# Virgo Vacuum System

## INFN LASA - Jun 13, 2024

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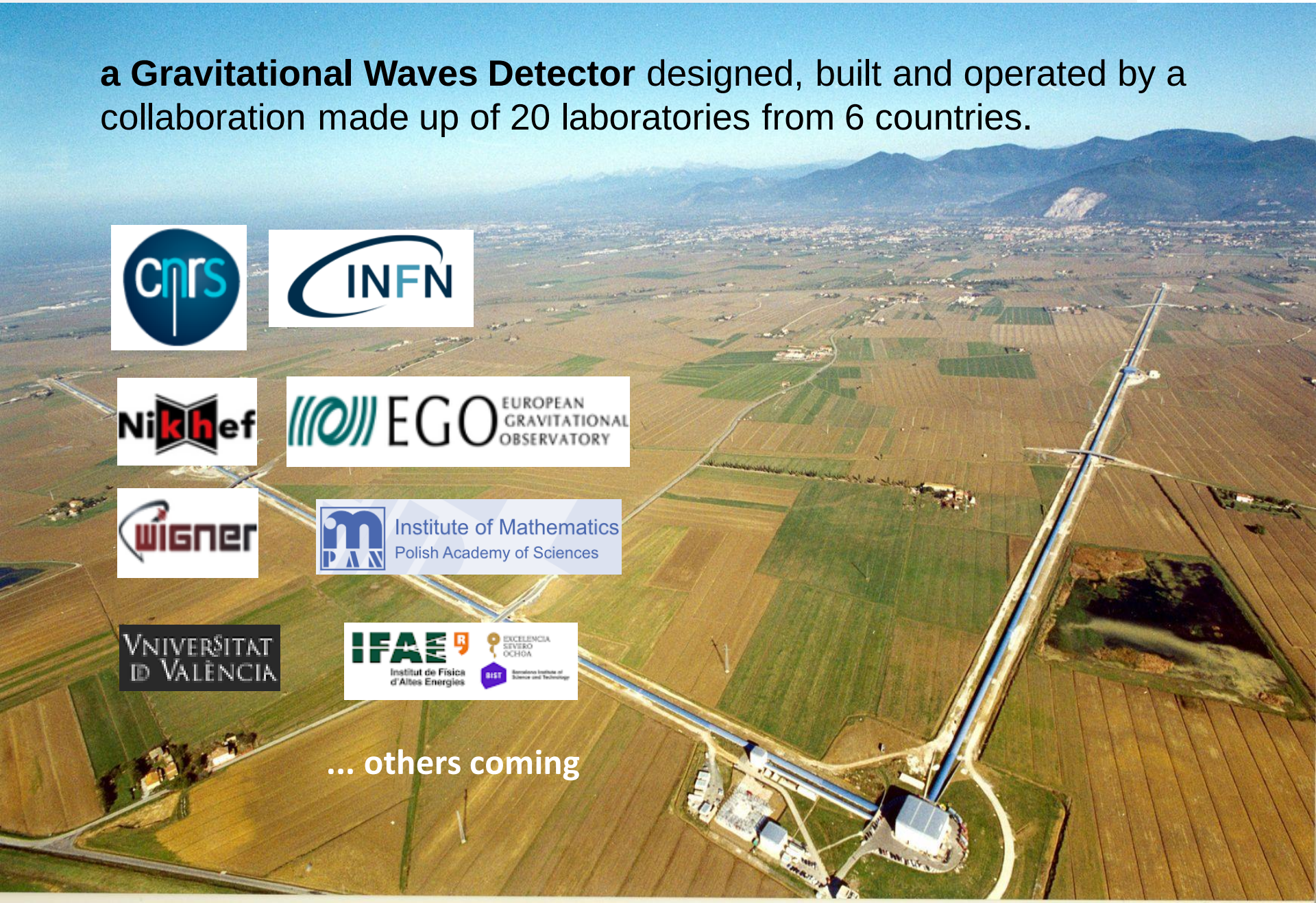
*A. Pasqualetti on behalf of the team that realized and operates the Virgo Vacuum System*

EGO - Virgo Collaboration

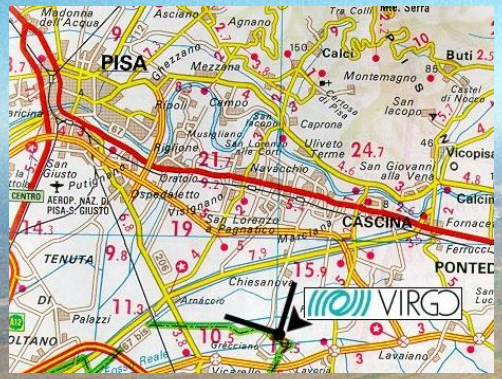
# VIRGO experiment

**a Gravitational Waves Detector** designed, built and operated by a collaboration made up of 20 laboratories from 6 countries.



# VIRGO experiment

**Gli interessati sono invitati a visitare il sito**



# SUMMARY

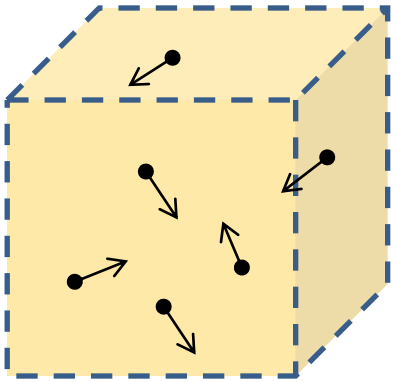
- Virgo Vacuum System
  - Overview
  - ‘Tubes’ and ‘Towers’
  - Materials compatibility
  - ‘Cryotraps’
  - Selected Experiences
- Prospettiva per ET
  - Key figures: layout, size, vacuum levels

- Introduzione per PID 14 Ottobre 2024

# Ultra-Alto-Vuoto

- Gas rarefatto con pressione residua dell'ordine di $10^{-9}$ mbar o inferiore. Sono presenti limiti differenti per le diverse specie molecolari, perché ciascuna può avere effetti specifici nelle varie applicazioni.

Pressione <=> densità e cammino libero medio



1 cm^3 contiene ~ 10^19 molecole @ 20°C , 1 atm
~ 10^7 @ 20°C , 1E-9 mbar

*Virgo, di volume 7000 m³, contiene circa 7 cm³ di gas equivalente a condizioni di 20°C e 1 atm.*

λ/d >> 1 nelle applicazioni di interesse (λ cammino libero medio; d dimensione caratteristica della camera da vuoto: λ > 1 km per $N_2$ a 1E-9 mbar ).

Nel regime UHV non avvengono urti tra molecole ma solo tra le molecole e le superfici del recipiente, il che può sembrare controintuitivo considerando il numero di molecole ancora presente. Se una molecola (< 1 nm) fosse grande come una pallina da tennis, il volumetto avrebbe un lato superiore a 1000 km!

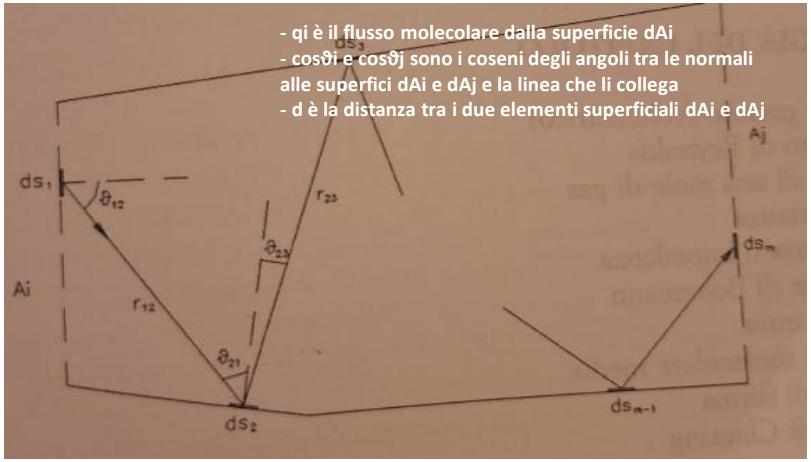
# Principi e relazioni fondamentali

- Equazione di stato dei gas ideali
- Processi isotermi: **V·P** utilizzato per descrivere la quantità di materia e la portata nei calcoli di flusso, come pratica alternativa alla massa kg ad es.
- L'equazione di base **S·P=Q**: in condizioni stazionarie o quasi-stazionarie, la pressione residua è in equilibrio tra il flusso di gas in ingresso (Q) e quello evacuato dalle pompe (S)
- **Q = q·A + leaks + permeazioni**

con q [mbar.l.cm-2.s-1] gas desorbito da superfici = il fenomeno determinante del processo, più eventuali perdite [mbar.l.s-1], es. Ø capello ≈ E-5 mbar.l/s

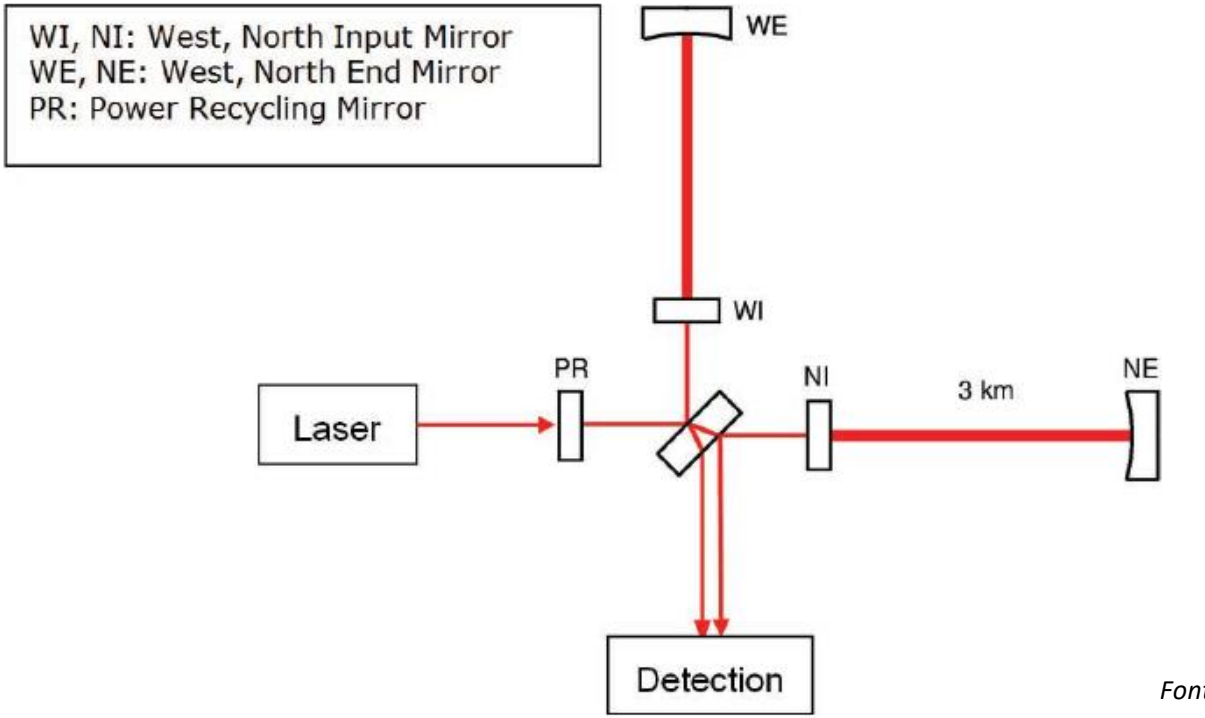
*Il flusso di molecole dalla superficie dAi verso la superficie dAj segue la 'legge del coseno'* *= **q dAi dAj cosϑi cosϑj / π d²** (in analogia allo scambio di calore per irraggiamento).*

*Flusso attraverso canalizzazioni: **Q = C(P2 –P1)** (C = probabilità di trasmissione geometrica x 'conduttanza' apertura $u_{ave}A/4$ ) .*




*Fonte: Ferrario, Calcatelli. Tecnologia del Vuoto, 1999.*

# Interferometro laser Rivelatore GW

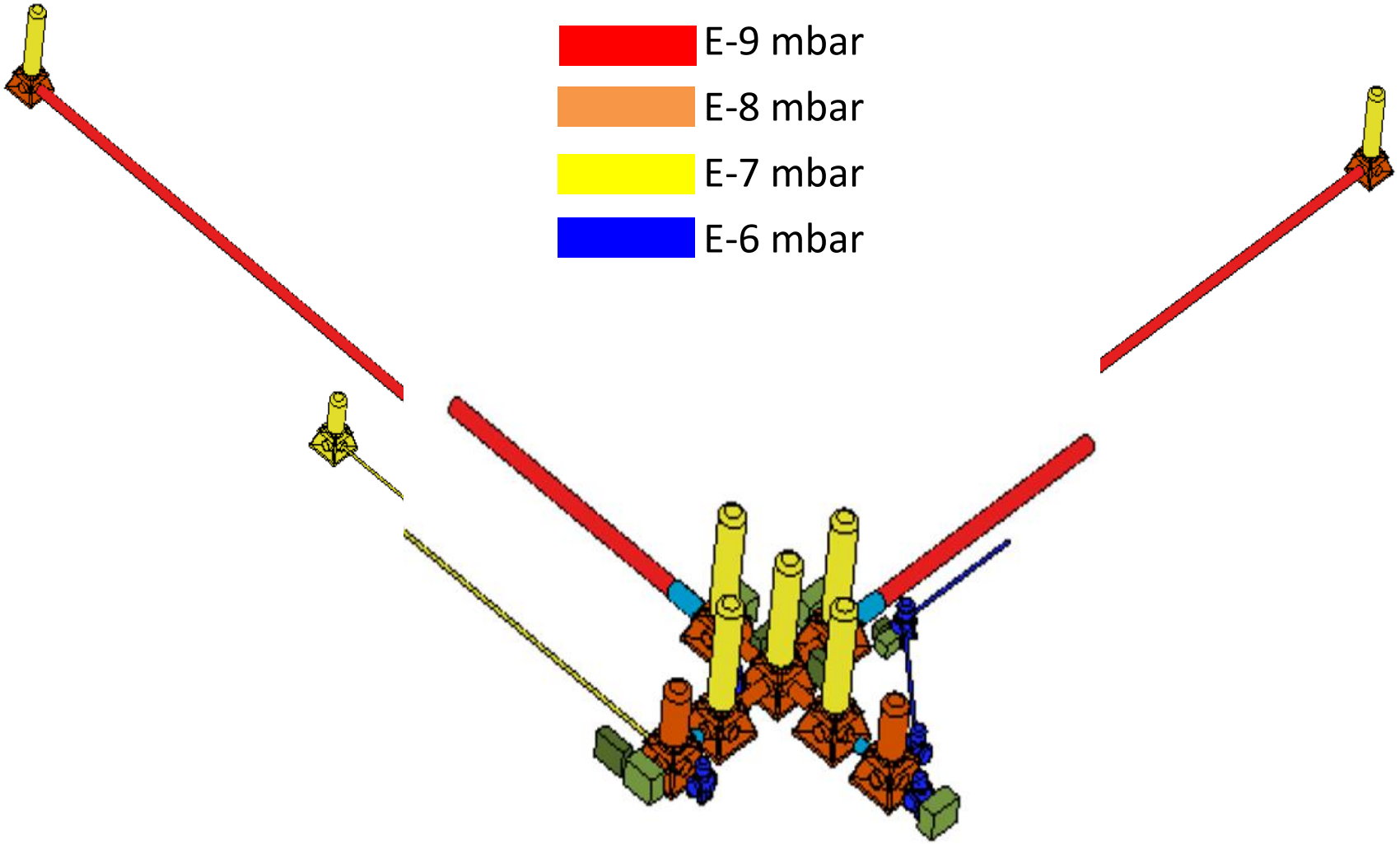



*Fonte: Virgo WEB*

Le parti sensibili dell'interferometro, inclusi gli specchi principali, i sistemi meccanici e il fascio laser, sono mantenute sotto vuoto per ridurre vari disturbi a livelli accettabili.

