

# Central Vacuum System PRE-TDR

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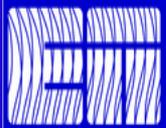
## **IV WShop on ET-LF TM Tower Integration**

*18 - 20 Mar 2026*

*Room 131 - Galileo Galilei (ground floor) INFN Sezione di Pisa*

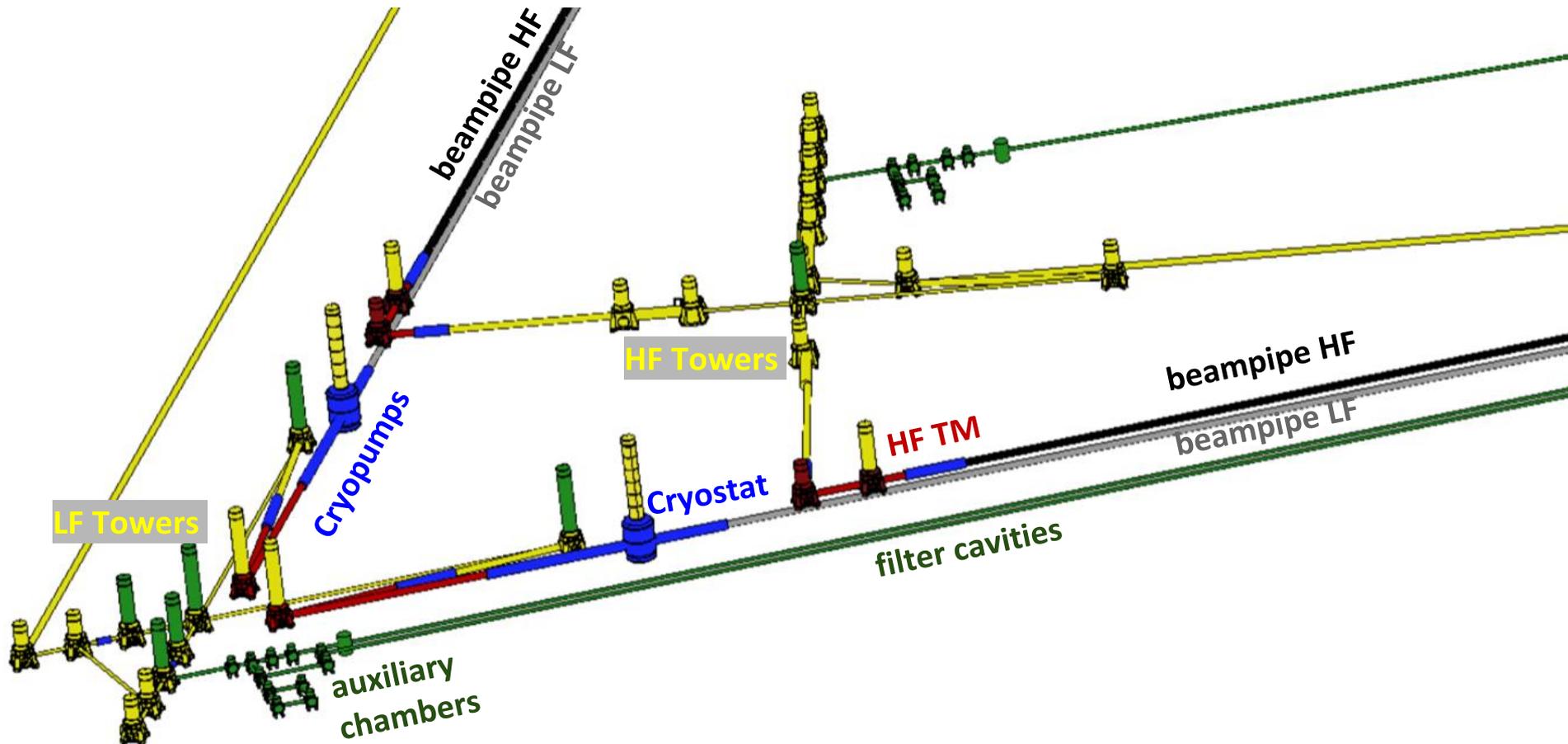
**A.Buggiani, J.Gargiulo, A.Pasqualetti , T.Zelenova and J.Wolf  
on behalf of WPIV.1 – ET Collaboration**

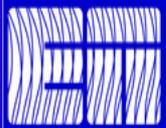
1. **Central Vacuum: items, battery limits , ET-LF case - *no news here***
2. **Residual pressure levels (requirements & design values)**
3. ***ET-LF 'shell' – Credits G.laquaniello***
4. **Baseline tower design/Alternative concepts**
5. **Contamination Control – Dust particles, Low-volatiles**
6. **ET-HF Highlights: TM towers 2L**
7. **LINKS – fully integrated in the central vacuum system - *no news here***
8. **Leaks!**
9. **Pumping: conventional, auxiliary cryopumps**
  - **1500W facility**



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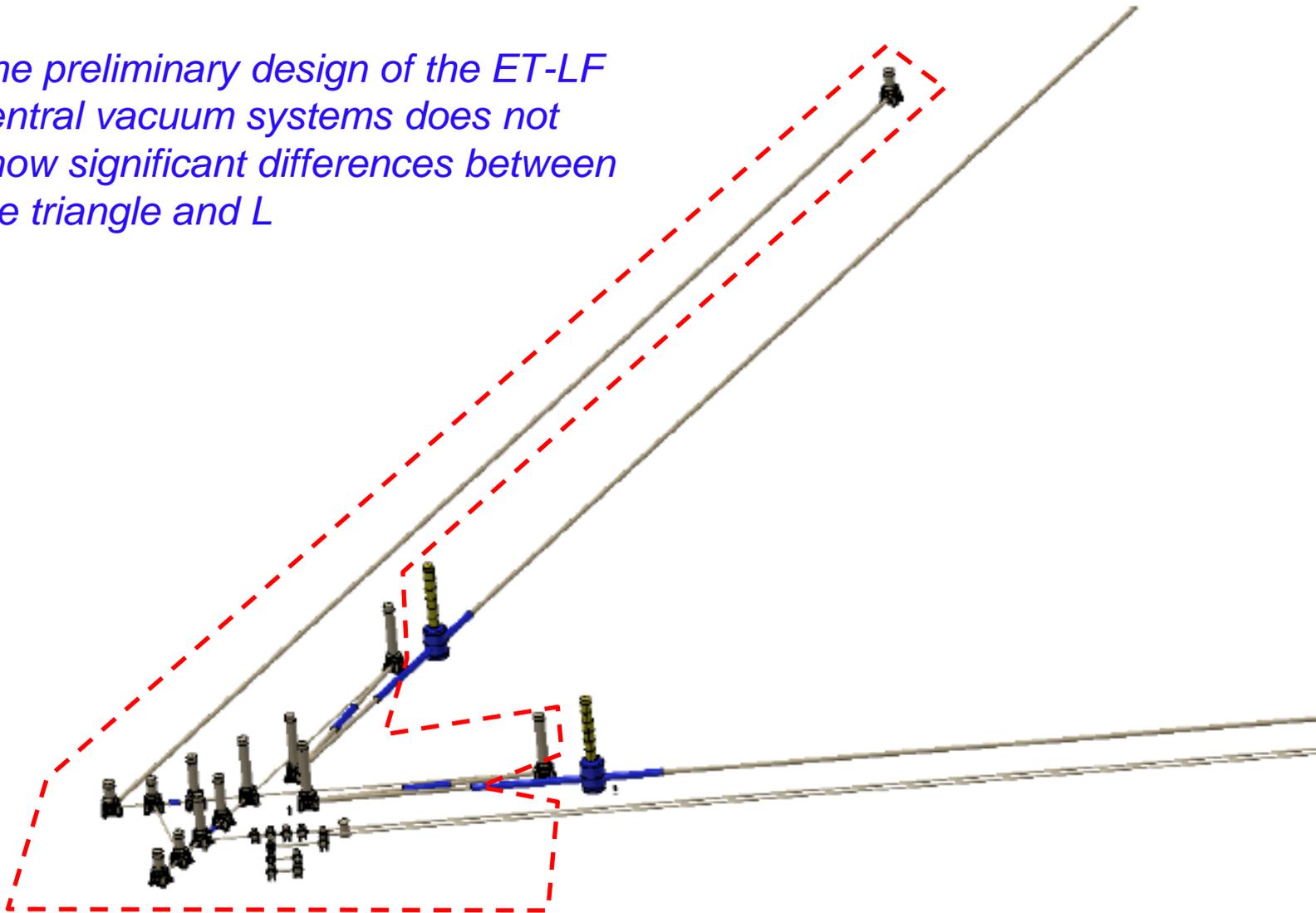
# CENTRAL VACUUM

