Advanced Virgo
VAC –Modifications for Protection from Dust for the Monolithic Upgrade

VIR-0464A-17

Virgo Change Request CRQ 2017/009

VAC Team, Clean Operation Team
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CHANGE RECORD

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1 Introduction

1.1 Scope of the document

This document is to describe the two new features of the 'towers' vacuum system - venting and primary pumps – and give details about the extraordinary cleaning procedure of the chambers with respect to the issue of dust pollution, to reduce risks of damaging quartz fibers by accelerated dust particles during venting or other operations
A preliminary plan for construction and implementation of the upgrades is also presented.

1.2 Overview

During the installation of AdV we experienced several failures of the monolithic fibers [1]. Our present understanding is that failures were related to migration of dust particles inside vacuum chambers. In particular we found that particles coming from scroll pumps (sized around 10 μm) can be injected inside chambers during the venting process, possibly travelling at high speed. This mechanism is promoted by the particular design of the venting circuit of UHV towers, where the pumping and venting processes share the same duct. This configuration has been replicated for test purposes on a separated vacuum chamber, getting a reasonable statistics of failures.

In order to remove the known causes of failure mechanism, the following operations are being considered:

- Venting circuit separation
- Scroll pumps substitution
- Extraordinary cleanliness of selected tower chambers

Same interventions have been applied in the test chamber, where a 'dummy' payload is suspended without failures after 3 months with several vacuum/venting cycles.

The goal is to be ready to start the upgrade for the mid of September, while the real start of the works is not yet fixed and will be decided when more convenient for the AdV project.

1.3 Reference documents

[1] VIR-0350A-17 Monolithic Suspension Status
[2] VIR-0172A-17 Meeting with CERN vacuum experts about monolithic issue in Virgo vacuum chambers – 01 Febryary 2017
[3] VIR-0278A-17 Meeting with LASA/DESY experts about dust migration in Virgo vacuum chambers – 22 March 2017
[4] VIR-0475A-17 F. Sorrentino, Optical system for dust contamination monitoring via Si wafer inspection
[5] CCI-vK GmbH Commercial solution for particle measurement on surfaces and in air
[6] A. Chiummo (personal comm., April 2017)
[7] VIR-0316A-17 Tower ports selection options
[8] Venting inlet port Technical drawings - ANNEXED in the TDS to the present document
[9] VIR-0516A-16 A.Vicerè, shock wave calculation
[10] Logentry 36886 I.Fiori Environmental noise tests
[11] VIR-0048A-15 H.Heitmann, Surface particle counting
[12] VIR-PRO-CAS-220-115 , VIR-PRO-CAS-2200-114, VIR-0348A-15 Some dust control procedures (original versions)
[13] NASA report "Contamination Control Engineering Design Guidelines for the Aerospace" 4740 (1996)
Buch, Barsh "Analysis of particulate buildup on Surfaces" SPIE Vol.777 43-54 (1987)

[14] Test plates Technical drawings - ANNEXED in the TDS to the present document

2 Requirements and proposed approach

The requirement about admissible concentration of dust particles on surfaces of vacuum chambers is not precisely known.
The vacuum chambers are considered as cleanrooms (class 100 or better) and they are accessed by parts and personnel via a specific protocol (HEPA flushing , dressing, …). The cleaning is done according to best-practice techniques, and finally the control is done by monitoring the dust collected on witness plates (Si-wafers) with offline apparatus.
The proposed approach is to keep on with the present method, but enhancing the real-time dust diagnostics in order to guide the intervention.
Appendix A reports a sketch of a tower chamber: it is divided in two compartments, a lower one (containing the optics) and an upper one (containing the anti-seismic filters SAT). The 'lower' one is the object of the cleaning operation.

2.1 Recommendations and experiences from external laboratories

The VAC modifications have been discussed at more stages with experts from external laboratories of CERN, DESY, LASA [2,3].

There is general consensus about the proposed redoing of venting circuit and about the replacement of scroll type pump.

Concerning the cleanliness operation of tower chambers, most of the received suggestions have been included in the proposed plan, in particular the diagnostics.

Other techniques, typical of semiconductors industry, have been evaluated but finally not included because considered as not coherent with the whole system, hence not advantaging in practice, as the use of porous diffusors .

3 Venting Circuit

3.1 General

The venting circuit of the 7 'mirror towers' (NI, WI, NE, WE, BS, PR, SR) has a recognized weak point: venting shares the same duct used also for pumping. This feature was originally conceived to gain from the equipment point of view (reduced number of ports, piping, valves) but it revealed improper with respect to dust contamination: during the venting process the air entering in the chamber entangles the dust particles present in the pipe, produced by the scroll-type pump itself (or possibly deposited in the duct during the chamber pumping phase). The particles can be injected in the chamber, possibly with significant speed at the beginning of venting process, when the gas inside the tower chamber is still rarefied.

Figure 1 shows a sketch of a tower chamber with the primary pump and the present venting circuit.
The pumping is done through a first valve VA and then through a pipe that splits in two to serve both compartments, through valves V41, V42 .

The venting is done via a first manual valve VF and then through the same pipe above described.

The modification consists in realizing a new venting circuit, separated from the pumping one, see Figure 2, red color.

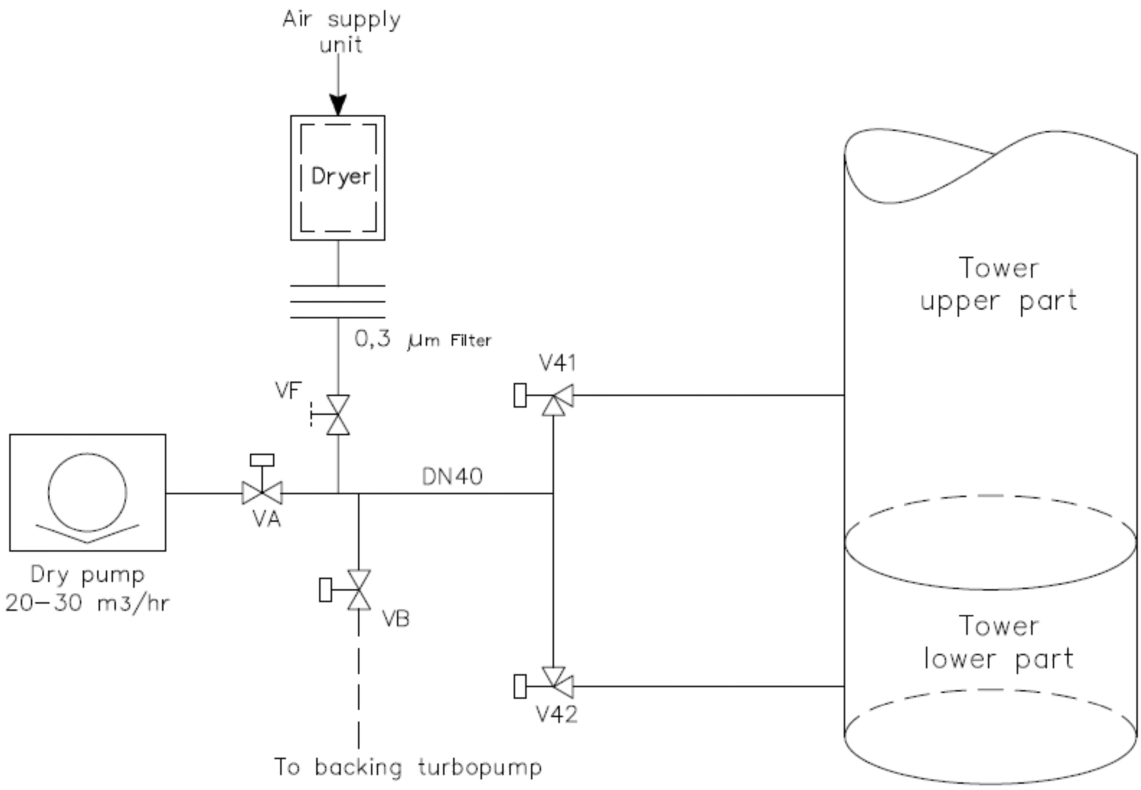


Figure 1: Sketch of venting and primary pumping circuits of a 'mirror tower'. The air supply unit connects to the tower by the same piping used for pumping. Note that both pumping and venting pipe splits in two, to process in contemporary the upper and lower tower compartments. Turbo-molecular pumps are not represented here for clearness.

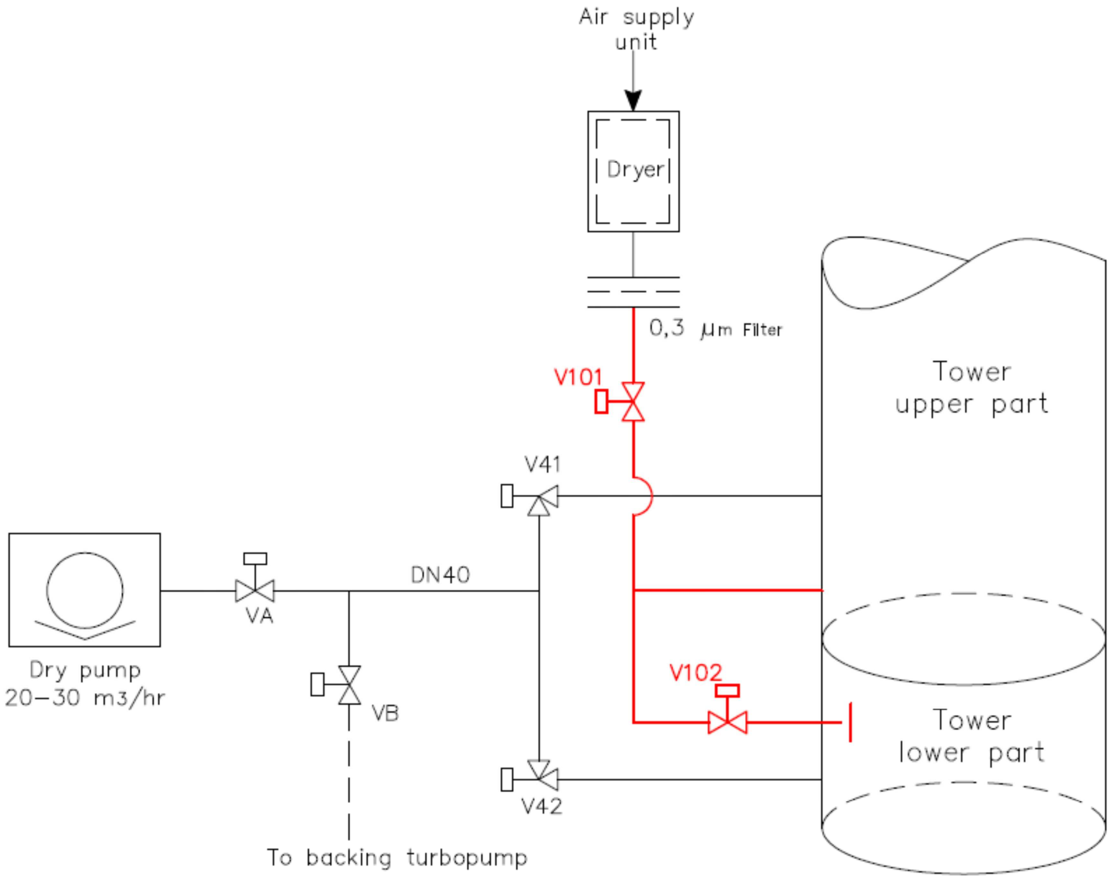


Figure 2: Sketch of new venting and primary pumping circuits of a 'mirror tower': The upgraded venting circuit is colored in red, completely independent from pumping one.

The new system will require various parts:

- Two venting ports equipped with shields, as described in the following.
- A new pipe section connecting the two ports with the air supply unit .
- Two vacuum valves, to allow the venting operations, V101, V102 .

The air supply unit will be the same already in use = the air is dried at around -30°C dew point (silica gel unit) and then filtered by 0.2 μm pore size PTFE filters; the supplied flow is about ~ 100 Pa.m^3/s (or ~ 1E-3 kg/s @1 bar inlet and outlet to full vacuum, room temperature) . The process of venting a tower takes > 12 hr, normally done overnight .

The valve V102 will be a DN40 angle valve with electro-pneumatic drive. The valve V101 will be 'soft opening' type, to get a reduced flux at the beginning of the venting process .

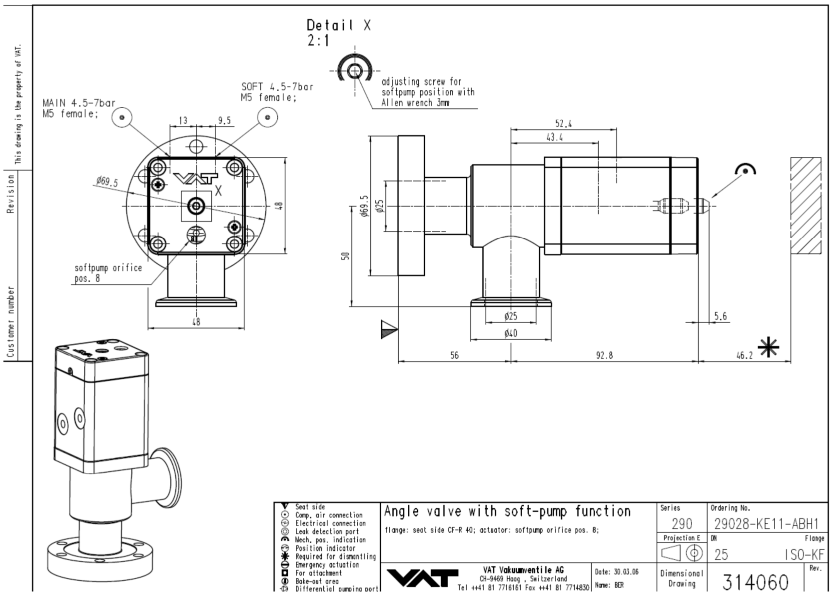


Figure 3: Venting valve V101. The valve opens in two times: at first an orifice, to limit initial flow and avoid the inrush of air from the dead volume existing between the valve itself and the filtered air supply unit (orifice sized to admit an inlet flow of 20 Pa.m³/s). After short time the valve shall be open fully (~ 30', tower pressure reaching a few mbar, and particles ballistic effects becoming less probable).

3.1.1 Control System

Both venting valves will be controlled by a dedicated PLC unit.
The monitoring and the operation will be possible by remote, the venting process will be activated in manual mode, as at present, through an interlock that will be installed close to the venting valve.

The control system will provide protection against wrong operations .