# VACUUM LAYOUT

- 2 x 3 km UHV arms
- Large chambers and cryogenics at extremities



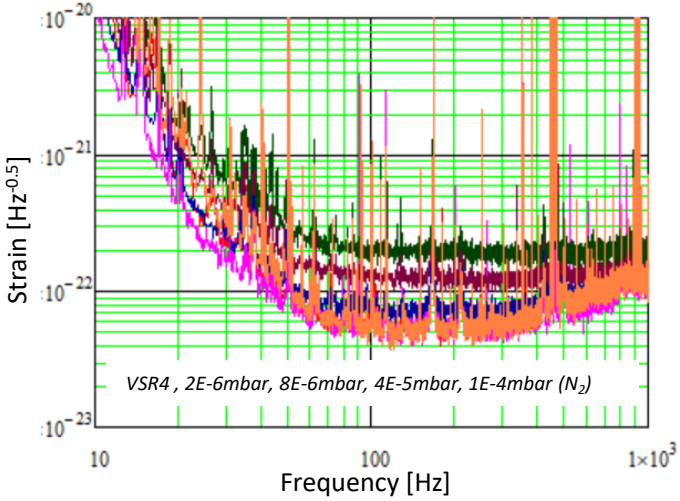
# Partial Pressure limits

**3 km UHV tubes**: **low E-9 mbar** ($H_2$ dominant) to lower the statistical fluctuation of the optical path (fluctuaction of residual gas density)

**Towers**: shall operate down to **low E-8 mbar** (TMs ones) **unbaked** . Molecules hitting the mirrors produce the so-called 'gas damping' effect *[Cavalleri et al. (2009). Gas damping force noise on a macroscopic test body in an infinite gas reservoir]*

**Mirror contamination**: **Low-volatile molecules < 1E-13 mbar** ('one-monolayer' conventional approach). The build-up of deposits on optical surfaces can increase 'absorption and scattering'. *[S. Tanioka et al. Optical loss study of molecular layer for a cryogenic interferometric gravitational-wave detector, Phys. Rev. D 102 (2020)]*

***Raising the pressure in the 3 km tubes***



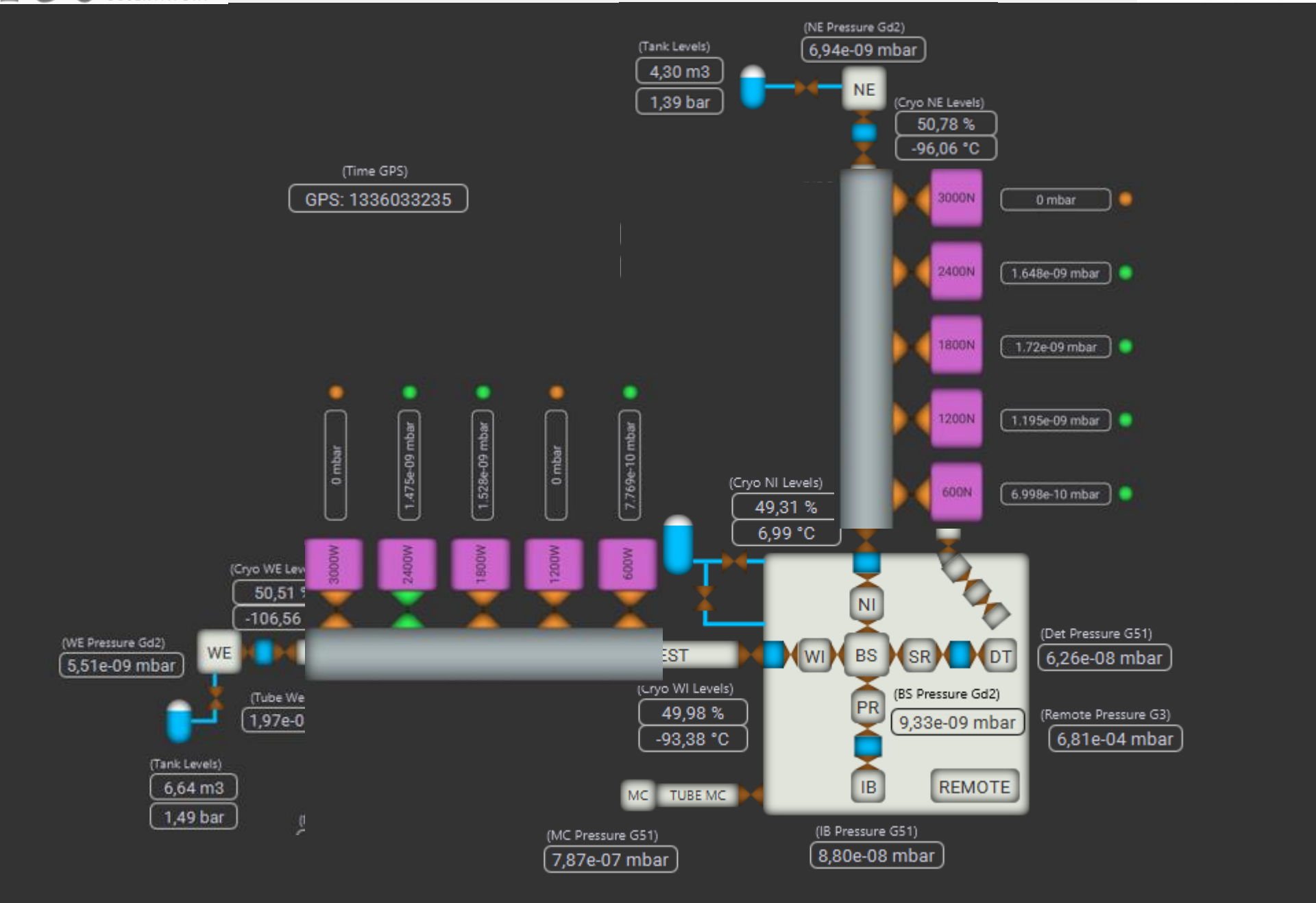

In principle all present gas species are to be accounted [1]. *Noise level* $\propto \sim \sqrt{P_i} * \sqrt[4]{m_i} * \alpha_i$

*Example, common species wrt* $N_2$ *at same pressure:* $CO \approx$ *x 1.1,* $CH_4 \approx$ *x 1.2,* $CO_2 \approx$ *x 1.8,* $\sim(\sqrt[4]{m_i} * \alpha_i)/(\sqrt[4]{m_{N_2}} * \alpha_{N_2})$

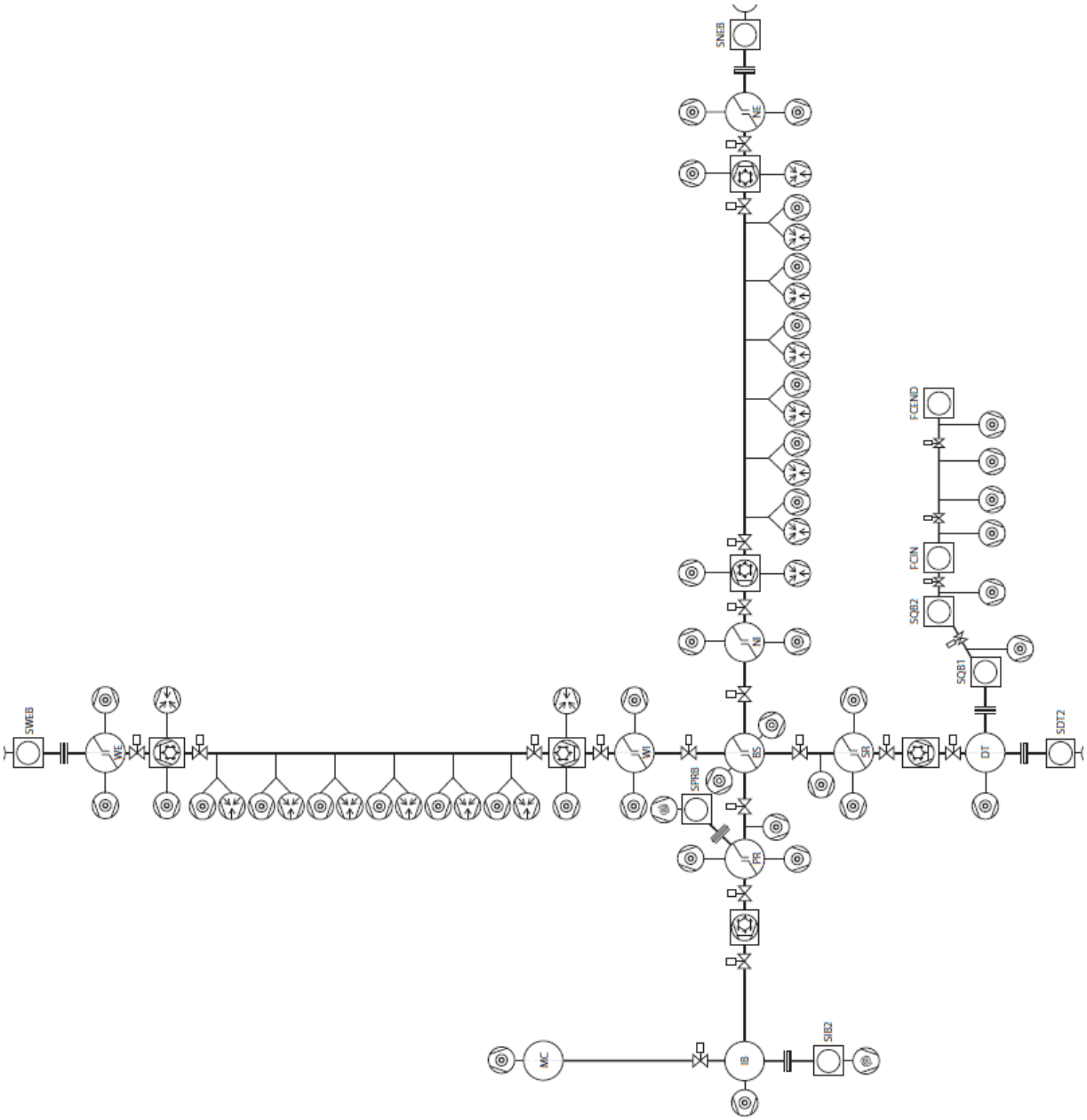
Contamination of heavy organics ('Hydrocarbons') shall be required as very low: challenging.


[1] *G. Cella et al., Residual pressure noise evaluation, 2008*
*M. Zucker, S.Whitcomb, Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer LIGO Project internal document*

