VAC FDR Jun2010 (draft-1)

Foreword

Here we report the technical design of the cryotraps as a part of the VAC chapter of the FDR document. The design of the remaining part of the vacuum system will follow in the next months, as soon as the optical configuration and the requirements of related VAC parts will have been discussed and established.

After the general review of the present document by IPRB, the constructive details and the documents for the call for tender will be discussed in successive engineering meetings and specific reviews.

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1 Requirements

1.1 Vacuum level

The enhancement of the Virgo sensitivity by a factor of 10 requires an improvement of the present vacuum level to lower the phase noise given by the residual gas fluctuations inside the 3km long arm tubes. At present the system operates at about 10^{-7} mbar (dominated by water) although it has been designed and tested to reach a base pressure below 10^{-9} mbar (dominated by hydrogen) after an overall bake-out.
The lowest point of the AdV sensitivity curve: 3 10^{-24} $Hz^{-1/2}$ at 200-400 Hz is not compatible with the present residual gas noise, at the level of 10^{-23} $Hz^{-1/2}$ [1],[2]. To be not dominant in AdV, this noise has to be reduced by at least a factor of 10 (about a factor of three below the AdV design sensitivity). The residual pressure in the tubes has to be reduced by a factor of 100, the noise being proportional to the square root of the partial pressure of the various gas species.

The proposed goal, expected after arm tubes bake-out, is shown in fig 0 *(link to the reference sensitivity plot in another chapter)* and reported in table 1 showing the contributions of the different gases are reported separately.

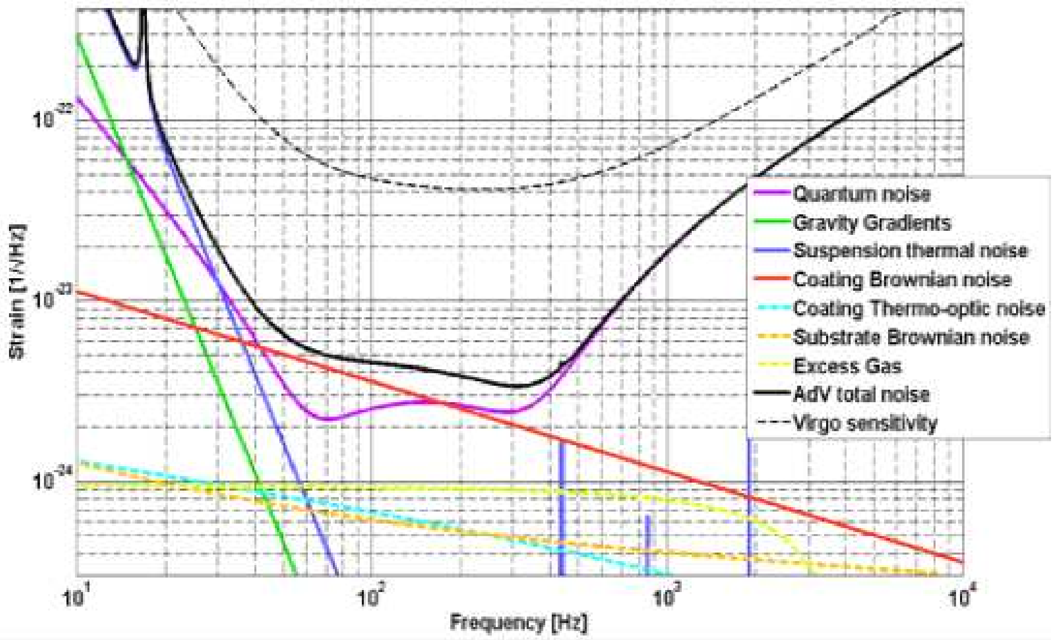


Fig. 0 Reference AdV sensitivity curve, including noise related to the goal vacuum level

Gas species	Pressure (mbar)	Phase noise ($Hz^{-0.5}$)
H_2	10^{-9}	$2.1\ 10^{-25}$
H_2O	10^{-9}	$7.0\ 10^{-25}$
Air +others	$5\ 10^{-10}$	$6.1\ 10^{-25}$
Total	$2.5\ 10^{-9}$	$9.5\ 10^{-25}$

Tab 1 Goal pressures and phase noise (baked tubes) in the intermediate frequency band [3]

The originally planned method of vacuum improvement was based on baking the whole system (the 3km tubes plus the 7 mirror towers) at 150°C. Baking of towers would have to be repeated after each opening of a tower. With the experience gained running Virgo, we have realized that the tower baking choice as foreseen is not opportune because:
• the long time needed after each tower opening affects excessively the interferometer duty cycle (about 1 month to achieve the bake-out procedure, to be compared to the present two-three days);
• unpredictable de-tuning effects may be produced by the warm-up of the lower stages of the anti-seismic suspension at 50°C or more, involving movements/stresses.
Furthermore the re-condensation of contaminants on mirrors and detaching of glued or silicate bonded parts are also risks to be considered.

The proposed goal can be met by:

- Installing cryogenic traps at tube extremities
- Performing the bake out of tubes

Cryogenic traps are the classical solution to stop the migration of water from unbaked towers to the tubes. Cryotraps have been already experimented in Virgo and in other large vacuum systems, and can be considered without a long phase of tests and prototypes.

Four cryogenic traps will be installed for AdV, one at each tube extremity, inside the link tubes between the relevant tower and the respective large valve[5], isolating the 3km tube. They will consist in 'hollow cylinder' cryostats, cooled at 77K with a bath of liquid nitrogen, 2m long and 0.95m of aperture. The setup will be completed by an additional large size valve (650mm aperture) and baffles of aperture 600mm (diameter) for diffused light and thermal mitigation.
Liquid nitrogen will be supplied with a 'standard' distribution plant based on large storage tanks (three in total) and vacuum insulated transfer lines. The estimated overall heat leak for each cryotrap is about 300W, while the losses of a good quality storage vessel are typically in the range of 1% per day of its content. The liquid nitrogen consumption has been evaluated in 850 l/day for the whole system, the refilling of exhausted tanks shall occur by truck coming on site once per week, during the weekly maintenance break.

The first cryotrap of the series is planned to be ordered in fall 2010 (prototype).

After extensive testing in factory and at NIKHEF, the first cryotrap will arrive on site by end 2011. It will be installed in 'West end' position, where conflicts with other construction activities are not foreseen, with the aim to have a final and complete test before ordering the remaining three traps. All traps shall be installed by mid 2013. The length of the 4 traps will be slightly different to cope with installation constraints, but not changing substantially the design.

The tube baking system is already implemented in Virgo [6] and will not be described here. Baking will be postponed with respect to traps installation and performed only when convenient for commissioning activity and necessary for sensitivity. A base pressure in the tube around 10^{-8} mbar shall be obtained without baking, allowing a first period of interferometer commissioning together with a favorable distribution of the manpower and of the economical effort. When required, tubes shall be baked during maintenance stops lasting about 1 month each.

1.2 Further vacuum upgrades

The different optical scheme and the larger beam waist of AdV require new link tubes with larger diameter and full height towers adding extra rings to either the Signal Recycling mirror or to the Detection and Injection benches; and also other possibilities could be envisaged. IVCs with a new design shall be probably needed too.
A different position of the 'mirror towers' of the central area is also required, eventually including the MC one. Depending on the number of concerned towers and on the required entity of displacements, the central area 'platform' structure shall be completely transformed.
The vacuum pumps installed at present on the links will be rearranged and in part substituted, moving the titanium-getter pumps on the tubes, downstream the large valves since more suitable to work in baked chambers, and installing additional Ion pumps in their place.
The scroll pumps shall be displaced away from the towers, and installed in an insulated room, to hinder their acoustic and seismic emissions.
Finally it is necessary to renew the control system of the vacuum apparatus. While being effective for today's needs, it requires to be revised, since it has been designed more than 10 years ago, based on the OS-9 standard, using components no more available on the market. The new architecture shall be based on industrial PLCs, which will collect directly most of the signals, and will ensure a control at 'overall level', being able to talk to each other. It shall be necessary to upgrade also the control logic, both hardware and software, to include the new devices and to protect the improved vacuum level. The design shall take in consideration also the environmental noise aspects, now emerging.

2 Cryotraps

2.1 Mechanical design

There is sufficient space to install cryotraps in between the towers and the existing DN1000 valves. Fig.1 shows the WE case, the vacuum vessels of the cryotraps will have different lengths to fit with the different AdV tower axis-large valve distances (in parenthesis the present distances and the foreseen changes):
WE towers = 6000 mm
NE tower = 5253 mm (6000mm – 747mm)
WI tower = 5400mm
NI tower = 5347 mm (4600mm + 747mm)

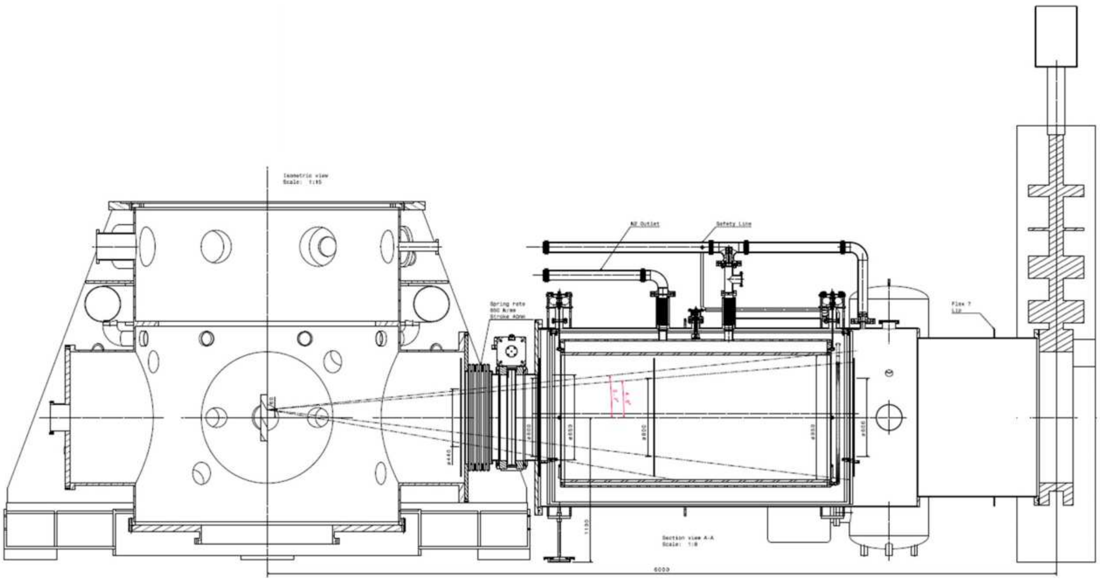


Fig. 1: Installation of cryotraps at the west end tower.

Adapter pieces of different length will be welded to the cryotraps to match with the different towers position. We strive towards producing four identical cold vessels inside the cryotraps, since they will constitute a small series for which a prototype can be built and successively installed as the first cryotrap, normally the WE one. Special adapter pieces may be needed to adjust the length of the cryotrap outer vessel to the different positions. The inner cryostat has a length of 2023 mm and an inner diameter of 950 mm. Optical baffles will be installed inside the stainless steel vacuum vessel via support bars, and spring lips shall be used to hold them, maybe welded to the inner cylinder.

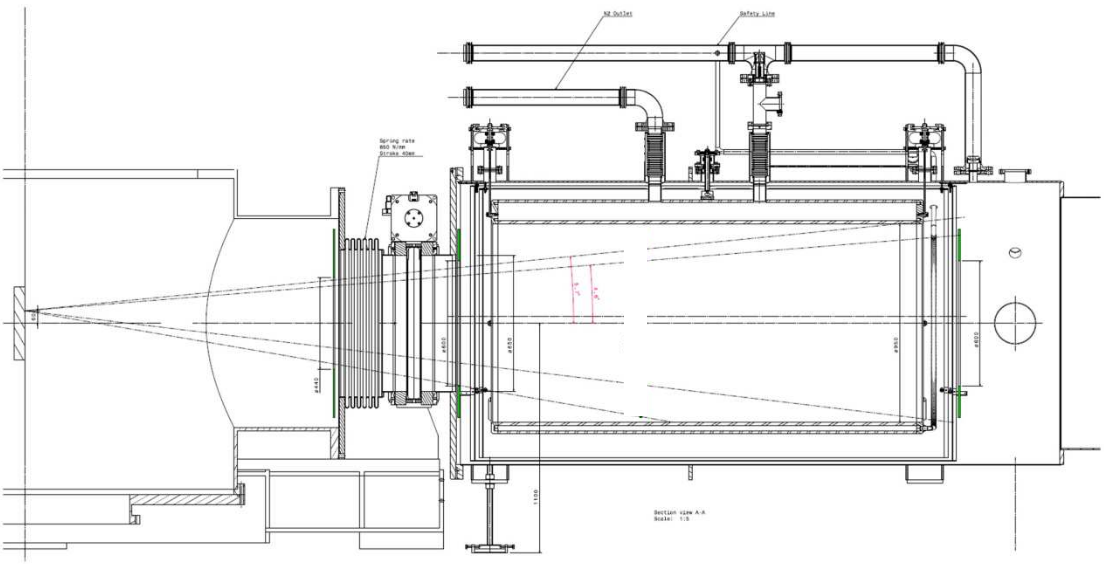


Fig. 2: Cryotrap with baffles for shielding the mirror from direct view of the cryotrap surfaces.

The outer vacuum vessel has an outer diameter of 1350 mm (not including the reinforcement ribs), and it will be constructed from stainless steel 304L. Reinforcement ribs are welded to the outside of the vessel to avoid buckling of the structure. Helicoflex seals are used to connect the various large size flanges. Double Viton o-ring connections are being evaluated for some selected flange to ease the installation on site.

The vessel is equipped with various pump-out and service ports. An isometric view is given in Fig. 3. A 100-150 mm diameter flange provides connection to a turbo-molecular pump station.

A section view is given in Fig. 4, while a top view is given in Fig. 5

A new large size valve (aperture 650mm) is installed in between the cryotrap and the tower, to allow venting independently the two chambers.