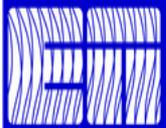




# CENTRAL VACUUM vs L

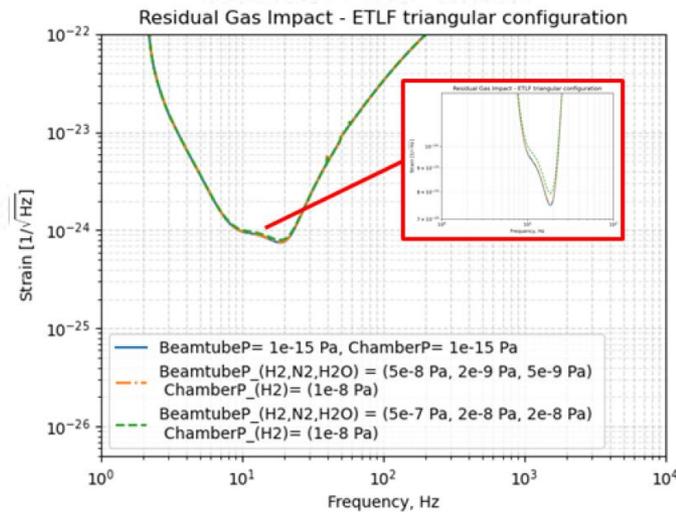
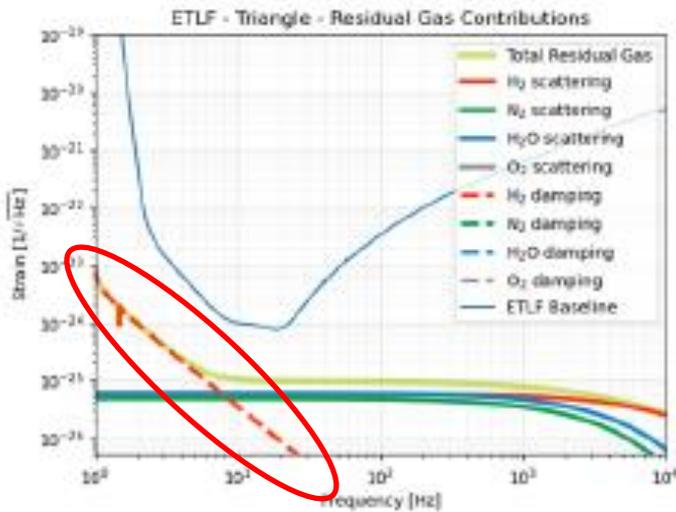
*The preliminary design of the ET-LF central vacuum systems does not show significant differences between the triangle and L*





# RESIDUAL GAS IN CENTRAL AREA

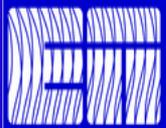
**DIRECT REQUIREMENTS (INTRINSIC NOISE COMPARED TO REF. SENSITIVITY)  
+ DERIVED REQUIREMENTS (INTERFACES CONSTRAINTS) →  
DESIGN VALUES (DESIGN MARGIN + LONG TERM PERFORMANCES)**



About Cryosorption on the cryogenic Mirror:

The main requirement applies to the HR surface of the mirror (the one facing the beampipe), while it is likely more relaxed for the not-HR surface (the one facing the other towers), as the incident power is much lower and the associated optical requirements are likely less stringent.

The tolerance to surface deposition on not-HR remains to be assessed.



# LF CENTRAL AREA (PRE-TDR)

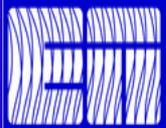
17 main Towers are foreseen for the LF interferometer, together with interconnecting pipes (links) and smaller SQZ and auxiliary chambers [1].

Description	Access	Largest piece [m]	Number of units
<b>LF interferometer</b>			
Main (cryogenic towers)	bottom	Sec. 3.2.12.7.2	4
Main (warm towers)	lateral	4 × 4 × 3.2	13
SQZ tanks	side, no entering	2.5 × 2.5 × 2	15
Auxiliary chambers	side, no entering	2.5 × 2.5 × 2	17

Table 3.20: Statistics of vacuum chambers for each LF interferometer - Calculated for the L configuration, almost equivalent for the Triangle.

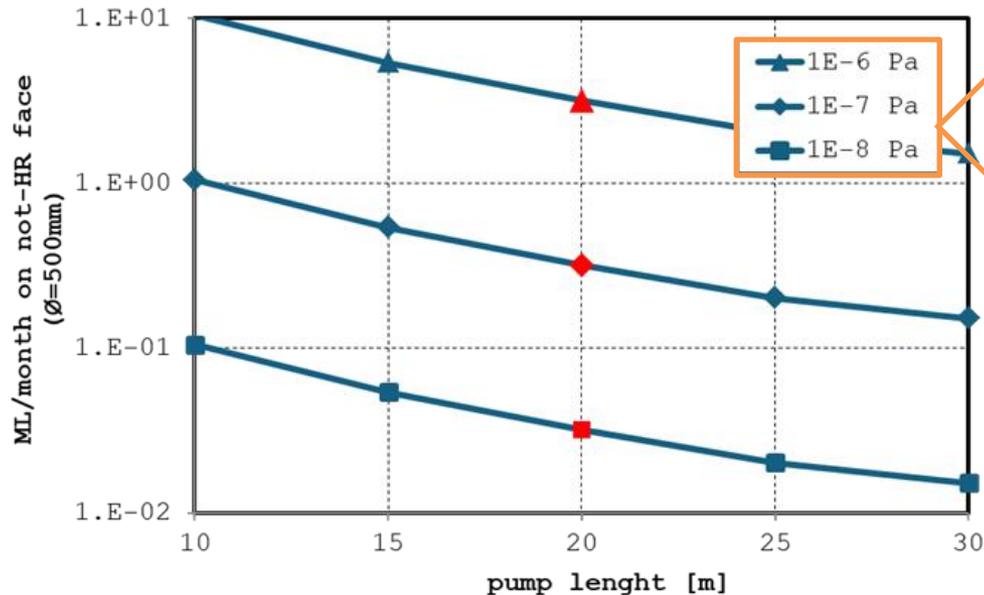
Table 3.21: Vacuum level targets in the central area. For the LF-TM regions, see also the preceding paragraph on pressure requirements. All values are to be confirmed during the finalization phase.

System / Area	Pressure Target [Pa]	Notes
<b>LF-TM region</b>	$2 \times 10^{-8}$	H <sub>2</sub> Gas damping
	$1 \times 10^{-12}$	N <sub>2</sub> + others, condensation
<b>Steering towers</b>	–	Intermediate between BS and TM towers
<b>BS and upstream towers</b>	$1 \times 10^{-6}$	Total Pressure (lower compartments)
	$1 \times 10^{-5}$	Gas damping (preliminary)
<b>Filter cavities</b>	$1 \times 10^{-5}$	N <sub>2</sub> , extrapolated from 2G
<b>Auxiliary vessels</b>	$1 \times 10^2$	N <sub>2</sub> , acoustic isolation



# RESIDUAL GAS IN CENTRAL AREA

Example: condensation on TM mirror not-HR side. Approx. water deposit on cryogenic mirror (the not-HR side) at CONSTANT upstream pressures. A ~few ML/year @ 1E-7 Pa of water (40m long link).



*Water pressure in the tower adjacent to the LF\_TM tower, on the central vacuum side*

### About Cryosorption on the cryogenic Mirror:

The main requirement applies to the HR surface of the mirror (the one facing the beampipe), while it is likely more relaxed for the not-HR surface (the one facing the other towers), as the incident power is much lower and the associated optical requirements are likely less stringent.