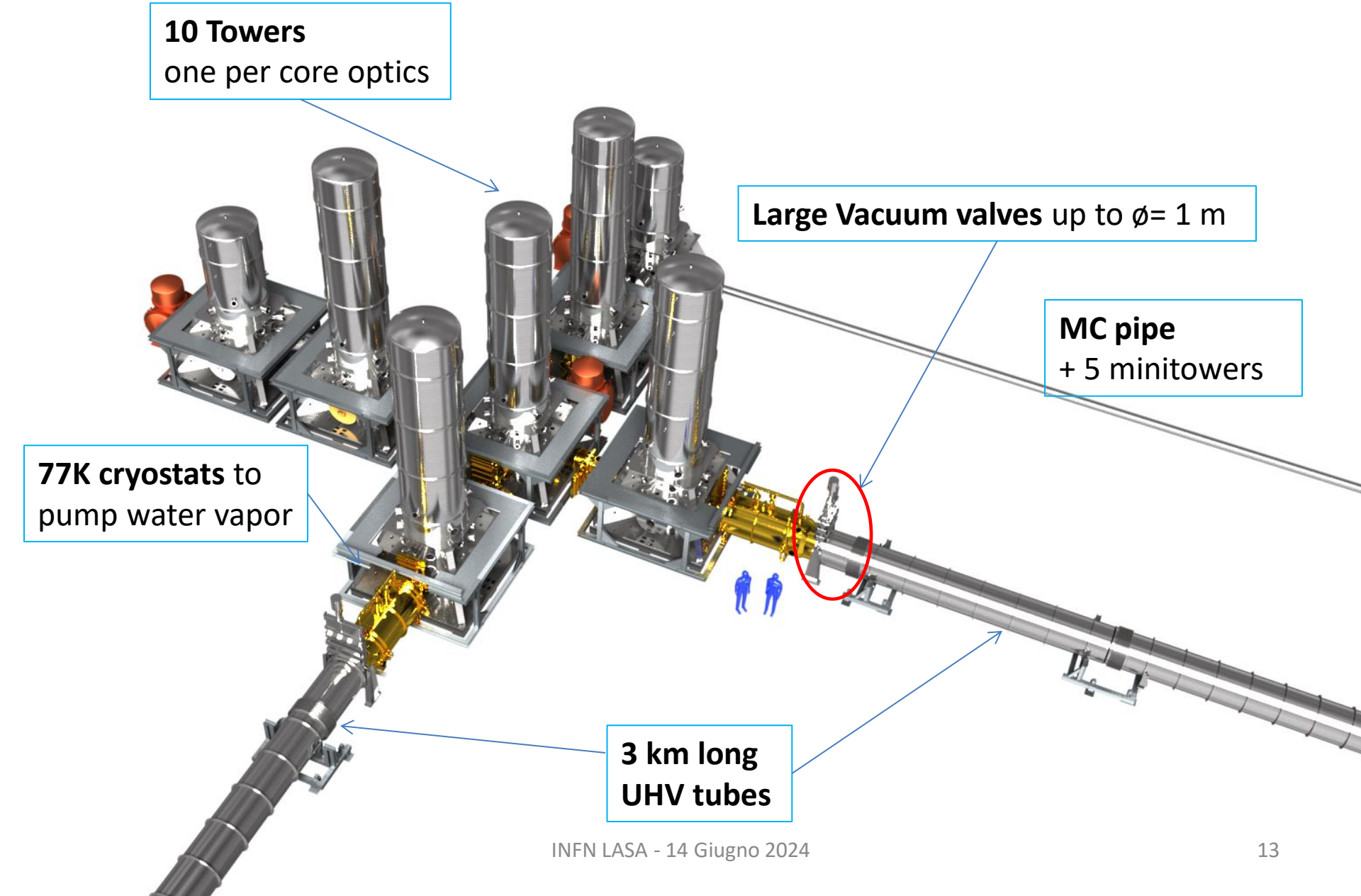
# VACUUM SNAPSHOT



# VACUUM SCHEMATIC



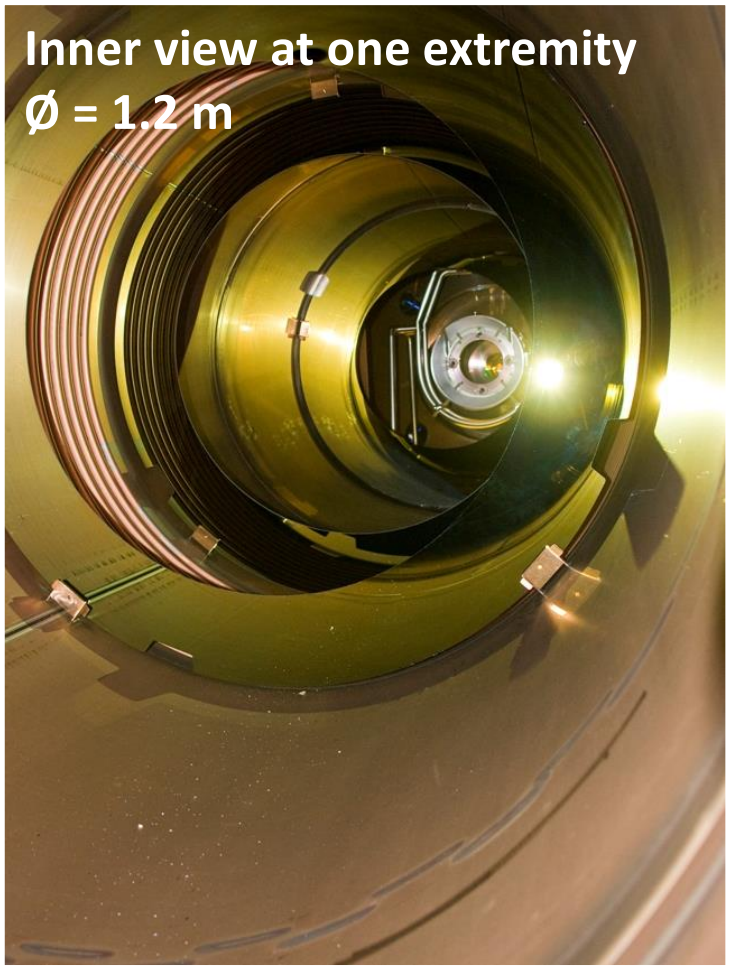
# VACUUM CHAMBERS



- UHV Tubes

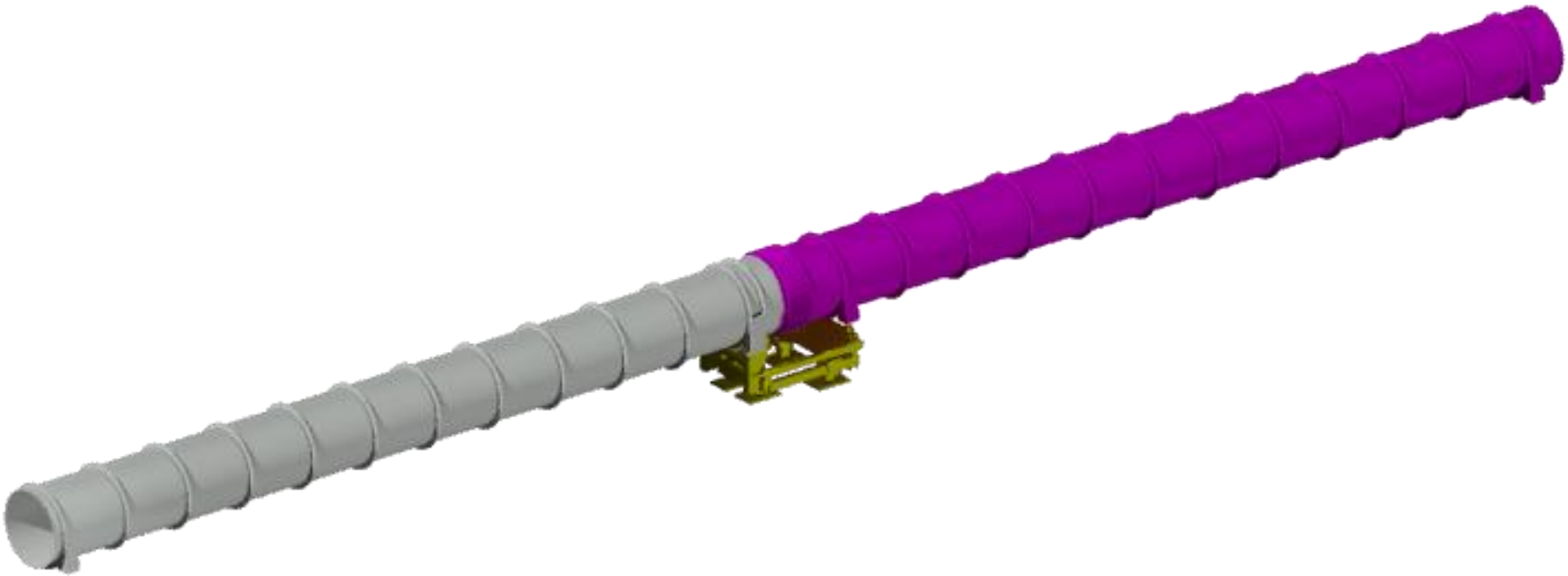
# 3 km UHV TUBES

- 24000 $m^2$ walls!
- They contain “only” optical baffles and the laser beam




# TUBE DESIGN: THE MODULE

- Prefabricated modules 15 m long, joined by welding ;
- Raw material 304L , plain walls 4 mm thick + stiffeners every 1.2 m;
- Bellows to allow heating up to 160°C (80 kgf/mm);
- Flanges: only a few on 3 km for pumps and gauges;

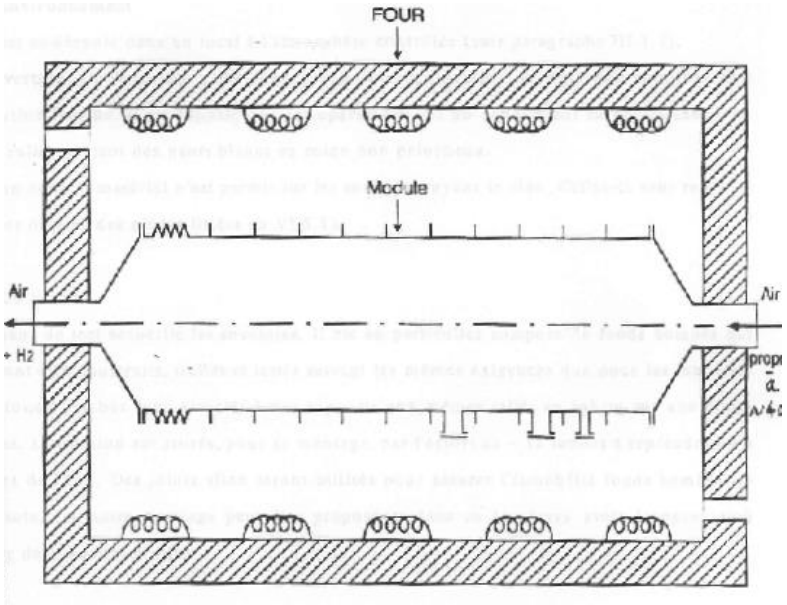


# AIR-BAKE OUT

*Base material conditioning was required to meet vacuum goals (24000 $m^2$ walls).*

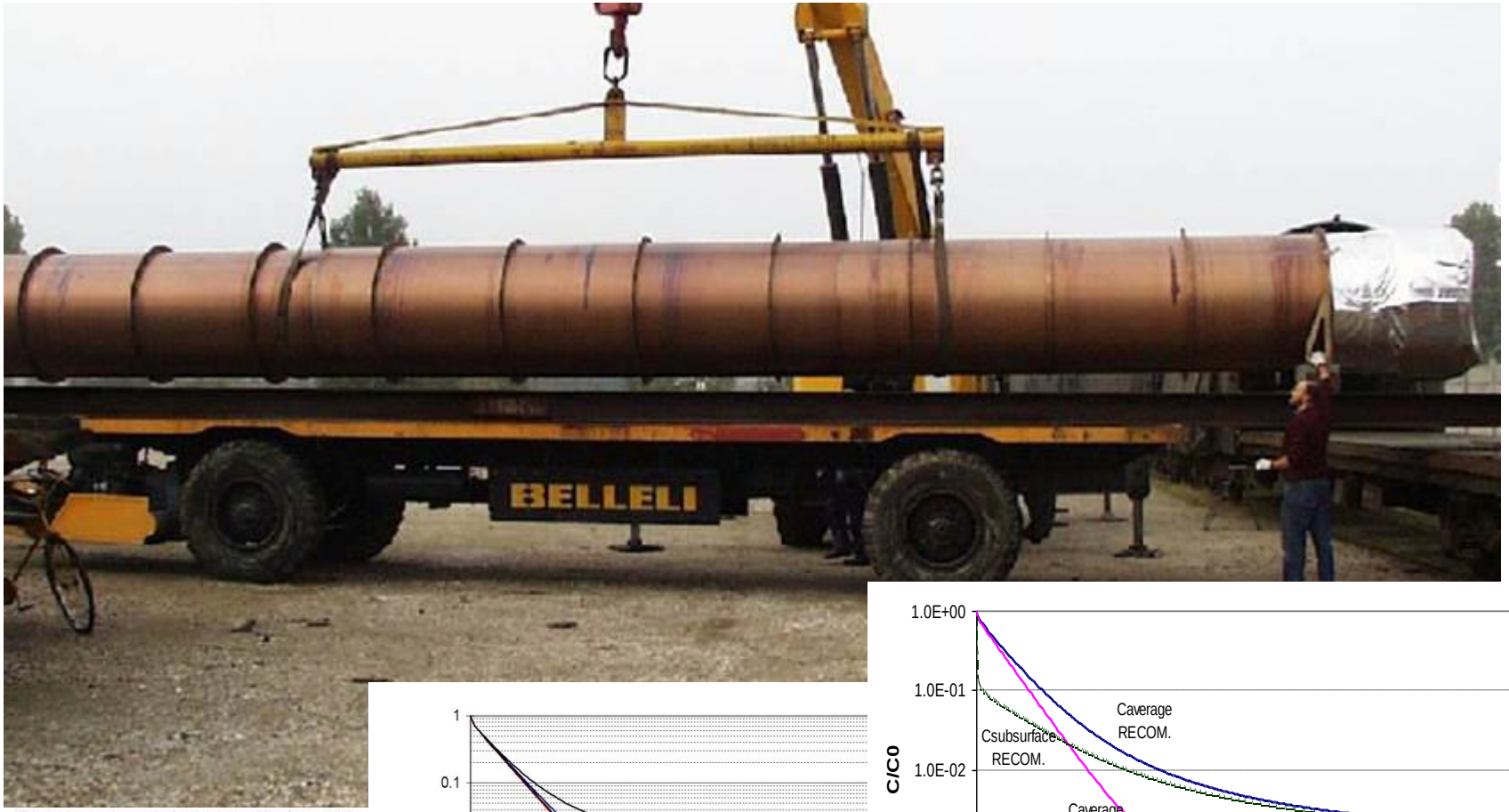
heating at ~ **400°C in air** involved a ''simple'' oven and reduced the hydrogen outgassing by a factor ~ 100; our result: **$q(H_2) \leq$ 3E-14 mbar.l.$s^{-1}cm^{-2}$ @ 20°C**

The industrial specification was: $q(H_2)$ = 5E-14 - NOT CONTRACTUAL -




- <u>Applied to finished modules</u>
- Electrical oven, 'sealed' modules
- 410°C +20/-10 , plateau 72h
- Hot air purge 8 $m^3h^{-1}$
- 5 days long cycle
- H content raw mat. ≤ 2 ppm wt - CONTRACTUAL -

# Past results about ‘air bake-out’





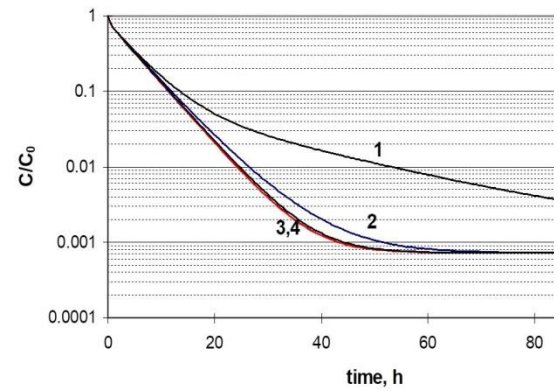
Air bake-out to reduce hydrogen outgassing from stainless

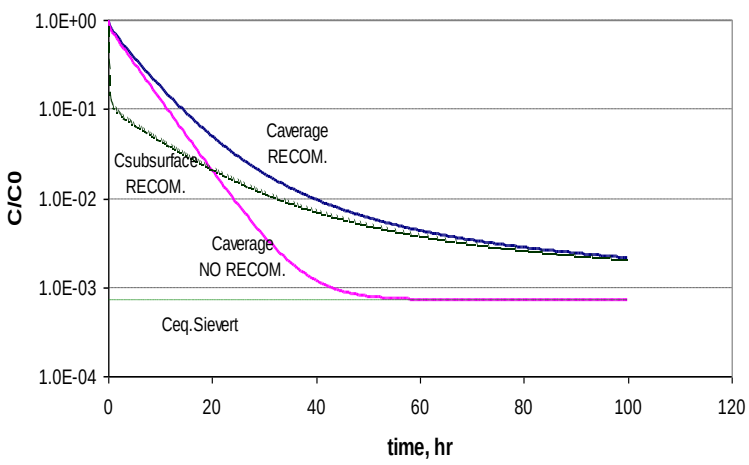
M. Bernardini, S. Braccini, R. De Salvo, A. Di Virgilio, A. Gaddi, A. Gennai, G. G
A. Giazotto, G. Losurdo, H. B. Pan, A. Pasqualetti,* D. Passuello, P. Popolizio,
F. Raffaelli, G. Torelli, and Z. Zhang

C. Bradaschia, R. Del Fabbro, I. Ferrante, F. Fidecaro, P. La Penna, S. Mancini
and R. Poggiani

P. Narducci, A. Solina, and R. Valentini

(Received 29 May 1997; accepted 19 September 1997)