3.2 Venting ports

Two inlet ports are needed on each UHV tower:

The upper port is less demanding, since the upper chamber contains a solid mechanical assembly less sensitive to dust. It shall be equipped with a shield embedded inside the port itself, technical drawings available in [8]. This device will be installable from outside .

The lower port is required to:

- Disperse the entering air flow and direct it away from the silica fibers
- Hinder the direct view of the payload to particles possibly present in the venting pipe or venting port .

It has been designed with following characteristics:
-Position: the selected port has a diameter of 100 mm and it is positioned at a lower quote than the original one (- 0.5 m). This would reduce the range reachable by possible particles exiting from venting port with ballistic trajectories. Quartz fibers are positioned above this level.
- Shields: see Fig.4. A first shield is positioned in front of the inlet with the function to impact the flow, a fine grid is positioned downstream and a final larger shield is installed inside the tower chamber with the purpose to direct the flow along the tower wall , in tangential directions.
The final shield has the upper sector closed, to prevent the flow toward the upward direction.

Technical drawings are available in [9]. Two views are shown in fig.5, 6, 7.

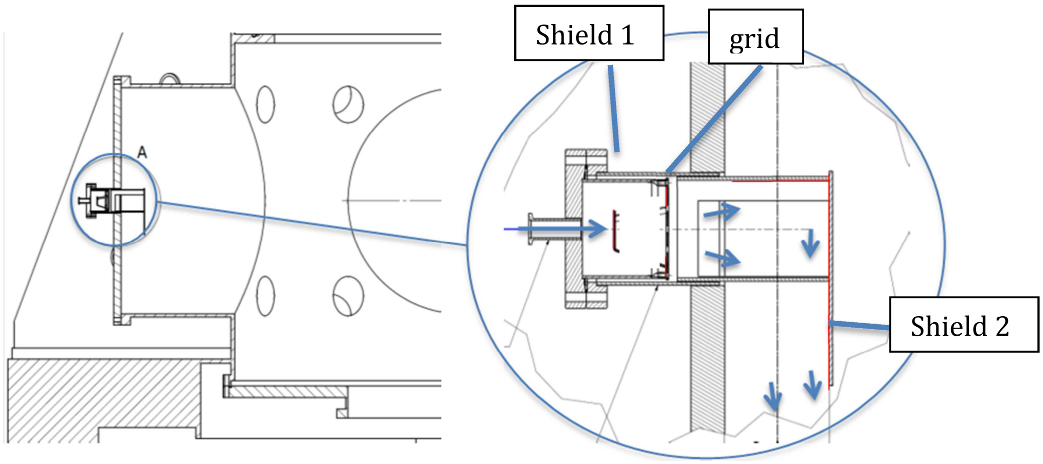


Figure 4: venting port sketch. The entering flow impacts on shield 1, goes across the grid, and is finally deflected by shield 2 .

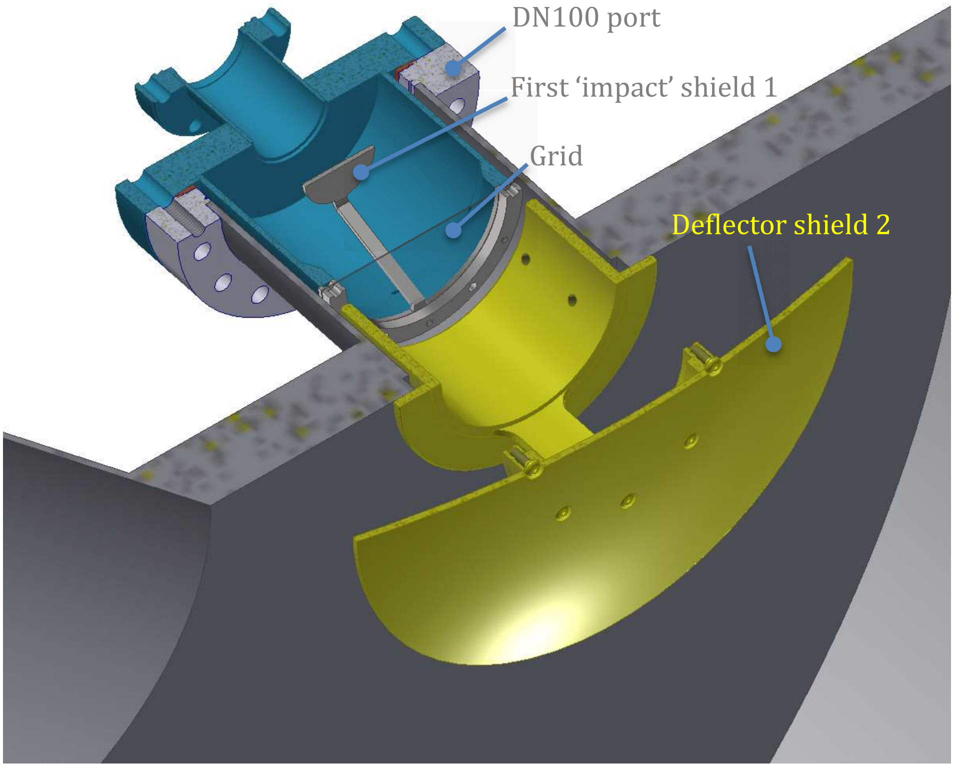


Figure 5: CAD drawing of the venting port parts (cross section). The grid is considered as not mandatory, it shall be realized with stainless steel mesh, wire size 0.3mm .

Figure 6: Assembly of venting port parts. The deflector shield shall be made in stainless steel and installed from interior. Its shape is curved to increase the mechanical stiffness, rising the vibration frequencies.

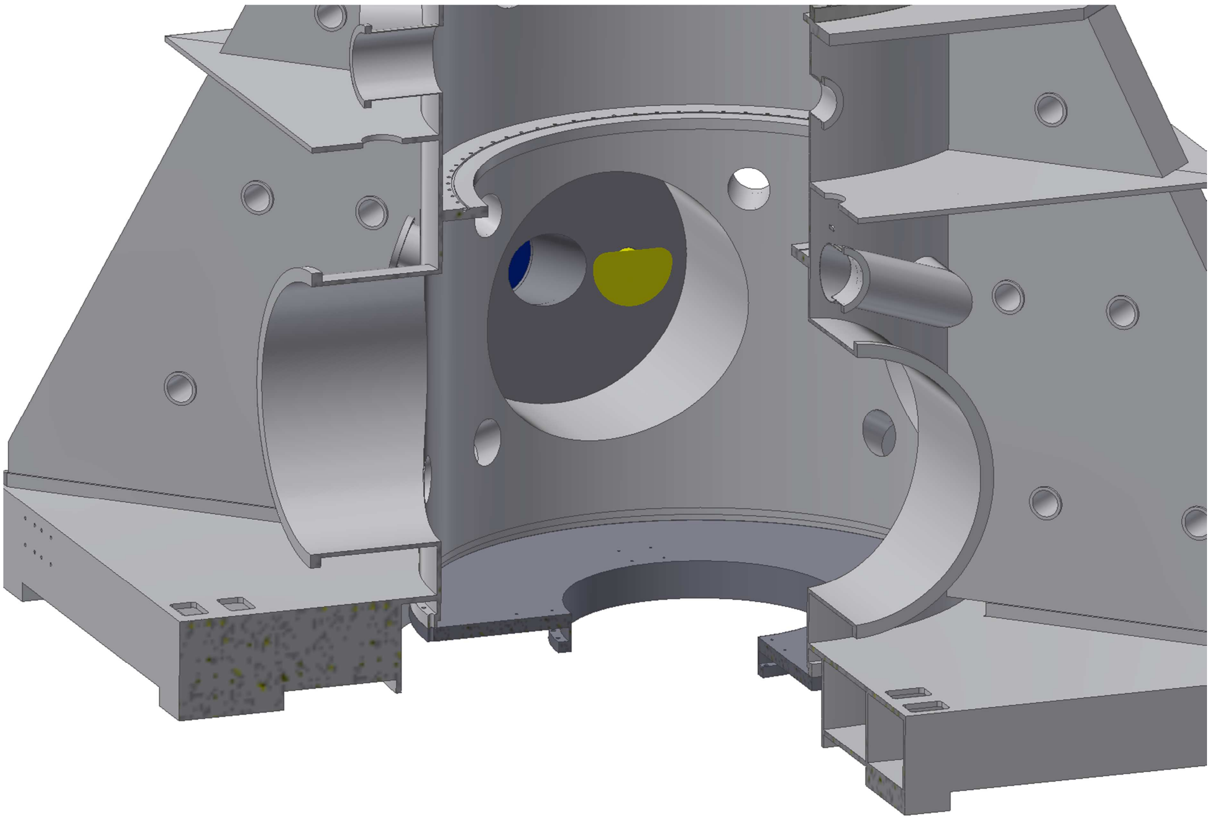


Figure 7: Inner view of the venting port, shield colored in yellow (shaped as in a previous design version).

3.2.1 Flow Pattern Study

Some simulations have been performed in order to study the flow pattern across the inlet port. Simulation of air flow is taken in the quasi-steady state after the start of the venting, where the main chamber pressure can be thought to be largely still at base pressure. The geometry has been simplified (2D axial-symmetric instead of full 3D). We consider it adequate to test the functionality of the flow shields.

We tested several distinct geometric configurations of the venting port, selectively including/excluding the first impact shield, the grid and the deflector shield. In each test we first solved the CFD equations with a commercial FEA software. In a further step we took the quasi-steady state solution (~ 1 s after the venting start) and simulated the particle release in the air flow from the venting inlet.

Two examples are shown in figs 8, 9 in order to visualize the air flow pattern. At rarefied pressure the air speed at the inlet exceeds 100 m/s , the first shield impacts the gas and strongly reduces its speed. Then gas runs through an enlarged cross section and a grid. Finally it is deflected by the external shield and enters in the main chamber at speeds of magnitude < 0.5 m/s .

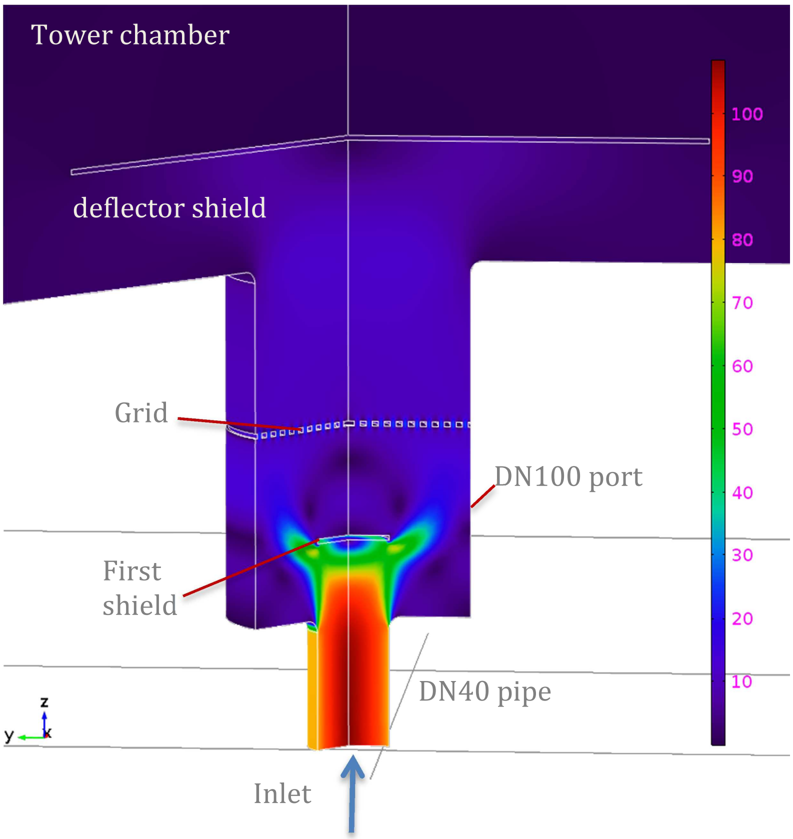


Figure 8: Flow pattern for a simplified geometry at beginning of venting, at the pressure of 1 mbar. Colors represent the velocity magnitude. The effect of the shields is to slow and deflect the gas flow, the direct ballistic projection of particles toward the payload is obstructed.

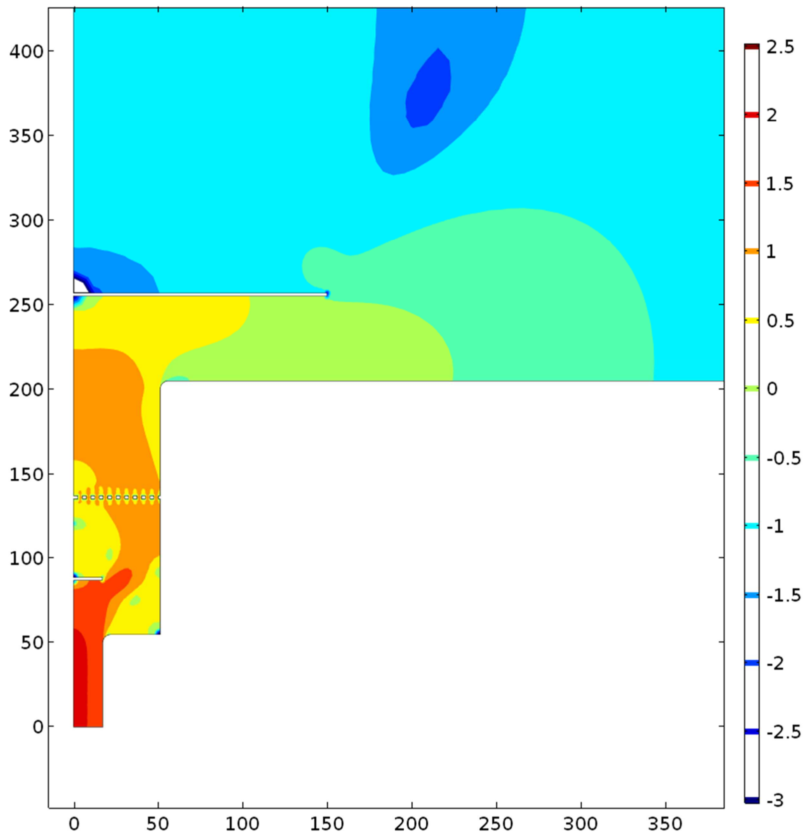


Figure 9: Same case presented in fig.8 but Log version to better visualize the conditions at exit (half geometry only is represented here). Velocity magnitude is about 1 m/s at the outside of the last shield, and about 0.3 m once in the main chamber.