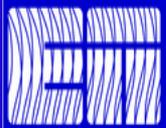
The tolerance to surface deposition on not-HR remains to be assessed. **ALLOWABLE ML TO BE SET**



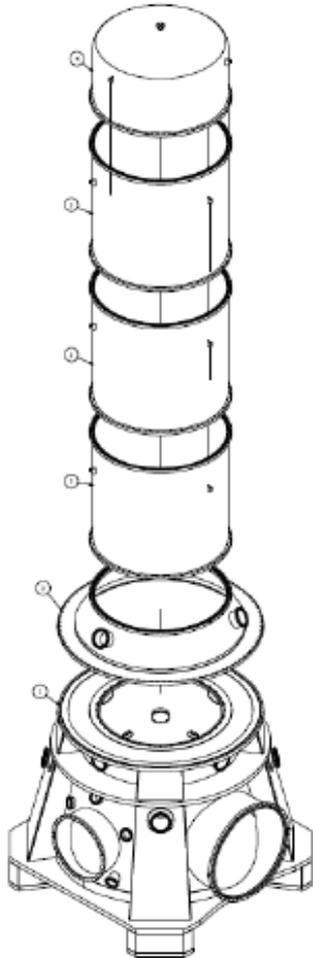
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# RESIDUAL GAS IN CENTRAL AREA

HF case, see directly the pre-TDR document



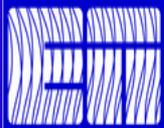
# WARM CHAMBERS BASELINE



Feature	Comment
Base material	Austenitic SS AISI 304L / EN 1.4307 (X2CrNi18-9)
Compartments	2
Access	Lateral or Bottom
Surface conditioning	$Ra \leq 0.8 \mu m$
Surface particle cleaning	ISO 14644-9 , SCP 3 grade
Surface chemical cleanliness	ISO 14644-10, NVR $< 1 \text{ mg/m}^2 (< 1 \text{ ML}) + \text{bake-out}$
Mechanical structure	Interface to suspension: tilt $< 250 \mu rad$ & 1st mode $> 20 \text{ Hz}$ (TBC)
Rated environment	ISO Class 5 cleanroom-compatible operations
Safety	Configured for personnel operation in confined spaces
Outgassing rate	$1 \times 10^{-12} \frac{\text{mbar} \cdot \text{cm}^2}{\text{s}}$ $< 1 \times 10^{-9} \text{ Pa} \cdot \text{m/s H}_2$ ; $< 5 \times 10^{-8} \text{ Pa} \cdot \text{m/s H}_2\text{O (unbaked @ 100 h)}$

Table 3.22: Main features of the baseline tower design

tower chamber (warm tower chambe

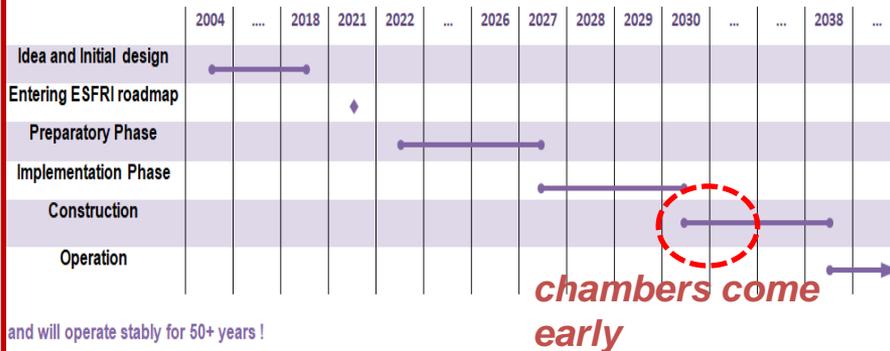


## *Need to align with industry for realistic plans and sound requirements*

### Ultra-high production rates:

#### Chambers per month = ?

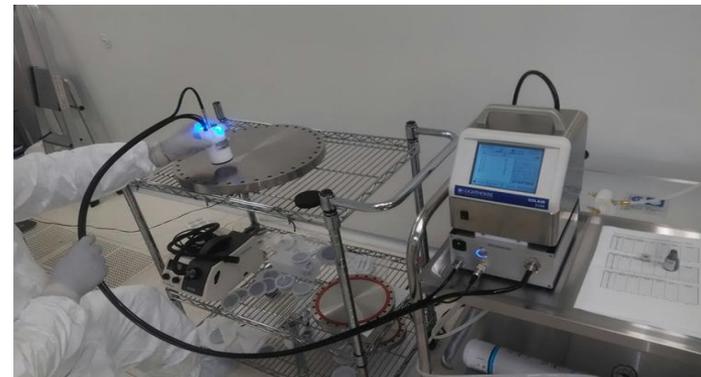
- demand for standardization
- engagement of major companies or consortia
- specific contracts covering years-long production and installation coordination



and will operate stably for 50+ years !

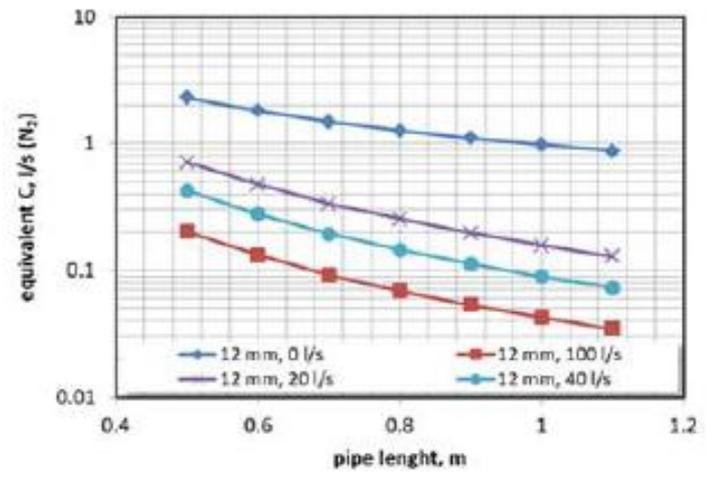
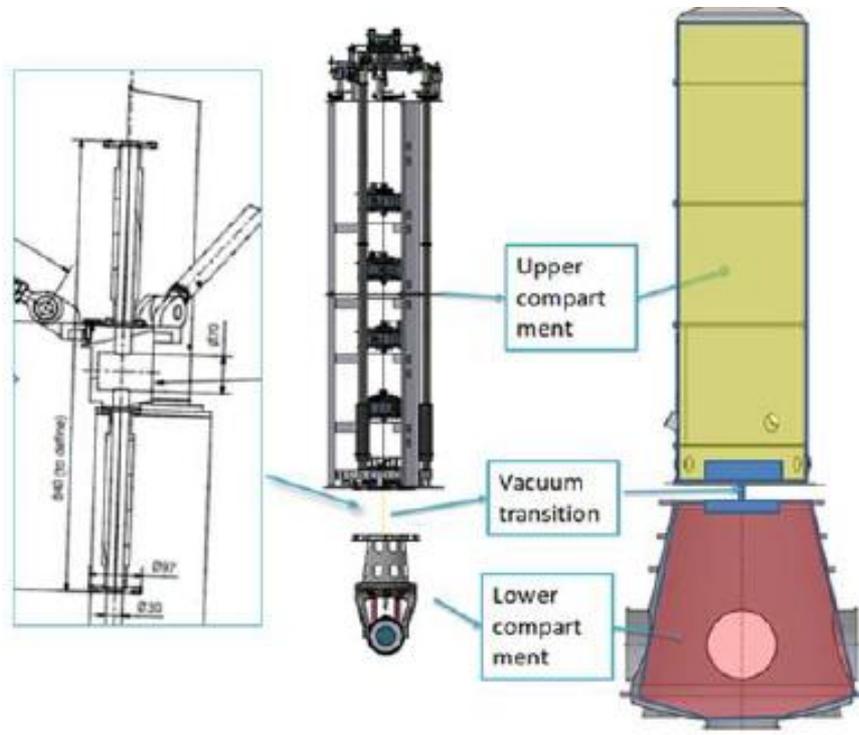
### Requirements for manufacturing:

- **Base material:**  
304L stainless steel, hot-rolled, up to 15 mm thick. Roughness (Ra) reduced to ~1 µm . Baked una-tantum. Large parts !
- ❗ **Surface finish: *Looking for novel methods* .**
- ❗ **Cleanliness: particle concentration level on the chamber walls should be added** (reference could be ISO 14644-9:2022). Specification of Low-Volatile contaminants as well (e.g. ISO 14644-10).