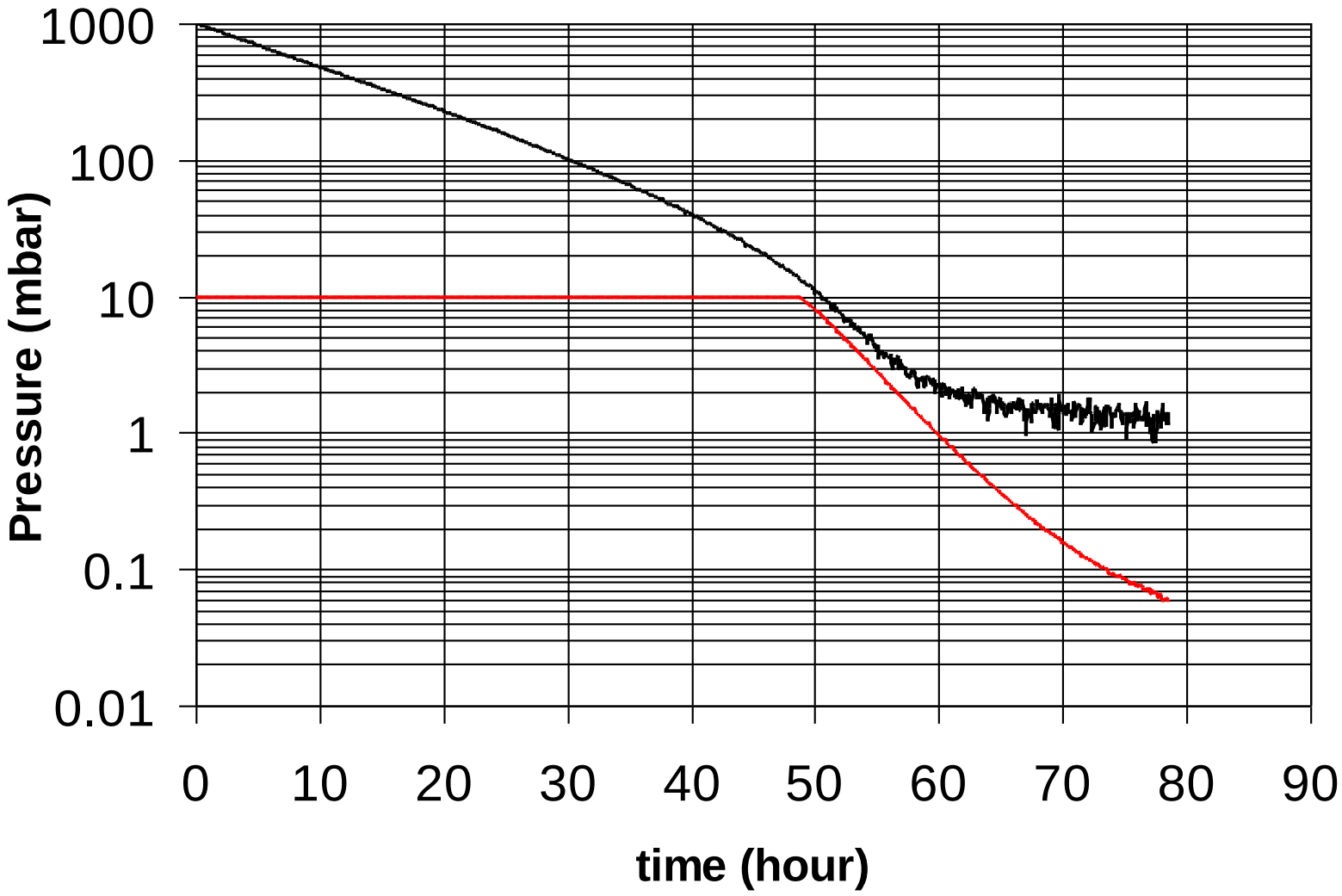



# TUBE PUMPING STATIONS

Every 600 m, taking advantage of the 'enormous' conductance compared to typical ducts in other applications

- Turbomolecular pump 1000 $ls^{-1}$ for the intermediate phase
- TSP/IP pumps 2000 $ls^{-1}$ $H_2$ for the permanent phase

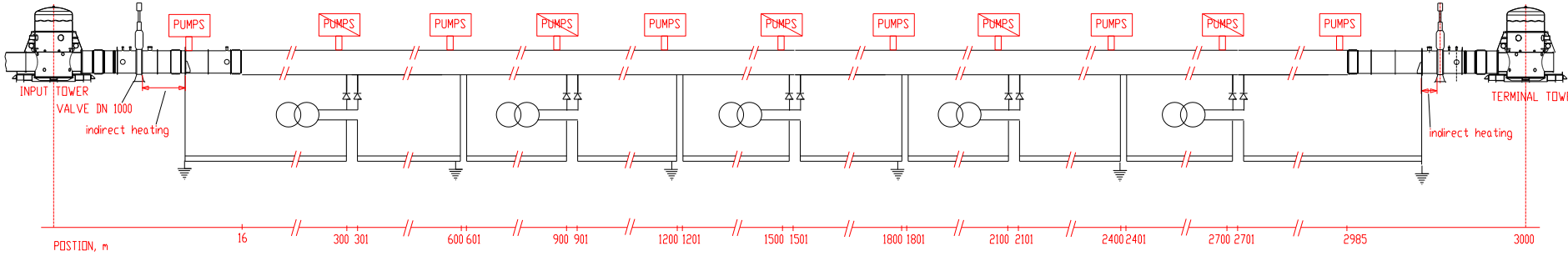

# 3 km ROUGHING DOWN

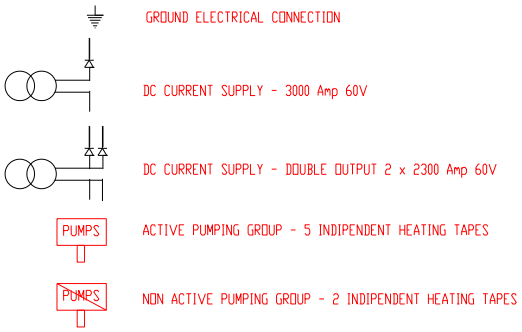


# TUBES: BAKE-OUT in situ

- Chamber at 150°C uniform and at a controlled rate ( ~1 week for SAT stage)
- 1 Mwatt to heat one tube (15 cm thick thermal insulation)
- Joule effect: 2000 A flowing through tube walls
- diesel generators: ~ 10^5 litres of fuel to bake one tube

***Normally to be performed just one time.***




VIRGO
CNRS INFN

VACUUM TUBE BAKE CIRCUIT

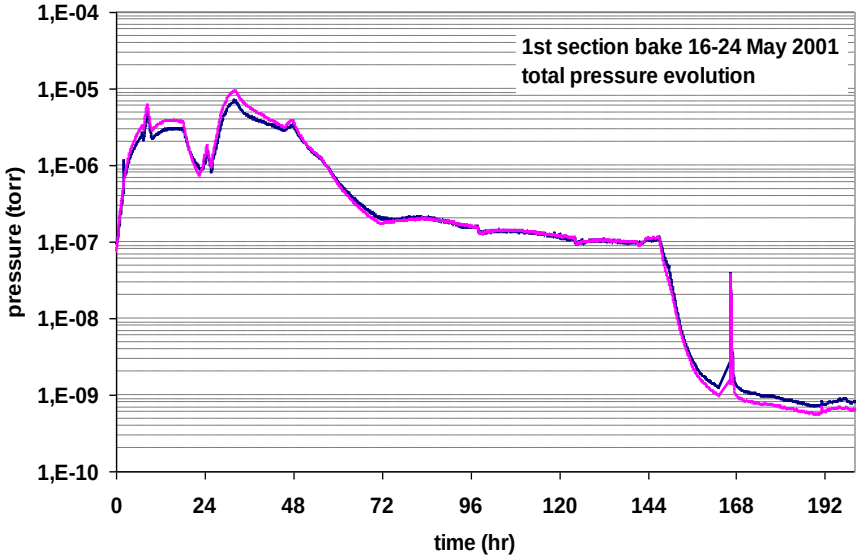
| INDEX | DATE | MODIFICATIONS |
|---|---|---|
| | | NAME/SIGN. |
| DRAWING | | |
| DESIGN | | A. PASQUALETTI |
| CONTROL | | |
| APPROVAL | | |
| FILENAME | | CIRCBAKE 2 |

20-03-0

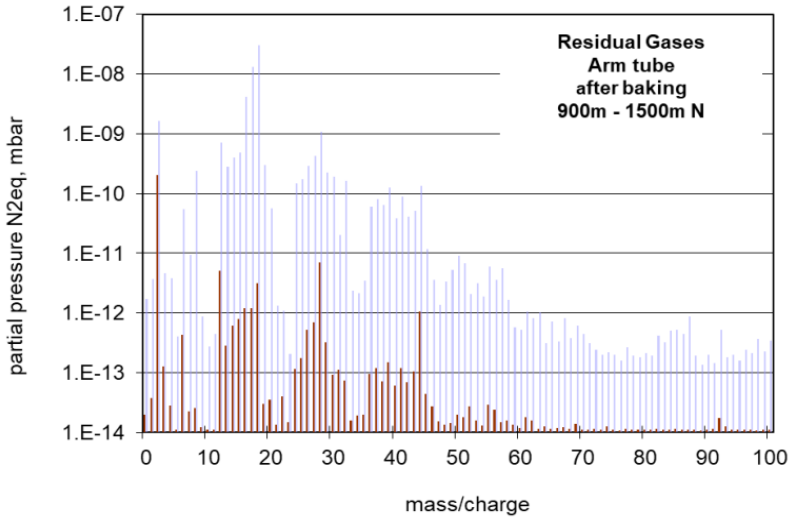
# SOME DATA of BAKED TUBES

- $H_2$ outgassing , our findings

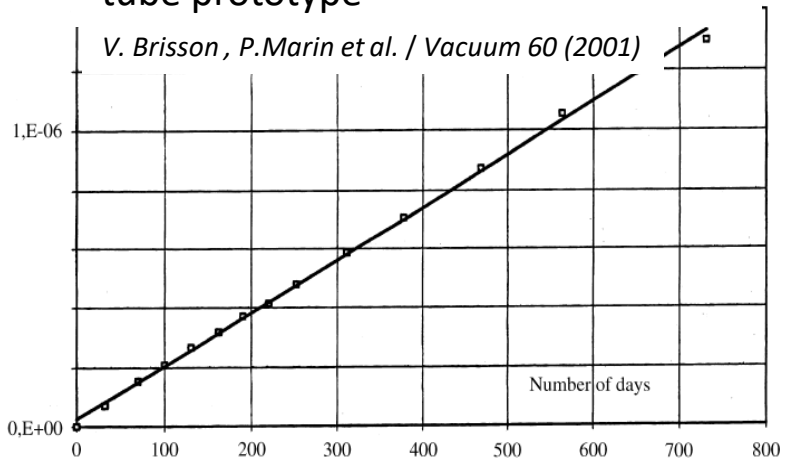
Module0 test: **= 3E-14**
Tube sections (check) **≈ 1E-14**
Pisa/LAL prototypes **< 1E-14**
[mbar.l.s$^{-1}$cm$^2$ @20°C ]




Typical RGA on 'tube' after bake-out

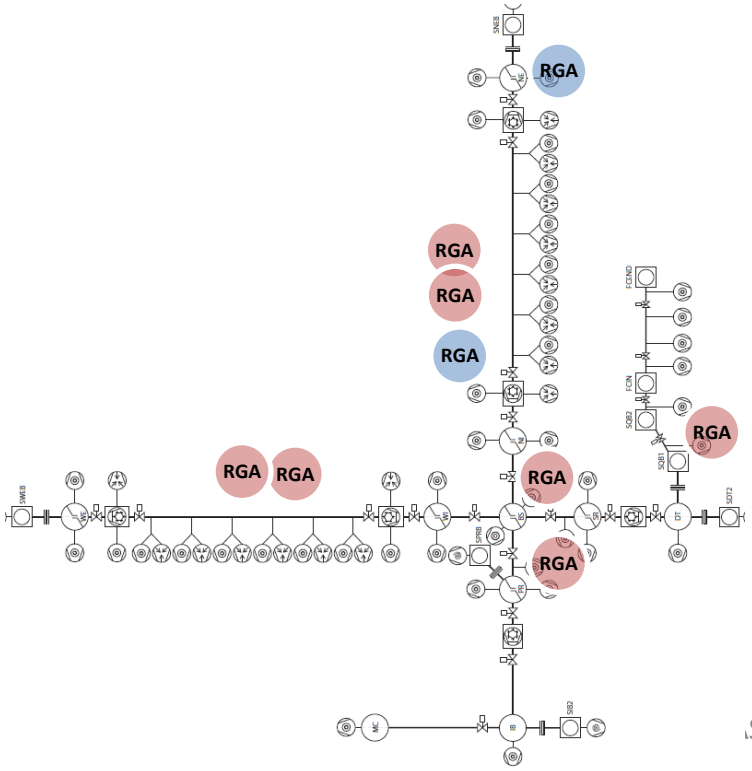


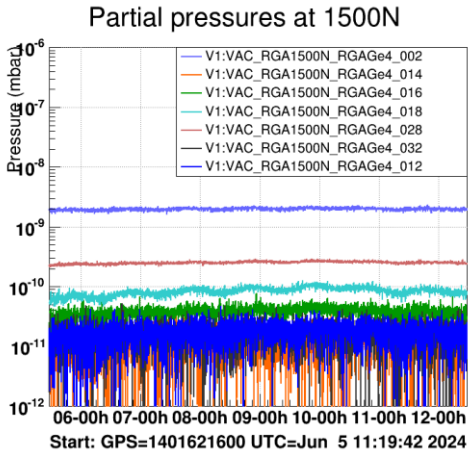

Accumulated gas over 2+ years on a 'tube prototype'

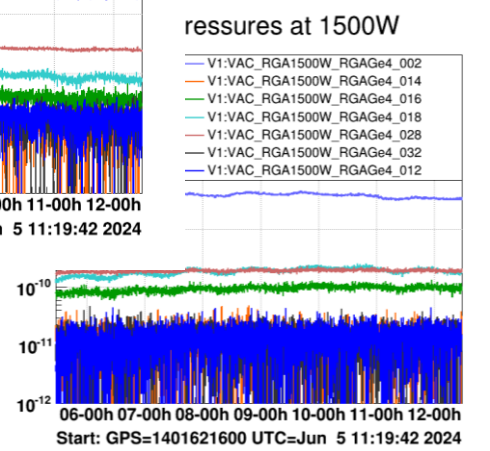


# Monitoraggio del vuoto con RGA

- Several RGAs (old) normally OFF, used for maintenances (1 per tower + 1 per tube station)
- Some RGAs, ‘in pairs’, online 24/7 . Mostly in ‘Faraday mode’, 50 uma or 200 uma range. Installed close to pumps or ‘in the middle’.
- Long term stability? Aging ? Spurius peaks build-up ?