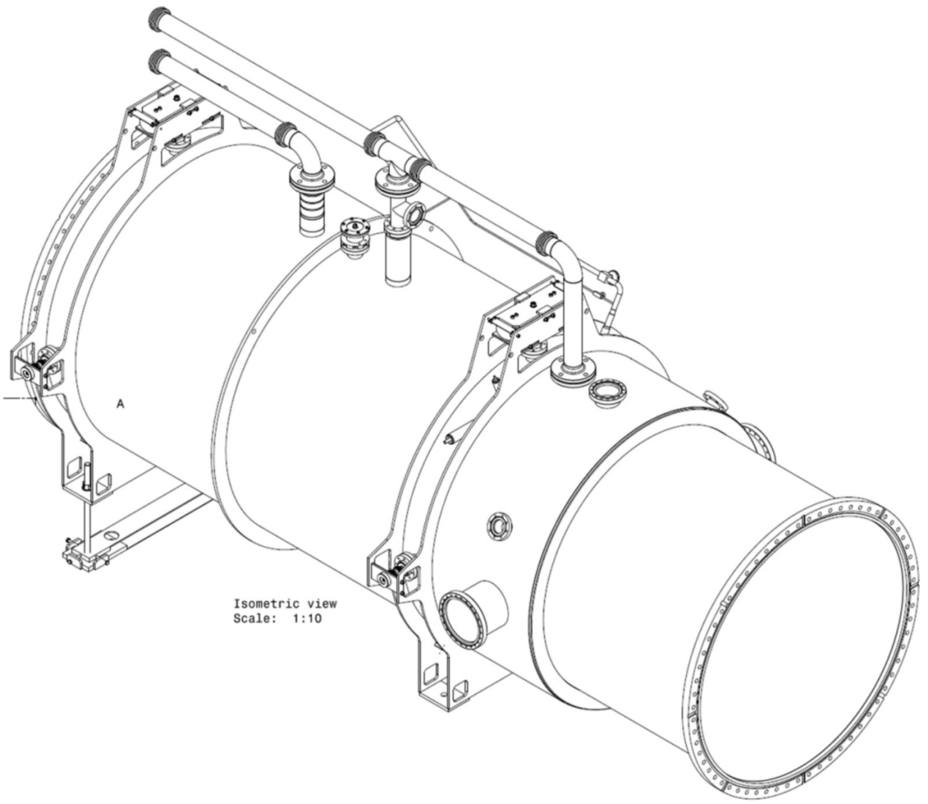


Fig. 3: Isometric view of a cryotrap for Advanced Virgo. The reinforcement rings and the suspension system are visible. At the top the large nitrogen exhaust lines can be seen.

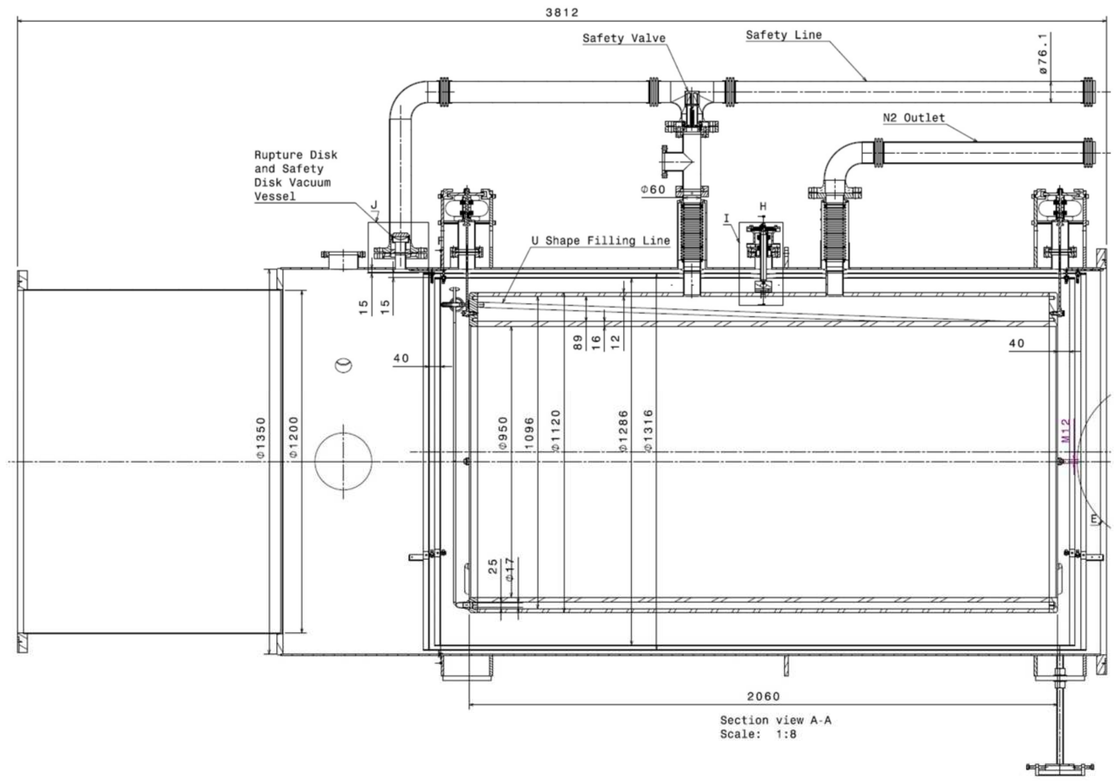


Fig. 4: Section view of a cryotrap for Advanced Virgo. Aluminum-stainless steel transition material is used to connect the inner vessel to the outside world.

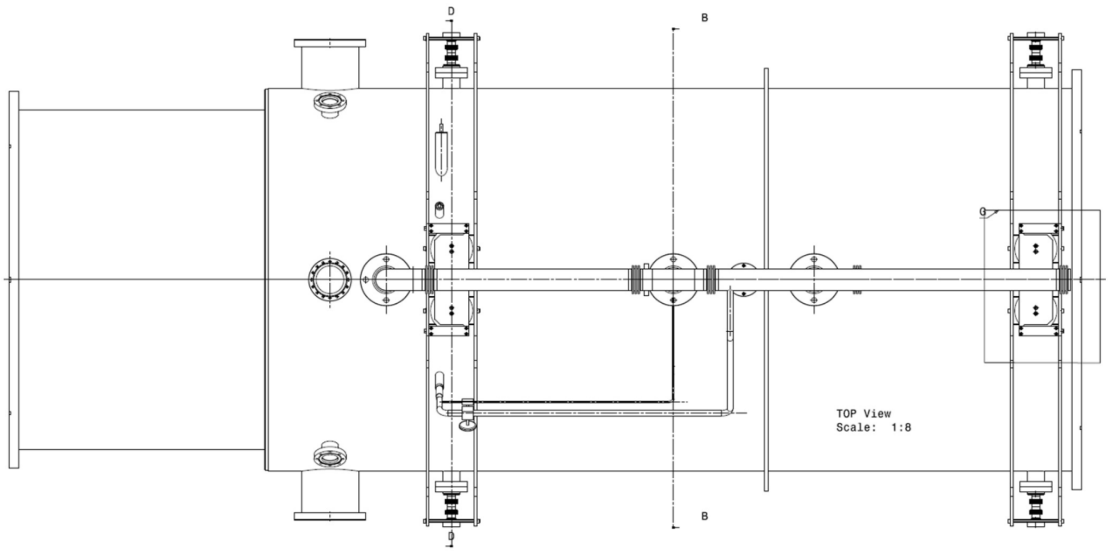


Fig. 5: Top view of a cryotrap for Advanced Virgo.

Fig. 2 shows that stainless steel hydro-formed bellows are foreseen as a connecting piece between the trap and the tower through the 650mm valve. These bellows have a 700 mm inner diameter and can accommodate expansion of the structure. This is needed during installation of the cryotrap, while also thermal expansion during bake-out must be accommodated. Its size has been verified to be compliant with optical constraints. The particular construction has been chosen in order to minimize the atmospheric load on the structures when the tower is vented. Moreover, the present design facilitates the assembly of the link. Fig. 6 shows a safety detail of the construction of the cryotrap.

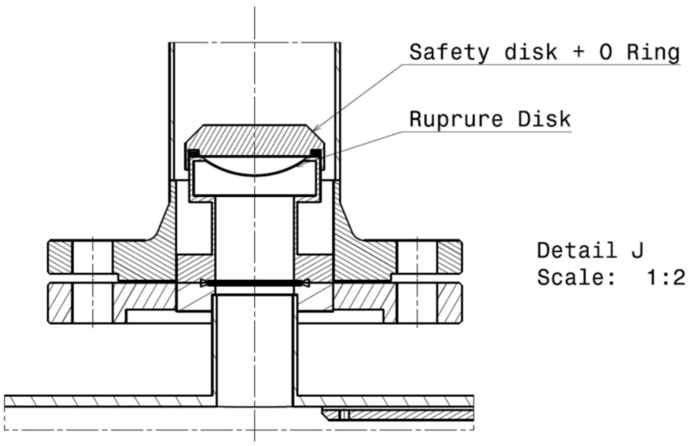


Fig. 6: Construction detail of the cryotrap: a rupture disk in combination with a safety disk on an O-ring are employed as safety device.

A possible different arrangement is to exchange the positions of the bellows and of the 650mm valve, installing the bellows on the trap flange and the valve directly attached to the tower. The bellows could be enlarged, up to 800mm of inner diameter for instance, and the advantage would be an easier baffling out of the valves surfaces, for diffused light purposes. This positioning choice is related also to room constraints, valve weight supporting and bellows design, and it shall be defined along with the executive design.

The cold part of the cryotrap will be constructed in aluminum and filled with liquid nitrogen; the volume of the bath is about 300 l. This bath is thermally shielded from the outer surface of the vessel by using a double aluminum radiation shield to minimize boiling and LN2 consumption.

Fig. 7 shows a cross section of the cryotrap. The inner cold link vessel is placed asymmetrically off-axis by 32 mm: in this way the boiling LN2 surface width is maximized to 550 mm over the full length of 2000 mm of the cryostat. A large gas/liquid separation surface is in favor of a smooth evaporation and a low bubbling noise.

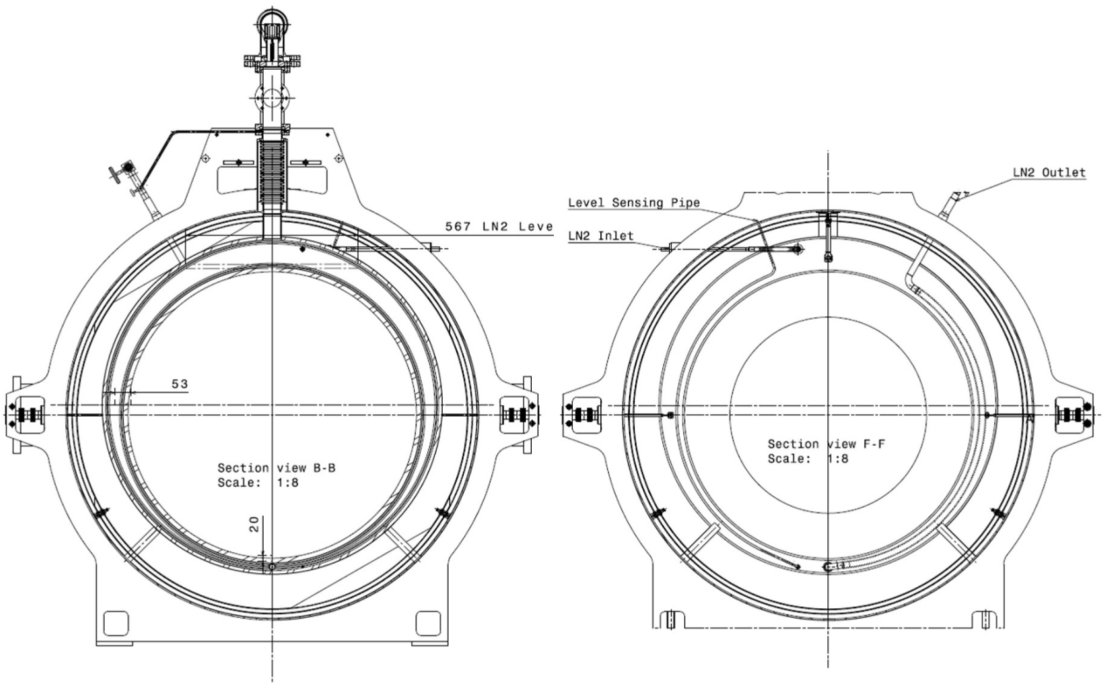


Fig. 7: Cross section of the cryotrap. The outer wall of the cryostat vessel is placed off-axis with respect to the vacuum vessel. The inner wall of the cryostat is placed on-axis

The inner aluminum cold vessel is suspended from the vessel by using two double air springs, in combination with longitudinal and transverse suspension systems (see par2.1.1). The design is shown in Fig. 8.
Since the inner cold surface will move due to thermal expansion (about 4 mm/m) with respect to the outer vacuum vessel, the suspension system needs to accommodate this. This system also acts as a heat bridge that minimizes thermal losses due to heat conduction.

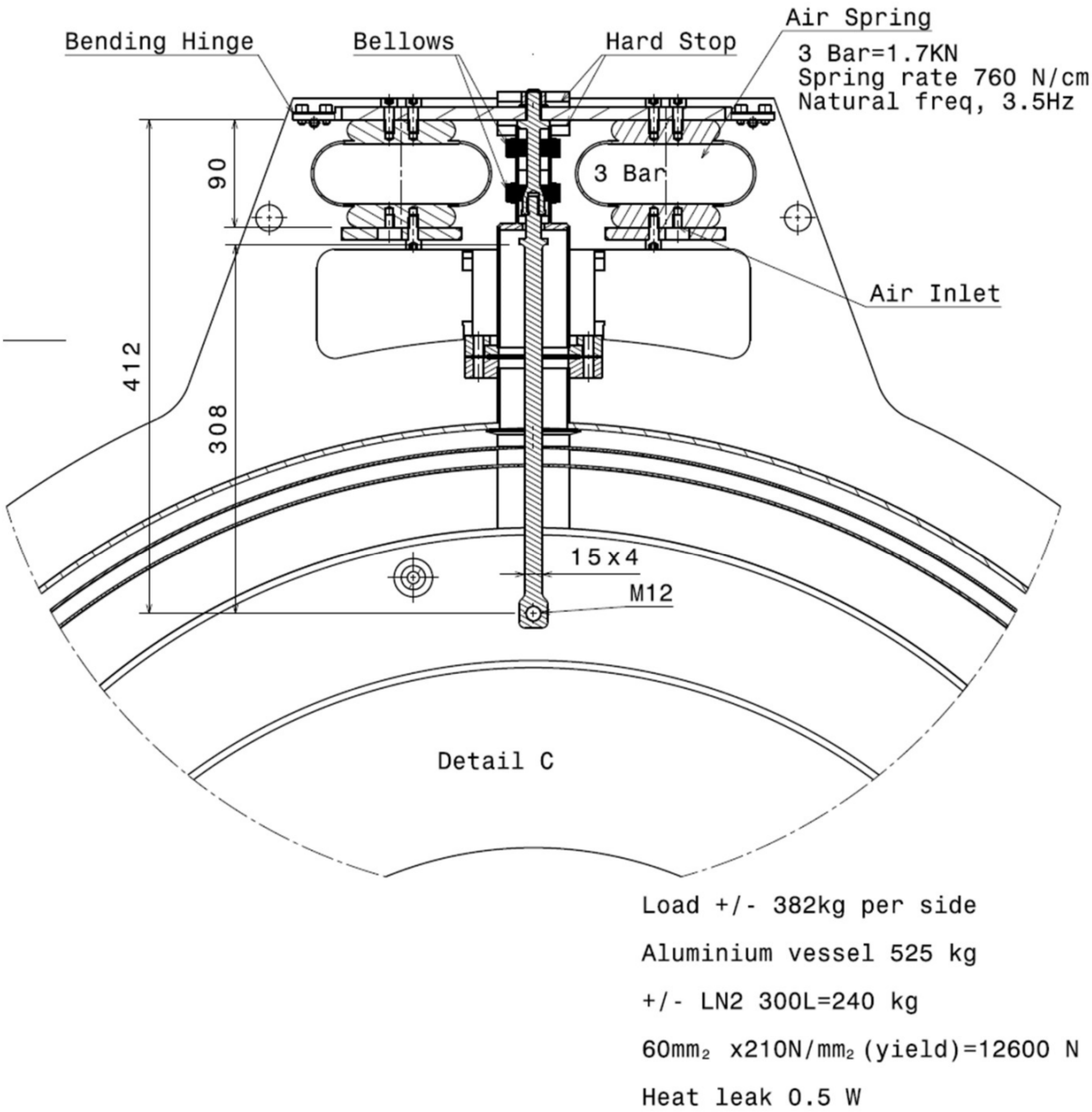


Fig. 8: The cold vessel of the cryotrap is suspended with air springs in order to isolate Advanced Virgo from possible bubbling noise produced by the cold vessel itself.