# Main warm towers chambers

- The baseline solution, no news here



- Other design solutions can be prepared : next talk

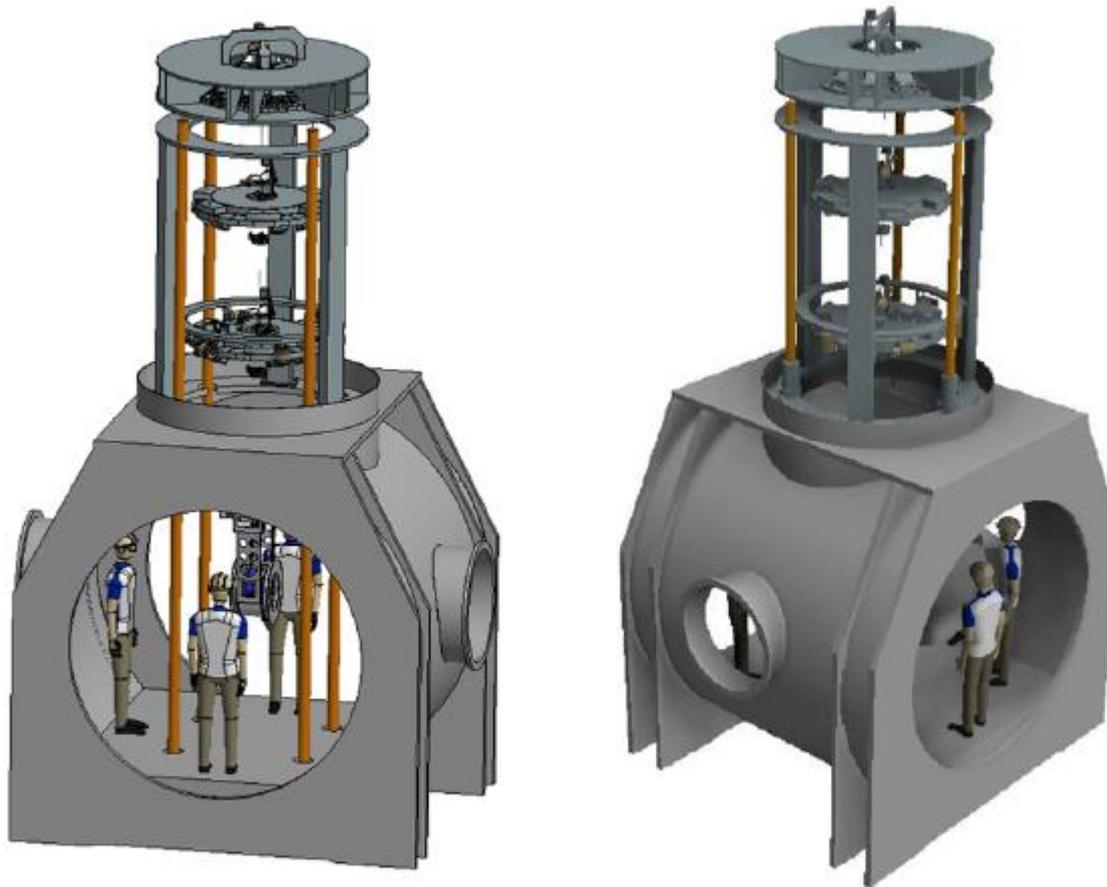
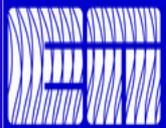


Figure 3.105: Alternative concepts. Chamber design can be adapted to different types of suspensions and alternative optical solutions such as large benches. The concepts shown here are for illustrative purposes only.



# DUST CONTROL

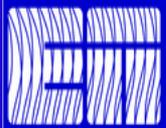
A *technical surface* is defined as any non-optical surface. Specifically, these are the internal surface of the vacuum chambers and vacuum-system components. Other surfaces inside the vacuum, such as benches, payload mechanics, and elements of the suspensions, fall within the same category.

Tower types / zones and assigned grades		
Test Mass Tower	Main optics	Grade A
Bench Towers	Full personnel access	Grade B
Upper compartments	Hosting suspensions	Grade C
Auxiliary chambers	Partial personnel access	Grade C

Grade	ISO Class in Operational Mode	In-vacuum equipment	CL (After Assembly)	CL (To be cleaned)
Grade A	ISO 5	ITF Vacuum system - Mirror compartment	< Level 100	Level 150
Grade B	ISO 5	ITF Vacuum System - Bench compartment	< Level 100	Level 250
Grade C	ISO 6 / ISO 7	ITF Vacuum System - Upper compartment hosting suspensions and Auxiliary Vacuum System	< Level 200	Level 350

Table 3.28: Cleanliness Grades and Application. The cleanliness class of the environment is indicated, along the minimum and maximum allowable cleanliness level of the technical surfaces.

**Quite stringent**



# CHAMBERS ACCESS

	Bottom Access	Lateral Access
<u>Configuration</u>	Requires a dedicated room underneath the chamber and elevators for personnel.	Requires a dedicated side room: additional floor space in the experimental hall is needed for this.
<u>Suitable for</u>	Virgo-style payloads (vertical, top-mounted).	LIGO-style payloads (bench-mounted), where bottom access is obstructed.
<u>Space Requirements</u>	Does not occupy lateral space. Exploit the bottom side of the tower.	Requires larger lateral flanges and dedicated lateral area of the tower not available for optics.
<u>Cost Considerations</u>	Should not be very large if cost is mostly based on added volume.	Here larger flanges are to be considered, depending on payload type.
<u>Cleanliness</u>	Good performance: vertical airflow, mirror orientation, and limited personnel improve efficiency.	Airflow direction typically lateral and large doors: must be carefully managed to maintain cleanliness.
<u>Flexibility</u>	No issues along beam direction.	Greater flexibility only if lateral movement is needed; floor must be adapted anyway.
<u>Long-term Suitability</u>	Compatible with large, pre-assembled external payloads.	May become a limitation if ET adopts Virgo-style large external payloads that can't be inserted laterally.

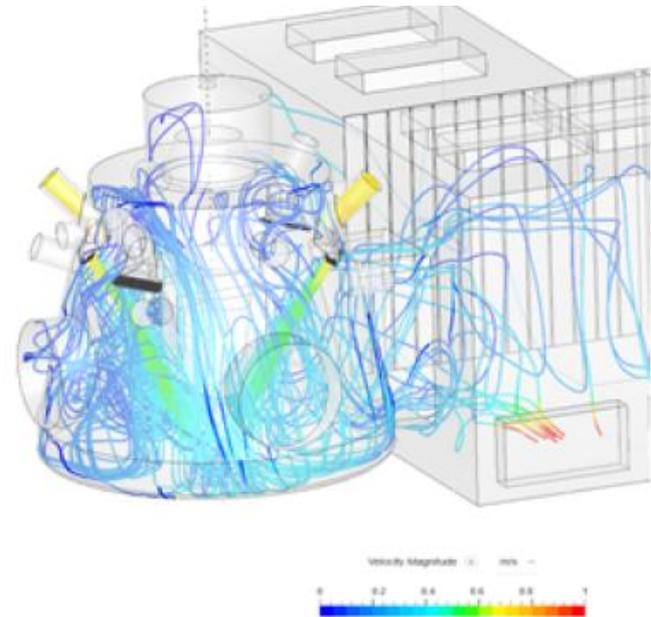
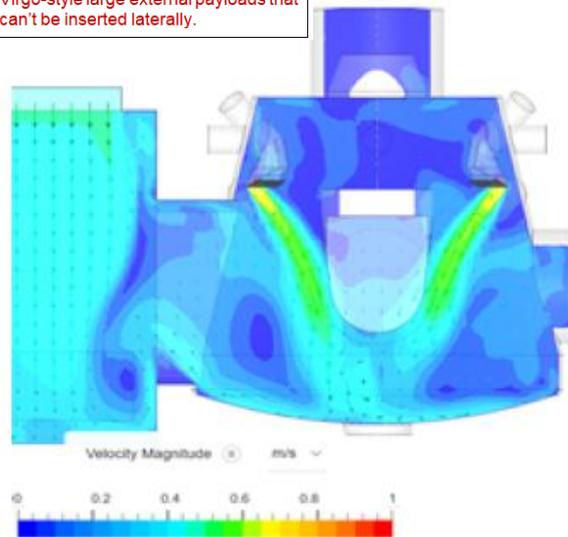
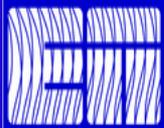


Figure 3.107: Base tower with lateral access, 500 m<sup>3</sup>/h clean-air flushing , aperture 1300 mm. View of external cleanroom located in experimental hall. - CFD simulation, Velocity Magnitude [m/s]



# CHAMBERS ACCESS LF-TM case

In practice, lateral access is considered for all chambers except for the four cryostat TM towers, both for the Triangle and the L-shape configurations. It is worth reminding that most of the towers in the BS area may also be accessed by bottom access.