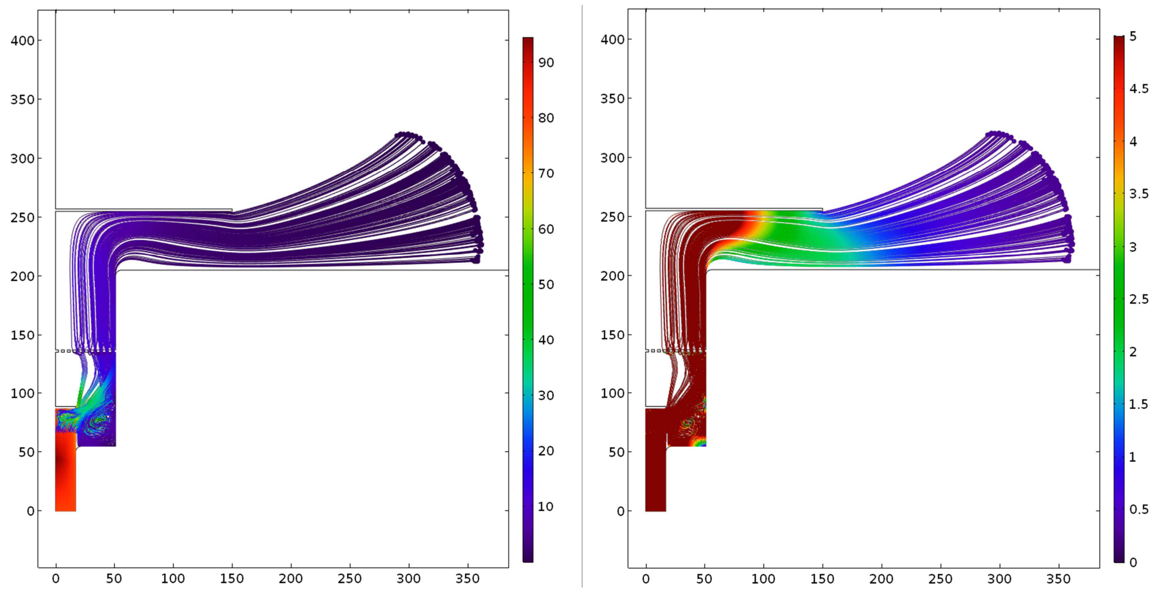


Figure 10: Trajectories of test particles (10 µm, 2200 kg/m3) released from the venting port. The trajectory colors encode the particle speed. Full velocity range (left) and on a 0-5 m/s range (right). Velocity magnitude of particles is < 1 m/s once entered in the main chamber, trajectories are tangential.

Trajectories of test particles released from the venting port are shown in fig.10. Test particles are assumed to be released from the venting port at the same speed of gas, conservatively. After bouncing on walls their speed is much reduced (we assume inelastic scattering) and they are practically transported by the air flow . Injections at high speed toward the main chamber are not present .

Further data and results are reported in appendix B.

Note: the grid appears as not affecting much the gas flow (simulated only schematically as a series of circular slits). It is considered as not mandatory but advisable.

3.2.2 Scattered light mitigation

Further requirements concern the scattered light issue: the last shield will be realized in stainless steel, and if necessary (normally confirmed by SLC [6]) shall be air-baked to improve its characteristics with respect to optical scattering . Also, its structure is designed in order to have frequency of mechanical vibrations modes above 150-200 Hz .

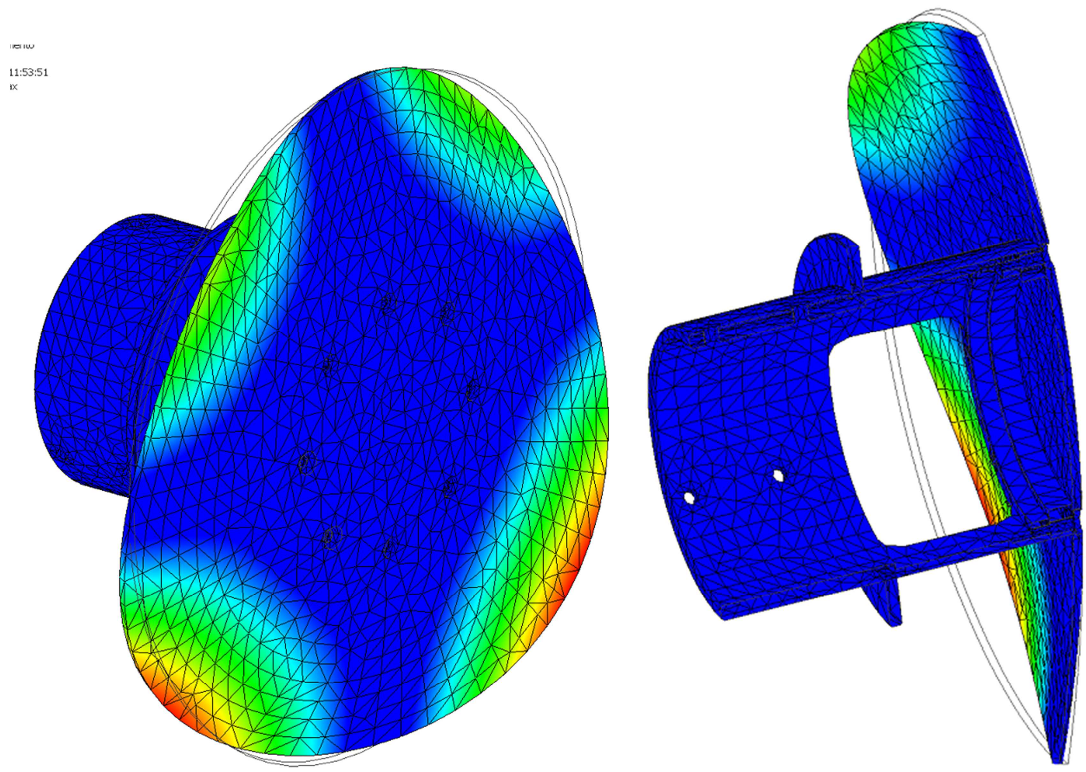


Figure 11: Mechanical frequencies of second shield, first mode is well above 200Hz .

3.3 Distribution pipe

It connects the air supply unit with the two venting ports.

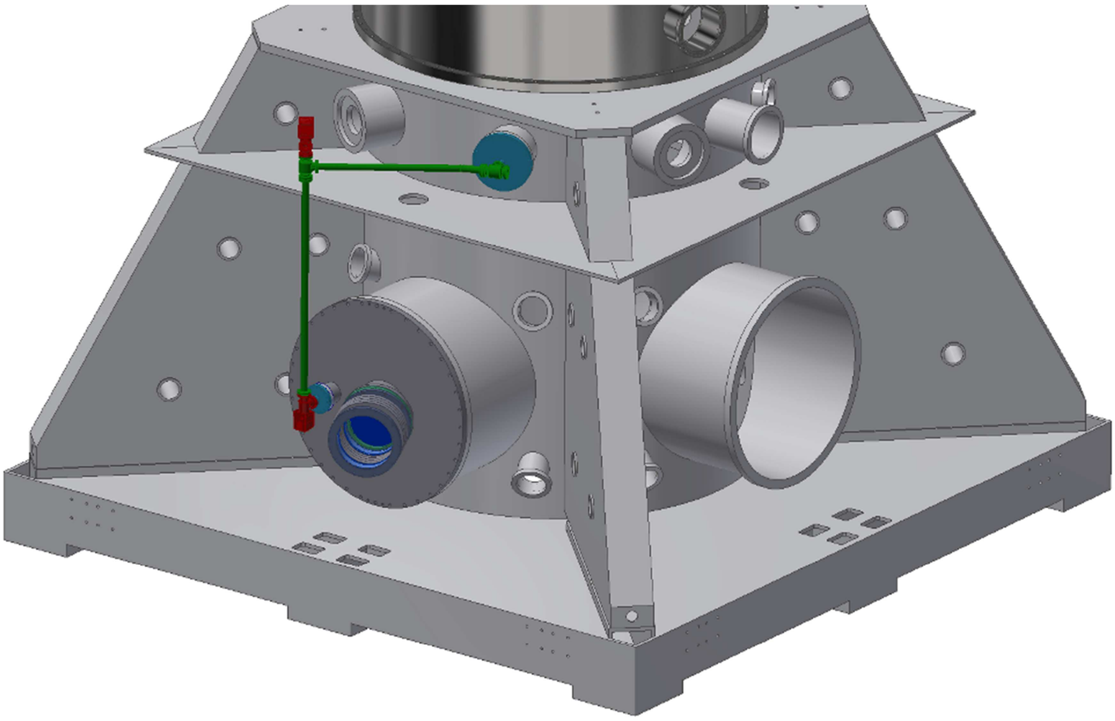


Figure 12: CAD model of a tower with the equalizer pipe, its exact path and positioning is adapted to each tower.

The pipe will be realized with DN40 CF rigid parts plus a short flexible section - bellows, and shall be protected against accidental hits by the personnel working around tower; its exact path depends on the specific tower; the different cases are given in the next paragraphs and reported also in [7].

3.3.1 Layout of NI, WI towers

For the input towers we shall use the spare port DN100 existing on DN1000 flange, tube side (fig.12). As alternative, we can use the spare DN100 port present on TCS – HWS flange. It is shown in fig.9. This last option is the preferred one for the SLC team, and likely it will be the selected one .

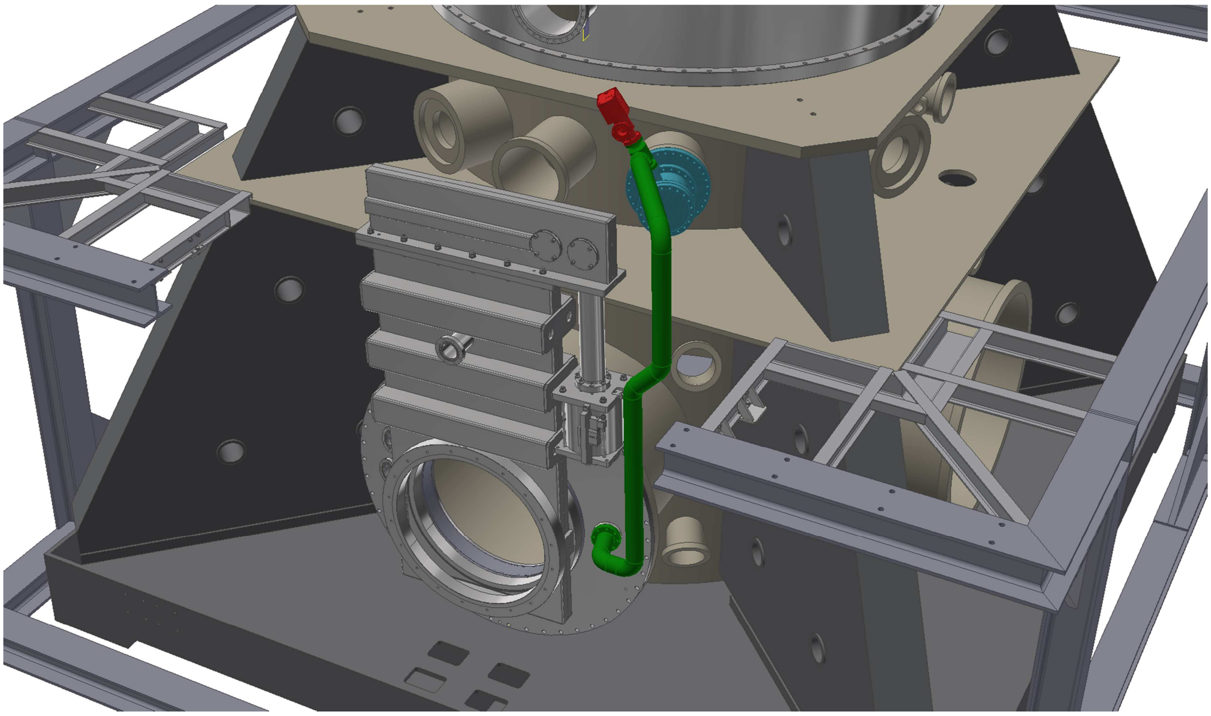


Figure 13: Distribution pipe, optional layout for input towers (earlier version).

3.3.2 Layout of NE,WE towers

For the end tower, we will use the spare DN100 ports present on TCS – HWS flange. It is shown in fig.12

3.3.3 Layout of SR,PR,BS towers

A similar port is selected also for these towers.

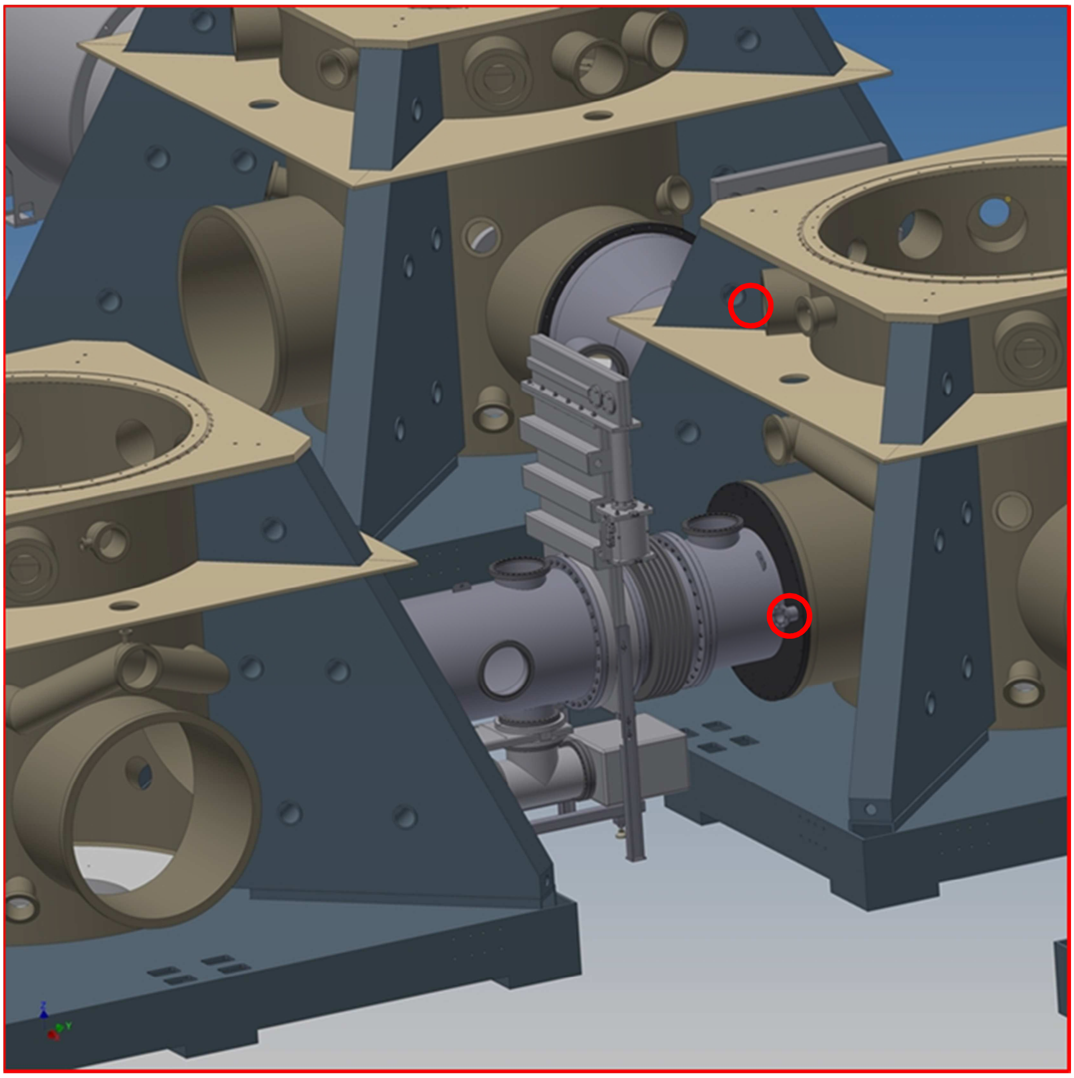


Figure 14: Venting ports selection for BS tower.

