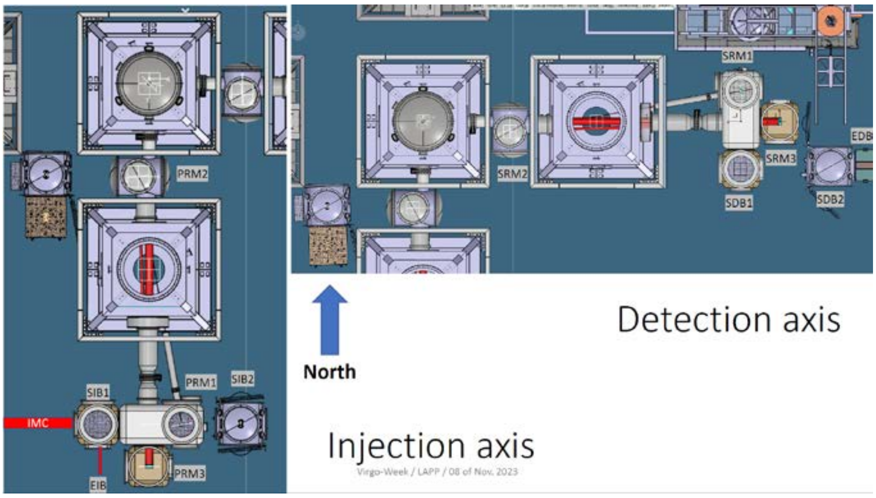


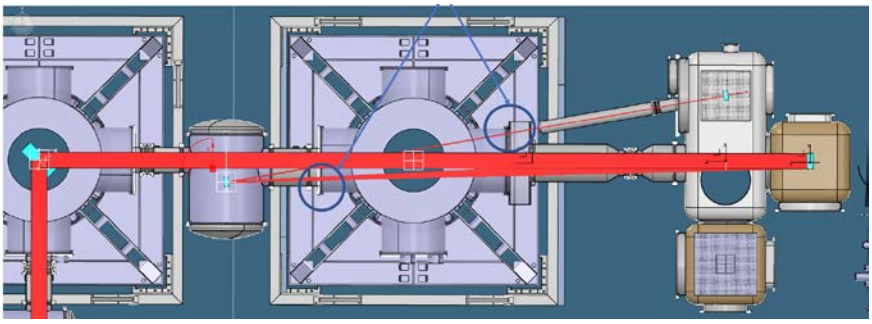
The light coming from the SR2 mirror is transmitted through the SR1 mirror and then through the output Faraday isolator. The same output Faraday isolator receives the squeezed vacuum beam from the quantum noise reduction (SQB1 On the picture) system and sends it towards the interferometer. The light transmitted by the Faraday isolator is sent toward the output mode-cleaner on the SDB1 bench and then toward the photodiodes on the already existing SDB2 bench.

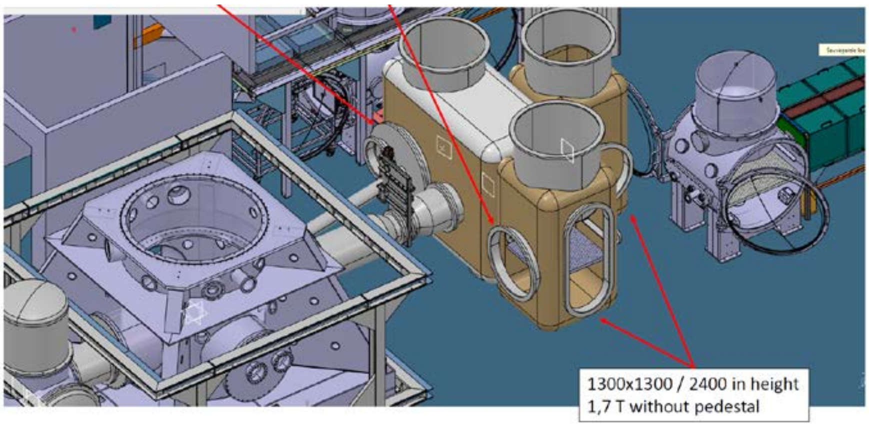
It is worth noticing that this solution does not require modifying the quantum noise reduction system. Moreover it considerably increases the space available on the SDB1 bench thus allowing it to be already prepared for the installation of the homodyne detection at the time of Virgo-nEXT.