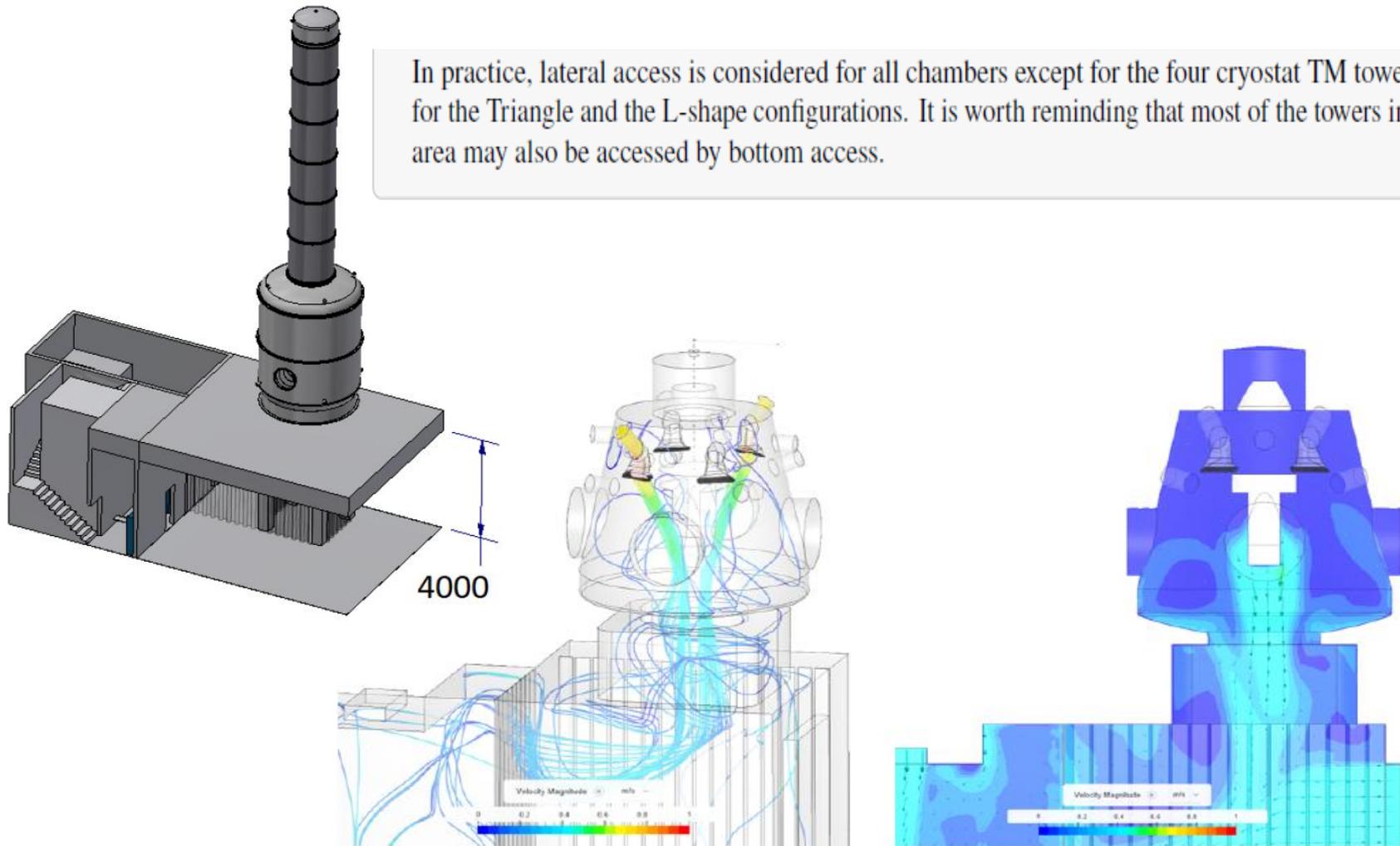


Figure 3.37: Base tower with bottom access with 500 m<sup>3</sup>/h clean-air flushing, view of external cleanroom located below the experimental hall. Access is provided through a flange located at the bottom floor of the tower, with a movable platform. CFD simulation.



**Not just 'PIPES'  
They include all the equipment**

Figure 3.43: The figure illustrates an ideal lir pumps, inner baffles and an enlarged section

Number of Link	Length [m]	Node #1	Node #2	Diameter [mm]	Comments
2	50	ITM	Z_2	1000	
2	35	Z_2	Z_1	630	
2	50	Z_1	BS	400	
1	5	BS	PRM	1000	2 beams
1	5	PRM	INJ	1000	2 beams
1	5	BS	SEM	1000	2 beams
1	5	SEM	SQI	1000	2 beams
1	110	IMC_I	IMC_E	1000	MC beam line
2	5000	FC_IM	FC_EM	630	SQZ beam lines
1	120	SEM	Periscope	630	

Table 3.24: Statistics of connecting pipes for a LF interferometer

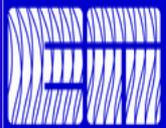
## Tolerable Leak

A realistic leak tolerance must be defined. In a system of this scale, a few residual leaks from flange seals or minor imperfections between upper and lower compartments are practically unavoidable. Table 3.66 reports three preliminary reference values for different regions of the central vacuum system.

Region	Total Leak Rate [mbar·l/s]
Squeezing and auxiliary region	$5 \times 10^{-6}$
Beamsplitter (BS) region	$5 \times 10^{-7}$
Test Mass (TM) region	$1 \times 10^{-8}$

Table 3.66: Reference total leak rates for the regions of the central vacuum system

Above figures does not apply to the cryogenic TM towers (cryostats), where specifications are different and temperature dependent.

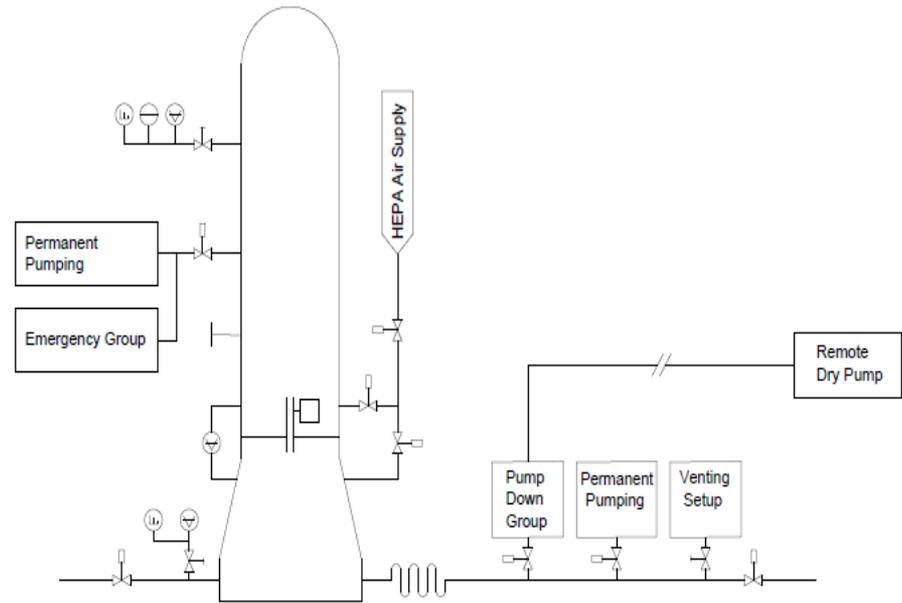


# PUMPING SYSTEM

- Each tower shall be operated and accessed independently (valves).
- Dry pumps and turbomolecular pumps to get E-6 range. IP(\*) and NEG solutions for the permanent phase

- Standardization needed -

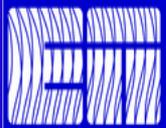
- Lubricant and dust free, low noise emissions.
- Cryopumps, installed between the towers, will provide the fundamental pumping
- Challenge: limiting recovery times
- Pumping equipment mostly installed along 'links'



Approximate statistics included for completeness

Category	Equipment	Qty (typ.)	Notes / Function
Pumping	Dry backing/roughing pump (remote)	1 (shared)	Typically installed in a service area; used for pump-down and backing of turbo stages.
Pumping	Turbo-molecular pump (TMP)	2	Used for pump-down to HV/UHV, with vibration/noise mitigation and remote backing.
Pumping	Ion pump (IP) / sputter-ion pump	2	Upper-compartment pumping during operation; IVC pumping; selected for low-noise operation.
Pumping	NEG pump	0-1	Optional depending on tower position, gas-load budget, and target partial pressures (e.g. H <sub>2</sub> ).
Valves	All-metal gate valve	1	Clean air supply.
Valves	All-metal angle valve	4-5	Rough-pumping ports; clean venting ports with particle filtration; service ports of ancillary chambers.
Valves	UHV gate valve	4	Isolation of TMPs/IPs; supports maintenance without venting the main volume.
Valves	HV small-size valves	8	Backing and roughing circuits; double O-ring circuits.
Gauges & diagnostics	Pirani / capacitance gauge (rough vacuum)	4	Pump-down monitoring from atmosphere.
Gauges & diagnostics	Cold-cathode gauge (HV/UHV)	4	HV/UHV monitoring.
Gauges & diagnostics	Extractor / ionization gauge (UHV)	0-1	Optional, for low-pressure accuracy at UHV.
Gauges & diagnostics	RGA (residual gas analyzer)	0-1	Optional, for leak and outgassing characterization.

Table 3.67: Indicative list of vacuum equipment for a tower. Quantities are typical and depend on the tower type and final layout.