3.4 Design options

One of the discussed options was about including diffusors in the venting line.
This is a sort of device (porous material or stainless steel filter + membrane) that has the function to filter and to disperse the flow at large angles, used in the semiconductor industry (or where needed to push filtration below 0.3 μm).

Typically this device is installed inside the chamber as the last component of the venting line, and in the tower specific case it would be installed in place of the last venting shield or just upstream of it. Two diffusors would be needed, properly sized, one at the upper port and another one at the lower port, respectively. Normally diffusors are supplied with an upstream pressure above 1 bar.
The option was discarded for practical considerations (shields are easier to setup and maintain).

3.5 Integration plan

The mechanical integration shall be relatively fast, the various parts of the circuit are relatively small, we envisage 2 days per tower.
The works will be undertaken by the vacuum team plus one technician from an external company (4+1 people) and support from clean operation team (1 people).
Once assembled, the pipe will be flushed with clean air.

4 Primary pumps

Each tower is equipped with a dry pump used for the rough evacuation phase and for backing the turbo-molecular pump. The present pump is a scroll type pump, nominal speed = 25m3/hr that is a source of dust particles produced by the wearing of the seals and other parts.

Modern multistage roots pumps are the proposed alternative in substitution of scroll ones. They are specifically built to avoid dust production (no friction/wearing inside vacuum) and free of lubricant inside the vacuum module. References from other large laboratories specialized in clean processes are good (CERN, Elettra (TS));

We consider the substitution more convenient with respect to a partial solution (maintaining scroll pumps and installing inline adequately sized dust filters), pursuing the logic of redundancy in dust mitigation interventions. This choice has been advised also by experts [2]. The new pump will be advantageous also in terms of running efficiency (longer maintenance interval = 22000 hr instead of 8000 hr).

4.1 Requirements

The requested pump is a dry pump, multistage roots type, suitable for UHV applications. Typical specifications are:

Pump type:	Vacuum dry pump type (free of lubricant inside vacuum module)
Dust emissions:	no friction/wearing inside vacuum module
Ultimate pressure:	< 0.1 mbar
Leak rate (static tightness)	< = 1E-5 mbar.liter/sec
Maximum inlet pressure:	operation with an inlet pressure of 1 bar
Pumping speed:	size range 25 m^3/hr
Mains supply:	220-240VAC 50Hz, 1 phase
Connections:	Inlet flange DN25KF or DN40KF
Cooling:	Air cooled
Environmental conditions:	indoor installation, temperature range 5°C to 35°C
Compliance:	CE conform

4.2 Market investigations

After a market investigations, 3 models have been considered:
Leybold Ecodry40, Pfeiffer ACP28, Ebara EVA10.

The first two pumps are similar concerning vacuum performances , ultimate pressure ~ 5E-2 mbar and similar pumping speed (fig.16 shows an estimation of pumpdown). One model is

more experienced and referenced (Pfeiffer) , while the other model is new on the market (Leybold).
Ebara proposed the model EVA10, which has a double size (and cost) of the mentioned competitors. It is made in Japan, and less diffused in Europe.

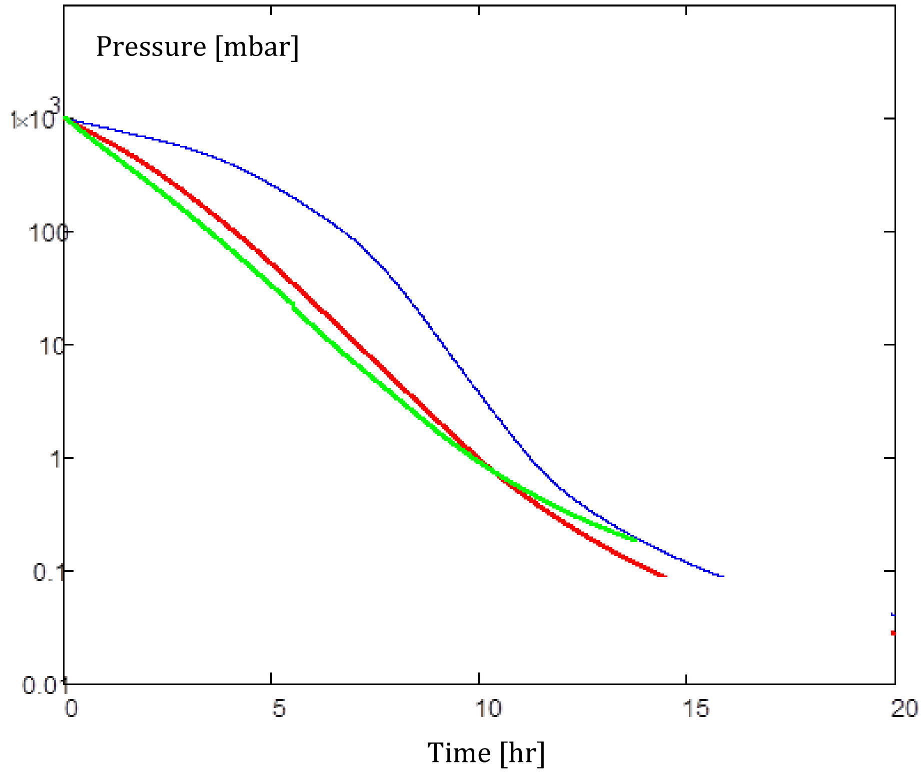


Figure 15: Estimated pumpdown curves for a 33 m³ chamber (tower) from atm to ~ 0.1 mbar, for comparison: red = ACP28, blue = ECOdry40 (this model has low speed when at high pressure), Green curve = measured one .

Assistance post-sale and service is in favor of Pfeiffer and Leybold.

4.3 Some experience

Some experience has been carried out on a Pfeiffer pump, model ACP28. It included a direct operation test on towers and its drive by the control rack, positively achieved.
Noise emissions were measured [13] and details about lubrication were exhaustively discussed with manufacturer. With respect to this issue, we have been guaranteed about the tightness of the vacuum module with respect to the gear lubricant (order of 100cc , tightness by double seal + centrifugal device).
Similar practice is starting on a Leybold ECOdry40.

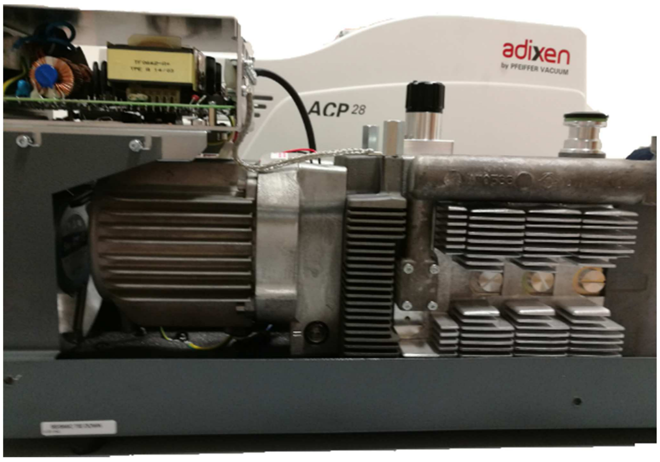


Figure 17: a multistage root pump being considered for the towers service

4.4 Costs

The investment would be relatively modest,~ 5 keur + taxes per pump (about the same as scroll pumps), 10 pumps needed. The delivery time is 1.5 months (Pfeiffer, Leybold).

4.5 Integration

The integration of the new pump in the system shall be simple, in practice a mere substitution. Together with the pump, it is needed to renew the related piping circuit (Figure 15). Part of the components will be deeply cleaned and reused (minor parts, fittings) while other parts will be replaced with new ones (longer distribution pipes). These pipes have been already prepared. Minor procurements are still missing (supporting frames). The implementation works will require 2 days per tower.

It is worth to mention the assembly conditions: the pipes will be cleaned according to the UHV practice, and they will be assembled in the central hall, class 100000 or similar. After the mechanical assembly, they will be flushed with clean air going out from tower chamber toward outside through the new pipe themselves.

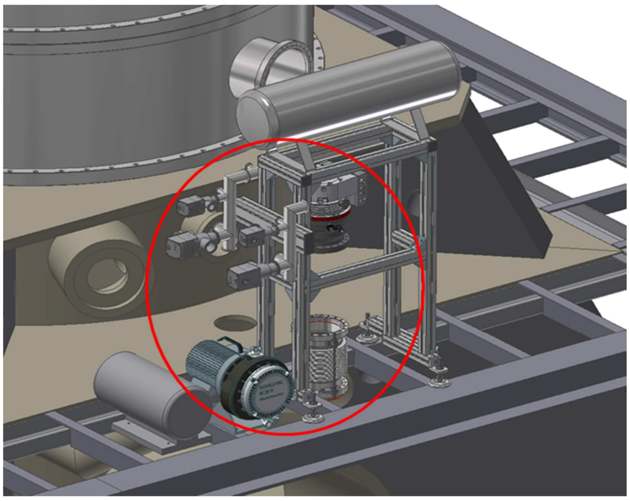


Figure 18: view of the tower layout relevant to primary pump and its piping system.

4.6 Turbulence from pumping

In order to limit particles migration, an usual recommendation is to avoid turbulent flows in the interested chambers.

During the rough pumping phase (with the ACP pump for instance) the Reynolds number in the Ø = 40 mm circuit is turbulent when at high pressure and becomes laminar after a few hours of pumping: Re ~ 4000 @ 400 mbar ; Re ~ 2300 @ 200 mbar ; Re ~ 1300 @ 100 mbar

Note that this is the situation inside the pumping duct, where the flow is directed toward the pump, hence not expected affecting the main chamber volume. It is considered as tolerable.

5 Extraordinary cleaning operation

An extraordinary cleaning of tower chamber walls is needed in order to prepare for the monolithic upgrade. Motivation is the removal of the dust particles potentially harmful for the fibers (larger particles) and for the optical surfaces (though, at present, there are not clues of dust contamination losses for test mass towers [6]).
The operation is to be performed after the removal of the payloads.

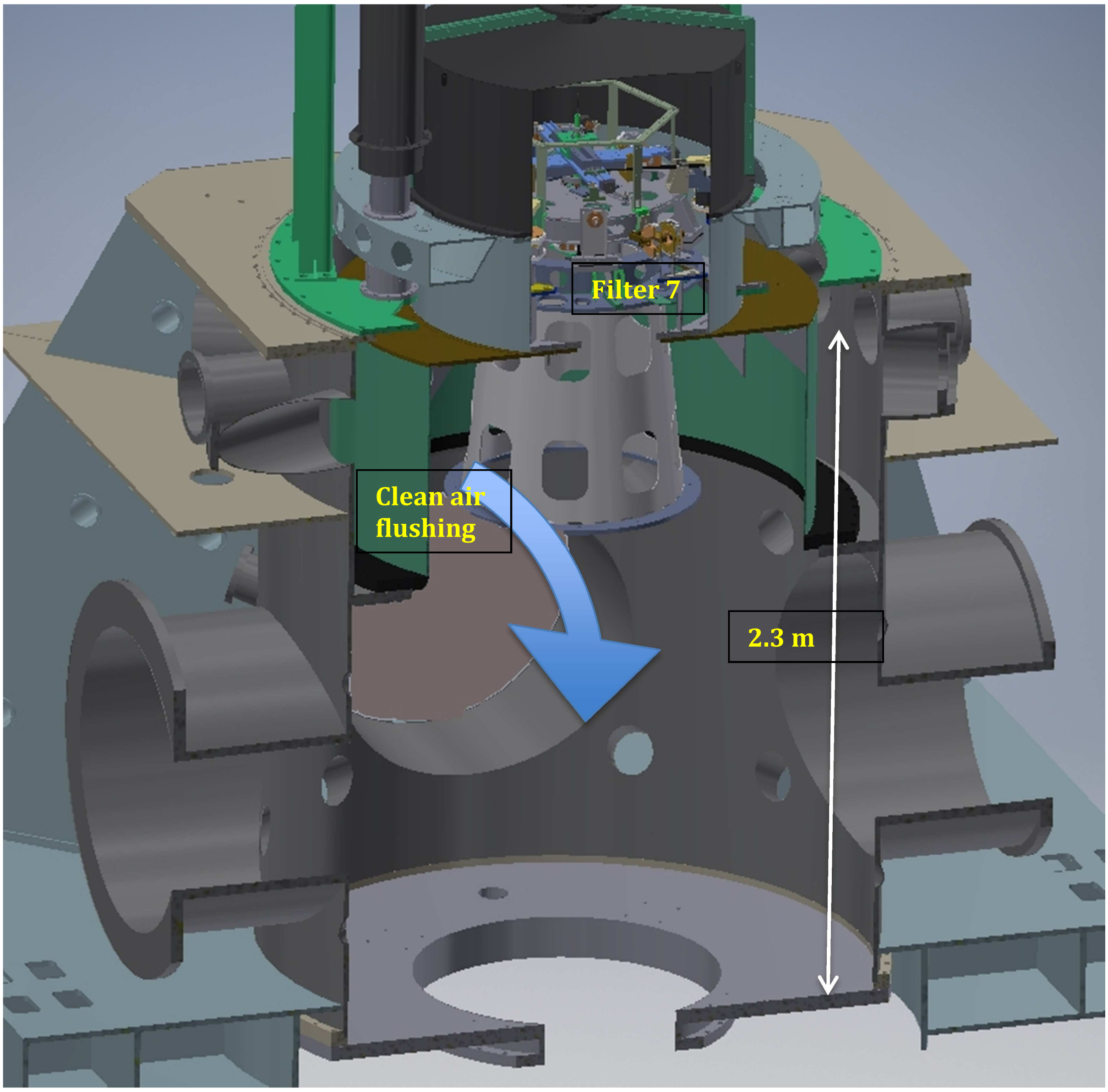


Figure 19: Tower lower chamber, with the last mass of the pendulum chain in position (stage #7) in position. HEPA filtered clean air shower put in evidence by arrows (flow speed inside chamber ~ 0.5 m/s). During the cleaning operations the payload will be removed.