A separate port is provided in order to admit hot nitrogen gas inside the cryostat in case a rapid heat-up of the structure is needed, as in case of regeneration. The cryotrap can be operated for more than one year between regenerations: during this time the water layer deposited on inner surfaces will reach a thickness of the order of the micron. This causes an increase of the infrared emissivity [14] from about 0.1 to about 0.2 (emissivity of the cold surfaces associated to the thermal radiation heat exchange). The resulting heat load turns out to be 250 W, and corresponds to a LN2 consumption of about 5.6 liters per hour. The estimated gas production is 1 l/s, assuming 80 K surrounding temperature in the vessel.
A value of 300 W has been conservatively assumed as heat load for dimensioning the LN2 supply plant.

In addition to the standard procedures for UHV chamber fabrication, cleaning and handling, some parts of the cryotraps (such as new parts of stainless steel exposed to vacuum and operating at room temperature) have to be `fired' (i:e: heated at 400° C in air or argon for about one week) as degassing treatment already applied to main Virgo chambers.

This treatment will be normally done in the factory during the production phase, unless we will consider performing it on-site (EGO or Nikhef) in order to save money.

Two-phase (liquid-gas) nitrogen flow modeling is being performed in order to optimize the design with respect to acoustic and mechanical noise due to bubbles. The work will be carried out in collaboration with scientists from EGO and the University of Pisa [4]. Laboratory tests shall be performed in a small scale test system, within the end of the year, to verify the effects of constructions details such as the different surfaces roughness and heat load concentrations. Sensors will be used to determine whether heat transfer takes places through convection cooling or bubbles are produced (microphone, visual inspection through fibers).

2.1.1 Cryostat suspension system

Seismic noise could be produced from bubbling inside the cryostat. We propose to incorporate a well-damped suspension system based on air-springs to isolate the outer part and the system in general from the cryostat. The system shall work in vertical, axial and transversal directions. The resonance frequency of the system shall be about 3 -4 Hz and the Q-factor less than 10.

The various elements of the suspension system are shown in Fig. 8 and Fig. 9. The silicon rubber spring for horizontal positioning allows movement from thermal contraction/expansion and specifically restricts motion in the xy-plane (transverse). The air-spring system for vertical isolation needs to allow vertical motion e.g. during bake-out. The flexible hinges located at the top provide guidance for vertical displacement (but not horizontal).

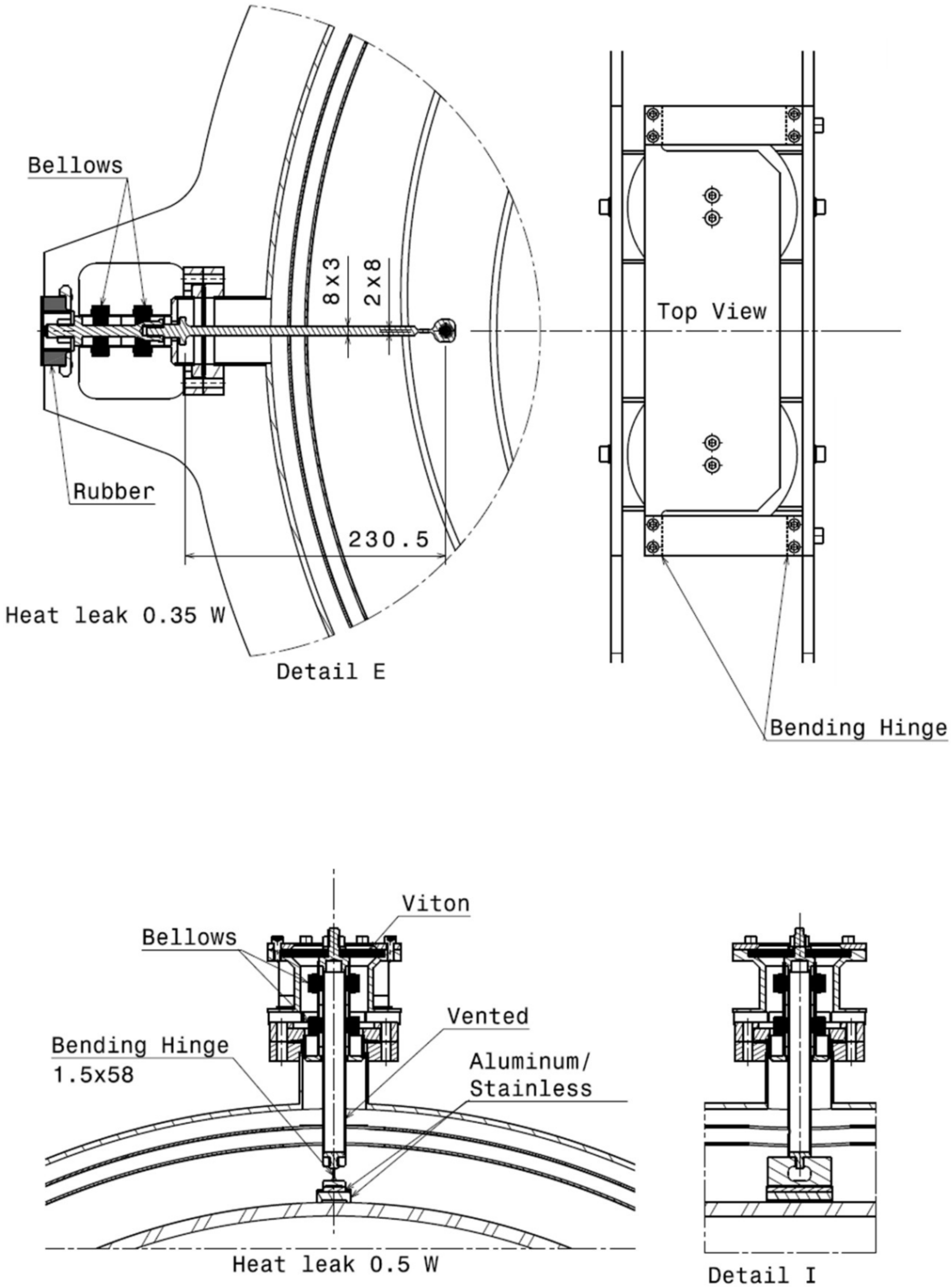


Fig. 9: Suspension system for the cryotrap.
Top left: silicon rubber spring for horizontal positionin. Top right: top view of the air-spring system (bending hinges). Bottom: axial motion damping system. See Fig. 8 for a cross section of the central air spring suspension system.

The air isolators will be mounted so that the shortest distance between points of support is at least twice the height of the centre of gravity above the plane of support. This minimizes wobble and prevents operational problems. The spring stiffness of an air

isolator results from the compression of the air volume it contains; the axial stiffness can be reduced further by using an auxiliary volume.
The aluminum vessel has a weight of 525 kg and will be filled with about 240 kg of LN2. This yields a 191 kg load per air spring (ContiTech AG FS 40-6). Each spring needs an 160 mm diameter installation space. The recommended height of the spring is 90 mm (minimum is 70 mm). This height can be achieved with different combinations of applied pneumatic pressure and force load. The pressure should range from 3 to 8 bar, the corresponding force load then ranges from 1.7 to 4.4 kN.
Spring rates range from 760 to 1820 N/cm changing the characteristic frequency from 3.5 Hz to 3.2 Hz.
The lateral stiffness of air isolators differs greatly from type to type. We intend to study the various schemes with the prototype. Attention will be paid to avoid slashing motion of the LN2.

2.2 Cryogenics

A schematic of the cryogenic piping is reported in fig.10, showing the cryogenic equipment .

The refill of liquid nitrogen will be done continuously via the automatic system here described; the LN2 level of the bath can be controlled to within 10 mm.
The LN2 inlet pipe is designed with an U shaped pipe (fig. 4, fig. 7) such that the liquid LN2 will flow smoothly into the bath while the gas will disengage along the path before entering in the bath. This shall minimize the possible noise from bubbling related to the refill.

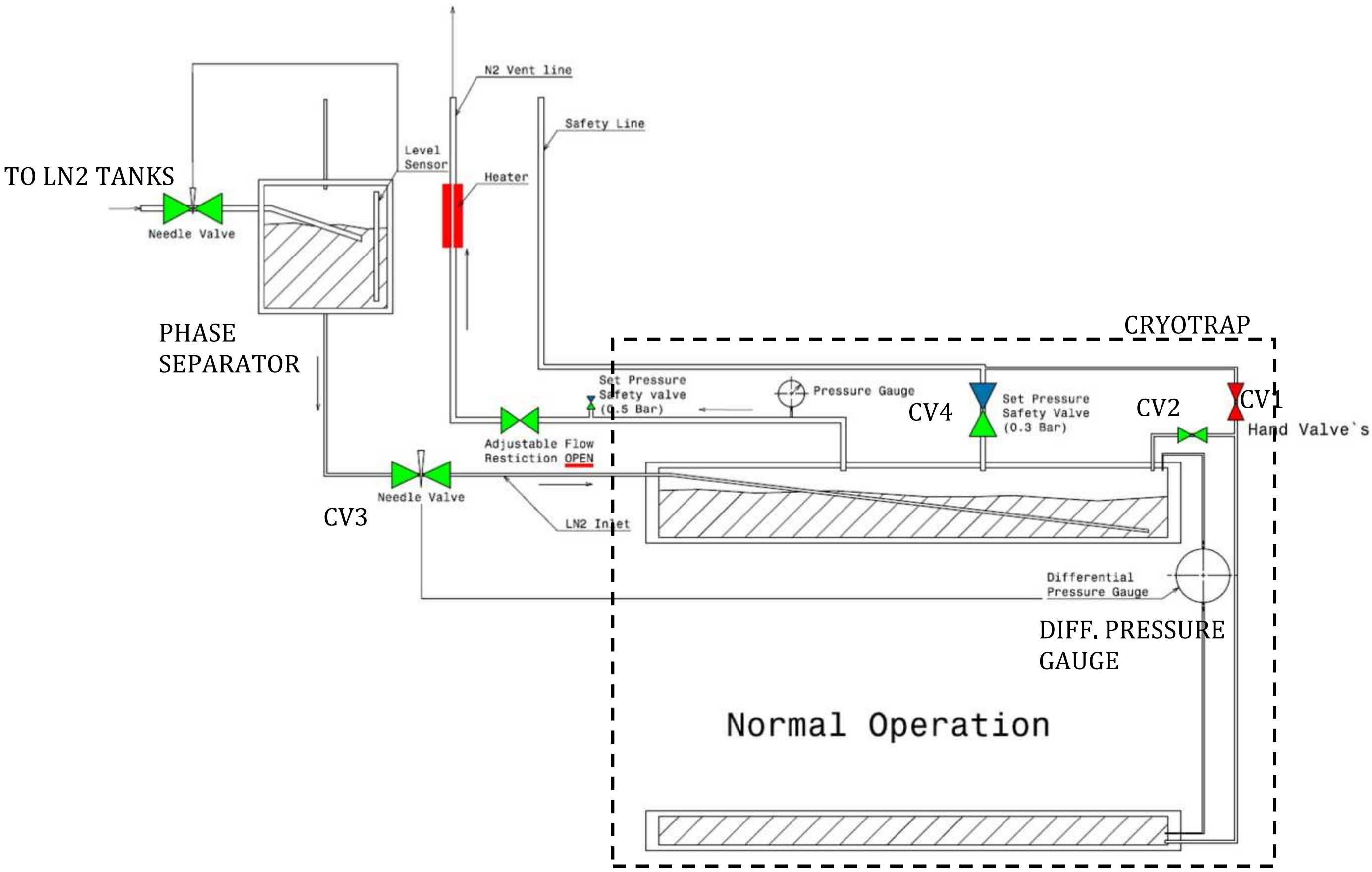


Figure 10: Schematic of the cryogenic controls during normal operation of the cryotrap (see also par 2.6 for a complete description of cryogenic piping equipment).

In normal operation, the LN2 level is maintained at 950 mm, covering completely the inner bore of the cryostat. The LN2 is continuously filled and the GN2 is exhausted . The inlet flow is regulated by two automatic valves (see paragraph 2.6) with proportional aperture. One of them is optional (the phase separator one) and could be just of on/off type, under evaluation.

The same system allows operating in 'regeneration mode' by emptying the cryotrap at first (through valve CV1) a fair overpressure. The second step is to admit heated GN2 in order to heat-up the cryotrap. The entire cryotrap can be warmed up to 150° C.

The control of the LN2 flow will be done via automatic valves driven by the signal of the bath level, read by a differential pressure gauge. The logic shall be based on PLC-systems already in use at Virgo (Crouzet control PLCs). The design and realization of the hardware and control software will be done in collaboration with EGO and LAL experts.

The various procedures should be worked out in detail and the corresponding software for the PLC should be developed. Subsequently, these procedures should be tested with the cryotrap prototype set-up.

Different cryogenic sensors will be used to monitor the temperature distribution and the LN2 level in the cryostat.
Signals will be sent to the general DAQ system as for the other parts of the vacuum system, for diagnostics during the ITF operation.