3.7 Vacuum

As anticipated in section 3.1 the installation of the short cavities solution requires changing part of the vacuum system in the central building. The present vacuum chambers, two meters in diameter mounted on a 4mx4m base, are adapted to support 10 m tall seismic isolators supporting heavy payloads. They are over dimensioned for the recycling mirrors and their suspensions. Thus, the proposal consists in removing the injection tower and using the free space to install three smaller vacuum chambers (1.3mx1.3m) hosting the PR3 mirror, the PR1 mirror and the injection bench (SIB1). Similarly the detection tower is removed and three smaller vacuum chambers are installed to host SR3, SR1 and the new detection bench (SDB1). Two additional vacuum chambers are installed between the beam splitter and the power recycling tower and between the beam splitter and the signal recycling to host the PR2 and SR2 mirrors and their suspensions. A drawing of the vacuum chambers implementation and of the links connecting them is shown in the pictures below.







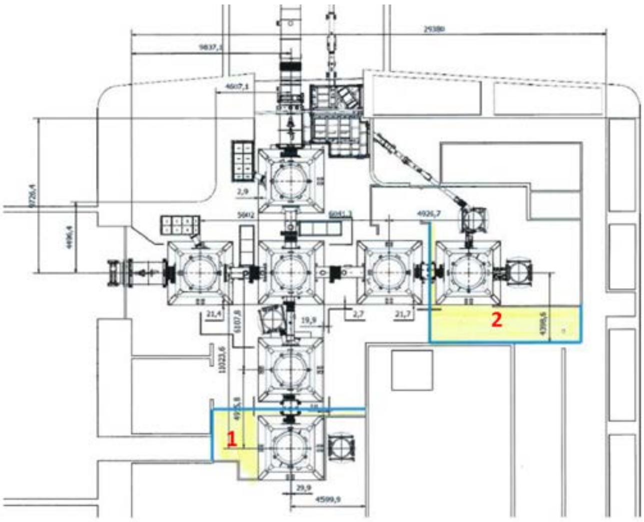
It is important to remark that it is not possible to remove the injection and detection towers with the crane since they exceed by far the maximum weight. After a discussion with companies it turns out that it is possible plasma cut the towers and remove them in smaller parts. To this purpose a 6mx6mx6m sealed box has to be assembled around the tower base. The sealed box is equipped with two apertures communicating with the outside of the building: one to evacuate the stale air and the other to inject fresh air. An alternative solution being investigated consists in making an opening in the roof and extracting the tower from the outside with a tall crane.

To summarize, the implementation of the proposed short cavity solution requires the removal of two large vacuum chambers from the central building and the construction of eight vacuum chambers, one for each optical component and its suspension. Additional investments will be needed for the links, the pumps and the valves.

3.8 Infrastructure

The infrastructure works are relatively limited compared to those needed for the long cavities solution.