Once vented the tower chamber becomes a cleanroom flushed with HEPA filtered air. Ambient dust is monitored at level of class 100 or less in absence of operators, going up to class 10000 during heavier interventions.
We have not precise thresholds about allowable particles concentration on chamber walls, Virgo follows a 'best practice' approach based on past experience, now revised and improved after a thorough discussion with experts of dust control issues in vacuum applications [3].

5.1 Tower cleaning practice

The existing procedure for cleaning the lower parts of towers chambers – case of critical optics not installed - is given in the following; see the appendix C for details on equipment.

All preparation must be in compliance with the Dust Control Procedures [12].

The following steps are executed:

1. *Cleaning of the area around the tower by mopping (2% Cleaner detergent in DI water)*
2. *Cleaning of the Hymo lifting platform by wiping (cellulose tissue with pure isopropyl alcohol) and by using the vacuum cleaner* ***at least one day before the opening of the tower***
3. *Opening of the tower bottom flange*
4. *Startup of the clean air flushing inside the tower*
5. *Maintain the clean air circulation in the tower during the whole intervention (air-blowing is expected to transport outside the dust particles generated during the intervention)*
6. *Cleaning of the tower chamber bottom part (first), of the walls and the ceiling of the vacuum chamber to remove eventually the contaminants (dust and particles), by wiping (cellulose tissue first, polyester tissue after, with pure isopropyl alcohol) and by using the vacuum cleaner*
7. *Blowing with the CO_2 Snowgun, wait about 20 minutes (to allow the clean air circulation in the tower) and blowing again with the Snowgun until obtaining a suitable particle count (volumetric counter in various positions of the chamber)*

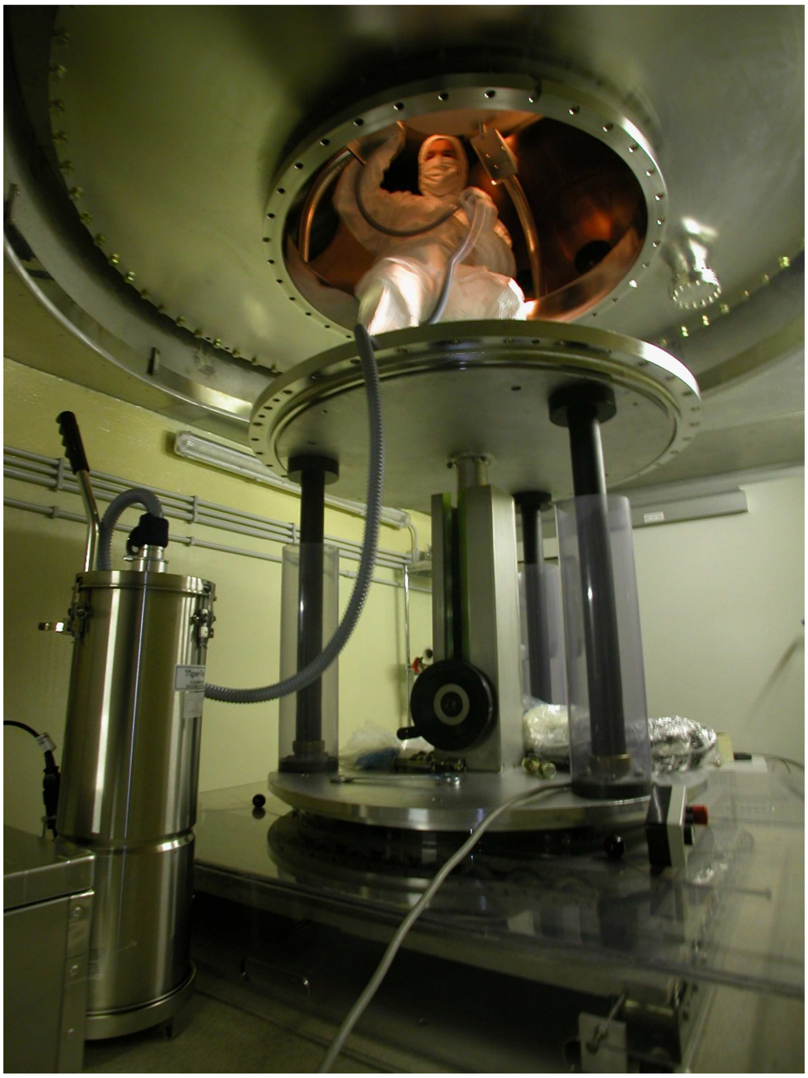


Figure 20: Cleaning of the vacuum chamber with the vacuum cleaner

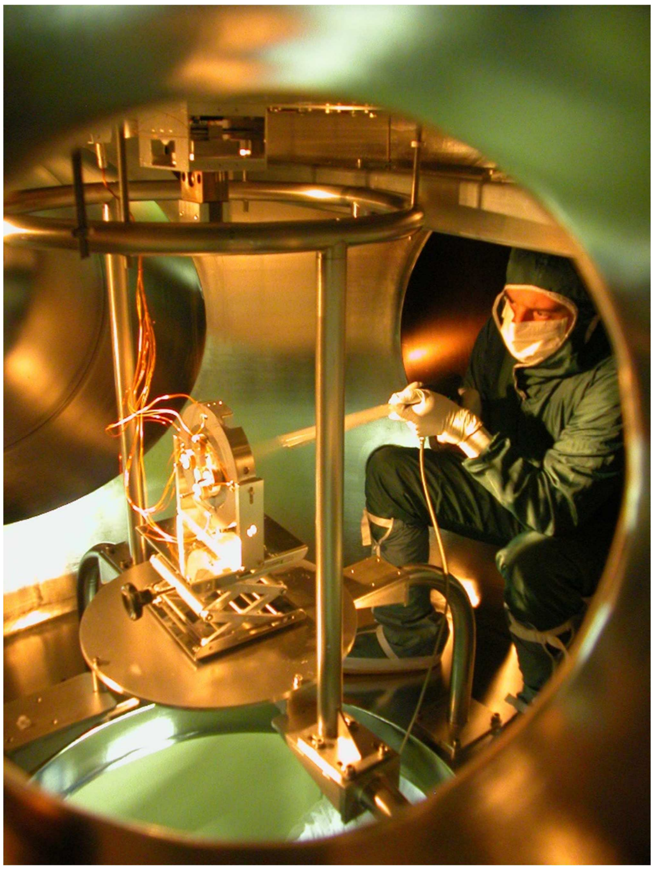


Figure 21: Cleaning of the vacuum chamber with the CO_2 snowgun (optics are removed here)

An example of the evolution of the air dust concentration inside a tower during a maintenance intervention is shown in figure 22.

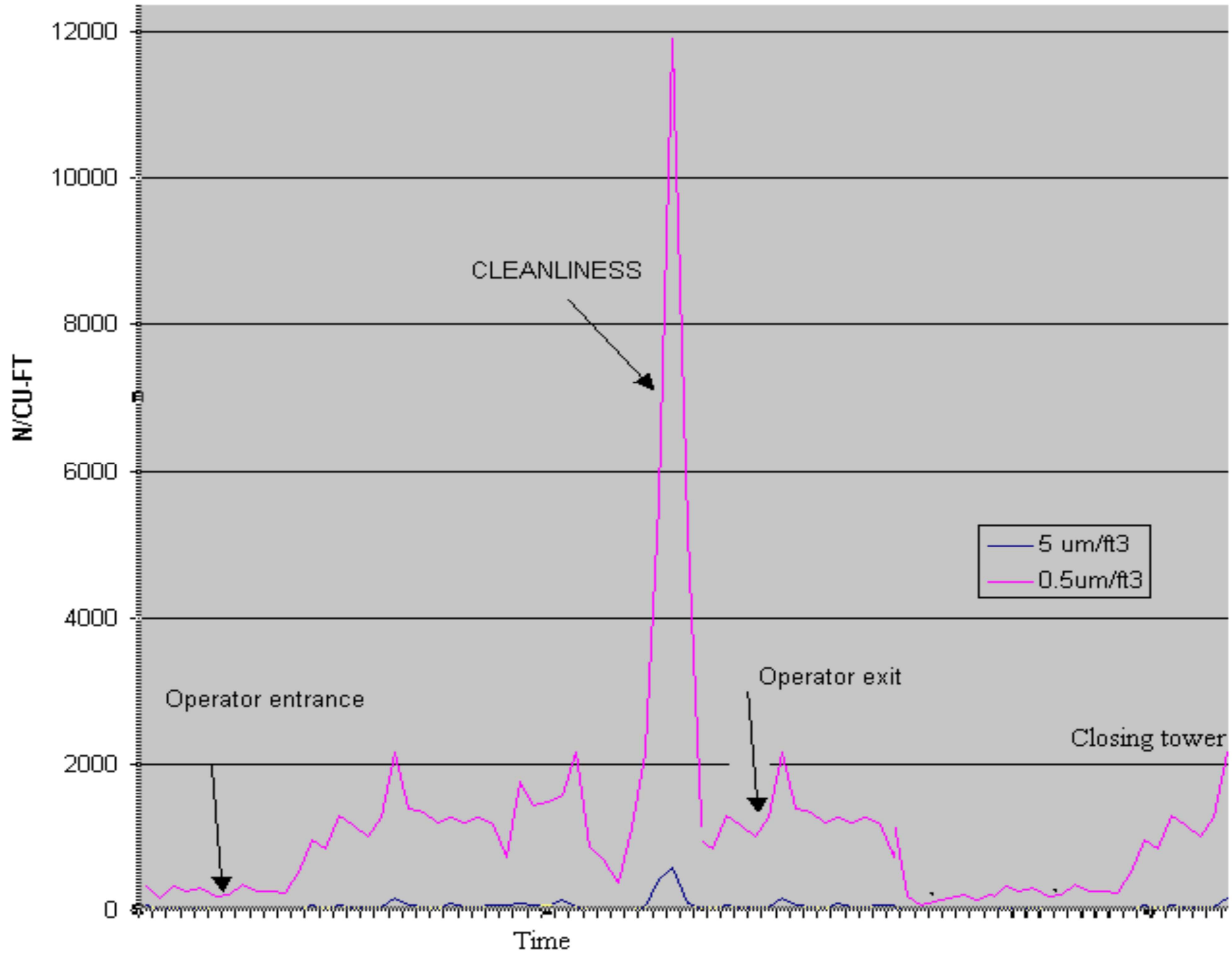


Figure 22: trend of two classes of dust particles during intervention inside tower lower compartment. The time duration is few hr, the particle counter is positioned close to the operator working zone.

5.2 Dust measurements on tower surface

5.2.1 Some data from past measurements

Measurements of dust concentration on test surfaces were routinely performed in the past: an example is presented in fig.23. Particles are collected on Si-wafers placed inside towers across a given period (usually months) and then counted at LMA Lab. One remark is that the quantity of particles differs significantly among the tested positions, while showing a similar distribution in size.

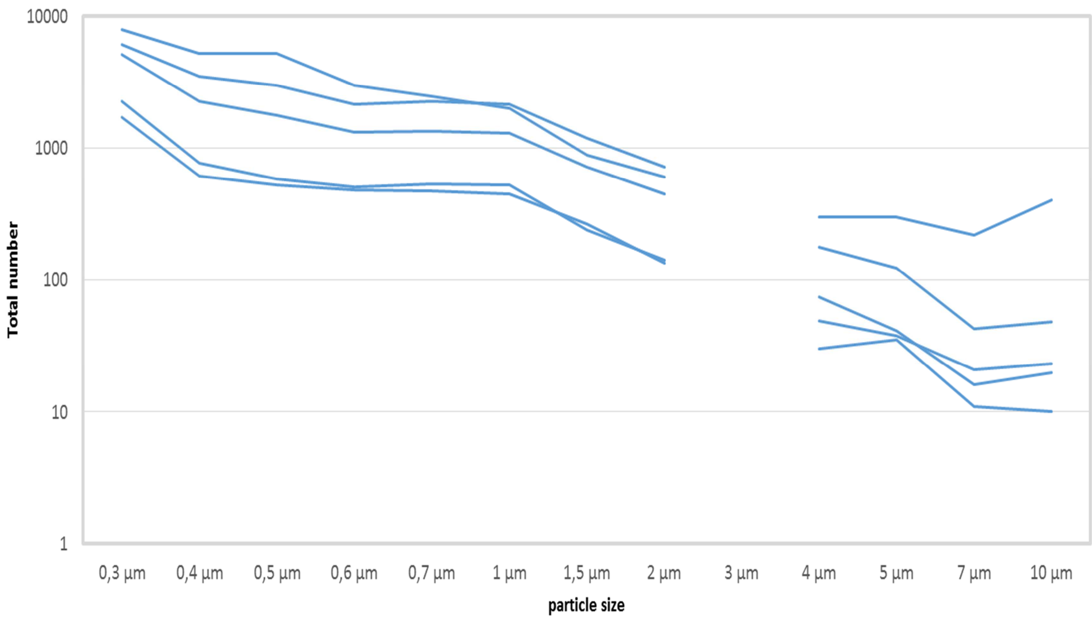


Figure 23: Number of particles counted on 3'' Si-wafers placed inside the WI tower over a period of about 4 months in 2008 (the 3 µm class has not been sampled). Different curves correspond to different positions. The details of operations performed during the test periods are not available.