The safety interlocks (closing valves in case of high-temperature alarms) will be implemented at PLC level, fully integrated with the vacuum equipment ones (the cryogenic signals will be acquired by the corresponding 'vacuum station').
Here is a preliminary list of cryogenic signals, per a single trap

a. LN2 level in cryostat from the differential pressure gauge, = 4-20mA
b. LN2 level in the external storage tank from the differential pressure gauge = 4-20mA
c. LN2 level in phase separator from the differential pressure gauge = 4-20mA, tbc
d. Pressure in the external storage tank = 4-20mA
e. Pressure in the cryostat vessel = 4-20mA
f. 8 temperature probes, PT100 type, installed in cryotrap = 8 x 4-20mA
g. Opening status of the needle valve to the cryostat = 4-20mA
h. Opening status of the needle valve to the phase separator= 4-20mA (or relays if on/off)
i. Status of the other cryogenic valves= several relays, tbc
j. Status of safety alarms (safety valves status, O2 sensors) = several relays, tbc
k. Electronics regulating the refill = rs232 or better standard for the full set of parameters

2.3 Vacuum performances

The proposed goal can be met by installing cryogenic traps at tube extremities and then performing the bake out of the tubes.

The baking system is already implemented in Virgo, tested and working, hence not discussed here [6].

Cryogenic traps are a proven solution to stop migration of water and of other vapors between different vacuum chambers: the water molecules condense on the surfaces cooled down to 77K and are thus removed from the gas phase, hence not transmitted through the two openings of the trap.
At 77K the water saturated vapor pressure is extremely low[4], much lower than our range of interest (10^{-9} mbar); hence the cryotraps have margin to work at vacuum levels better than required.
Traps could work also at slightly higher temperature, around 100K for instance, tolerating a thick icy deposit on pumping surfaces, as it would happen after years of intense operation without regenerations.

Both in AdV and in the present Virgo, the water vapor is coming out from the tower chambers because of their frequent venting and consequent water recharging (exposition to humid air). This effect is enhanced by non-metal components that absorb water in their bulk and release it slowly once in vacuum. An example of the present vacuum behavior (without cryotraps) is shown by Fig.11: the pressure inside the tube rises orders of magnitude above the AdV requirements.

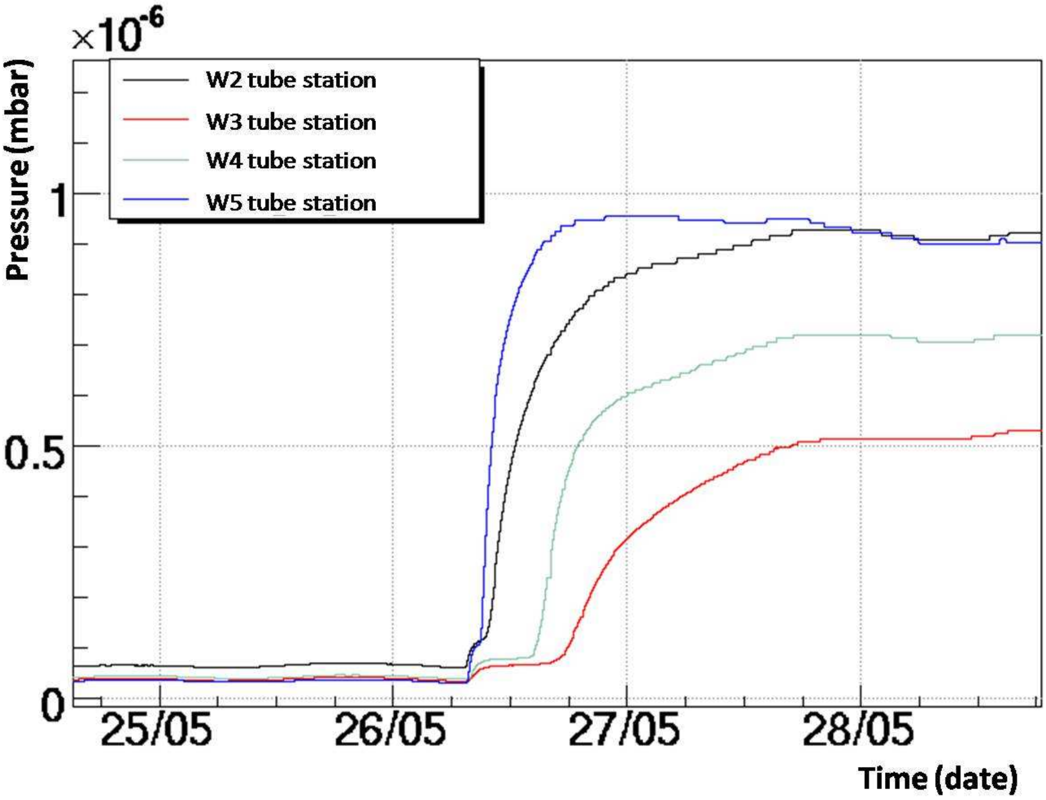


Fig. 11 Pressure recorded inside the W arm during ITF restart after a recent intervention inside the WI tower. Base pressure of the tube is below 10^{-7} mbar (at valves closed) and it grows up near 10^{-6} mbar when opened to the towers. The various curves are measured by gauges at different distances from the valve.

For AdV the cryotraps shall avoid this behavior maintaining the tube water pressure below 10^{-9} mbar.
Cryotrap performances are summarized in the following table, which reports the water pressure evaluated in the tube near the trap outlet in different scenarios:

	Case	Water load (mbar·l/s) for a single trap	Tube pressure near trap exit (mbar)
1	*Input or End tower opening to the tube after 2 days of pumping)*	$4\cdot10^{-4}$	$5\cdot10^{-10}$
2	*DT/IB tower opening after 4 days of pumping*	$5\cdot10^{-4}$	$7\cdot10^{-10}$
3	*Data taking period (towers with original Virgo payloads)*	$\sim1\cdot10^{-4}$	$\sim1\cdot10^{-10}$

Tab 2 Pressure calculated at trap outlet for different scenarios of AdV operation.

For all the different cases of the ITF operation the water pressure in the tube results below the goal=10^{-9} mbar, even in the unfavourable case of high gas loads at tower opening.

The magnitude of the water load has been estimated on the basis of the experience in Virgo. According to PAY the AdV payloads shall have similar vacuum characteristics to the original Virgo ones. The plastic-like parts inserted in the new V+ monolithic payloads will be replaced for AdV with suitable parts realized with ceramic and titanium, more favorable for vacuum.

The water load estimation remains anyway not perfectly determined, because depending also on assembly details, fabrication and cleaning treatments, history of the exposition to atmosphere. In the worst cases extra pumping time shall be adopted before restarting the ITF: 1 week of pumping would be enough to get an acceptable load ($5\ 10^{-4}$ mbar.l/s) according to the high 'gas load' experience got with the recent monolithic payloads (2nd evacuation of input towers, May 2010).

The calculation of the trap output has been carried out using a Monte Carlo method (by ray tracing and evaluating the pressure from the hits on pipe walls). Geometry is the design one: 0.95m cryostat inner diameter, 2m cryostat length, sticking factor=0.9, glass baffles with 600mm aperture installed at both trap extremities and at the tower port, uniform pressure in the tower.

The criterion is that the trap has to ensure the AdV requirement in the tube (10^{-9} mbar) independently from the status of the other pumps.

Distributed pumps contribute to lower the average pressure along the tube, and they can be considered as a safety margin on trap performances.

The estimated profile of the water pressure along the 3km tube is shown in Fig.12, the averaged value is below 2.10^{-10} mbar. The plot is done for baked conditions, considering the outgassing rates experimentally obtained during the qualification of the installed tube sections.

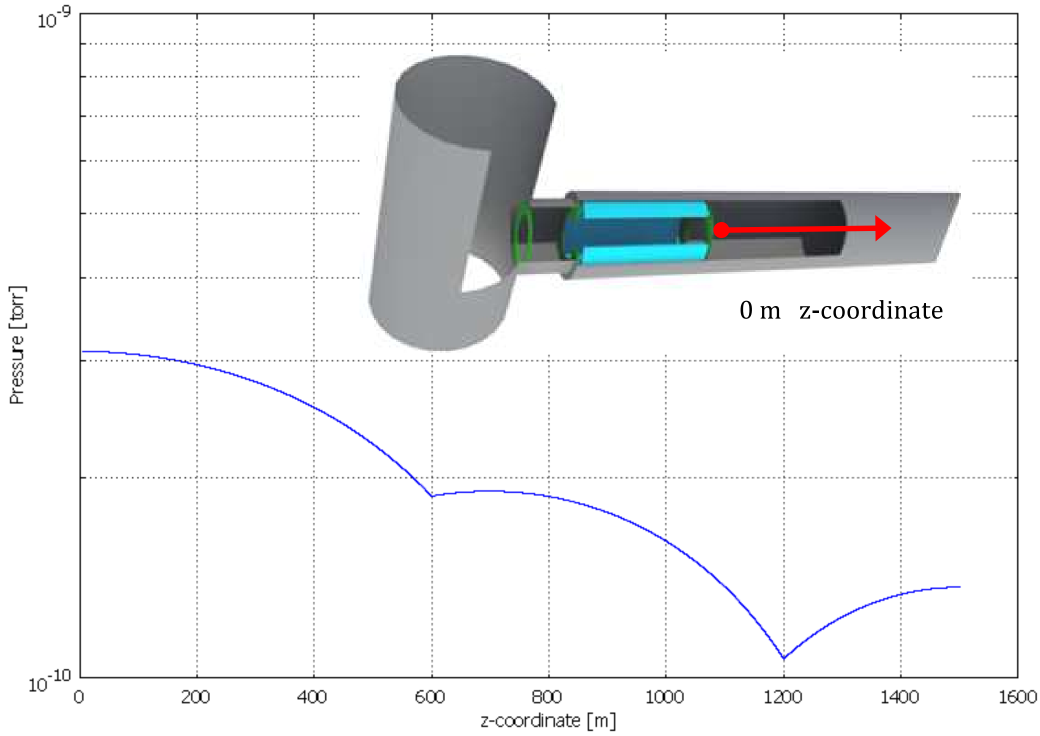


Fig. 12 Water pressure profile along the 3km tube calculated for the selected trap geometry (water load 5 10^{-4} mbar.l/s).

Trapping effect is described by Fig 13, which reports the density of the molecular tracks inside the trap (more precisely the tracks per unit of cross-section area and unit time)[7],[8].

Both radius and length profiles are shown: the molecules closer to the trap axis travel closely packed at the inlet and get sparse at the outlet (tracks density decreases to about 3%). The molecules far from the trap axis are affected by the presence of the baffles installed at the trap extremities (aperture radius 300mm): the inlet baffle limits the inlet flow within its aperture and the outlet baffle stops and bounces backward the impacting molecules.

The ratio between inlet and outlet molecular densities integrated along the apertures gives the fraction of water load that is not trapped and reaches the tube (about 3%).

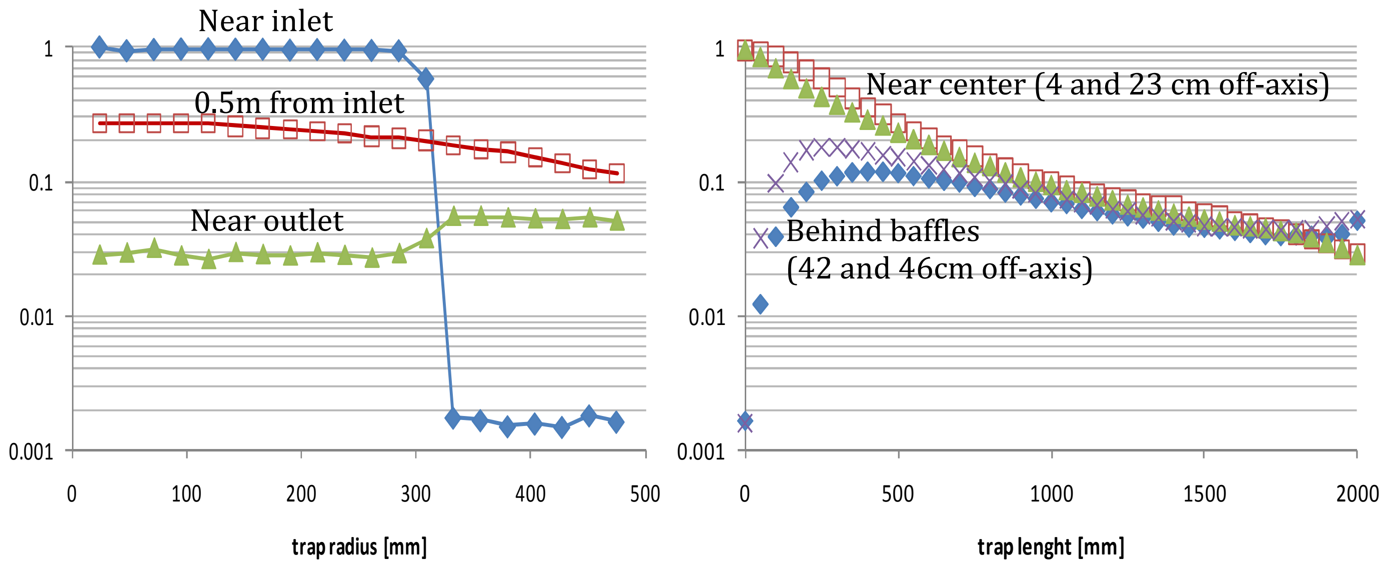


Fig 13. Normalized density of molecule tracks inside the trap along the trap radius at different length positions (left) and along the trap length at different distance from trap axis (right). The ratio between outlet and inlet values shows the escaped molecules fraction, about 0.03. (Molecules re-entered from the tube are not shown, to put in evidence the trapping effect). Baffles (aperture radius=300mm) installed at trap extremities affect the molecules distribution.

Experience with 'cryogenic traps' exists in Ligo (their traps are very similar to the proposed ones) and also in Virgo, thanks to the small trap installed between DT and SR towers.
The picture below shows the effect of the present trap after venting an input tower: the total pressure in SR suddenly increases once the valve towards the input tower is opened, while the pressure increase in DT tower, isolated by the cryotrap, is very limited. RGA shows that this increase in DT is composed of air (coming from the restarted tower and not pumped by the trap) and also of water, according to estimations (less than 10^{-8} mbar).