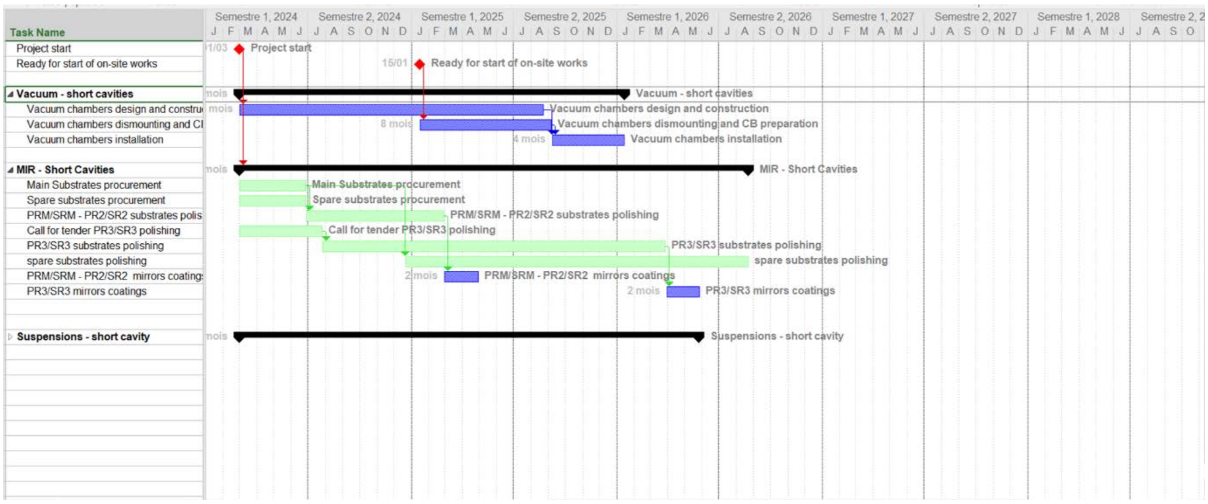
Similarly to what is already done for the suspended benches since the time of Advanced Virgo, the ensemble of payloads will be installed from the outside of the vacuum chambers without the need to enter inside the vacuum chamber (nevertheless an additional access from below will be kept for the PR3/PR1/SIB1 vacuum chambers and for the SR3/SR1/SIB1 vacuum chambers). In order to make the installation in clean conditions the existing injection clean room will have to be extended to include the PR3/PR1/SIB1 vacuum chambers. Similarly the detection clean room will also have to be extended to include the SR3/SR1/SDB1 vacuum chambers. The scheme of the extension is shown here below.



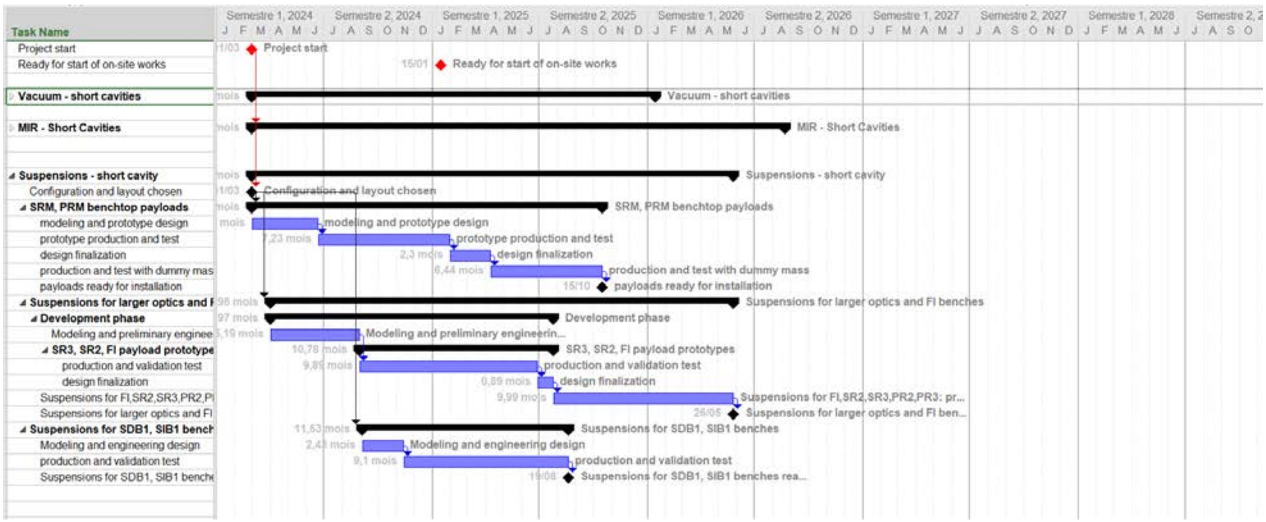
Moreover, below the injection and detection towers there are 2.5mx2.5m holes in the floor that allow entering into the towers from the lower gallery. These holes have to be partially filled. The possibility to do this work by extending the structure of the floor is being investigated. An alternative solution will be to put in place a rigid metallic chassis on which the vacuum chambers will be fixed.