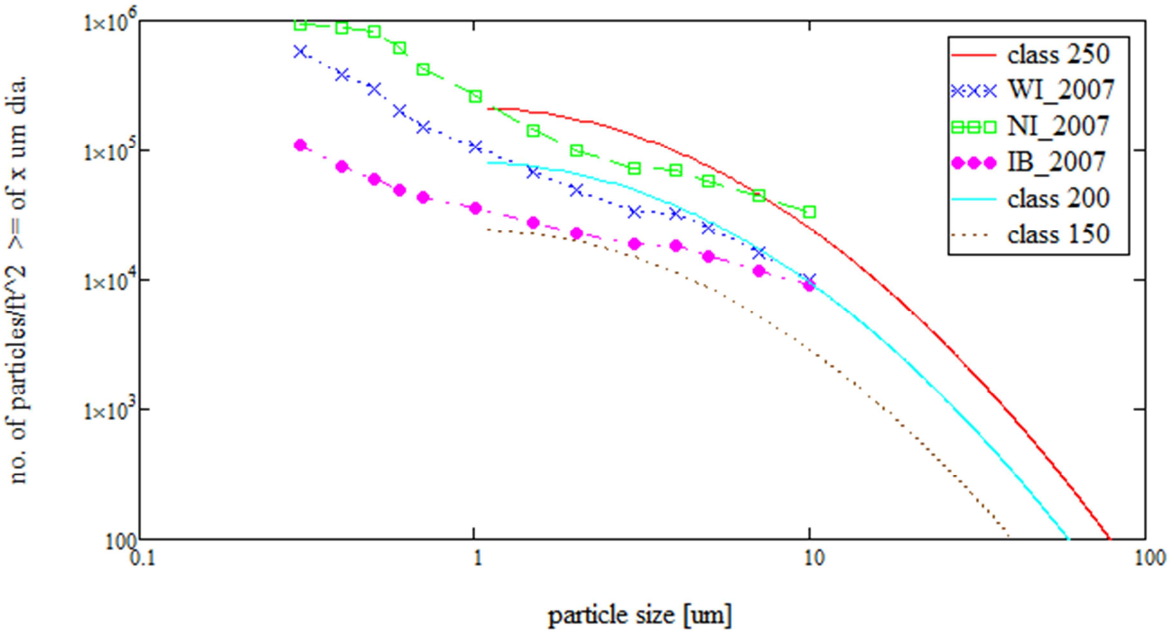


Figure 24: 3 towers measurements compared with reference curves MIL-STD-1246A (classes 150-200-250). With respect to the range of size considered until now, the standard is limited at 1 um and extended to much larger size.

Another example of the available data is shown in fig.24, where Si-wafers from three different towers are compared each other and vs an existing standard for surface particle contamination [11],[13] (here the size distribution is plotted in cumulative mode: > 0.3 µm, 0.4 µm, 0.5 µm, ...).

The continuous curves correspond to cleanliness level as defined by MIL-STD-1246A dedicated to dust control (general or space applications). The considered examples fall near "Particulate Cleanliness Level" = PCL 150 – 250.
The range covered by standard curves is shifted toward larger particle size and it is not valid below 1 µm. The distribution of particle sizes of the standard curves seems not closely corresponding to the given examples.

In conclusion:
_ to get a representative evaluation of the dust level in a tower chamber a minimum number of positions have to be tested. Normally we shall use the same positions in different towers .
_ the comparison with reference curves seems not straightforward, its usefulness will be appraised along with operations.

5.2.2 New tools for surface particles counting

The established procedure of dust control done via Si-wafers collection and offline measurements at LMA lab will be continued. This will remain a 'reference' method to characterize the dust concentration in towers with high accuracy. It is out of the scope of the present document.

An additional method to measure surface particles concentrations directly on site is needed to drive the operations during the cleaning process.

Two solutions are being prepared in parallel:
_an optical system based on a high quality camera coupled with a precision mechanical mount (suitable to count particles > 10 µm collected on Si-wafer samples). It is described elsewhere [4].
_a commercial probe used to adapt a 'standard' volumetric air counter for surface measurements. Some specifications of such a system are reported in appendix D.

5.2.3 Surface test procedure

The dust surface will be counted by one (or both) of the above mentioned devices.
At first we describe the case of the commercial probe:

i. The system is a portable one, and will be used directly inside tower chambers (the probe inside the chamber, the counter unit on the bottom flange). The mains and data cables will be routed to the nearby external sockets.

ii. We envisage two operation modes: a 'direct' one and a 'protocol' one.

a. '**Direct' mode test**
test directly tower walls (flat portions) . To be done during early cleaning operations. The aim is to provide a continuous feedback.

b. 'Protocol' mode test
A more controlled method will be needed in a second stage, to test the effect of vacuum/venting cycles.

- Make use of 6 test plate realized as in Fig.25 [14] , test surface ~ 2", equally distributed on the chamber floor (They are preferred to Si-wafers for this use because easier to handle inside towers while not intended for optical analysis)

- Measurement before and after each vacuum/venting cycle.
  Note : measure immediately after the opening of the tower access, BEFORE starting the clean air flow .

- The data will be automatically recorded through an ethernet connection and stored in Virgo frames .

Typically a measurement run will take ~ half an hour, to be done by two operators.

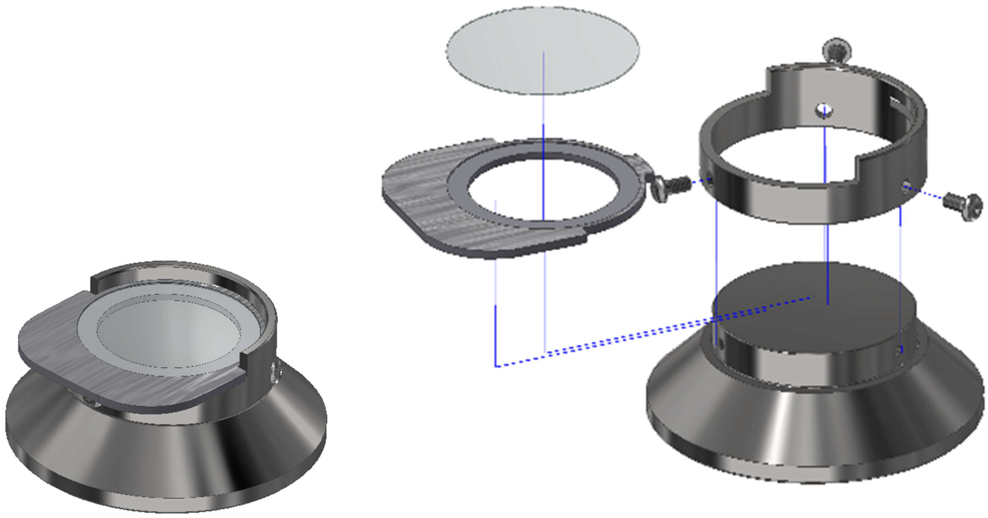


Figure 25: Test plates drawings: made out in stainless steel, 30mm high and 90mm in diameter, with engraved numbering identification. Test-surface Ø =2'' with roughness < 1 μm (dimension are similar to the probe aperture). The test plate can be used also as holder for 2" Si-wafer, adding a suitable ring + small sheet . The functionality of the present design will be verified directly on the first sample.

Concerning the use of the camera based system, the test procedure will be similar.

_The 'protocol' mode characterization will be done in a completely analogous way. As a difference, we will use 2" Si-wafers, and test plates shall become Si-wafer holders.
There will be the need to extract and transport the Si-wafer from the tower chamber to the camera setup, to be placed nearby inside the same cleanrooms.
The Si-wafers will be handled with the help of a suitable sheet (fig. 25) and will be stored/transported in their standard housing.

5.3 Proposed cleaning cycle for monolithic upgrade

Tools and operations shall be the same already in use.
A direct monitoring of the dust level along the process would be the principal upgrade of the proposed procedure.

The following stages are foreseen:

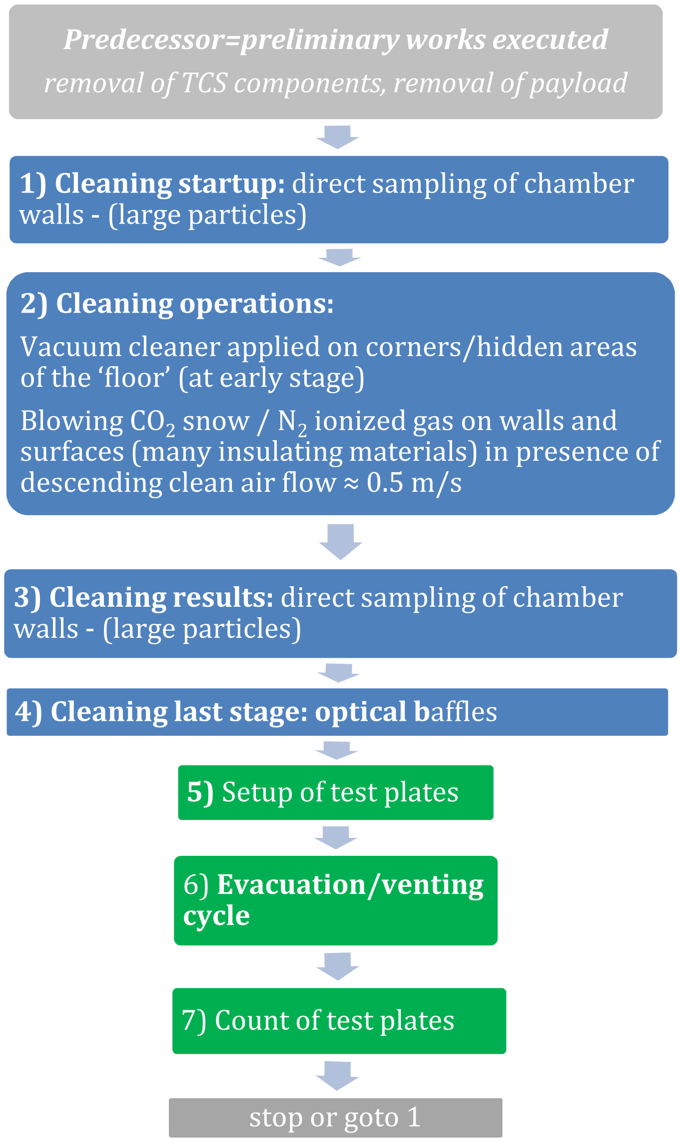


Figure 26: Tower cleaning stages.

<u>Remarks</u>
_The evacuation/venting cycle is not intended as a cleaning process (it will cause a displacement of particles, more than their removal). It is considered a verification step, to put in evidence the entity of residual migration effects.
_ The operation will focus on larger size particles (…, 7, 10+ µm) as the more dangerous ones. Smaller particles are likely difficult to be reduced (higher adhesion forces, electrostatic effects).

5.3.1 Special parts

Excluding payloads, that will be removed before the cleanliness intervention, the tower contains other critical parts that could interfere with cleaning operations: in-tower TCS optical components, and optical baffles, mounted at tower walls.
TCS components will be dismounted, together with payloads.

Optical baffles will remain in place. They will be subjected to the entire cleaning procedure:

- they will be exposed to the particles fallout during top-down blowing of tower walls. Even if mounted vertically a significant particles deposition is to be considered.
- The baffle cleaning will be the last operation of the cleaning process.
- Being made out of insulating glass, it will be necessary to use N2 ionized gun over all surfaces to displace particles. On the contrary, the use of CO2 snowgun is delicate, because easier to get cooling spots and moisture condensation effects. Wiping is not foreseen.
- The N2 ionized gun cleaning operation will be carried out by two operators, one using the volumetric particle counter close to the N2 gun to monitor the status of surfaces through the count of nearby in–air particles.

In addition, each tower contains:
The ‘stage #7’ complex, with articulated mechanical parts and hidden areas (Fig. 19).
It will be cleaned mostly with the CO2 snowgun with a special tool to reach its top face.
To be remarked that ‘stage #7’ is positioned at a quote above the inlet of ‘clean air’, so that particles removal will be aided mostly by gravity.
It will be processed with repeated applications.
Vacuum valves of diameter 200 mm, 400 mm, 600 mm respectively. They will not be dismounted, and will be kept in closed position, to maintain the tower chamber isolated. They will be cleaned mostly using the vacuum cleaner, taking care of removing possible debris near the seal areas.

In conclusion, there will remain some hidden areas difficult to reach and clean. We consider that dust in such spots will be likely less susceptible to migrate.

5.4 Data management for dust control

The measurements will produce a series of data structured as shown in table 2. The instrument will be interfaced with the Virgo DAQ and data written in the ‘slow data’ frames. There will be flags to indicate the pertinent tower and position, a short description of the intervention type, and finally the insertion/removal dates of the test plates shall be recorded (for instance from GPS times). A proper SW will allow to retrieve present and old data to build time trend plots .

Tower X	Intervention type: **vacuum/venting**							Intervention type**: equipment tuning**						
	Initialization date: **dd-mm-aaaa**							Initialization date: **dd-mm-aaaa**						
	Removal date: **dd-mm-aaaa**							Removal date: **dd-mm-aaaa**						
data	0.3	0.5	1	3	5	10+	Valid	0.3	0.5	1	3	5	10+	Notes
Pos.1	**900**	**620**	**300**	**20**	**30**	**50**	**Y**	...	...	...	...	...	...	...
Pos.2	**800**	**420**	**300**	**20**	**30**	**50**	**Y**	...	...	...	...	...	...	...
Pos.3	**700**	**520**	**300**	**20**	**30**	**50**	**Y**	...	...	...	...	...	...	...
Pos.4	**500**	**620**	**300**	**20**	**30**	**50**	**None**	...	...	...	...	...	...	...
Pos.5	**900**	**1200**	**900**	**100**	**90**	**90**	**N**	...	...	...	...	...	...	...
Pos.6	_	_	_	_	_	_	**N**	...	...	...	...	...	...	...
Pos.7	**500**	**620**	**300**	**20**	**30**	**50**	**Y**	...	...	...	...	...	...	...

Table 2 for each operation we will record 7 positions (6 + 1 spare) and their relevant data (printed in bold).

5.5 Plan

Processing a single tower will take ≈ 7 - 8 days (main cleaning stage + 2 evacuation cycles + 1 day for leak testing of new joints), to be tuned with real experience. The clean operation team will be fully involved (2 people) during the first cleaning stage , while the evacuation will be driven by a vacuum technician, with the involvement of clean operators for the in tower dust measurements at the end of each cycle (0.5 days).

Risks: Effectiveness of the cleanliness operations will be known during the process itself. Performances and duration of the cleaning operation could vary.

Costs: the procurement of dust analysis tools (camera based equipment, commercial probe) are intended a 'laboratory investment' and are considered separately from the present CRQ document. Their cost is modest.

6 Construction Plan Summary

A summary of the deliverables is presented below, together with the estimated costs and installation time duration.

Deliverable	Cost (keur)	Integration task (days duration)	notes
Venting equipment	30.5	2 days per tower	Shields 10.5, pipe 5.5, valves 14.5 (7 towers)
DRY pumps	55	0.5 days per tower	10 units
Pumping piping – frame support	5	2 days per tower	Other parts are already available
Control system upgrade	7	0.5 days per tower	Preparatory works anticipated
Tower extraordinary cleaning	_	8 days per tower	Can progress also during week end (vacuum/venting cycles)
Total	97.5	_	

Table 3: Costs (taxes excluded) and integration durations of main deliverables

Piping of venting and pumping will be installed in parallel (2 days foreseen, 4 people team); the connection of pump and control system will be relatively short. The activity about the control system will be mostly anticipated .