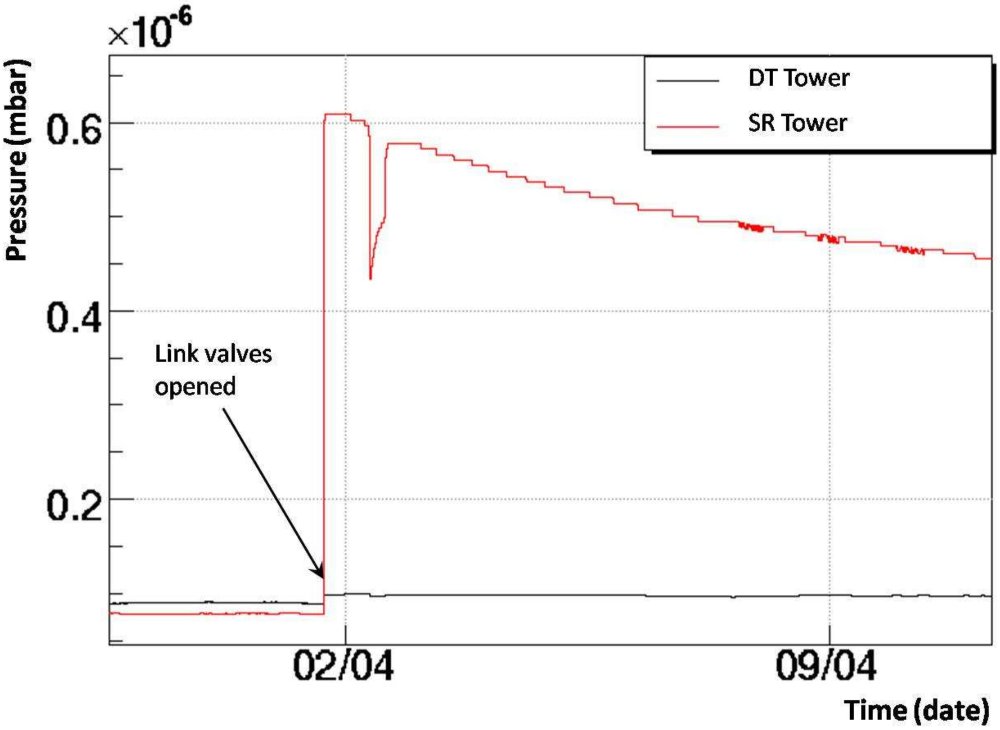


Fig 14. Pressure recorded in SR and in DT at the opening of valves towards an input tower 'restarted' after a venting. The base pressure of SR tower ~ 10^{-7} mbar, suddenly increases near 10^{-6} mbar. The pressure in the DT tower, separated from SR by the existing cryotrap, is almost unchanged. The pressure drop at the middle of SR curve is due to a temporary opening of large valves towards the tubes, which pump the central area towers reducing their pressure.

Another interesting experience from the small DT trap is about the behavior of CO_2, present inside the vacuum system and pumped by the trap surfaces depending on their temperature (it is probably adsorbed instead of condensed like water). In particular, we observed clear releases of CO_2 by RGA when surface temperatures increase above 90K. Thus monitoring CO_2 is a possible way to detect when the ice layer covering the cold surfaces becomes thick and thermally insulating, and a regeneration process becomes opportune.

An estimation of the deposit build up is reported below, calculated for 1 year of operation in two load conditions: commissioning phase and run phase. In both cases the ice thickness is sufficiently low, of the order of the micron, so that regenerations are not envisaged more than once per year.

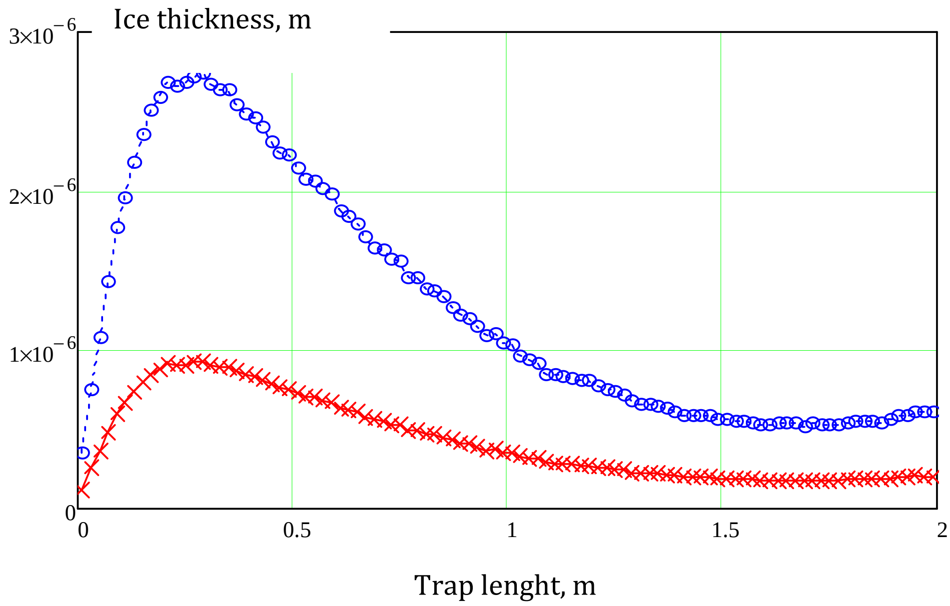


Fig.15. evaluation of the water deposit developed inside a trap after 1 year of service. Red curve='run' conditions (~2g of condensed water); blue curve= commissioning with very frequent tower openings (~6 g, considering venting every 2 months)

Finally, a benefit of using cryotraps is a large enhancement of the pumping speed for 'hydrocarbons', more than 10000 liter/s per trap, increasing by over 10 times the present one. This shall lower the partial pressure of contaminants around mirrors by more than one order of magnitude, approaching the level obtained during the baking test of a complete tower, 10^{-12} mbar.

2.4 Vacuum system

An auxiliary vacuum pumping system is needed to evacuate, regenerate and monitor the trap. The sketch is shown below on Fig. 16.

A large size valve (1) is installed between the trap and the tower, to separate them during tower venting and during trap regenerations. The valve shall be an UHV type one, 650mm aperture, with metal seal on bonnet, bellows feed-through and metal gasket flanges. Gate shall be Viton sealed, properly degassed as normally established for Virgo. Valve actuator shall be driven by compressed air or by electrical motor, to be evaluated during the call for tender consulting the selected manufacturer.

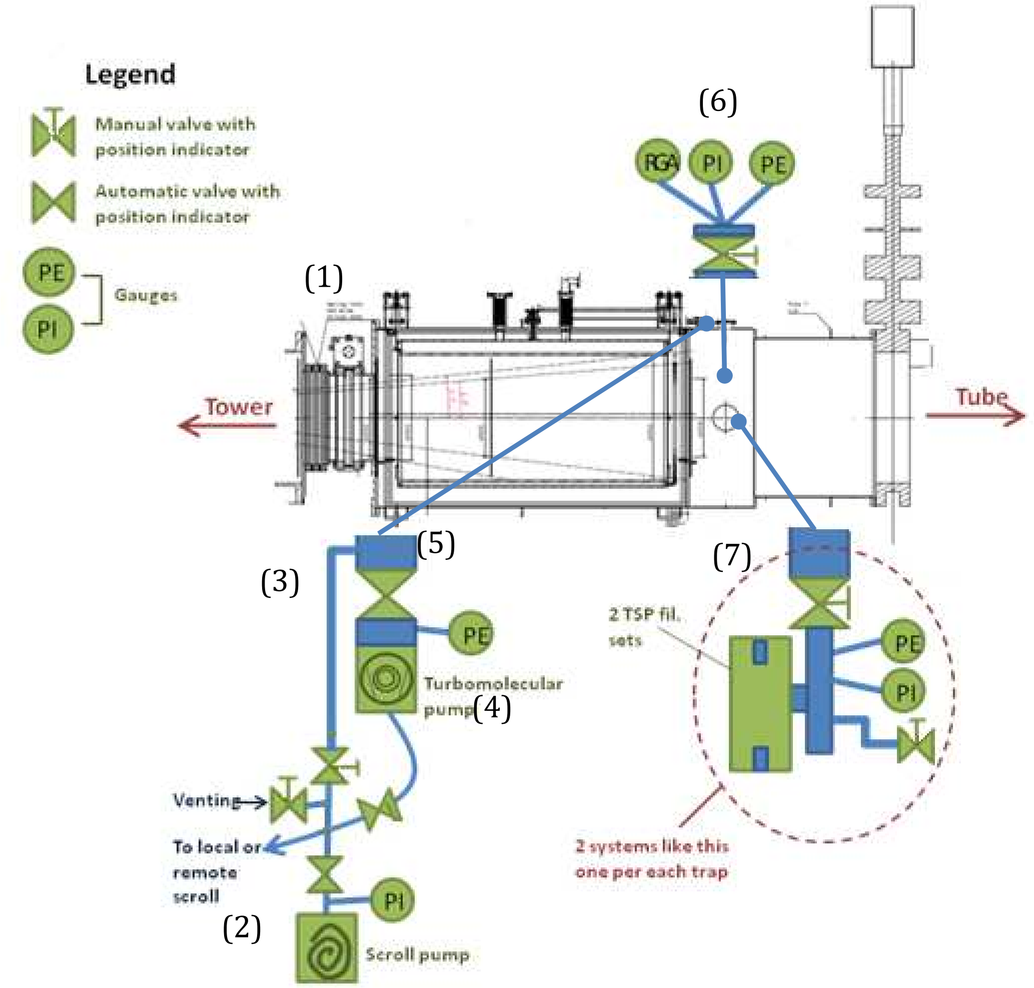


Fig 16 Sketch of the auxiliary vacuum system.

The system will be evacuated with a dry pump (2) through a dedicated port (3) 40mm diameter, for about 3-4 hours to reach 0.1mbar . The port will be equipped with an all metal angle valve DN40.
Then a turbo-molecular pump (4) shall be used through a 150mm port (5), via an UHV gate valve lowering the pressure below the 10^{-6} mbar range. A moderate baking will further improve the vacuum, which shall be monitored using the RGA (6), Pirani and Penning gauges.

Item / quantity	Item / quantity	Item / quantity	Item / quantity
Turbo-molecular pump / 1	PI gauges / 4	TSP pumps (filament units) / 4 (2 systems)	DN40CF manual all metal angle valve / 4
Dry pump / 1	PE gauges (1E-10 mbar range) / 3	RGA	DN25KF HV electro-pneumatic angle valve / 1
DN150CF UHV electro-pneumatic gate valves / 1	DN200CF manual UHV gate valves / 2	DN63CF manual UHV angle valve	DN25KF HV manual angle valve / 1

Tab. 3 Vacuum equipment for each cryotrap

The bake-out of the trap shall be done at least once, for cleaning and testing purposes at the installation time. It could be probably necessary to warm up also the large valve, by using the existing relevant apparatus, to avoid excessive water re-condensation on its large surfaces.

To put the cryotrap in service, the following step consists in cooling down the trap progressively, by flowing liquid nitrogen. During the cool-down, the temperature shall be accurately monitored and the nitrogen flow shall be adjusted in order to avoid too fast and not uniform temperature change, potentially dangerous for the mechanical structure and for welds in particular.
Another He leak test shall be repeated after the cooling down, in particular for the welded joints.
The whole procedure will take about 1 week or slightly more, and will be repeated during trap regenerations. It shall be convenient to regenerate all the traps together to save ITF time. Suitable systems dedicated to trap regeneration have been included in the LN2 supply plant for each cryotrap, see paragraphs 2.6 and 2.2.

Finally, two titanium sublimation pumps (7) will be used in UHV regime. These pumps are currently installed on central area towers but not suited to work for unbaked systems. They shall be moved on the 'tube side' of the traps, contributing to pump hydrogen, air and other gases not pumped by the cryotraps. Turbo-molecular and scroll pumps will be stopped in the normal working phase.

All this equipment will constitute one 'vacuum station', and will be part of the 'vacuum control system', undertaken by the LAL team.

They will be integrated also with cryotrap signals, as described in a previous paragraph.

2.5 Impact on the interferometer

2.5.1Diffused light

The criteria applied in Virgo to moderate the diffused light noise are based on the following considerations.

The highest probability processes contributing to diffused light noise involve at least two scattering (casual) processes plus one or more "reflection" (deterministic) process: a photon impinging on a mirror is diffused out of the Gaussian beam, then it is reflected by some (quasi)mirror surface towards a mirror, where a successive diffusion brings it back into the resonating beam. The noise is caused by the phase modulation gained by this photon at any reflection on objects linked to ground and excited by the seism (or, in the case of cryotraps, excited by boiling liquid Nitrogen). Processes involving further diffusions can be in general disregarded, having a much lower probability (third order with respect to scattering rate).

Diffused light, due to mirror roughness, is expected at the level of 10 ppm for AdV mirrors.

In addition to diffused light originated by mirror roughness there is that produced by photons belonging to the Gaussian beam hitting any object limiting the aperture left free for the beam. This last component may remain negligible keeping the free aperture radius about 5 (4) times larger than the local average beam radius; the Gaussian beam intensity fraction travelling outside this radius is of the order of 10^{-22} (10^{-14}).

If nothing is done for killing the potentially harmful photons (generated noise larger than 1/10 of the sensitivity), the most important effect results from scattered beam photons impinging directly and quasi-reflected by the tube surface towards the second mirror. So a baffle system has been installed in the long tubes, and a different one in the tubes close to the towers.

In the main part of the arm tubes, between two Large Valves, all the inner surface is hidden by conical stainless steel baffles, with respect to the beam spots on the mirrors.

At the ends of the Virgo arm tubes (between any IN/END tower and the respective Large Valve) black glass baffles (transmission $<10^{-7}$) have been installed, in a configuration responding to the following criteria:

- the minimum free aperture radius is about 5 times larger than the local average beam radius
- any discontinuity (potential reflecting spot) of the vacuum enclosure is hidden by suitable absorbing glass baffles, with respect to the beam spot on any mirror
- no point of the smooth surface of the vacuum enclosure can be seen contemporarily by the beam spots on two facing mirrors.

This configuration has proven to be largely safe for Virgo. It has been impossible to detect any noise enhancement on the dark fringe signal, even shaking the tube ends much more than the natural seism. This result remains true also for the input towers, where the baffle B6, close to the mirror, has an aperture diameter of only 230 mm (here the average beam radius is 22 mm).

A very similar configuration (Fig.2) has been chosen for the Cryotraps to be installed between IN/END towers and the respective Large Valves. The size of the additional valves and the position and diameter of baffles have been optimized with respect to diffused light.

To this aim all processes reflecting diffused light onto a mirror have been evaluated:

1. Splinters on baffle edges
2. Grazing reflection on baffle edges
3. Diffraction on baffle edges
4. Backscattering off inner trap surface.

Calculations by J.Y. Vinet [10],[11] show that all diffused light noise sources are well below AdV sensitivity as summarized below.

- Splinter on baffle edge

If it has an area of 1 mm^2 and is oriented in a way to reflect right to the mirror, within 0.1°, with a mirror diffused light at the level of 10 ppm and a seismic excitation of $10^{-6}/f^2$ m/Hz $^{1/2}$ the contribution to the noise is 10^{-25} $Hz^{-1/2}$ at f = 10 Hz, and 10^{-27} $Hz^{-1/2}$ at f = 100 Hz. The calculation has been done for splinters on inner edge of baffles with a 600 mm diameter aperture, sitting at 1 to 5 m from the mirror.