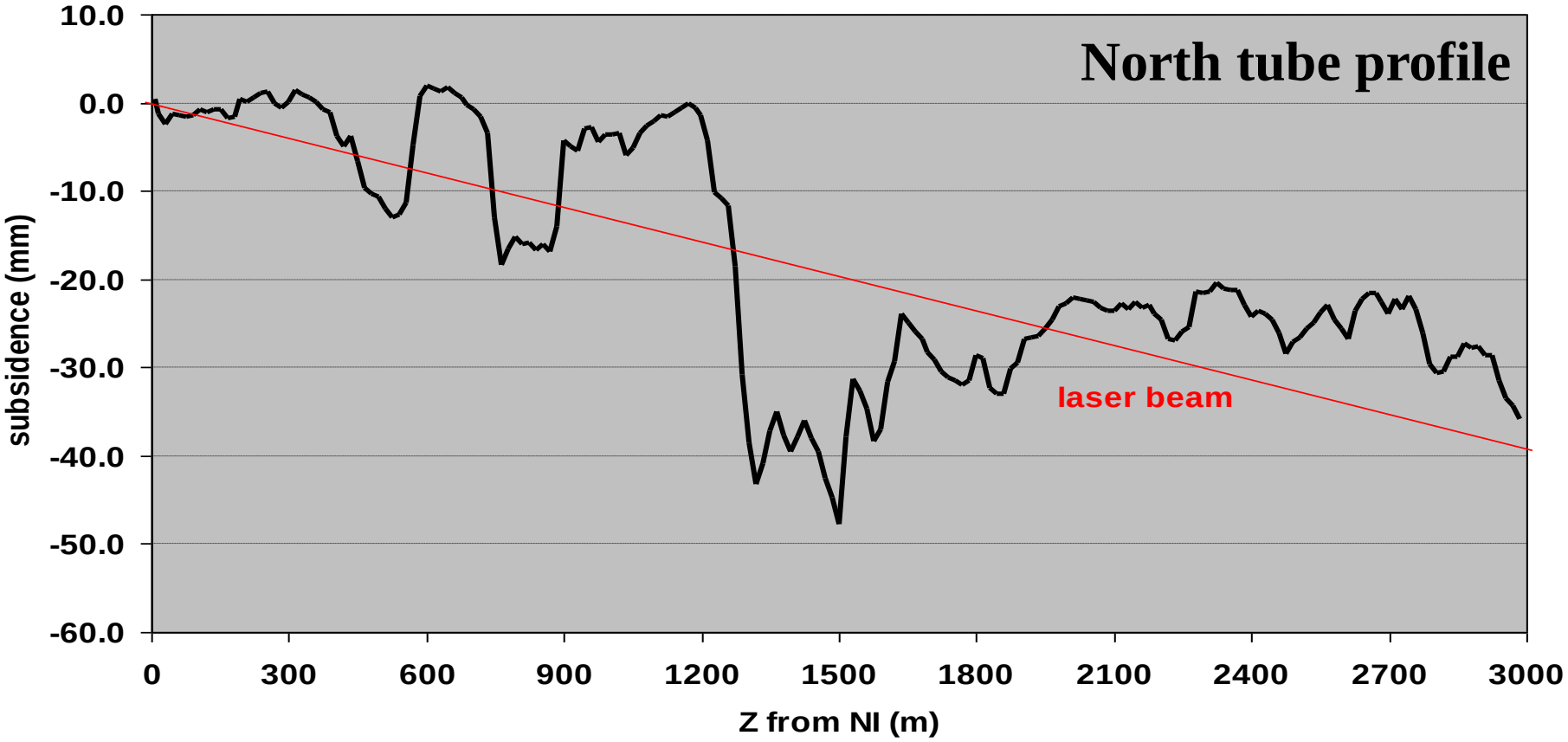


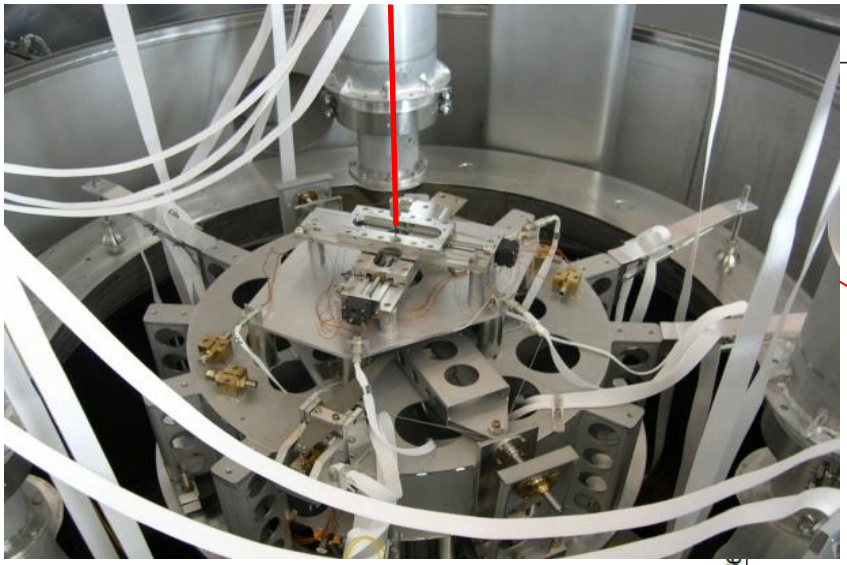
# ACTUAL TUBE GEOMETRY

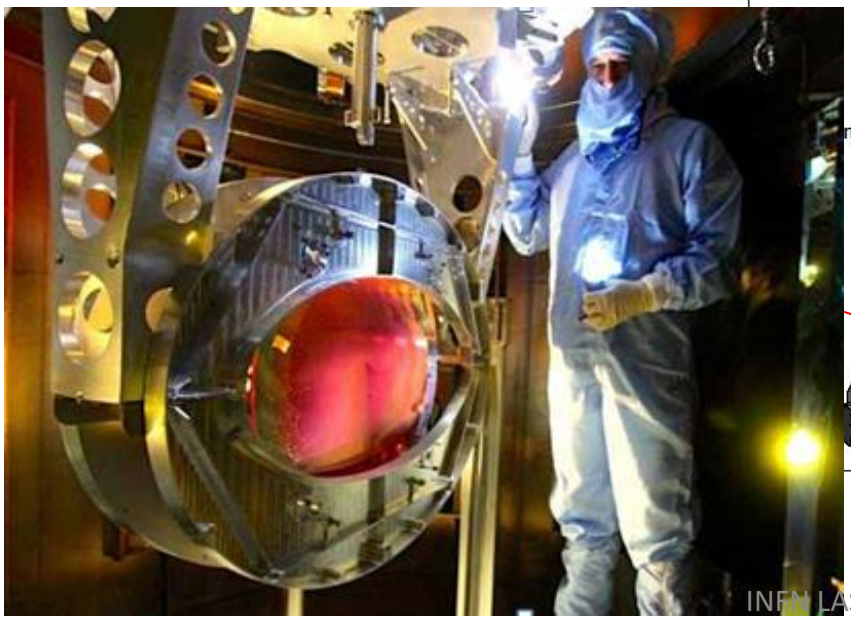
Due to GROUND SUBSIDENCE, tube foundations are sinking at a speed of the order of 1mm/month. Tubes are surveyed and periodically realigned to avoid mechanical stress.

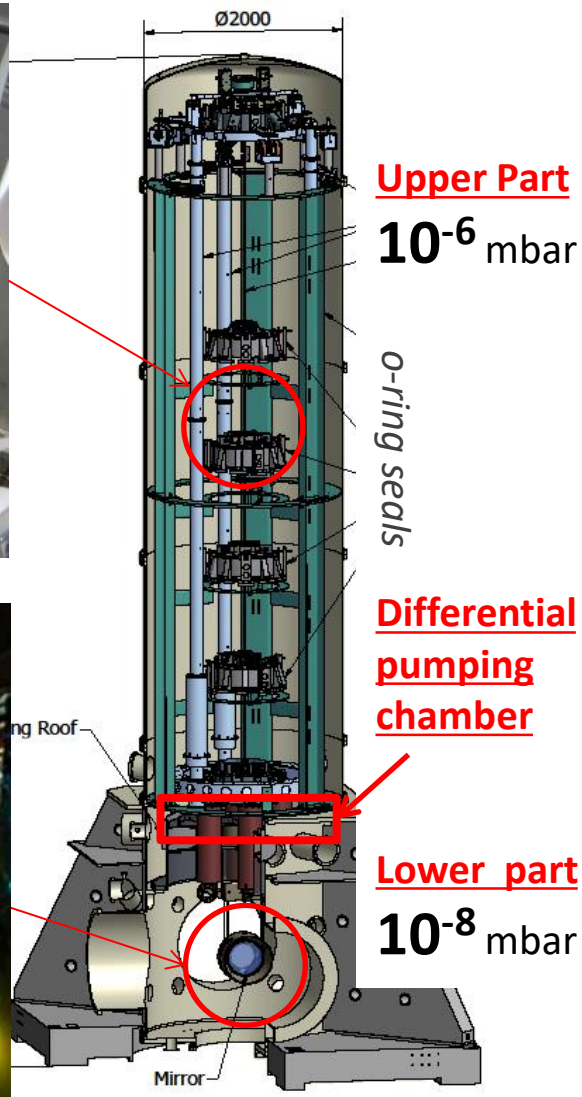


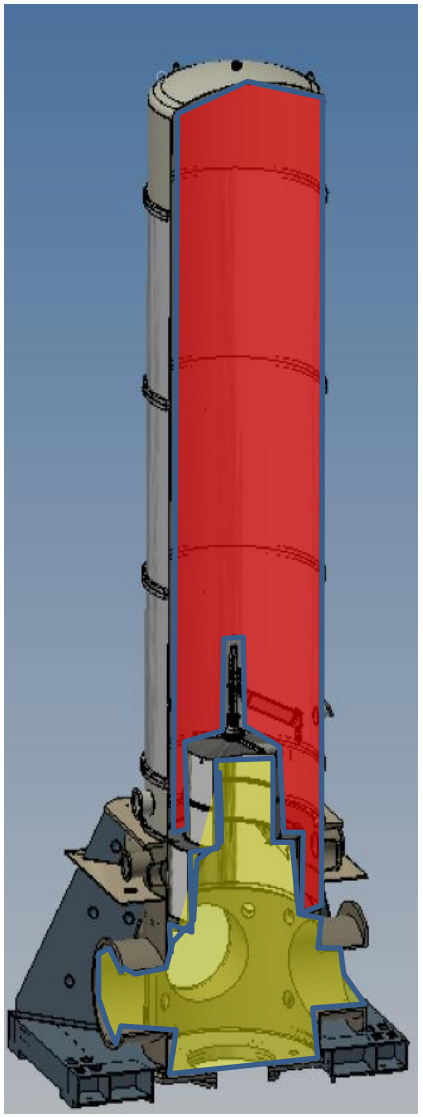
- Towers

# TOWERS: two (three) vacuum levels

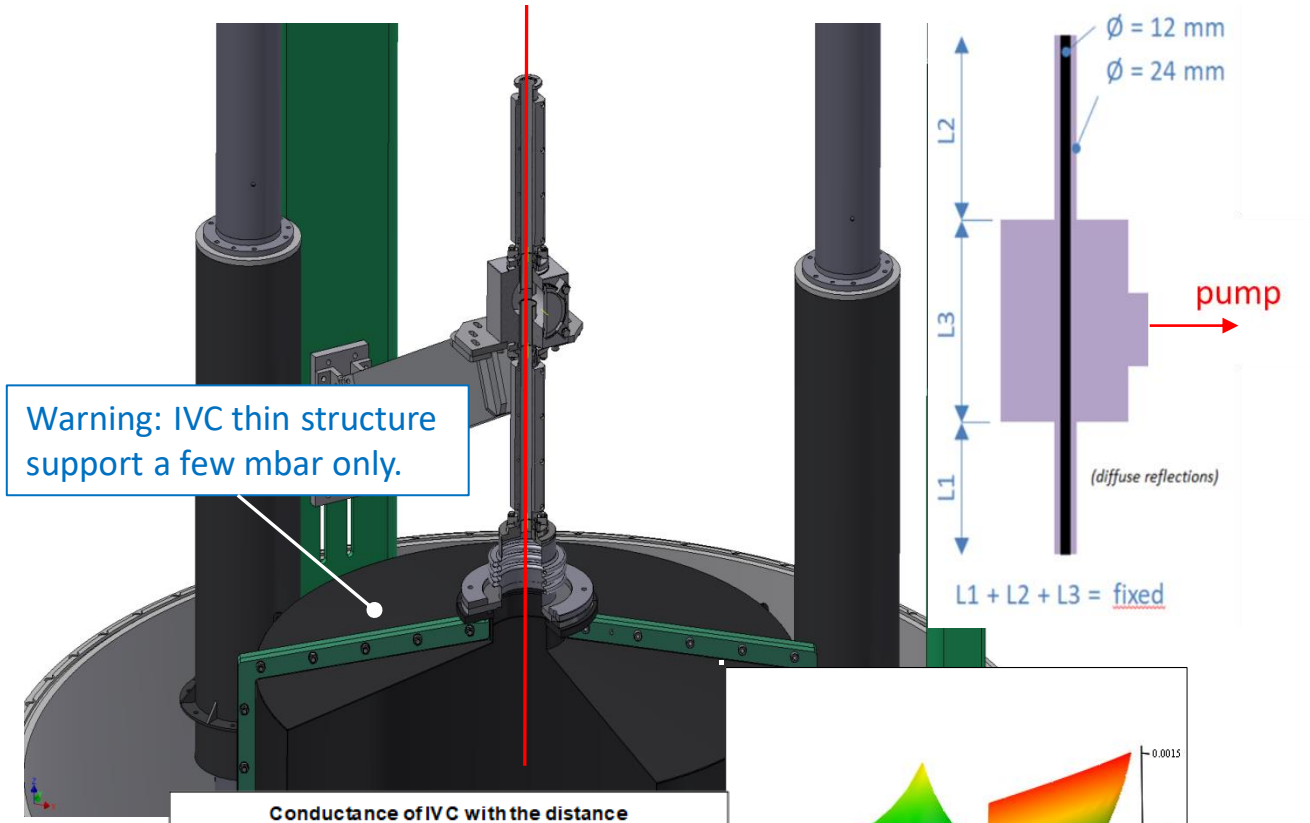


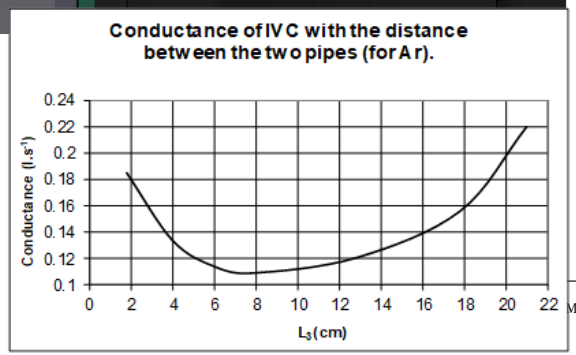


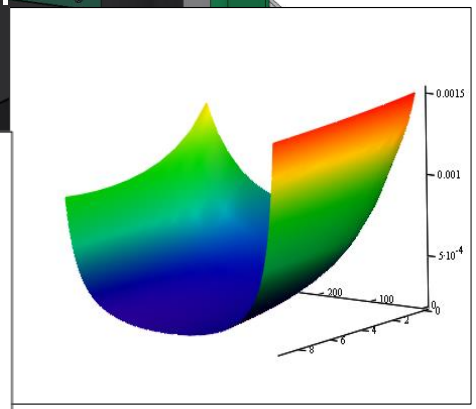


# IVC



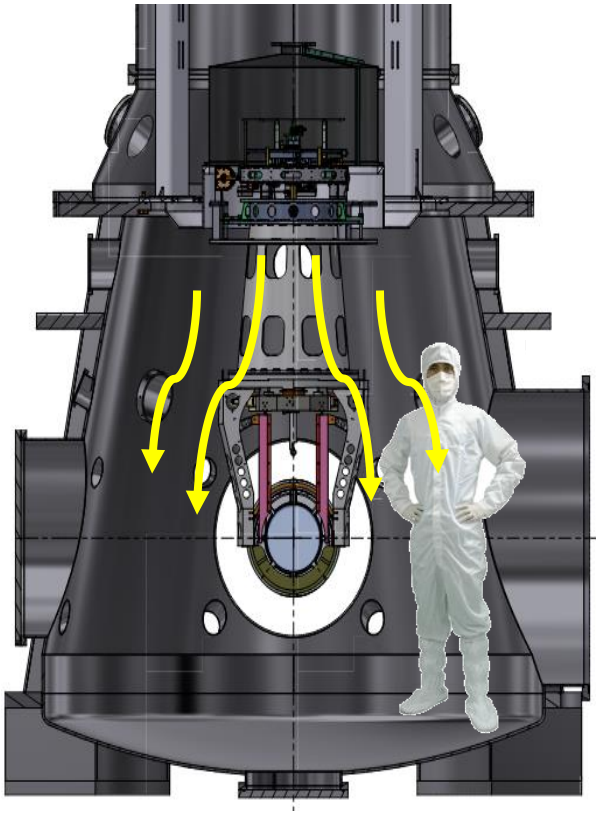




*Allows the suspension wire passing through in a small pipe with a few mm of clearance.*
*Possible pumping with external ion pump (not used).*