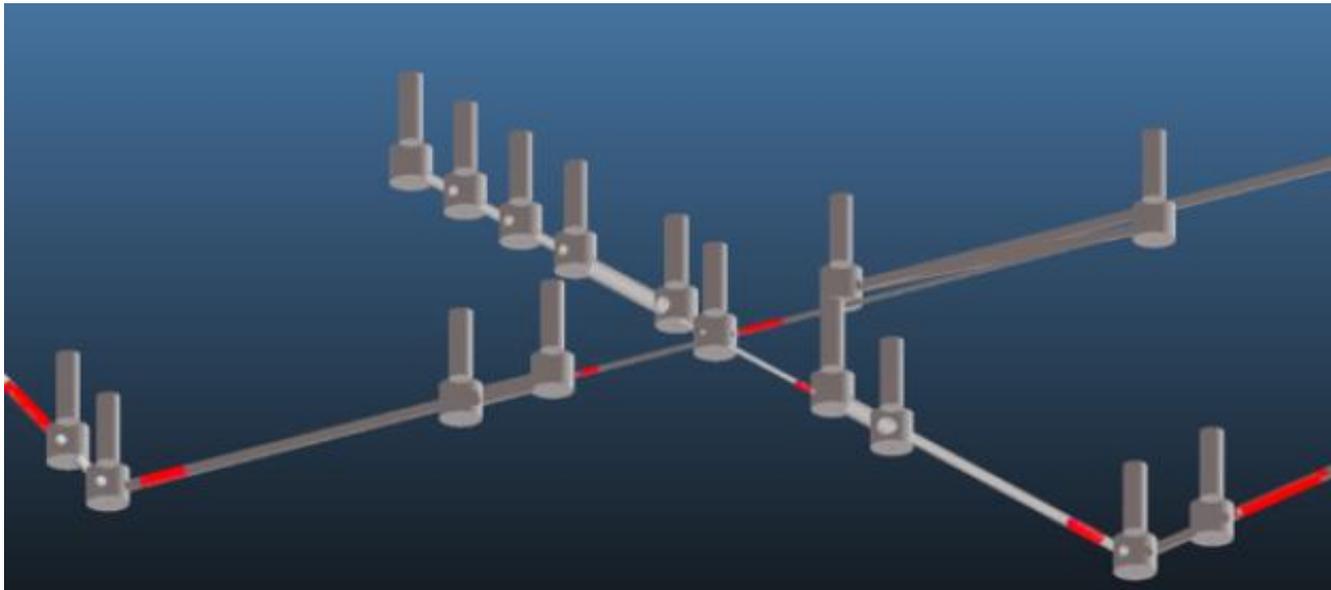
## Operational Modes

It is useful to identify different operational modes and pumping system configurations:

- **Maintenance mode:** slow rough pumping and ultra slow venting, with controlled filtered-air or inert-gas flushing.
- **Long-term post-maintenance regime:** hydrogen becomes the dominant species in the central vacuum system, as the pumping speed for water and other species is significantly higher due to cryogenic pumping, together with the continued decrease of water and readsorbed species.
- **Commissioning mode:** frequent pump-downs; extended use of sensors; and continuous RGA monitoring.
- **Data-taking mode:** minimal active pumping; some sections of the cryogenic pumps may be switched off; steady-state operation with maximal stability.

## Auxiliary cryogenic pumps

Cryogenic pumps constitute the principal part of the central vacuum system. Their role is to manage the high gas loads originating from towers, allowing the required pressures in the beampipe and LF-TM towers. Pump water and residual air released from unbaked materials periodically exposed to atmosphere, as well as hydrogen: next next talk.



# EXAMPLE (HF)

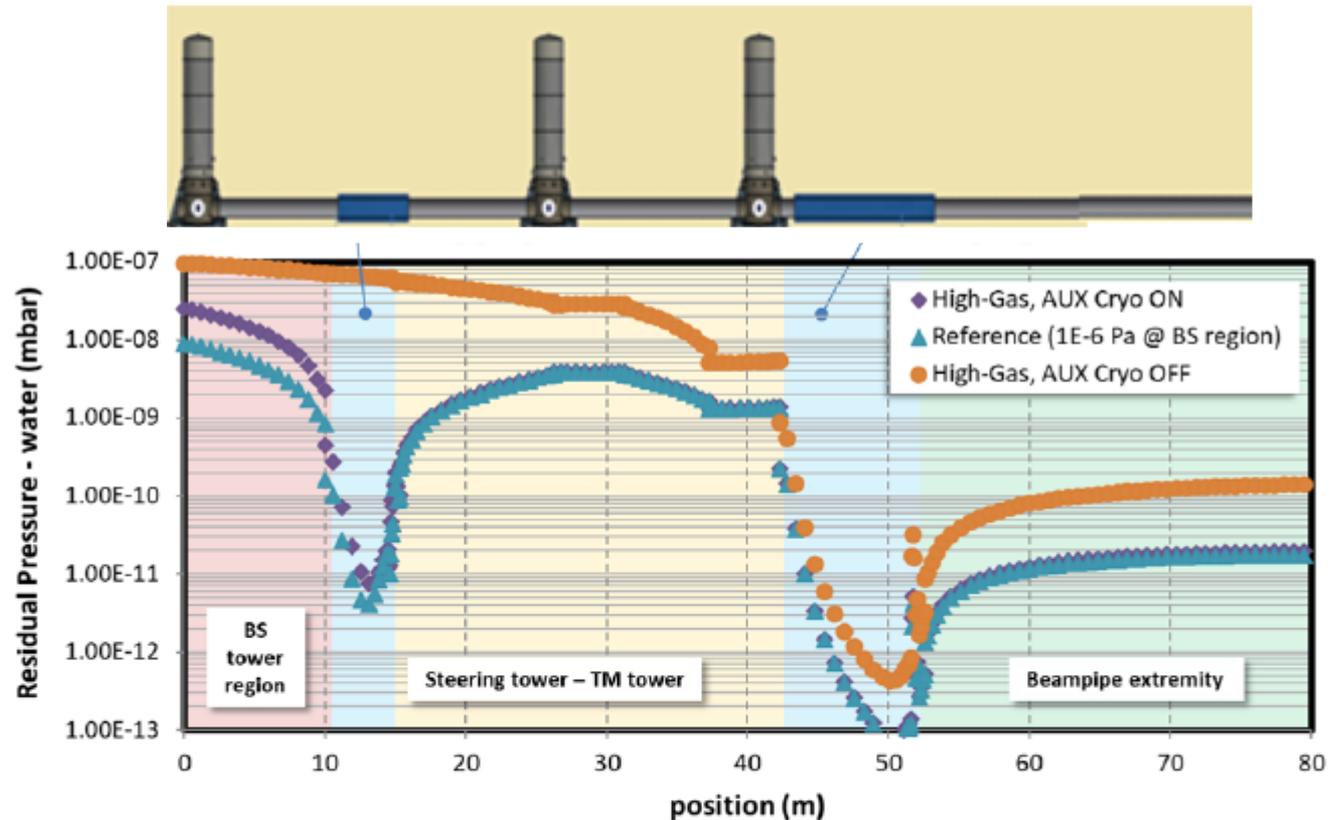
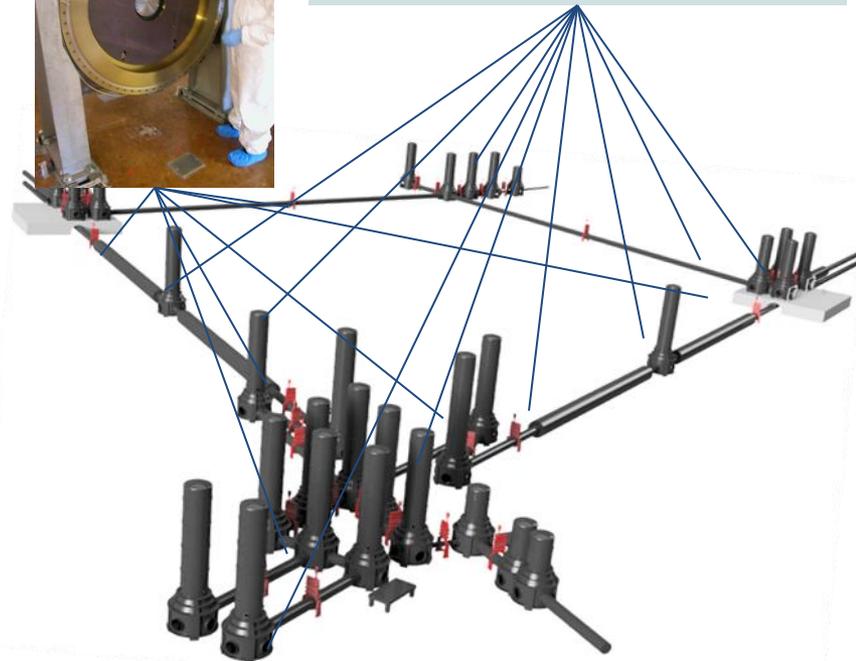