An inspection with a microscope allows saying that the size of splinters on glass baffle edges is not larger of 0.01 mm (surface 10^{-4} mm^2) and that their density is not larger than one splinter with the correct orientation per mm of edge length. Hence the total "bad" area on a 600 mm baffle edge amounts to about 0.2 mm^2, giving a negligible contribution to diffused light noise, always more than three orders of magnitude below AdV sensitivity.

- Grazing reflection on baffle edges

This can happen if the baffle is misaligned (it is not perpendicular to the beam axis) in such a way that some of the cylindrical surface of its inner edge reflects the light diffused by one mirror exactly on the facing mirror at 3 km distance. If the required alignment error is more than 2° (about 35 mRadians), it can be avoided by a careful installation. Baffles where an alignment error of less than 2° may be dangerous, can be misaligned on purpose by a larger quantity (e.g. 5°). Another possible remedy is cutting the inner baffle edge with some inclination (e.g. 10°), obtaining a conical surface.

- Diffraction on baffle edges

This noise source is shown to be by far negligible.

- Backscattering off inner cryotrap surface

The corresponding noise has been evaluated in VIR-0344A-10 for a cryotrap very similar to the chosen geometry, made of stainless steel; it is 2.5 10^{-27} $[10\ Hz/f]^2$ $Hz^{-1/2}$. For an aluminum cryotrap, even allowing a scattering probability one order of magnitude larger, the noise remains a few orders of magnitude below the design sensitivity. This result is in agreement with the introductory consideration, being backscattering a third order process with respect to scattering probability.

The choice of trap diameter is based on the same criterion already used in Virgo to mitigate the diffused light inside tubes and links. The selected trap diameter (inner diameter =0.95m, similar to that of the links) leaves most of the trap walls out of the mirrors sight, masked by optical glass baffles and respects the noise estimations described above.

Larger trap diameters would not fit easily with room constraints and would increase the LN2 consumption. Smaller diameters would expose a larger surface of the cryotrap at narrower view angles, generally less favorable for diffused light; furthermore it wouldn't bring significant cost reduction.

2.5.2 Thermal effects on Test Masses

The relative proximity of cryotrap surfaces cooled to liquid nitrogen temperature with respect to the test masses (TMs) will induce thermal effects on the TMs themselves through radiation (see Fig. 17).. The relevance of these effects, in terms of structural and optical curvature of the test masses, has been analyzed independently by the NIKHEF and Roma Tor Vergata Groups with finite element thermo-mechanical simulations [13].

The two main effects are:

- a change of radius of curvature of the test mass surface of about 2 m, negligible with respect to its original value of about 1500 m
- a change in optical path length inside the test mass (see Fig.18).

Both are smaller and of opposite sign with respect to the changes due to the YAG beam absorption.

In summary, the thermal and structural effects of the cryotraps on the TMs are negligible.

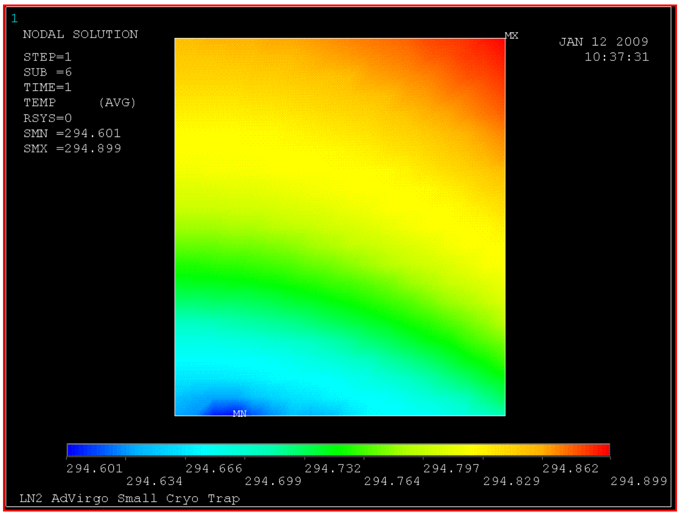


Fig. 17: TM temperature map. Induced ΔT is approximately 0.4K (only half of the mirror is represented, the effect is axial-symmetric)

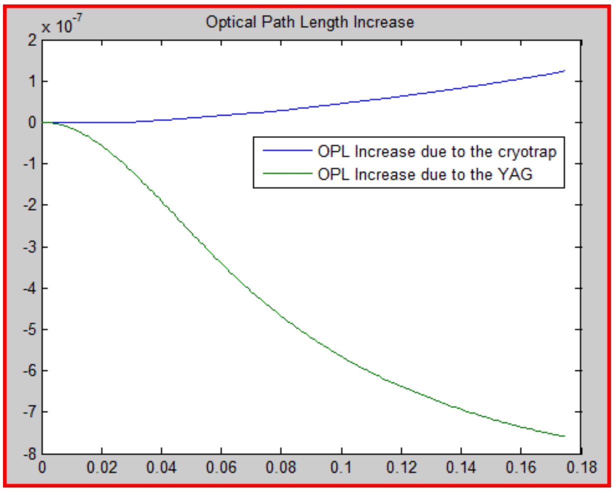


Fig. 18: Optical path length (OPL) increase due to thermal effects in the TM. The blue curve is the OPL increase due to the trap, while the green curve is the OPL increase due to the absorption of YAG power.

2.5.3 LN2 Bubbling

About 6 liters/hour of liquid nitrogen will evaporate in each cryotrap: the intention is to minimize the mechanical vibrations that could be produced by the boiling process. As it happens in the DT small cryotrap, seismic vibrations are produced in the band 60Hz-120Hz[12] immediately after the refill operations and tests indicate that they may be due to the bubbling of the bath which enhances some mechanical resonances of the trap structure.

The analysis of LN2 boiling process shows[9] that various regimes are possible in general, and that in our design boiling should take place by 'natural convection', which takes place without formation of bubbles.

Bubbles could arise only at some spot on the surface, in presence of concentrated heat fluxes (heat bridges) or in case of anomalous amount of nucleation sites. A careful fabrication of the cryostat shall take care of these effects, and could ensure the suppression of bubbling with no detriment in performances.

The other way to mitigate seismic effects of bubble noise is to isolate mechanically the cryostat structure from the outer vacuum chamber. A 'suspension' system of the trap has been designed and it is explained above in par.2.1.1. It will be valuable in case of unforeseen occurrence of bubbling, in order to avoid the transmission of vibrations to the tower and to nearby equipment.

Furthermore if bubbling would occur, the frequencies are expected to be above 50Hz, and the proposed 'low frequency system' would cut them effectively.

These effects are largely related to the practical realization of the cryotrap mechanical details, and cannot be completely determined during the design phase. The suspension system, the surface quality, the thermal bridges need to be verified and in case corrected. The full scale prototype is considered necessary to limit risks on cryotrap performance.

Other seismic disturbances could come from the external LN2 tanks (see par.2.6), due to the propagation through the soil of their own vibrations:

Mechanical shocks could be originated by thermal dilatations of metallic structures induced by daily change of external temperature. Strong wind could cause oscillations of the tanks too.

To handle these effects the tanks will be thermally insulated with standard rockwool jackets (following the experience of LIGO who faced similar problems). Furthermore suitable damping rubber pads will be positioned on their concrete foundations.

The entity of the expected seismic disturbances emitted from tanks shall be characterized by directly testing one tank of similar type among the ones in service near the Virgo site, in collaboration with the company presently supplier of LN2.

2.6 Liquid Nitrogen supply plant

The design of the liquid nitrogen (LN2) distribution plant is based on the following parameters:

- Volume of one trap 200 l
- Heat load on one trap 300 W
- Cold mass 500 Kg
- Number of traps 4
- LN2 input flow in each trap 7.10 l/h
- Evaporated nitrogen (GN2) 4.5 m^3/h
- LN2 for cool-down 650 l
- Working hours between tank refilling 840 h (35 days)

We also considered, only for the estimation of the costs, a nominal operating life of the plant of 10 years and a cost of the LN2 of 0,094 €/l.

<u>Components of the LN2 distribution plant</u>
The plant consists of the following equipment:

LN2 storage tanks;
LN2 transfer lines;
Automatic (PID) valve for the regulation of the flow of liquid into the trap;
GN2 venting lines (LN2 evaporation, cool-down, regeneration and baking);
Vaporization and heating system for the regeneration and baking of the traps.

2.6.1 Storage tanks

The solution for the placement of the storage tanks is different for central and terminal buildings:

Tanks in the central building

For the main building we considered two hypotheses of storage:

One storage tank for each trap, in order to minimize the length of the transfer lines connecting the tank to the cryogenic trap (approximately 25 m);

A single storage tank for the two traps, in order to minimize LN2 losses for self-consumption and the cost of the tank investment. In this case the transfer line length will be 52 m for the trap in the W arm, and 54 m for the trap in the N arm.

The optimal solution is to install a single 20,000 l tank, common to both traps (see Fig. 19). The choice is dictated primarily by:

An economic rationale:

- the cost of the infrastructure is much smaller in the case of only one storage tank;
- The optimization of LN2 consumption: a single tank has lower losses than two tanks of the same total capacity. The savings due to a lower length of the transfer lines (both in the cost of the lines and in their losses) in this second hypothesis (two tanks) is not enough to support this choice.

A logistic reason: it is convenient to minimize the installations around the central building;

With a capacity of 20,000 l and the given total consumption of LN2 the time between refilling will exceed one month.

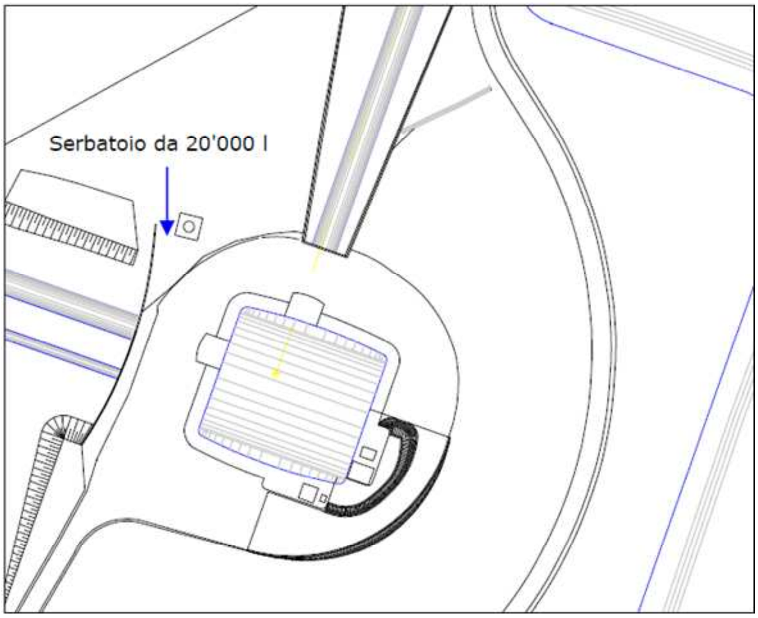


Fig. 19: Schematic layout showing the position of the tank in the area of the central building.

Tanks towers area W and N

For the two end towers, one 10,000 storage tank dedicated to each trap and placed outside the building is required (see Fig. 20). Again this capacity will guarantee a time between refillings greater than one month. The transfer line length will be 22 m; the lines will enter the tunnel under the vault and will run parallel to the vacuum tube to the trap.

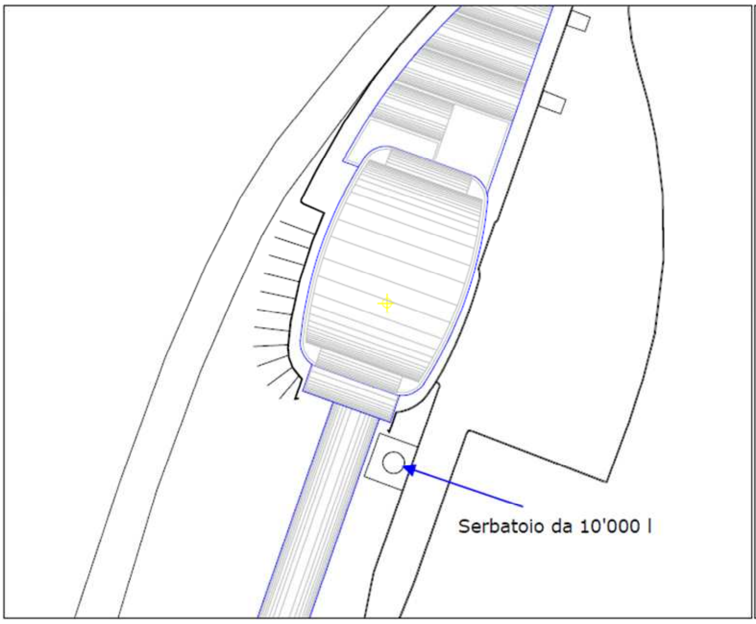


Fig. 20: Schematic layout showing the position of the storage tank in the area of the North end building.

<u>Types of tanks</u>

There are two types of cryogenic tanks of large size: tanks insulated with perlite and intermediate vacuum; and super-insulated tanks under high vacuum.

The choice depends essentially on the comparison between the losses of the tanks, integrated over the life of the plant (lower for super-insulated tanks), and the initial investment (higher for super-insulated tanks, see Tab. 4 and Fig. 21).

Standard tanks

Size	Self-losses		10 years consumption	
[l]	[% / day]	[l / day]	[l]	[€]
10,000	0.32%	32	116,800	10,979
20,000	0.28%	56	204,400	19,214

Super-insulated tanks

Size	Self-losses		10 years consumption	
[l]	[% / Day]	[l / day]	[l]	[€]
10,000	0.05%	5	18,250	1,716
20,000	0.04%	8	29,200	2,745

Tab 4. Comparative table of storage tanks, by type. Estimated cost of liquid nitrogen is € 0,094 / l.