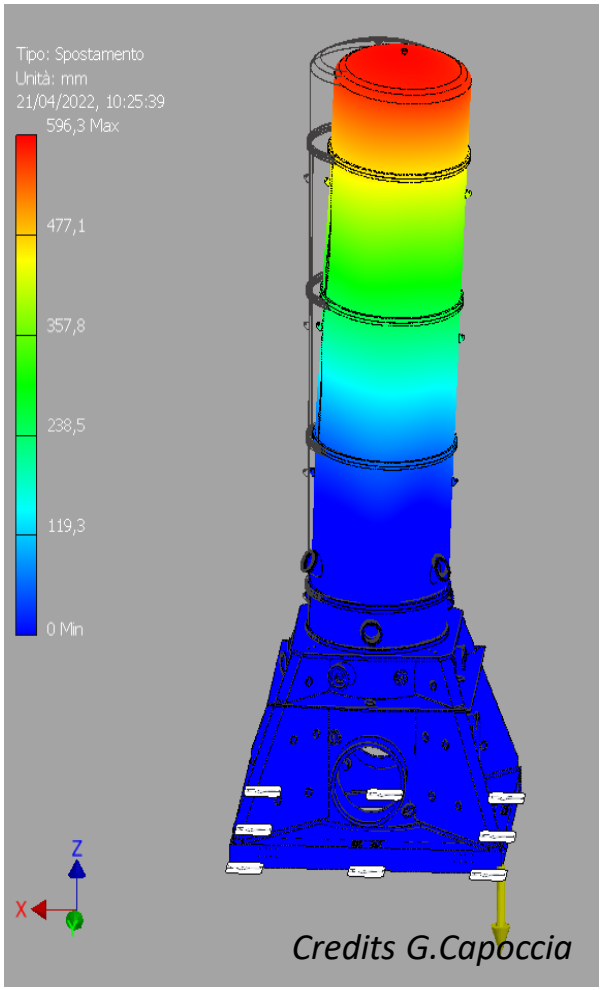
*Equivalent 'conductance' evaluated from 1.5 l/s to 0.1 l/s N2 if pumping.*
*Field tests: bypass effects in some towers increase Ceq up to 4-5 l/s.*

# TOWERS: mechanical features

- Ø = 2m, up to 11m high, > 20 ton;
- House complex mechanics (chambers frequencies > 15 Hz, within seismic-attenuator range);
- When in air, they works as a cleanroom: allow clean and ‘easy’ access of personnel to work close to inner optics;



*Credits F.Bianchi*



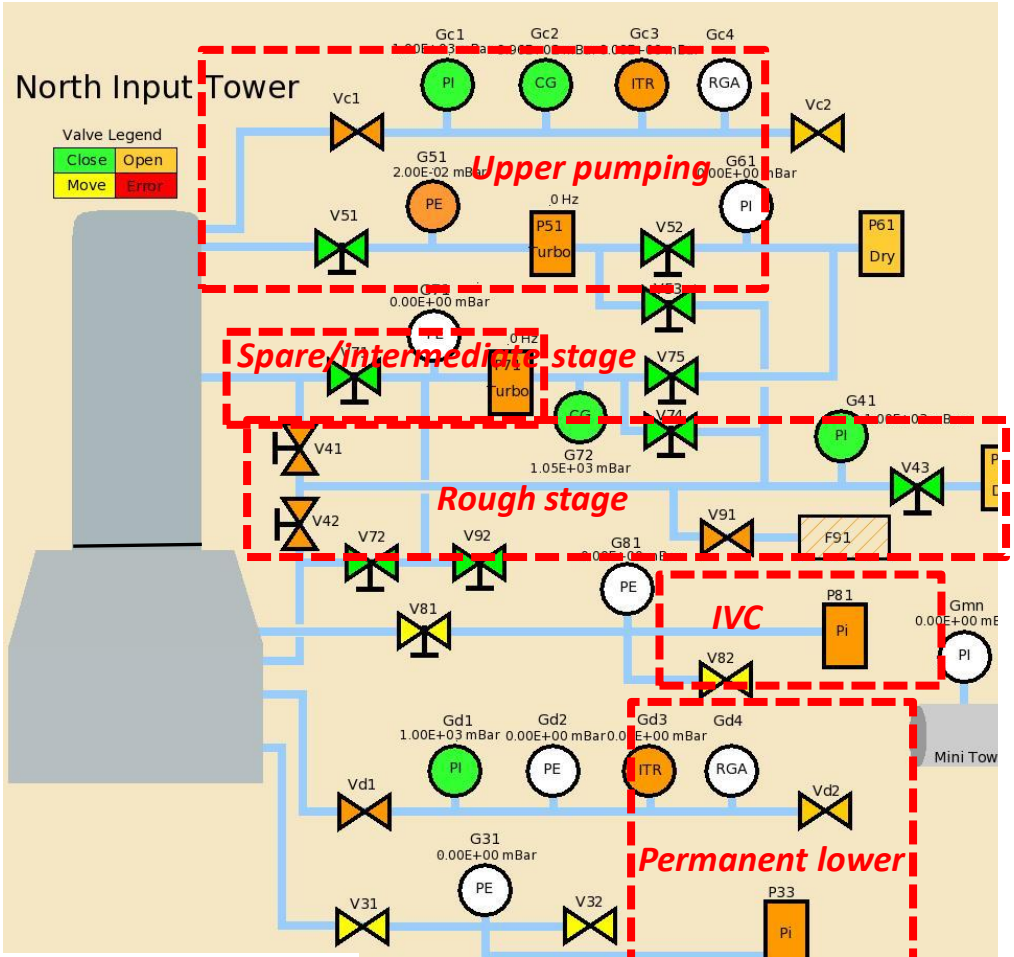

*Credits G.Capoccia*

# Flanges and seals

- Helicoflex® for not-accessed flanges, 20+ years ‘welded-like’ lifetime.
- Double o-ring (*any experience? e.g. wrt residual water permeation*)
- Single o-ring (upper parts)

# PUMPING SYSTEM

**Main requirements:** oil free pumps against contamination risk, low acoustic / seismic / magnetic emissions , long maintenance intervals to preserve duty cycle.

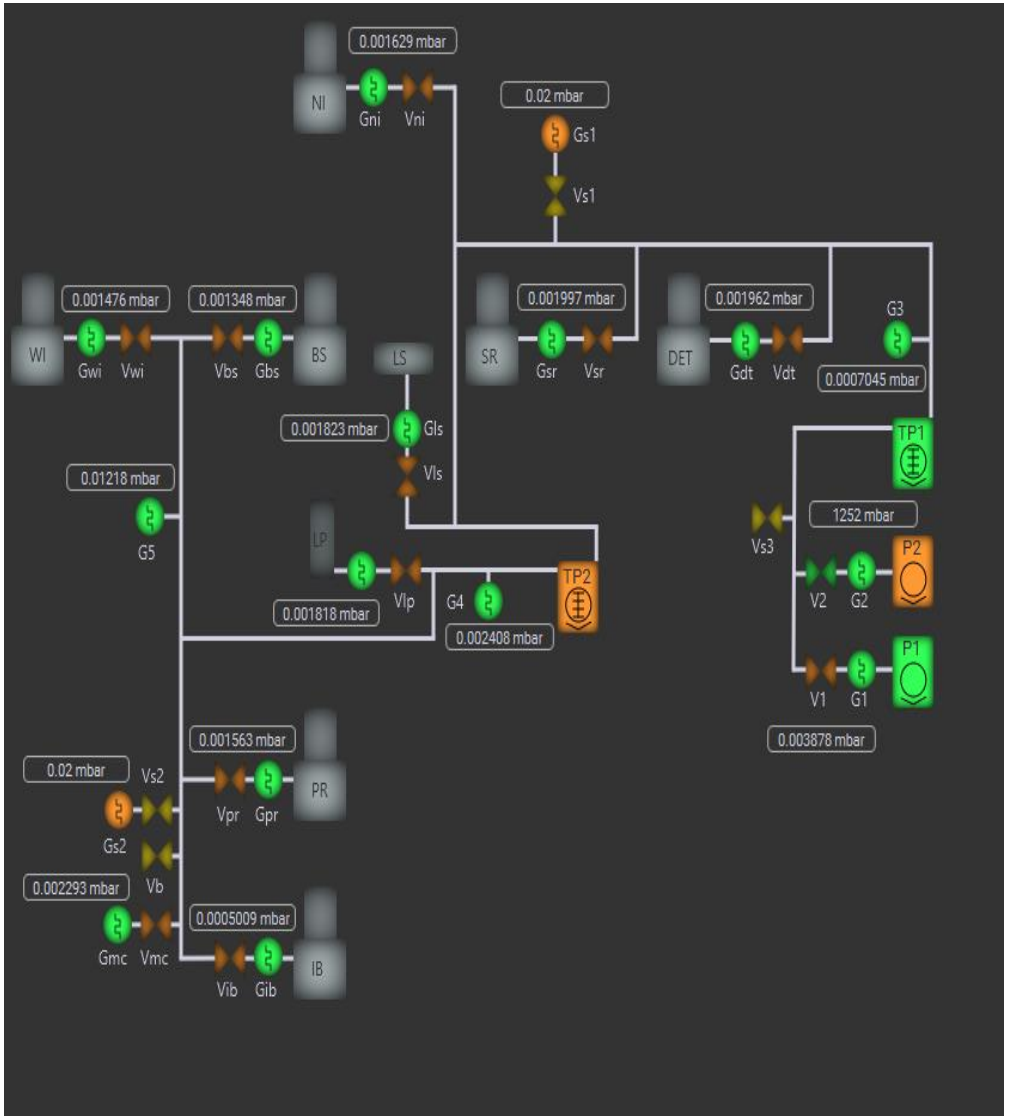



**Tower synoptic**

**Statistic (not updated)**

| | |
|---|---|
| 22 | Roughing/backing dry pumps |
| 21 | Turbo-molecular pumps |
| 25 | Ion pumps |
| 20 | Residual gas analyzers |
| 221 | Angle valves |
| 111 | Gate valves |
| 4 | Large valves ø=1000 mm |
| 153 | Gauges |

# Remote backing pumps




*A more recent upgrade: Turbo-molecular pumps permanently running on each tower upper compartment (typical size 1000 l/s) are backed remotely to limit acoustic/seismic disturbances (or discontinuously , this not optimal for hydrogen)*

# CONTROL SYSTEM HW & SW

- Local or remote operation
- Logic of operation is managed by a PLC
- Interlocks by Supervisor SW


- Data fully integrated in Virgo DAQ (5000 channels @ 1 Hz , < 0.1 % of the total)

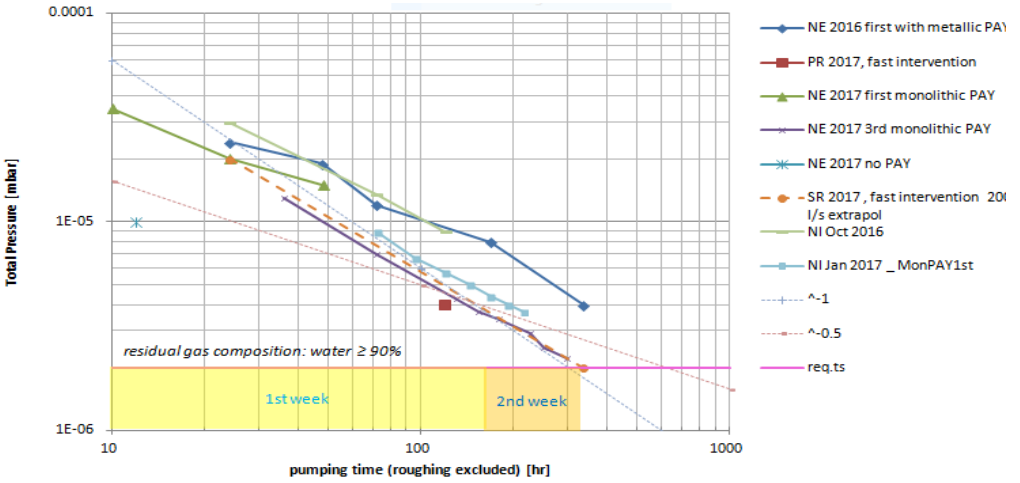
by LAL team

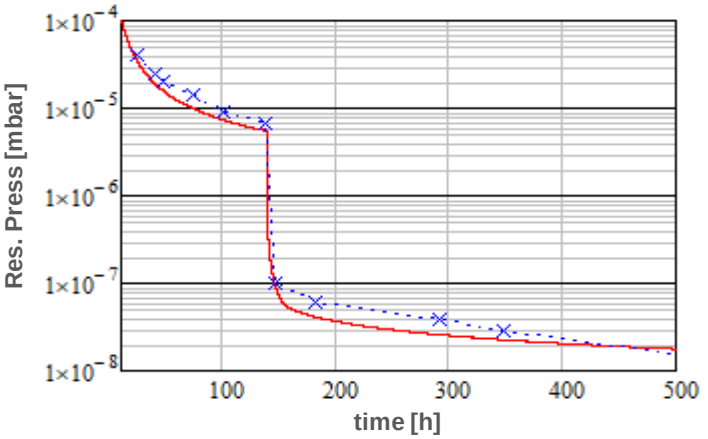
# LIVELLO DI VUOTO DELLE TORRI

The gas load is largely due to the added inner materials!

Increasing along detector upgrades (from V -> V+ -> AdV -> AdV+) while aiming to improve the vacuum in the tubes…

*Beyond the 'steady state' level, the recovery time is also important for the duty cycle.*