3.9 Schedule

A preliminary schedule is shown in the planning below. The planning covers the period until the completion of the vacuum system installation and includes the works necessary to build the suspensions and the mirrors. The time at which the mirrors become available after their coating is also shown. The suspension and mirrors installation, their pre-commissioning and the commissioning of the interferometer are not included. The detail of this part of the plan has to be worked out but it is plausible to imagine two more years of work before starting observation around spring 2028.



It is worth noticing that the critical path passes through the realization of the suspensions. The detailed planning of these works are shown in the figure below. The capability to realize this planning is in the hand of the collaboration as the required expertise is in house.



3.10 Budget

The estimate of the budget required to build the short recycling cavities is given in the table below. This estimate includes VAT. It does not include the cost for suspensions, control electronics and additional data acquisition channels. On the other hand, it includes 20% of contingency.

	2024 (k€)	**2025 (k€)**	**2026 (k€)**	**TOTAL (k€)**
INFRASTRUCTURE	100	500		**600**
VACUUM	1750	1250		**3000**
MIRRORS	1300			**1300**
SUSPENSIONS	1000	1500	800	**3300**
INJECTION/DETECTION		500		**500**
QNR MODIFICATIONS				**0**
Contingency	830	750	160	**1740**
TOTAL	**4980**	**4500**	**960**	**10440**

The table also shows the commitment profile. Please note that some of the works last for more than a year (e.g. mirrors) so the spending profile will be distributed over a slightly longer period.

4 Conclusions and outlook

On the basis of the results of this study, it is possible to install stable recycling cavities in Virgo and it also seems possible to do so within the present infrastructure. Overall the short solution can be implemented in a shorter time and at a smaller cost with respect to the long option even if an exact estimate of the time required for the preparation of phase 2 requires the integration into the schedule of the other planned activities, which will only be possible after the preparation of the technical design. The schedule of the long cavity solution is dictated by the time necessary to build the new infrastructure, install the additional vacuum systems and realize more larger mirrors. The construction of the infrastructure in particular requires to proceed in parallel with the realization of the two buildings, the two tunnels and the modification of the central building to complete all works within thirteen months. Infrastructure, vacuum and mirrors are also the main ingredients of its cost. The schedule of the short cavity solution, instead, is dictated by the time necessary to realize the required new suspensions which are also the largest expenditure.

Both solutions require suspending the signal recycling and power recycling mirror on the top of suspended benches. This part will require the development of a prototype. The other suspensions required for the short cavities solution are based on technology already used in the Virgo vibration isolation systems and payloads. In these cases, prototyping can be limited to that necessary to verify transfer functions and test the installation procedure. In terms of flexibility, the short solution provides more space for optical benches at the injection and detection ports thus easing the installation of options like e.g. the installation of the balanced homodyne detector expected in Virgo_nEXT or the suspension of the input mode-cleaner flat mirrors.

Neither solution is risk-free; for this reason, in order to move forward, a detailed risk analysis was started to evaluate the risks of each of the solutions in terms of performances, schedule, cost and flexibility in view of the Virgo_nEXT upgrade. The methods and results of the risks analysis evaluation will be reviewed by an internal review committee. Such a committee is already in place and should be in position to deliver its conclusion by the end of January 2024. The current plan is to have the final choice approved by the collaboration in early February 2024. From there, the plan is to prepare a detailed technical design report for the chosen solution and an updated global plan for Phase II. The latter will be submitted to the review of an external review committee.