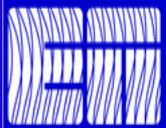
Figure 3.115: Pressure profile in the region of HF-TM tower in different scenarios: reference (water @ 100h of pumping in HF-TM tower and in Steering Tower, pressure of  $1 \times 10^{-8}$  mbar at boundary); High-Gas ( $5 \times 10^{-4}$  mbar  $l s^{-1}$  at boundary ) with/without AUX cryopump. The model is driven by outgassing from in-tower components. Chambers walls re-adsorption is not included at this stage, yielding a conservative reference model. Re-adsorption effects will be evaluated at a next stage in particular for the section downstream

- Will be a relevant part of the final the design
  - **Large metal seals** (~1000 units)
  - **Gate Valves  $\varnothing \sim 1\text{ m}$**  (~50+ units)
  - **Viewports**
  - *even if already on the market, require optimization by industry*



- Metal seals for not-accessed flanges (50 years lifetime) ;
- Double/single o-ring: access & separated compartments



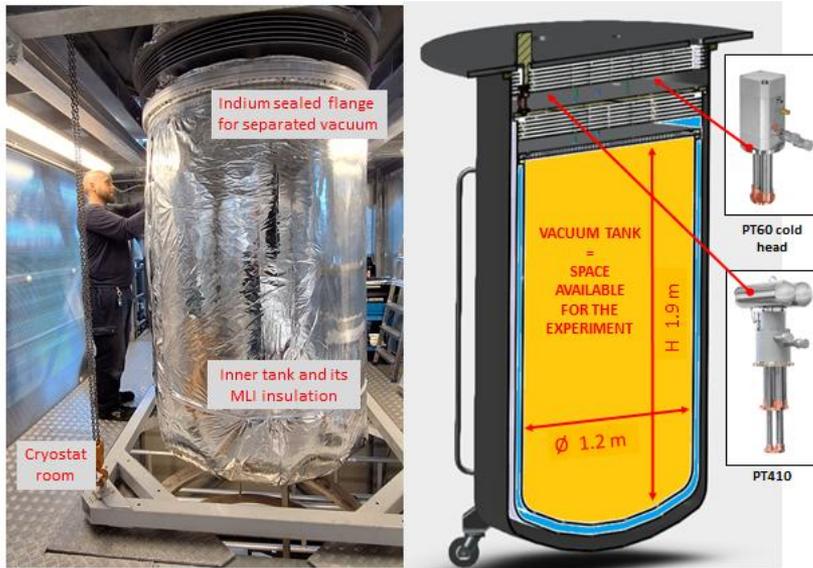


# CONCLUSIONS

- ❑ **PRE-TDR also as a way to discuss within ISB teams and help design finalization**
- ❑ **Industry engagement is essential**



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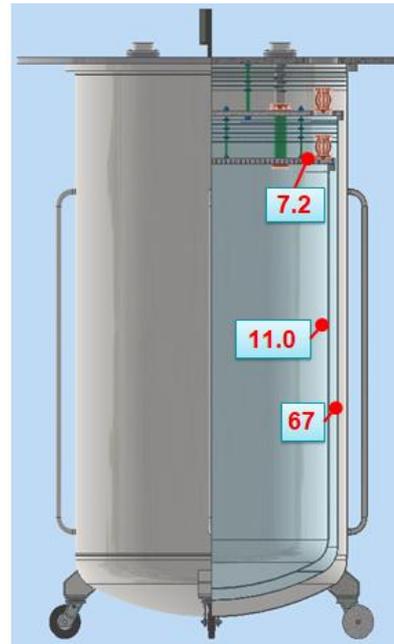
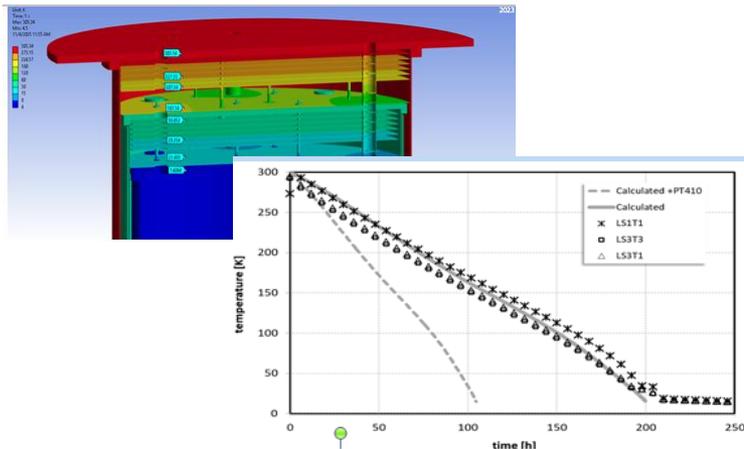


## Open for studies within the ET Collaboration

*Plans include the use of viewports for the 'local controls' of the optics and methods for measuring pressure in the inner tank*

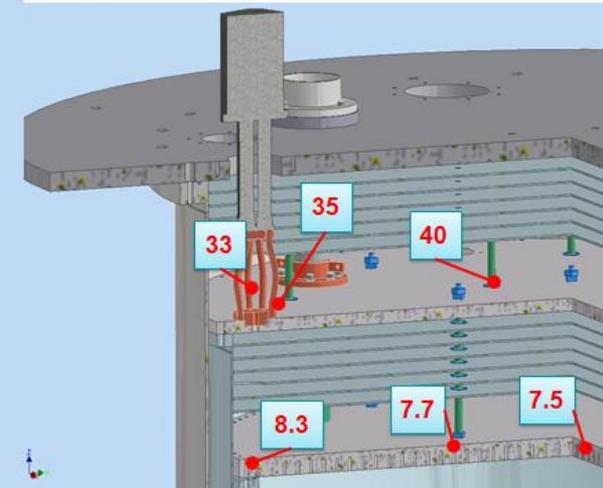
### The cryostat:

Installed on a structure that facilitates the integration of the experiment, which is fixed to an aluminum top flange designed as an optical table with an M5 hole



### Measured performances:

Temperature data [K] recorded in July 2025. The 'cold table' reached a temperature of 7.5 K – 8.5 K, measured at four points using silicon diode sensors (Lakeshore® DT-670).

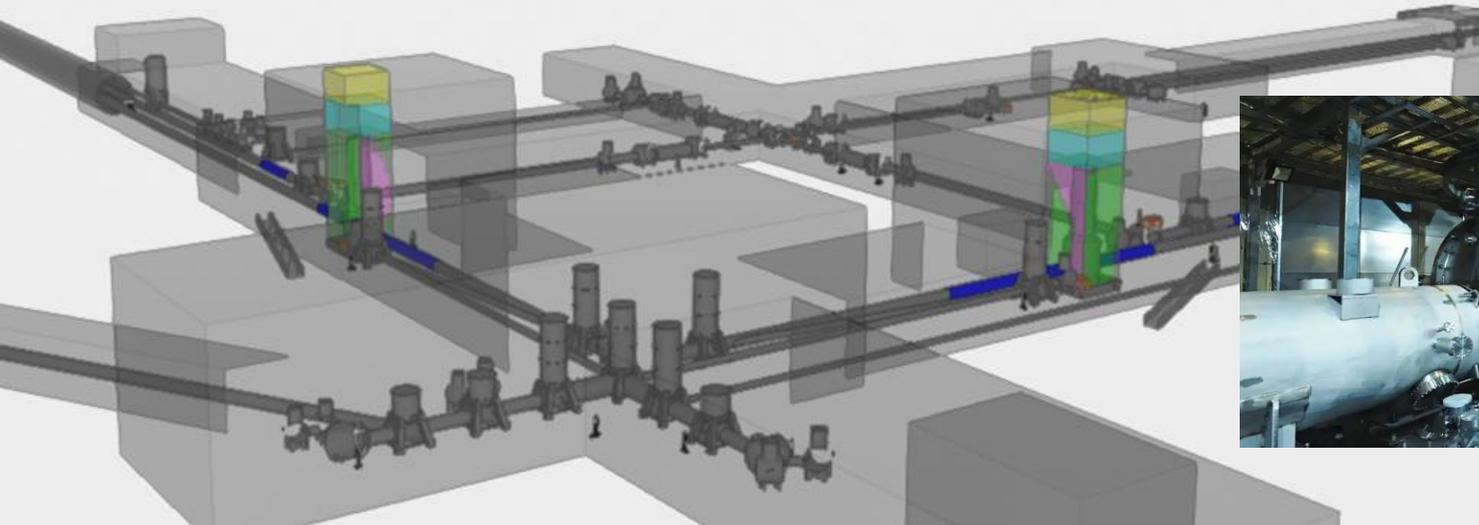


- Backup slides



# Starting from 2G experience

Towers and Cryogenics are concentrated at the 'corners' inside 'Caverns'.  
These are the experimental halls, normally accessed by personnel .