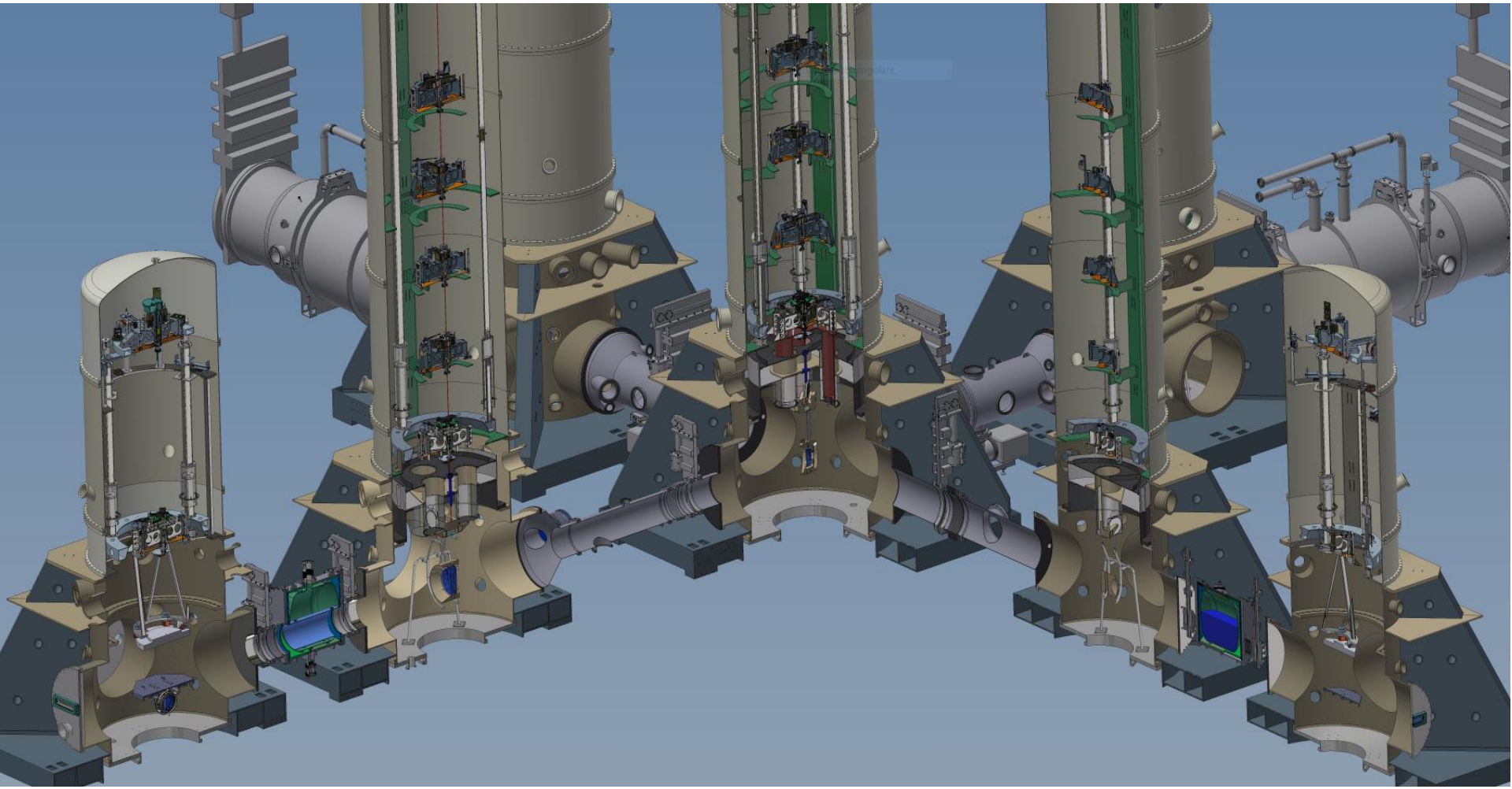




**OLD: xls table**

| For 1 base tower | --> | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Material | Surface (cm2) Hyp | q100h | q1000h | qH2 | qN2 100h | Q100H | Q1000H | QH2 | N2 and al. 100H |
| Walls (AISI 304L) | 400000 | 4.00E-11 | 2.00E-12 | 1.00E-12 | | 1.60E-05 | 8.00E-07 | 4.00E-07 | |
| Alu - AW_6082 | 100000 | 3.00E-11 | 3.00E-12 | 4.00E-14 | | 3.00E-06 | 3.00E-07 | 4.00E-09 | |
| Glass | 15000 | *2.00E-09* | *2.00E-10* | *TBC* | *TBC* | 3.00E-05 | 3.00E-06 | | |
| Kapton (cables…) - METER | 500 | *9.00E-09* | *2.00E-10* | *1.00E-09* | *2.00E-09* | 4.50E-06 | 1.00E-07 | 5.00E-07 | 1.00E-06 |
| Other materials (StSt, Titanium, Rame, PTFE, etc.) | 50000 | *1.00E-09* | *2.00E-10* | *2.00E-12* | *5.00E-11* | 5.00E-05 | 1.00E-05 | 1.00E-07 | 2.50E-06 |
| Macor (thick polymer material) | | | | | | | | | |
| **Estimate 2022** | | | | | | | | | |
| *Ideal Case* | | | | | | | | | |
| | | | | | | | | | |
| Allowable leak (double Oring) - AREA M2 | | | | | | | | | |
| "Extra" materials - Margin | | | | | | | | | |
| PEEK (thick) | | | | | | | | | |
| **Total - non Ideal only** | | | | | | | | | |
| | | | | | | | | | |
| **All - Total** | | | | | | | | | |
| **Taking into account the unknown "TBC" - TOTAL** | | | | | | | | | |

**NEW: via CAD, in progress**

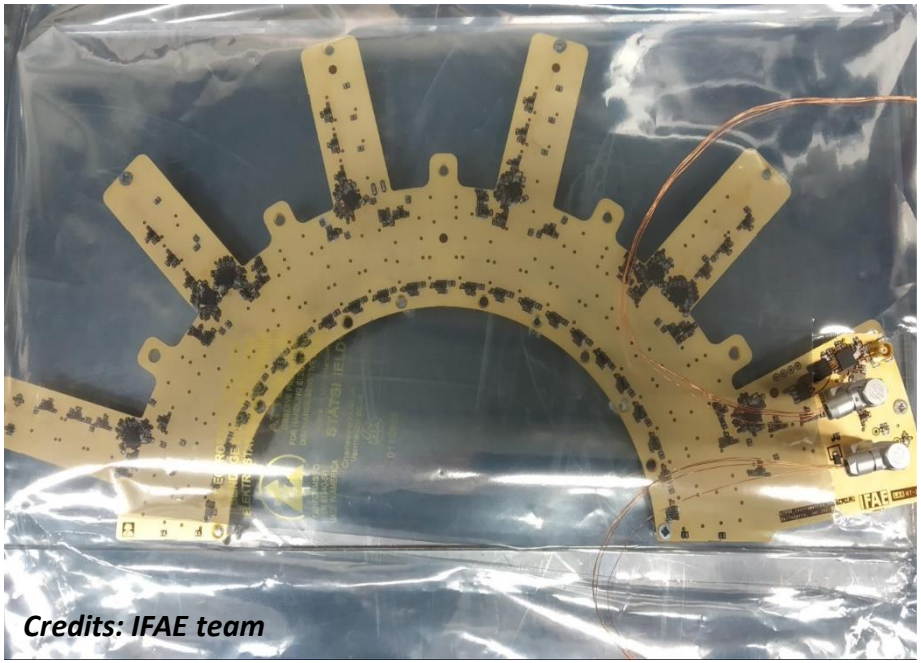
Main optics and critical systems concentrated in this area. The challenge is to limit environmental emissions such as mechanical, acoustic, and magnetic vibrations. Turbo-molecular pumps: bellows and separate base, shielding of the cable. Not ideal choice. Alternatives? Ion pumps? Dispersed charges… Cryogenics? Noise … NEG? High load… All of them are present, in different positions.



# IN-VACUUM COMPONENTS



In-tower components are checked for vacuum compatibility to obtain a sufficiently low overall outgassing (i.e. of water vapor, air species, hydrogen). Partial pressure of potentially contaminating species are to be kept under control as well.



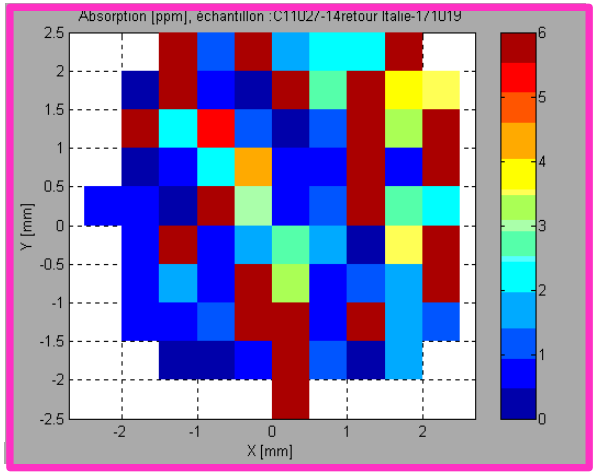
*Credits: IFAE team*

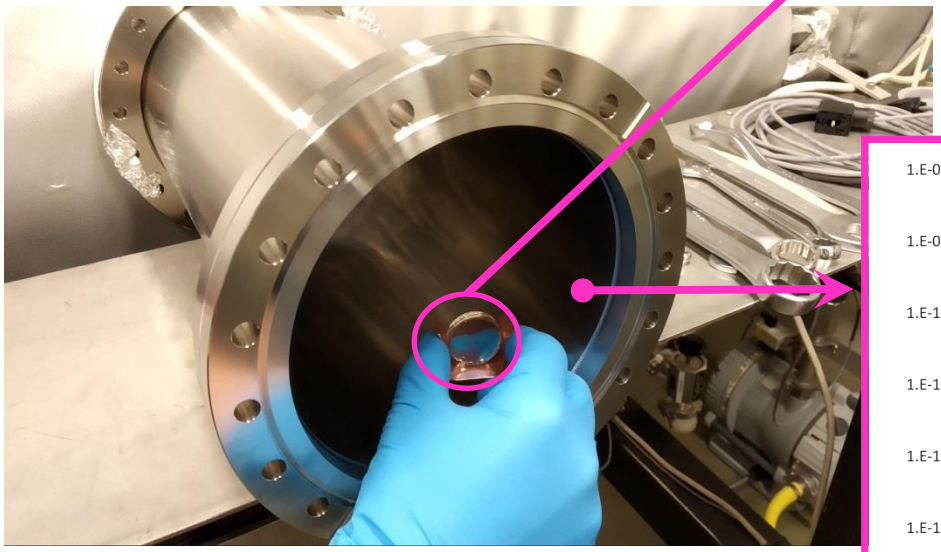
# IN-VACUUM CONTAMINATION CONTROL

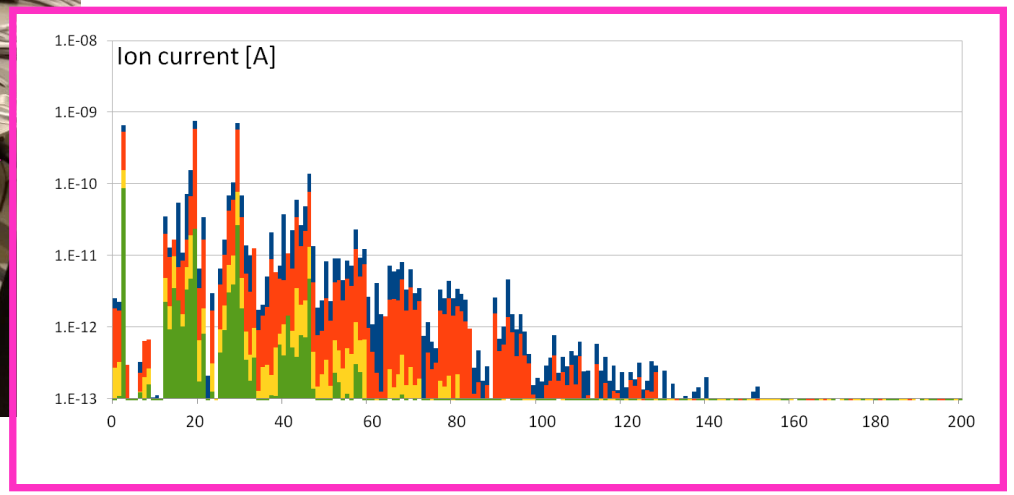
**Deposition of low-volatile species = crucial risk for Virgo optics.**

we qualify materials checking the:

1. residual gas analysis
2. optical losses on dedicated samples

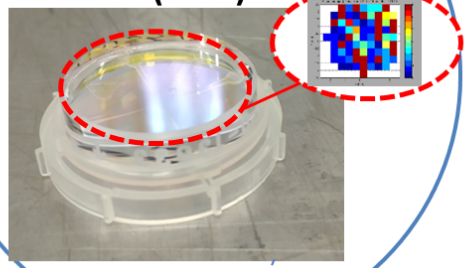




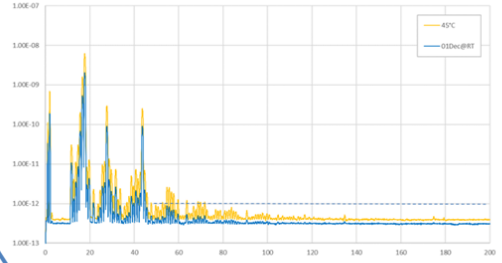
# IN-VACUUM CONTAMINATION CONTROL

**OPTICAL LOSSES MEASUREMENTS (LMA)**

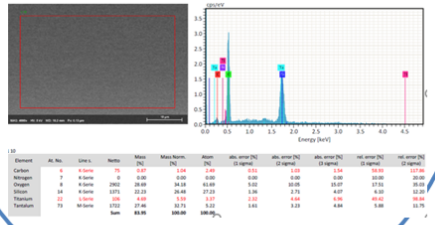


*No clear correlation between the detected contaminant level in the gas and the measured optical losses*

**RESIDUAL GAS ANALYSIS**



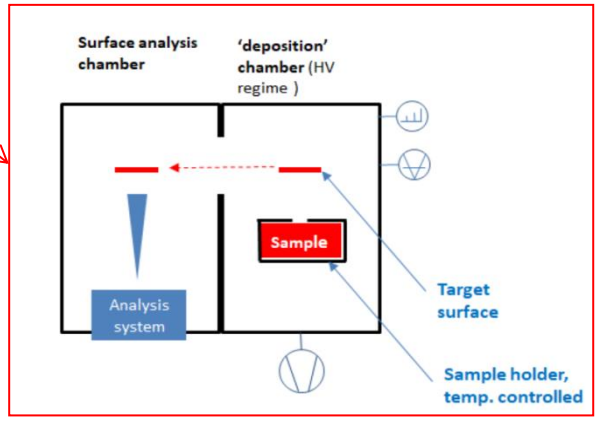
**SEM for GROSS contamination identification**



**MISSING**

1. **Identification of deposited species**
2. **Quantification of deposited film**

**?**

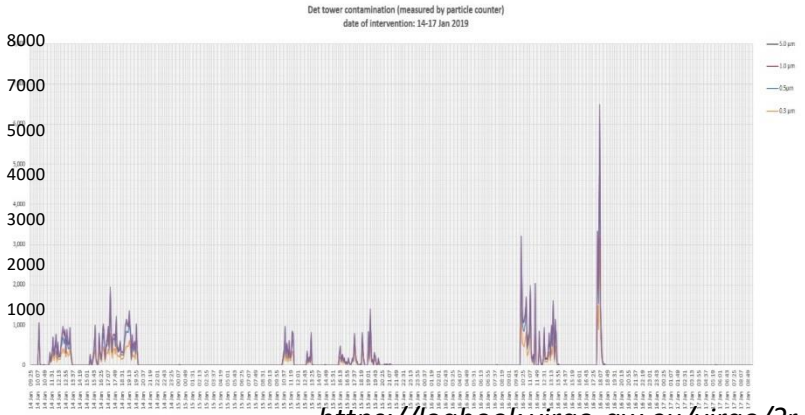



*Trials with XPS thanks to E.Placidi [J. Vac. Sci. Technol. B 42, 034003 (2024)]*