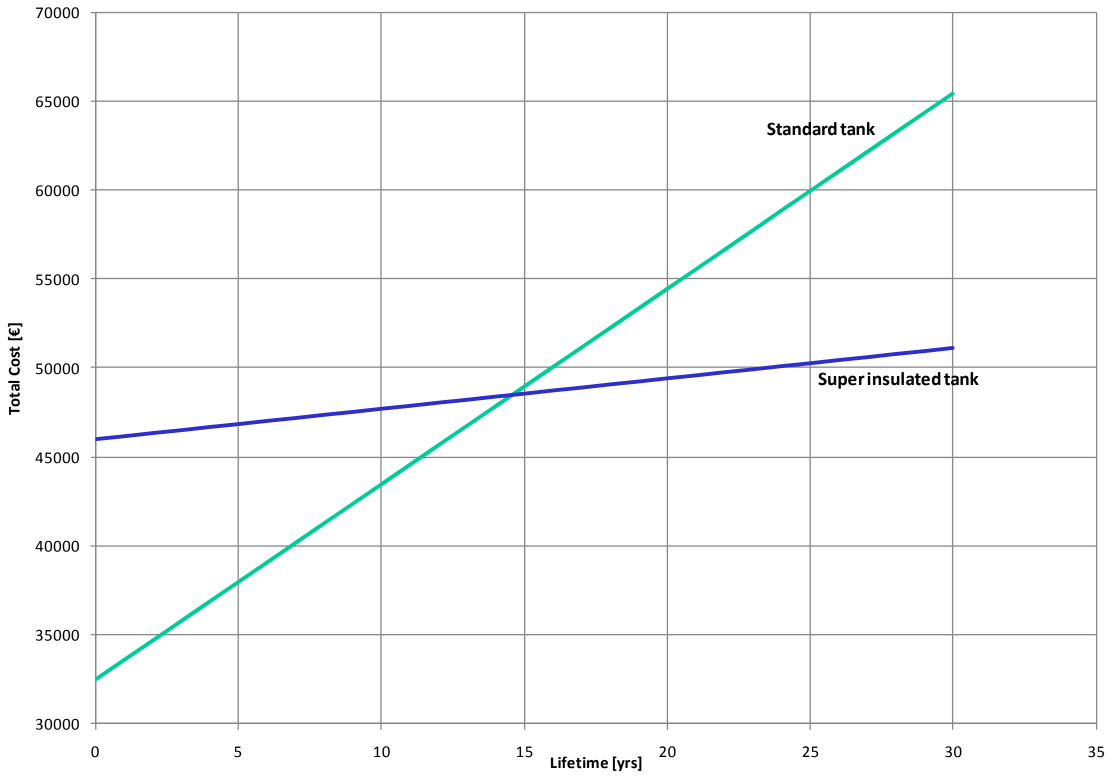


Fig. 21: Total cost (initial investment and running cost) for the two types of tanks. The higher initial cost of the super-insulated tanks is compensated by the lower losses after 14 years of life of the plant.

<u>Specifications</u>

The main technical features of the storage tanks will be as follows:

Fluid	Liquid nitrogen
Design pressure	14 bar g
Design temperature	-196 ° C
Useful capacity	≥ 9'500 for the end buildings north and west
	≥ 20,000 for the central building
Applicable standards	CE marking according to Directive 97/23 EC
Materials:	
inner receptacle	18-9 stainless steel X2CrNi EN10028-7 or equivalent
outer container	S235J2 carbon steel EN10025-2004 or equivalent
pipes and valves	18-9 stainless steel X2CrNi EN10028-7 or equivalent
Daily consumption	≤ 0.38%

The tanks also must be designed to be installed on site according to available data concerning the actions of wind and earthquake, according to the law DN 18/01/2008.

The minimum set of instrumentation and valves will be as follows:

Line load from above and below, with isolation valves;
Line of use, with isolation valve and economizer gas;
Bleed line liquid, isolation valve;

Vent gas line, isolation valve;
Mechanical pressure regulator upstream to maintain the pressure in tank at constant values, adjustable.
Circuit subjected to pressure;
Indicator local level;
Preparing the remote signal level for transmission in control room;
Over-protective outer shell and inner pressure and related pipes.

The typical layout, is shown in Fig.22

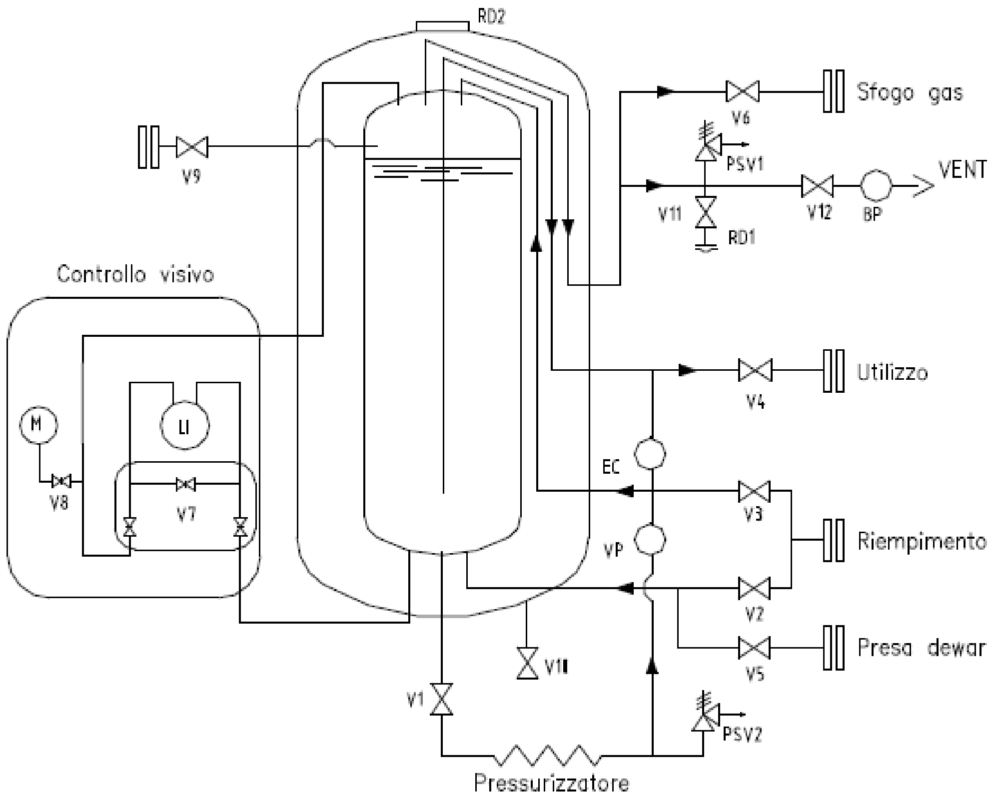


Fig. 22: Typical layout of the LN2 storage tank.

2.6.2 Liquid Nitrogen Transfer Lines

In order to reduce the evaporation of LN2 along the path from the storage tank to the cryogenic trap, the transfer line must be super-insulated with intermediate high vacuum (see Fig. 23).

The flow rate of LN2 inside each line will be approximately 8 l/h. The line has to be designed to guarantee, with the given LN2 flow rate, low losses, stratified flow (good gas-liquid separation) and low pressure drop.

The optimal trade-off among these requirements is given by the DN15 line, with the following technical parameters:

- Inner conduit F 21.3x1.65 mm ASTM A312 Tp 304
- Outer conduit F 60.3x1.5 mm AISI 304
- Design pressure 16 bar
- Working temperature -196 °C
- Linear heat loss 0.4 W/m
- Linear weight 3.7 Kg/m

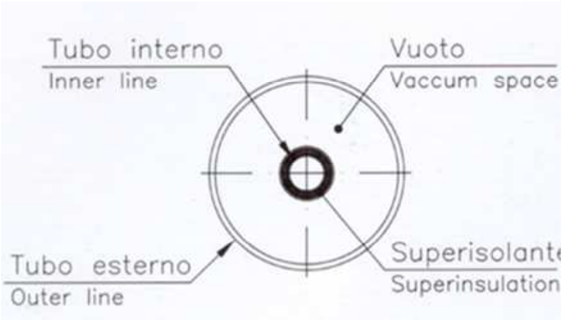
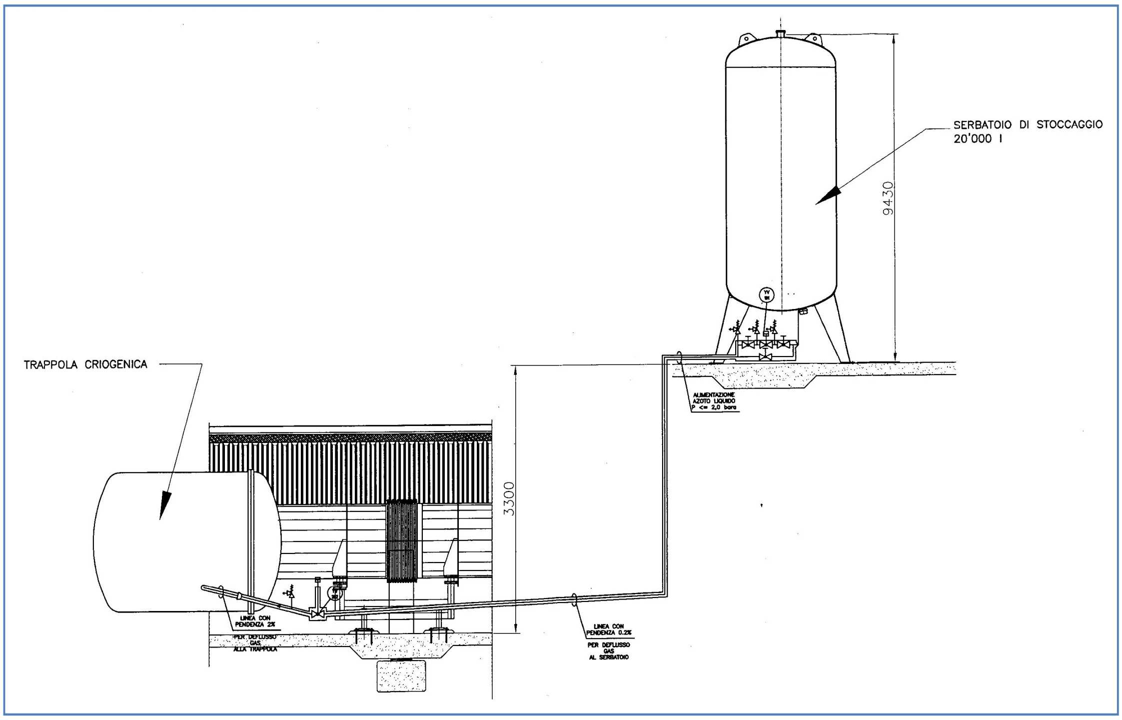


Fig. 23: Cross-sectional layout of the LN2 transfer line.



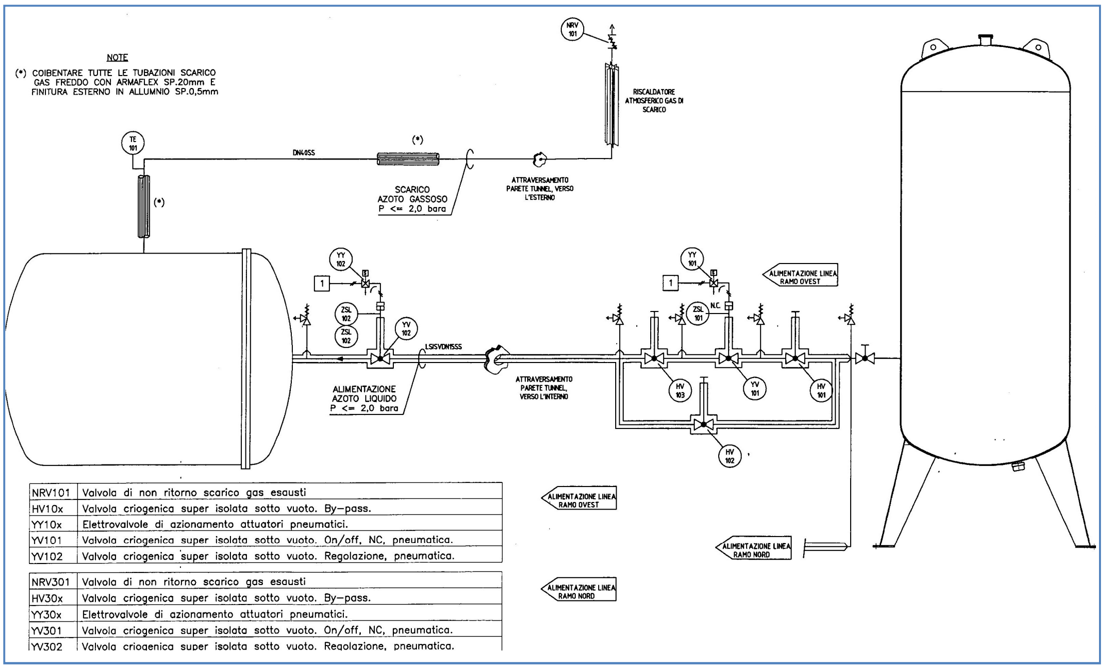
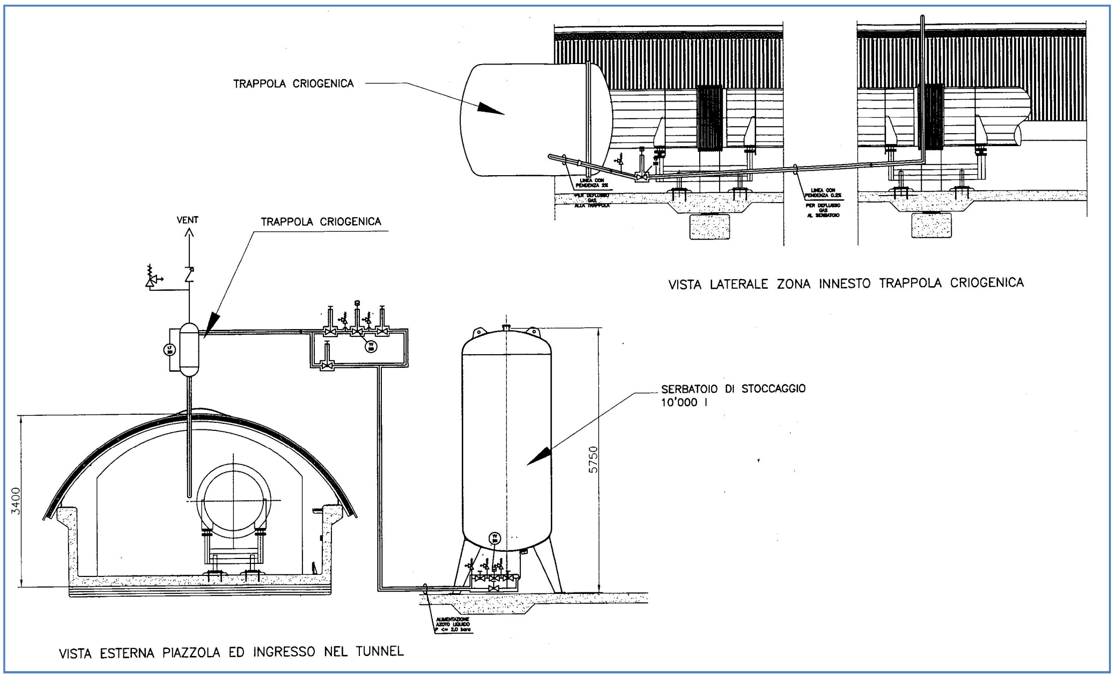