Other tasks not reported in the table are:

_ A series of tests with the 'surface probe' are foreseen starting from mid July (order placed).

_ Piping mounting test: a prototype of pumping pipe has been purchased and is being mounted as a prototype.

Resources: the upgrade task it will require the entire effort of the Vacuum + Clean operation teams. In addition 1 Technician from external company will join for mechanical integration.

Other contributions will come from 0.25 FTE of Genova Technician and 0.5 FTE from EGO operation team.

1 FTE will be contributed from the EGO electronics team for cabling.

A total of 12 days is envisaged to implement all the modifications (venting circuit, pumping substitution, extraordinary cleaning) to a tower.

A view of the general planning is reported in fig. 27, (where other preparatory works are reported).

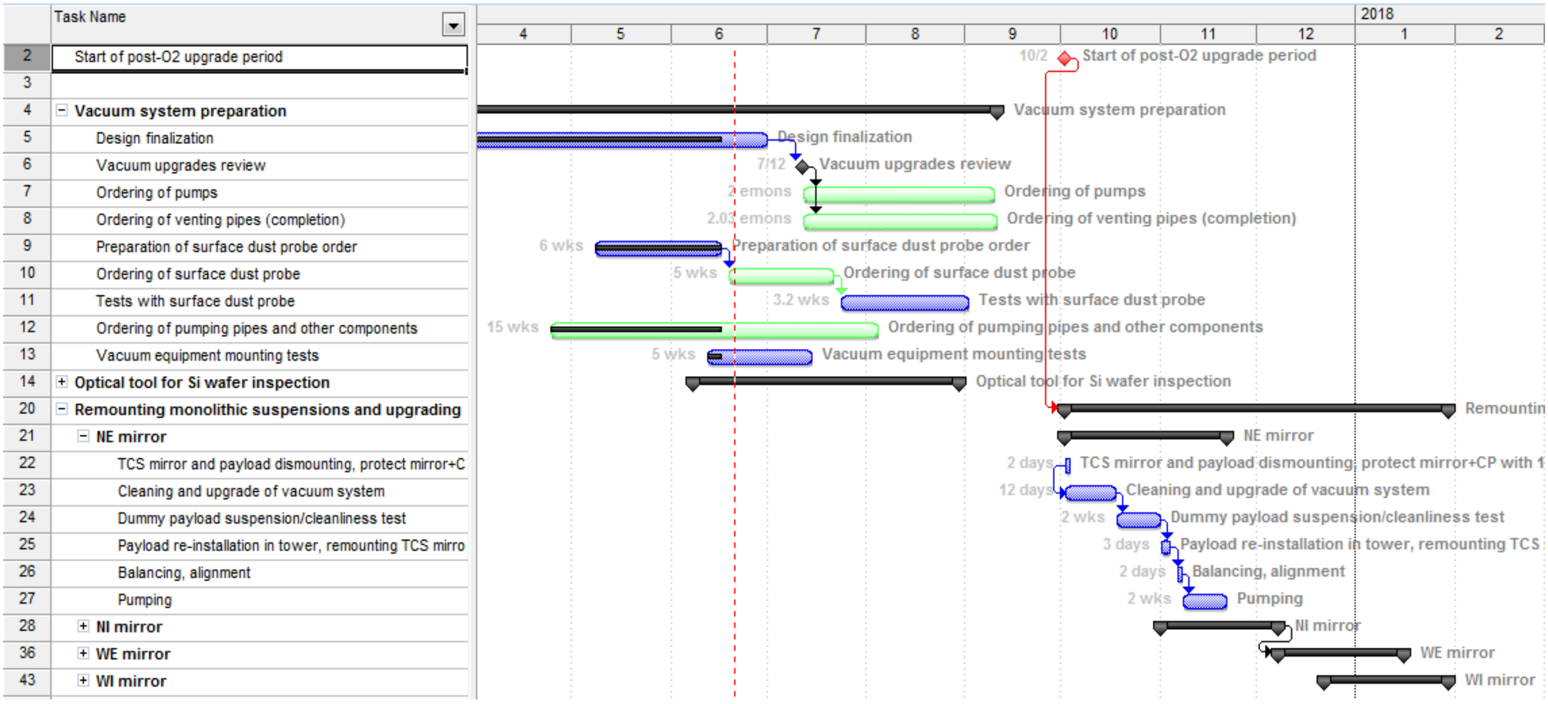


Figure 27: Implementation Plan of Vacuum modifications

Appendix A – Tower chamber

The vacuum towers have been conceived to host in vacuum the interferometer optical elements and their antiseismic suspensions, called Superattenuators (SA). The various optical elements require seismic isolation at different levels, hence SA's and the respective towers have different height. The main mirrors (Beam Splitter, Power Recycling, North Input, North End, West Input and West End), acting as gravitational test masses, have long suspensions inside 11 m high towers (Mirror towers). The Mode Cleaner mirror, the Input Bench and the Detection Bench have short suspensions and 6 m tall towers (Bench towers). A tower chamber (mirror tower) is shown in the following picture, chamber alone on the left and equipped with main experimental apparatus on the right.

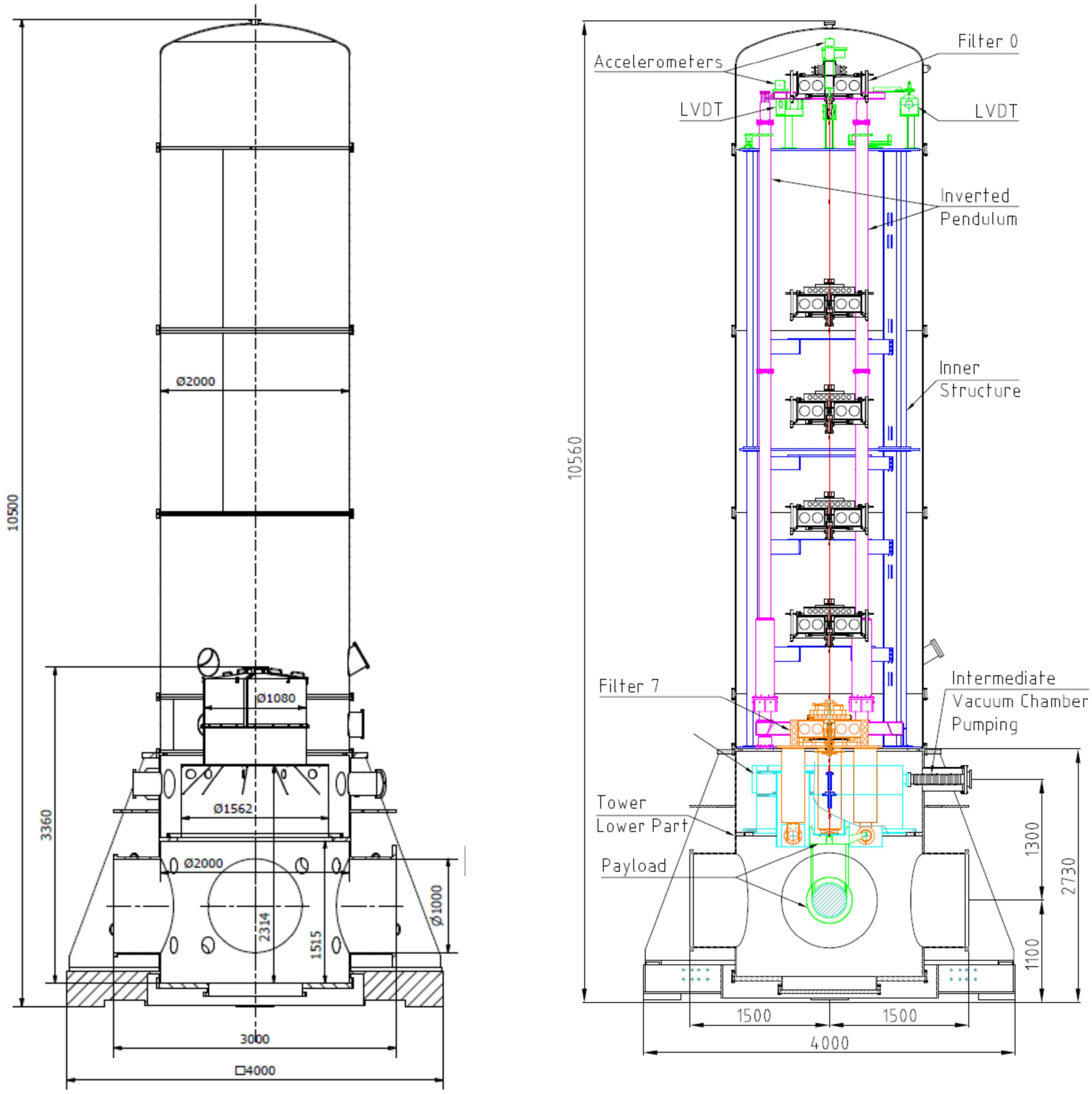


Figure A1

The mirrors towers are divided in two compartments: the lower one containing the mirror itself plus the stage of the suspension (stage #7) at a Vacuum level of ~ 10^{-8} mbar and the upper one containing the electromechanical elements of the suspensions at a Vacuum level of ~ 10^{-6} mbar. They are connected just by a small hole for passage of the main suspension wire.

In order to keep the conductance between the compartments as low as possible, the hole is equipped by an 80 cm long "conductance pipe".

The tower lower compartment consists of a cylindrical tank (2000 mm diameter, 2740 mm height, 15 mm wall thickness), having four large perpendicular ports, in the horizontal plane, at the interferometer beam level, i.e. 1100 mm above the building floor. The ports are used for the passage of the main interferometer beams, through the link tubes. Several smaller ports and optical windows are present for the other control beams and cameras, and for the pumping system.

The bottom floor of the tower has a 1 m diameter aperture, closed by a flange. The 1 m aperture allows the installation of the payload from below, through the clean gallery existing under the floor of the buildings.

The tower upper compartment is composed by a series of 4 cylindrical rings (2000 mm diameter) plus a cupola.

The upper and the lower compartments are pumped by two similar groups, each one made of magnetic bearing hybrid turbomolecular pump (a 1600 l/s for the upper one, 400 l/s for the lower one, respectively) and of a 25 m^3/h scroll pump, serving both as roughing pump and backing pump.

The tower lower compartment is then connected to the entire vacuum system, where large cryogenic pumps and additional turbomolecular pumps further increase the pumping speed.

Once in standard operation conditions, the scroll pump is stopped because disturbing the experiment with produced acoustic/seismic noise, and it is substituted by another backing pump remotely positioned in an insulated room, serving all the towers.

Roughing and venting processes take about 15 hours, and are normally executed overnight.

Once vented, the tower lower part becomes a cleanroom and can be accessed by operators to install or adjust the optical and mechanical components:

To prevent dust entrance, each tower is equipped with two 200 mm pipes blowing-in 1200 m^3/h of HEPA filtered air, derived from the main clean room air system. In this way, when the tower lower compartment is opened, the filtered air flow acts as an air shower, keeping clean components and operators entering from the underneath clean gallery. In order to establish a convenient circulation of clean air, appropriate apertures, close to the gallery floor, suck-in air returning it to the filter units. The established regime is not at all a regular laminar flow, due to the insufficient inlet aperture and to the relatively large dimensions of payload and operators, with respect to the UHV chamber.

Appendix B - CFD study of venting port

Simulation parameters:

Base pressure	1 mbar
Air flux (inlet to lower compartment)	10 Pa $m^3/s(10^{-4}$ kg/s)
Gravity	none
Turbulence model	k-ω
Main chamber volume	~ 0.4 m^3
Model type	2D – axially symmetric
Viscosity and density	embedded table from material [air]
Temperature	300 K

Particle simulation parameters:

Particle density	2200 kg/m^3
Particle diameter	10 um
Total number of particles	250
Particle-particle interaction	none
Particle-wall interaction	Diffuse scattering (inelastic)
Charge on particles	none
Particle-flow drag force model	Stokes

Mesh density is rather high and was set to ensure stability and rapid conversion of the CFD solution. Particles tracing is run for 0.4 seconds.

Test configurations

Configuration	First impact shield	Grid	Deflector shield
Test 1	X	X	X
Test 2		X	X
Test 3			X
Test 4	X		
Test 5	X	X	
Test 6	X		X

Results

Conf. #4 and #5 are not recommended because of the high directionality and speed of the final particle flow.

Conf. #2 and #6 are very similar to the reference configuration (#1).

Conf #3 is in the middle, although the slightly lower dispersion and higher particle velocity would make us lean towards the rejection of the configuration.

The presence of a grid does not seem to improve on the quality of the dispersion and particle speed. This statement though is biased by the axially symmetric modeling, in which the grid is represented as a sequence of circular slits. Besides, mesh and computational speed considerations made us limit the slit size (in our simulation the slit width and the radial spacing are both 2.5 mm).

A closer look at the comparison between air and particle velocity suggests that after some number of inelastic scattering, particles and air speed are approximately equal.

A selection of cases are shown in the following plots.

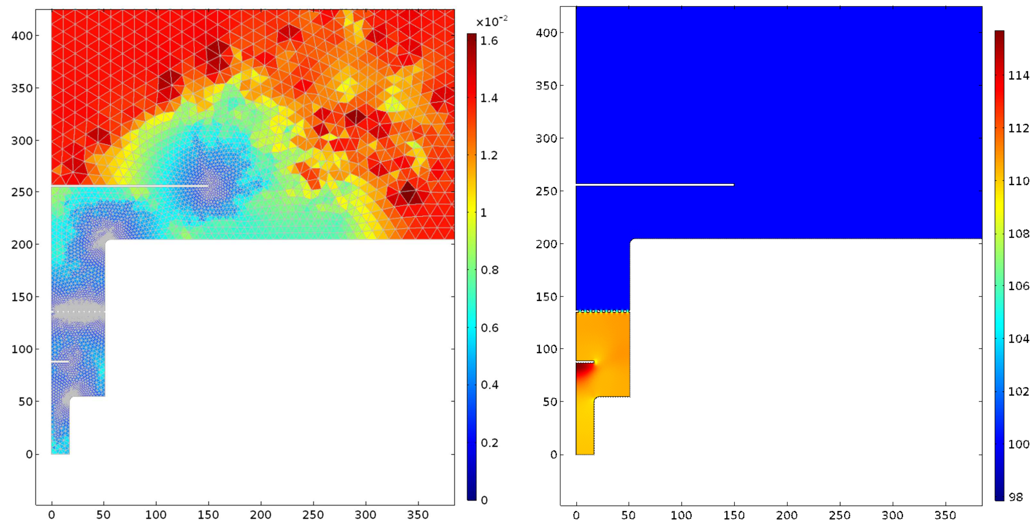


Figure B1 Mesh (left) and pressure (Pa) of cases #1.