Source: KAGRA

Source: LIGO web

*Credits: ETO Task Force,  
Detector Layout, 2L  
Configuration - 06/2025*



Virgo Hall



## Material Selection - Gas Load - Warm Towers

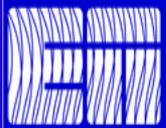
The gas load is the primary factor determining the vacuum level in the towers. Accurate values will be consolidated once the design of the in-vacuum components (payloads, suspensions) is completed and after a full series of experimental measurements. In this section we establish a gas-load budget, representing the maximum load compatible with the target vacuum level. The outgassing from tower materials is characterized by the unbaked configuration (baked only once at the beginning) and by a strong time dependence (water, air traces) of gas reloaded during each air exposure and then gradually desorbed during vacuum operation. The currently considered gas load is:

Region	H <sub>2</sub> O @100 h	H <sub>2</sub> O @1000 h	H <sub>2</sub>	N <sub>2</sub> + others @100 h
Upper compartment	$1 \times 10^{-3}$ (total)	$1 \times 10^{-4}$ (total)	–	–
Ideal case - Lower compartment	$1 \times 10^{-4}$	$2 \times 10^{-5}$	$2 \times 10^{-6}$	$< 1 \times 10^{-5}$
Nominal case - Lower compartment	$5 \times 10^{-4}$	$1 \times 10^{-4}$	$2 \times 10^{-5}$	$2 \times 10^{-5}$

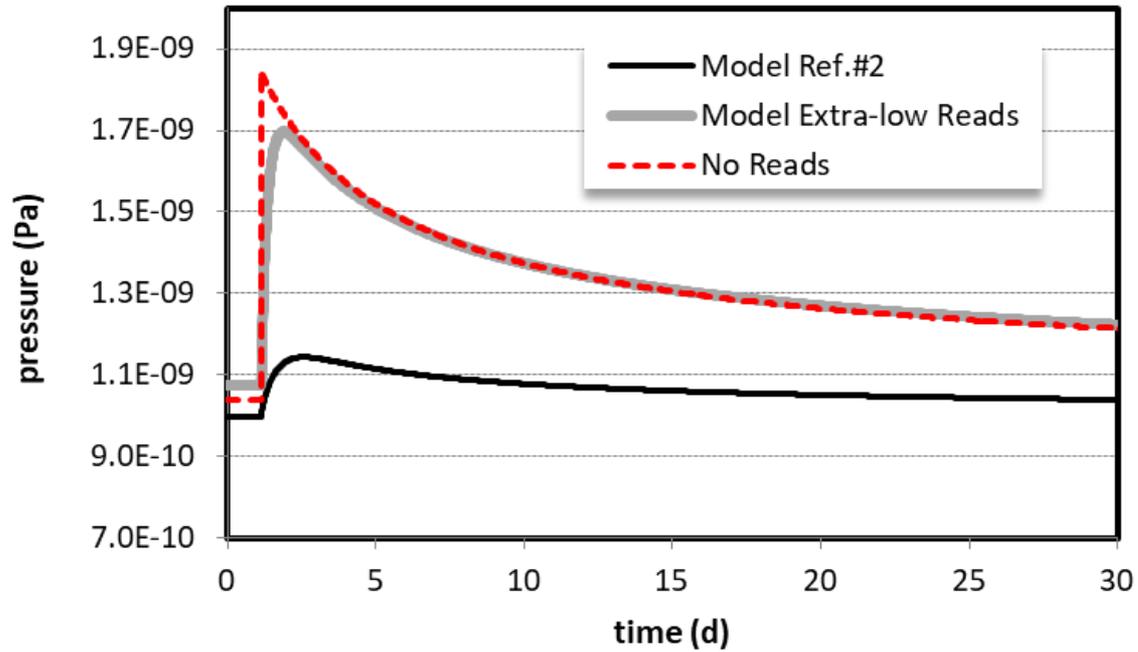
Table 3.25: Gas-load budget for a warm tower for different gas species after different pumping times [mbar-l/s]. Numbers are based on large scale experimental test and the compilation of the different materials expected in vacuum (Ref. Outgassing Database [135]). To be upgraded progressively along with design finalization. The Cryogenic Towers are not included.

A complete inventory of materials and components foreseen for installation under vacuum (Suspension, Payload, and Optics) will be provided to support the finalization phase

Uncertainties on material outgassing rates arise from measurement accuracy, surface condition variability, and modelling assumptions. These uncertainties are expected to remain within the figures assumed for the gas budget and represent the principal input for the design of the central vacuum system, for which appropriate design margins must be defined. They will be further quantified during the executive phases through dedicated measurements on prototypes.



# DOWNSTREAM 'CRYOTRAPS'





## Initiatives on multidisciplinary Aspects

within WP IV we highlight:

- Frost and static-charge mitigation via electron irradiation
- Static-charge neutralization under vacuum at room temperature
- Passive methods for static-charge mitigation
- Trying Low-volatiles estimation by spectroscopy
- Outgassing measurements

**Frost and Electrostatic Charging mitigation method by low energy electron irradiation**

Isolated and Cryogenic optics are affected by detrimental effects due to **frost formation** (residual gas cryosorption) and inhomogeneous **electrostatic charging**

**Proof of**

**Active Mitigation Method:** Low energy electrons irradiation can remove frost and cure electrostatic charging

**Material outgassing properties characterization**

**LNF «LATINO» - Outgassing Facility**

Two Chamber for samples (ø200 x 260mm and ø250 x 450mm)  
Background  $\approx 10^{-13}$  mbar/l s cm<sup>2</sup>; two RGA analyzer

**Passive mitigation method for electrostatic charging**

**Limit free electron imping on optics**

Studies on the emitted electrons from ion pumps

- Mes. Of Number of emitted electrons
- Emission configuration

From the Virgo experience: Electrons coming from Ion pumps

Studies on the electron's propagation along the beampipe

- Numerical simulation of propagation
- Mes. of Number of propagated electrons
- SEY of beampipes material

**LNF-Virgo/EGO**

Challenging partial pressure measurement due to the requirement on the hydrocarbon contamination (100 amu)

$S_0(f) = \int_0^L \frac{(kms)^2 \rho_{in}(z) e^{-2\mu(z)z}}{v_{in}(z)} dz$

The strain noise puts requirements on the pressure of the vacuum system

$\sqrt{S_0(f)} \sim 10^{-12} / \sqrt{Hz}$

$p_{hy} \sim 10^{-14}$  mbar

Hydrocarbons contamination: Volatile Residue (VR) and Non Volatile Residue (NVR) components of very light hydrocarbons.

NVR component: residual amount of hydrocarbon we can measure (FTIR, XPS) on the internal surface of the tube after the cleaning process.

VR component: partial pressure of hydrocarbon we can measure in the internal volume of the tube in UHV conditions (RGA, Cavity Ring Down Spectroscopy).

high-reflectivity mirrors

Layout of the CRDS UHV system

Background pressures:

$p_H = (1.1 \pm 0.2) \cdot 10^{-10}$  mbar  
 $p_V = (0.3 \pm 0.2) \cdot 10^{-10}$  mbar

Contribution to outgassing estimation of internal optical elements (mirror and PZT).

$p_{hy} = 2 \cdot 10^{-14}$  mbar

charge the surface

**Dis-charging of surfaces under vacuum**

Static charge can build-up after months of in-vacuum service (in Virgo around E-9 C)

Possible sources:

- Particles escaping Ion pump (and/or UV and/or soft x-ray emission)
- Residual charged particles from First Contact removal
- ? Still quite mysterious

Need a neutralization method under vacuum (-> no need of venting)

Radio-Frequency Neutralizer at work

© A. Gamba, M. Badi, T. Bai, M. Andros-Cerasari, G. Ciani, L. Comi, L. Degano, E. Della Porta, M. Lodi, M. Mariani, A. Raccosta, V. Riva, S. Sestini, C. Sestini, E. Tassi, P. Tassi, T. Tassi, "ET Beamline Requirements", ET-Doc E7-0004-04 (2016)



# Large Scale Prototypes

Several major prototype initiatives are currently underway from leading laboratories and institutions:

- **GRAVITHELIUM at KIT**
- **ARC at La Sapienza University**, including a large cryostat and payload
- **CAOS at INFN/University of Perugia**, hosting 2 full size ET towers
- **ET-Pathfinder, Maastricht University & Nikhef (NL)**

*and many others not directly linked to the tower vacuum system.*