Fig. 24: LN2 transfer line - Central building



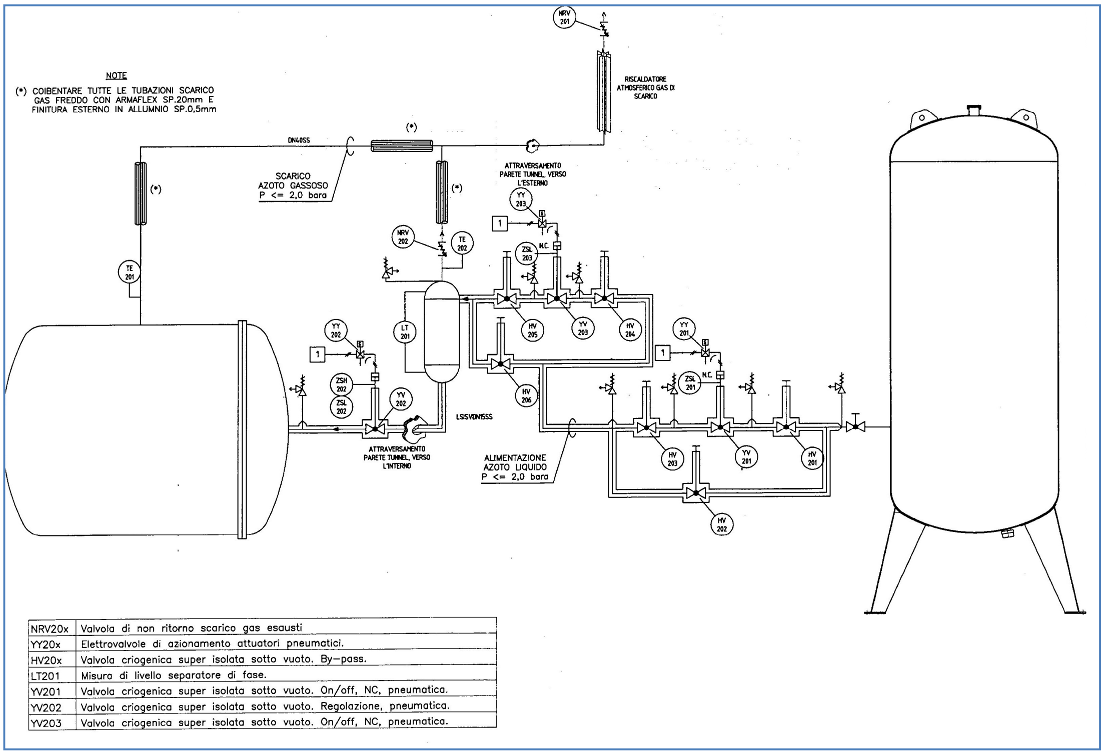


Fig. 25: LN2 transfer line - End building

Automatic cryogenic valve

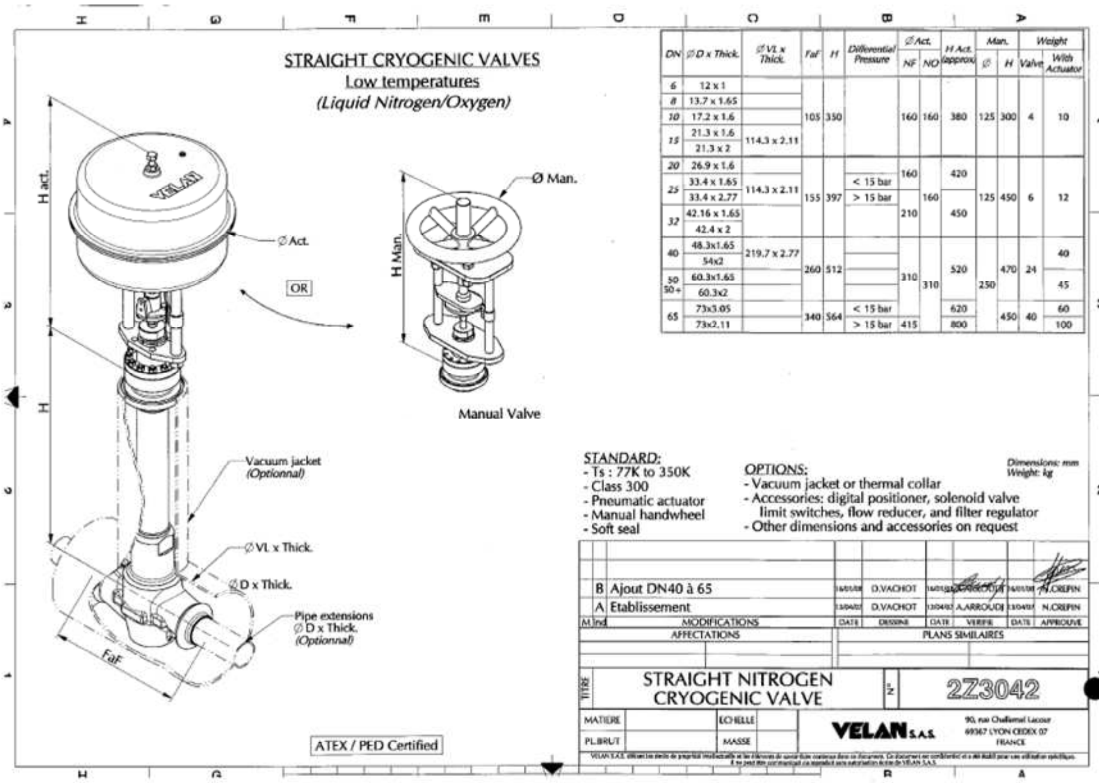


Fig. 26: Possible solution for the cryogenic valve for the automatic regulation of the LN2 level inside the trap

The valve should be placed near to the trap, as shown in Fig. 24-25. After the valve the trap operates at atmospheric pressure, while before the valve, the pressure will be the working pressure of the tank plus the pressure due to the height of the column of liquid. In the worst case, in the central building, we will have at the level of the valve on the tank side approximately 1.3 bar. This causes a sudden expansion across the valve with the formation of 0.12 g/s of GN2, corresponding to 0.08 m^3/h. This is much less than the GN2 produced into the trap in normal operation (4.5 m^3/h), and therefore should be considered negligible.

2.6.3 Regeneration and Baking

During the normal operation water will condensate and accumulate on the cold surface of the trap, increasing the emissivity and the LN2 consumption. For this reason a system for the regeneration of the trap will be implemented. The system will be based on atmospheric vaporizers, to evaporate the LN2 taken from the storage tank, and on an electric heater to heat the GN2 up to the desired temperature. The same system will also be used for the bake-out of the trap, if needed. A rough estimation indicates that the regeneration will take place once per year, while the bake-out will not be needed more than once in several years.

For the regeneration the following design parameters were considered:

- Temperature 50 °C
- Duration 4 days
- Transient 6 hours
- Gas load 415 Nm^3/h (transient)
  50 Nm^3/h (regime)

- LN2 consumption 3,800 l + 1,870 l/d

While for the bake-out the corresponding parameters are:

- Temperature 160 °C
- Duration 4 days
- Transient 22 hours
- Gas load 170 Nm^3/h (transient)
  50 Nm^3/h (regime)

- LN2 consumption 5,800 l + 1,870 l/d

Electric heater power 10 kW

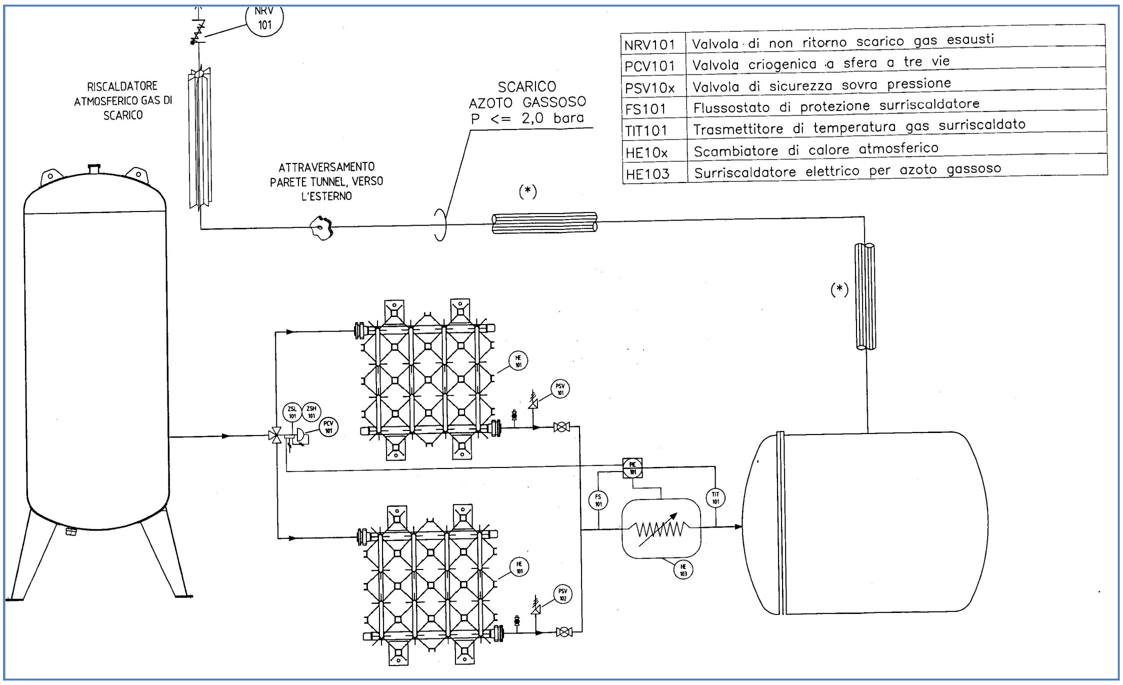


Fig. 27: Layout of the regeneration and baking system

We note that two vaporizers are needed for each trap. This is due to the fact that after 8-10 hours of operation these devices have to be heated-up to eliminate the frost accumulated on their surface. With two units, and a device for the automatic switch between the units, a continuous operation of several days is possible.

<u>GN2 exhaust Lines</u>

The GN2 produced during the normal operation of the traps will be piped to the outside of the buildings by suitable insulated venting lines. The GN2 produced in the normal operation of trap is 4.5 Nm^3/h. A much higher gas load is foreseen during the cool-down of the trap (500 Nm^3/h), and during the regeneration and baking (415 Nm^3/h). For this reason the venting lines are dimensioned to withstand these higher fluxes.

The main design parameters are

- Max load 4.5 Nm^3/h (normal operation)
  500 Nm^3/h (cool-down)
  415 Nm^3/h (regeneration and baking)
- Design pressure 0.5 bar g
- Design temperature -196 - +150 °C
- Nominal diameter DN80

2.6.4 LN2 total inventory and refill strategy

	Central building	North building	West building
Transfer line lenght (m)	106	22	22
Line loss (l/d)	38.39	7.97	7.97
Tank size (l)	20,000	10,000	10,000
Tank loss (l/d)	56	32	32
Trap consumption (l/d)	340.8	170.4	170.4
Refilling interval (days)	35	35	35
Total consumption (l)	15,232	7,363	7,363
Cool down (l)	1,680	840	840
Total incl cool down (l)	18,592	9,043	9,043

Tab. 5: Total inventory of LN2 consumption

The total inventory of LN2 is shown in Tab. 5. In the last three lines the total amount of LN2 needed during a period of five weeks is shown, both without and with the amount of LN2 needed to cool-down the traps, showing that it is within the capacity of the storage tanks.

<u>Refill strategy</u>
To minimize the impact on the interferometer operation, we foresee to refill one tank per week, during the weekly maintenance period. This means that the tank have a capacity for at least three weeks of continuous operation. Actually, to have a significant safety margin, the tanks are designed for five weeks of continuous operation. Another important aspect to consider is the time needed to refill.

Currently, the scheduled maintenance is 4-5 hours per week. The refill operations are carried on within this time window since the needed time will be approximately 45’ for the 20,000 l tank, and 30’ for the 10,000 l tanks.

2.7 Safety

Risks connected to employing cryogenic fluids are carefully considered both in technical equipment construction and in operation procedures.

Risks are related to:
_ development of large quantity of gas from small quantity of liquid
_ physical contact may produce injuries similar to burnings
_ excessive concentrations in room atmosphere reduce Oxygen and may cause asphyxia danger; cold vapors can accumulate in the lower rooms .

The equipment described in the above paragraphs shall be produced, inspected and tested in agreement with the Italian laws and European Directives relative to pressure vessels for cryogenic service.
In particular: overpressure relief valves and burst disks are foreseen to prevent explosion hazards, as shown in par 2.1, 2.6.
The safety equipment will be periodically checked and validated by competent authorities. LN2 external storage tanks will be declared at Italian authorities for safety at work ISPESL, and then ASL for yearly inspections.

Concerned areas will be constrained and proper advertising will warn the personnel, in particular for the external storage tanks. The involved personnel will be trained on equipment handling, related risks and first aid procedures.

Among the personnel protection systems, oxygen sensors will be installed in selected areas, and air extraction systems are under evaluation. Clean rooms are particular areas of concern since located at a lower floor and often have reduced ventilation.

2.8 Prototype action items

The first trap of the series shall be built in advance, with a separate contract, to serve as a prototype and undergo to a sequence of tests.

Successively the prototype shall be installed as the first cryotrap (in WE position). The remaining three cryotraps will be realized after the testing and a new call for tender, minimizing the performance risks.

Here we give a synthetic list of actions to be undertaken with the prototype:

<u>Finalization (within fall 2010)</u>

a. Finite element analysis of cryotrap vessels to determine the mechanical characteristics, resonances and stress levels.

b. Engineering review to finalize the cryostat damping system design, establish a requirement for the Q at low frequency (microseism up-conversion effects)
c. Review the precise positioning and size of the optical baffles
d. Completion of production design
e. Engineering review to define constructive details (flanges, adapting pieces, ground supports, bellows, baffle holding systems…)
f. Preparation of technical documents for the call for tender , including quality controls, requirements and specifications for sensors.
g. Prepare the specification for the level control electronics
h. Prepare a detailed assembly procedure
i. Prepare a detailed regeneration procedure
j. Define the need of 'firing' treatment
k. Study the two phase flow and LN2 bubbling
l. Prepare documentation about safety
m. Contract assignment

<u>Production (starting end 2010)</u>

a. Final discussion with contractor and agreement on executive design
b. Prototype production and follow-up (inspection of cleanliness and fabrication methods …)
c. Contractual acceptance tests in factory (geometrical, mechanical, cool down, evacuation and leak tightness, safety equipment…)
d. Reception and transportation to Nikhef lab

<u>Tests on site (at Nikhef lab from mid 2011)</u>

a. LN2 consumption
b. Vacuum performances and cleanliness
c. Bubbling noise
d. Damping system performances and mechanical frequencies
e. LN2 consumption for different water layer thickness
f. Design changes, if necessary
g. Transportation to Cascina (end 2011)
h. Installation at WE position
i. Startup and full functional test

3 Enlarged Links and towers vacuum system modifications (not yet ready)

4 Control System (not yet ready)

5 Towers upgrade (not yet ready)

6 Towers displacement (not yet ready)

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