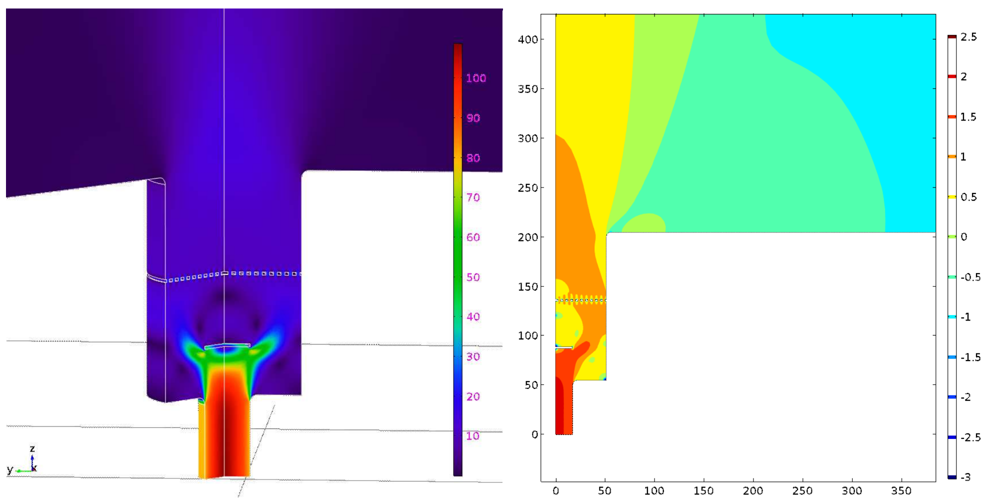


Figure B2 Flow pattern of case #5. Colors represent the velocity magnitude Velocity in linear and 10-based-logarithmic scale.

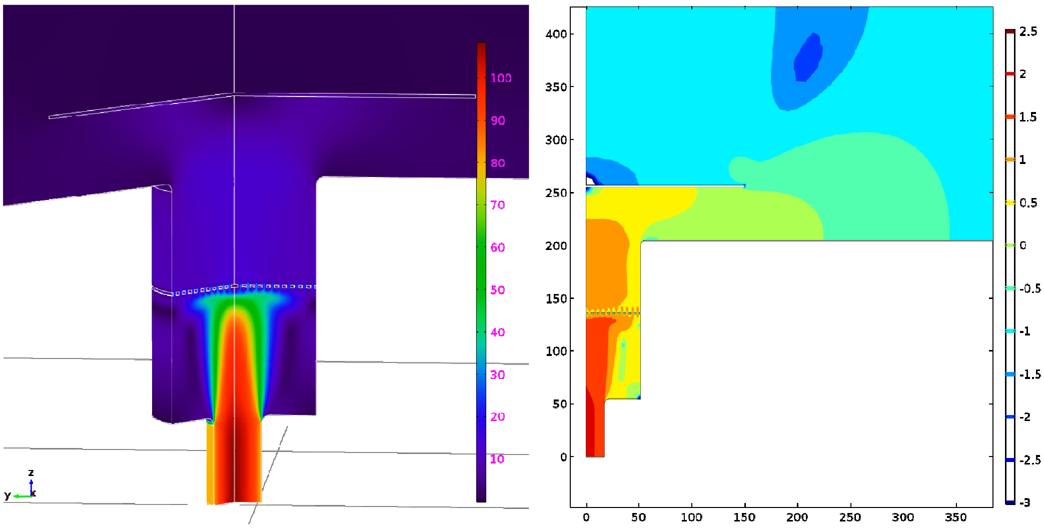


Figure B3 Flow pattern of case #2. Colors represent the velocity magnitude in linear and 10-based-logarithmic scale.

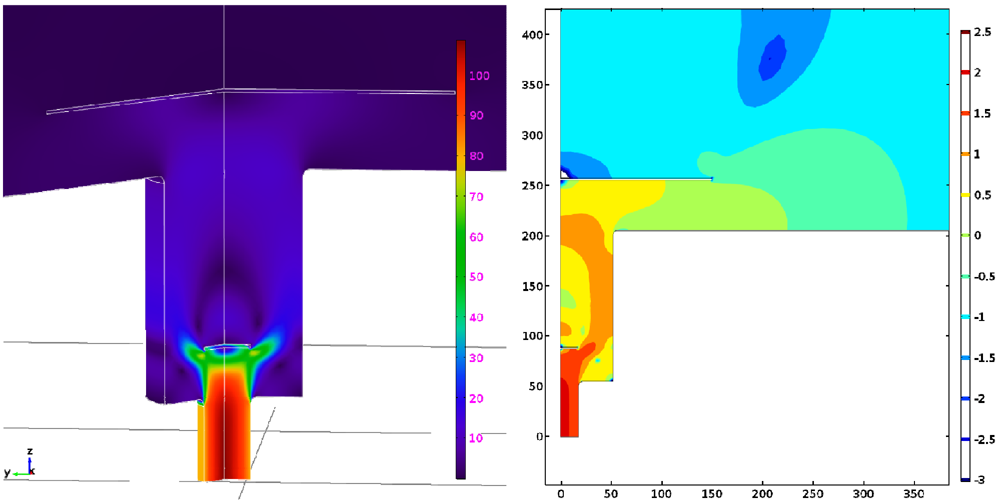


Figure B4 Flow pattern of case #6. Colors represent the velocity magnitude in linear and 10-based-logarithmic scale.

Appendix C

Tower Cleaning Procedure for Monolithic upgrade

All preparation must be in compliance with the Dust Control protocols [16].
The following steps are to be executed:

Preparation

1. *Cleaning of the area around the tower by mopping (2% Cleaner detergent in DI water)*
2. *Cleaning of the Hymo lifting platform by wiping (cellulose tissue with pure isopropyl alcohol) and by using the vacuum cleaner* ***at least one day before the opening of the tower***

Cleaning

3. *Opening of the tower bottom flange*
4. *Startup of the clean air flushing inside the tower*
5. *Maintain the clean air circulation in the tower during the whole intervention (air-blowing is expected to transport outside the dust particles generated during the intervention).*
6. *Make use of the volumetric counter. Keep it running not directly exposed to the 'air shower' flux.*
7. *Make use of surface counter and measure a few positions on chamber vertical walls and of suspension stage#7 (cage, TBC), tower floor . Record data (in local) as Run 0*
8. *Wiping: to be applied only on clean air ports, with lint free tissue and isopropanol.*
9. *Start the CO2 phase: Apply the* CO_2 *snow to the selected elements in top-down direction, wait about 20 minutes (to allow the clean air circulation in the tower) and blow again until obtaining a suitable particle count on surface counter (*).*
   Process the following elements in the indicated sequence:
   Suspension Stage #7
   Chamber walls
10. *(*) Make use of surface counter and measure a few positions. Compare data with Run 0.*
11. *Cleaning of the vacuum valves and links nearby surfaces by using the vacuum cleaner only*
12. *Cleaning of the tower chamber floor by using the vacuum cleaner only*

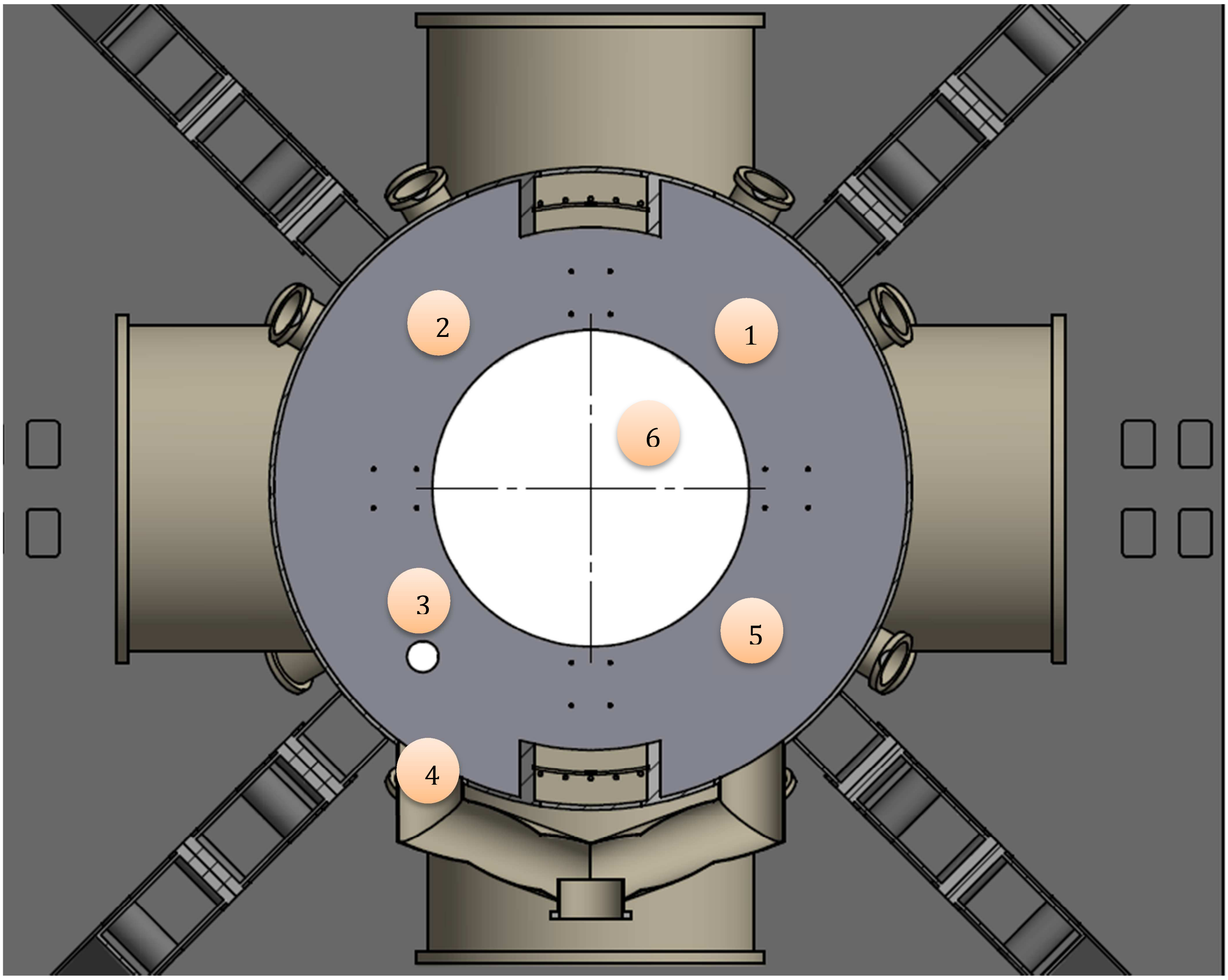
Verification

13. *Position the test plates and initialize them (use a form similar to the attached one), record the data as Ver0*
14. *Close the tower , stop the flushing air*
15. *Execute the Vacuum/Venting cycle*
16. *Opening of the tower bottom flange*
17. *Measure the test plates directly inside the tower, record data as Ver1 , compare with Ver0*
18. *Start and maintain the clean air flushing inside the tower*
19. Evaluate surface dust concentration, if considered convenient, goto 7.

TEST PLATES POSITIONS FORM

TOWER …………………………..

DATE: ……………………………..



NOTES:

Appendix D – Surface probe

Partikelmessung auf Oberflächen DLS / VFP
Particlemeasurement on surfaces DLS / VFP

CCI – von Kahlden GmbH

Vergleich DLS / VFP

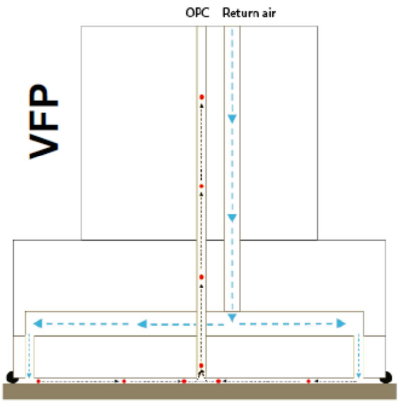
CCI bietet ein breites Sortiment an Probenahmesonden mit unterschiedlichen Durchmessern und Arbeitsweisen. Die PCU ist ein essentielles Bestandteil des Messsystems, da sie den Volumenstrom für die Probenahmesonden steuert.

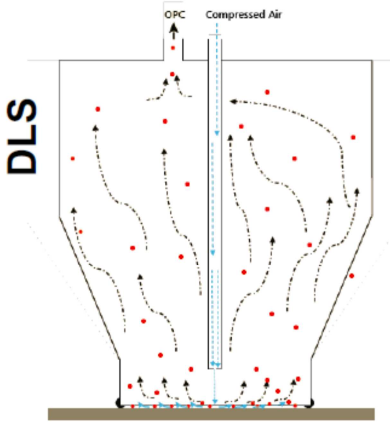
VFP vs. DLS: Beide Probenahmesonden nutzen Luft um Partikel von der Oberfläche zu lösen und diese mit dem optischen Partikelzähler zu zählen. Die VFP-Probenahmesonde nutz die gefilterte Rückluft des Partikelzählers, wohingegen die DLS-Sonde gefilterte Druckluft verwendet. Die Druckluft wird in der Sonde durch eine Düse auf die Oberfläche geschossen, welche sehr hohe Luftgeschwindigkeiten erzeugt und somit eine höhere Ablösekraft ermöglicht. Die Ablöserate der DLS liegt etwa bei 300% im Vergleich zu einer VFP-Sonde. Der Düsenkopf der DLS-Sonde kann abgesenkt werden im Vertiefungen wie Löcher oder Gewinde besser messen zu können. Die saubere Druckluft muss vor Ort zur Verfügung gestellt werden und kann nicht durch das System erzeugt werden.

Comparison DLS / VFP

CCI provides a wide range of probes with different diameters and with different working methods. The air flow of all probes is controlled by the PCU which is an essential part of the measuring system.

VFP vs. DLS: Both probes use air to remove the particles from the surface. The VFP probes use the filtered return air of the particle counter to remove the particles from the surface whereas the DLS uses compressed air. The compressed air is shot through a nozzle to reach high velocity and as result more force to remove particles. Due to the higher forces the DLS has a higher remove rate, which is about 300% compared to the VFP probes. The nozzle of the DLS-probe can be lowered to reach inside holes or threads. The clean compressed air must be provided on site which makes the system a bit less mobile compared to the VFP probe.





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