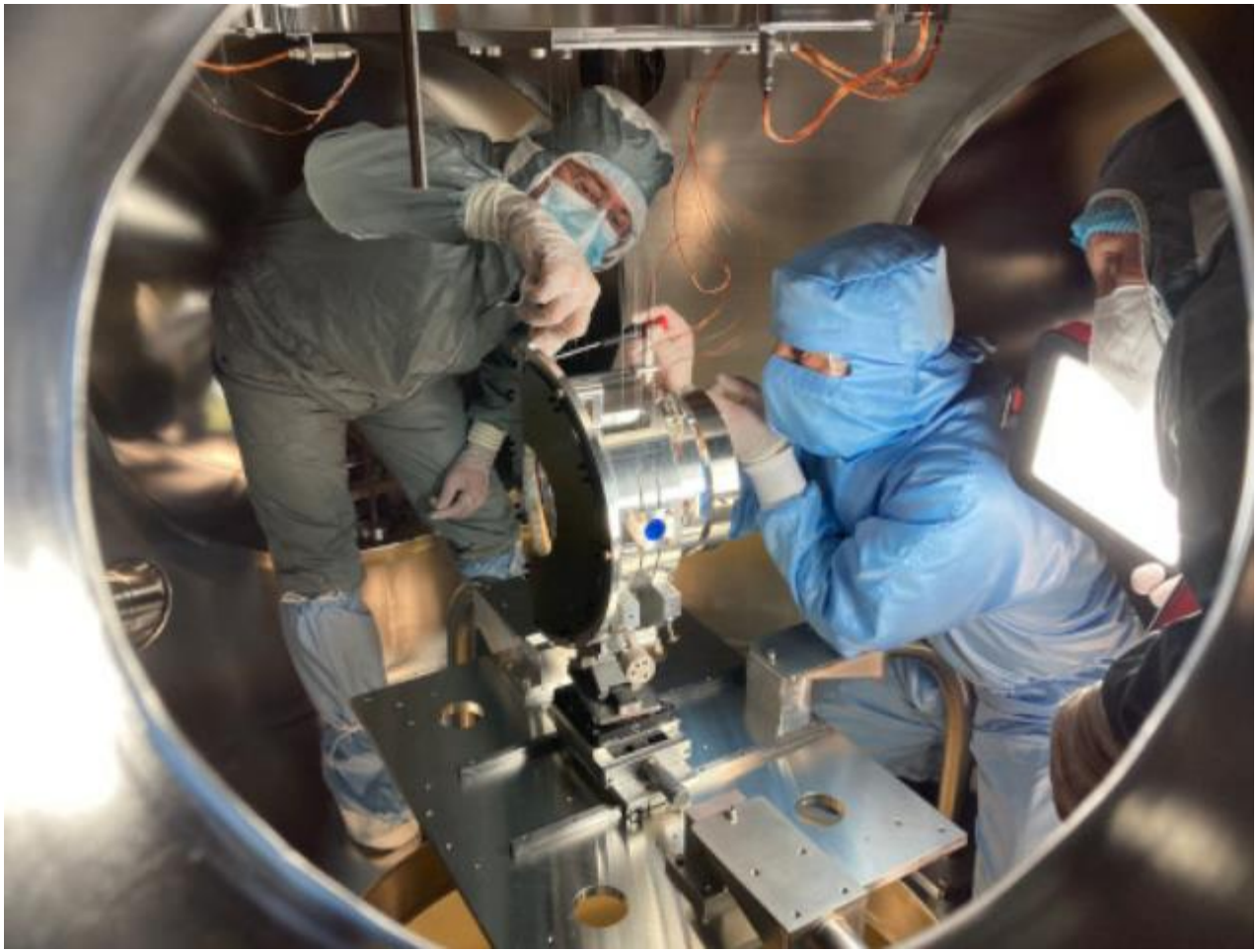
# Cleanroom service


*Credits: M.Perciballi*

- *Towers lower compartments are a 'classified' environment for dust particles concentration (airborne)*
- *Flushed with HEPA filtered air and kept monitored*



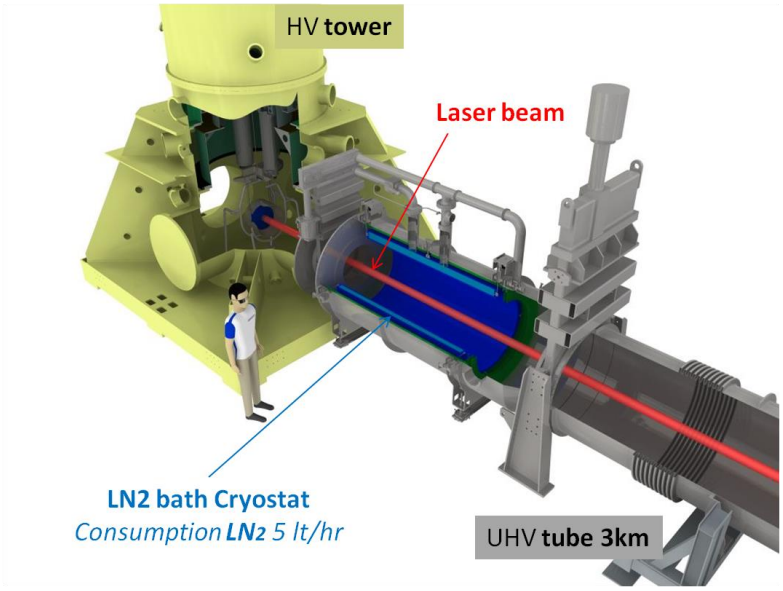

*https://logbook.virgo-gw.eu/virgo/?r=444*



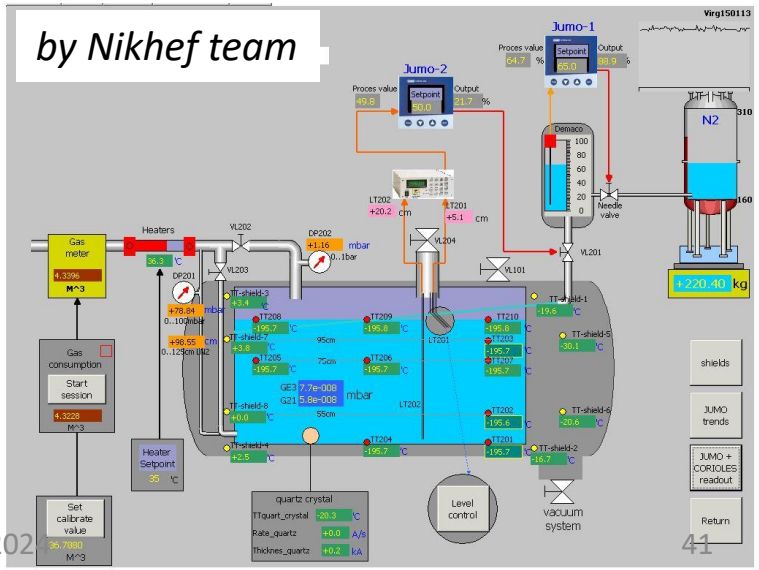
- Cryogenics

# CRYOGENIC PUMPS & EQUIPMENT

Installed between ‘unbaked towers’ and ‘baked tubes’ *(added in a second stage)*
LN2 consumption 2000 l/day from 3 ‘horizontal tanks, 50 $m^3$ total capacity. Refill operations affect the scientific duty cycle.



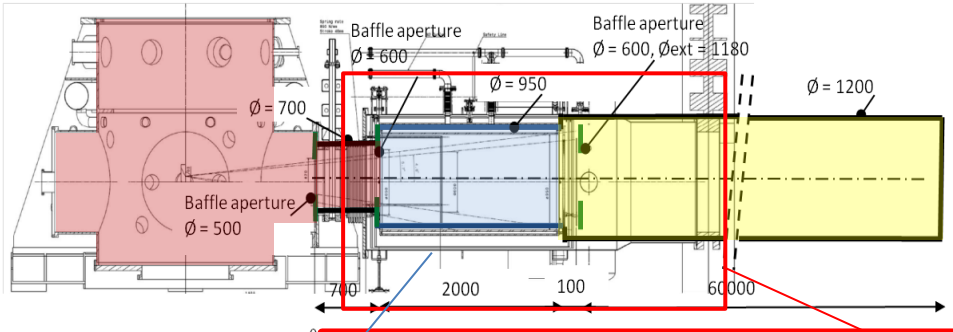


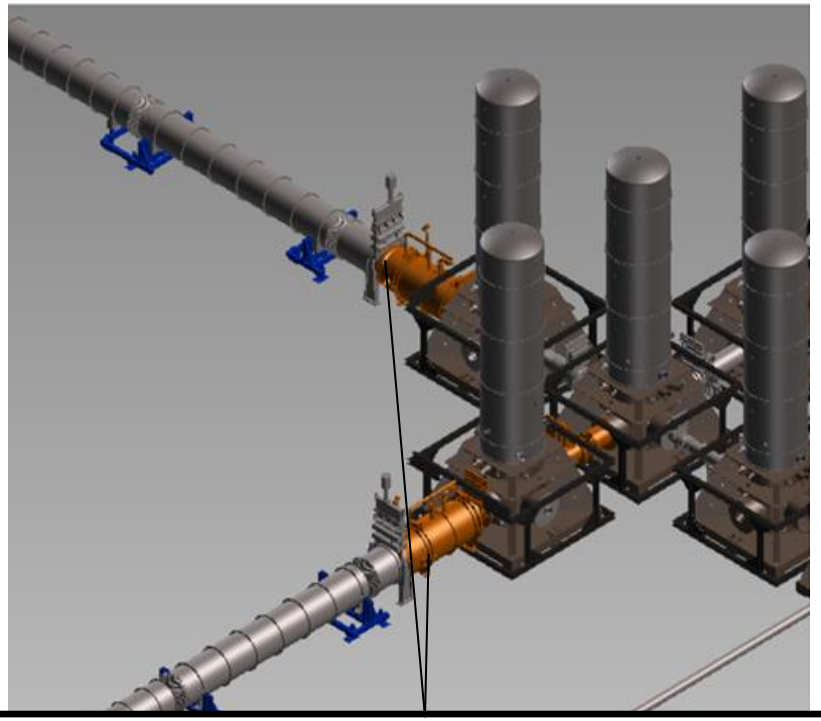


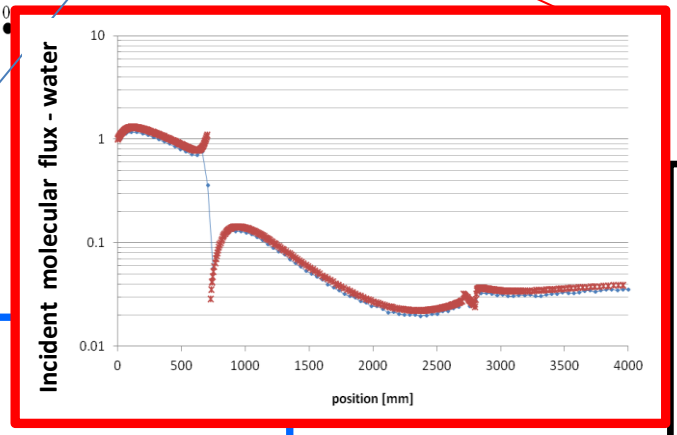

*Function is to pump water vapor coming from towers*

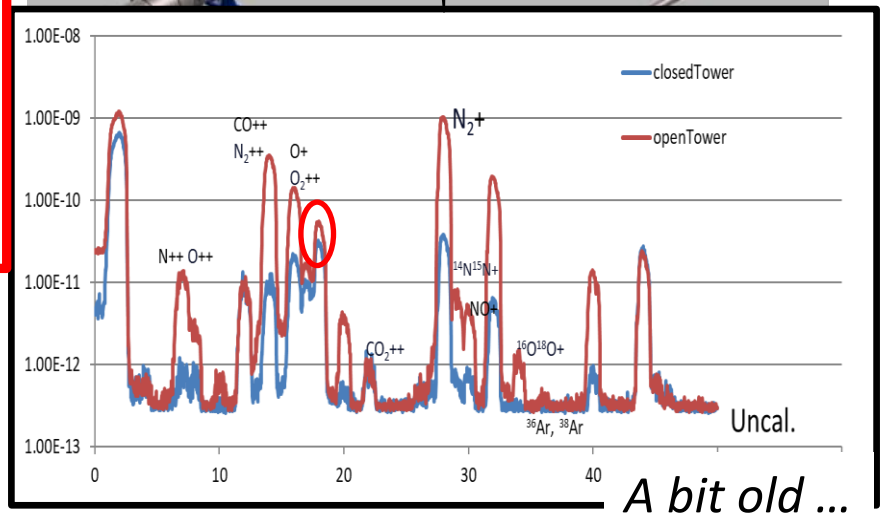
# CRYOGENIC PUMPS & EQUIPMENT

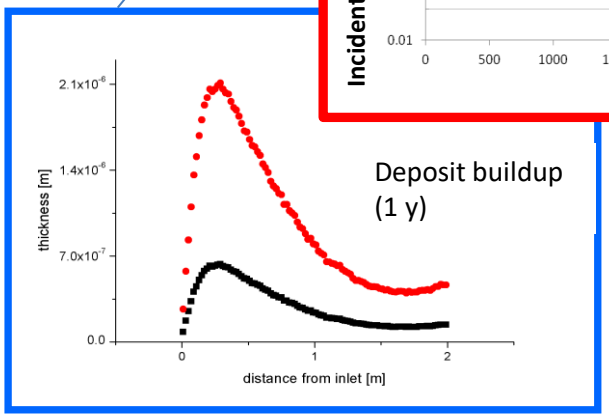
a 2m long cylindrical section cooled at 77K pumping the water vapor coming from 'towers' chambers *(originally used by LIGO)*.





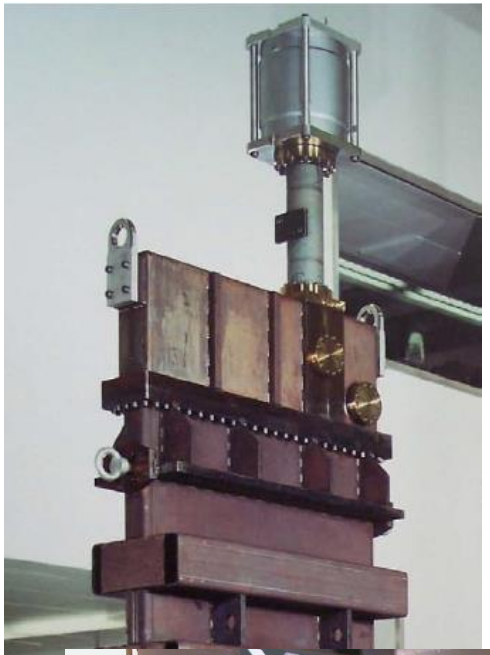




*A bit old …*

- Special topics

# LARGE VACUUM VALVES




❖ **4 DN1000 Valves to isolate the ‘tubes’ from the ‘towers’**

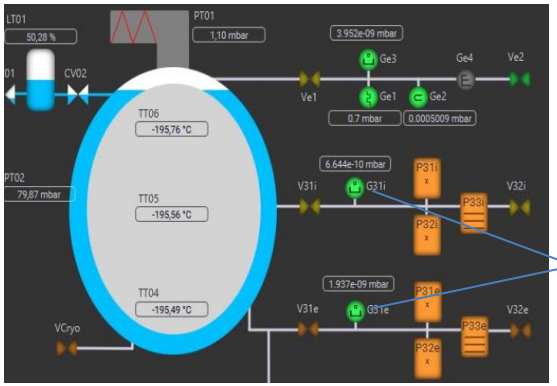
- *Stainless steel body, air-baked*
- *Metal sealed(the only large flanged joint)*
- *Viton o-ring on the gate (single)*
- *Bakeable at 150°C*
- *Expensive*

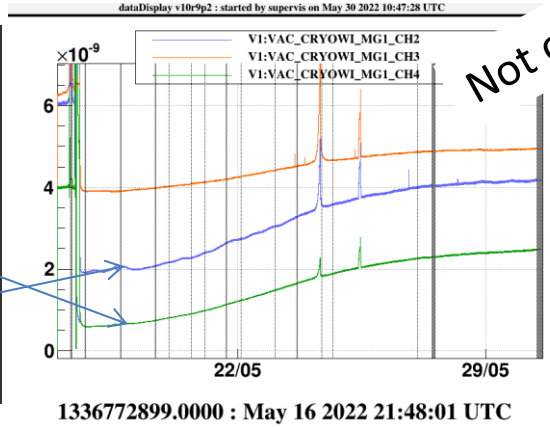
Outgassing data *(old, meas. in factory):*
< 5E-8 mbar.l.s$^{-1}$ - stainless steel body, $H_2$
< 5E-7 mbar.l.s$^{-1}$ - Viton® seal on the gate , baked;

❖ **7 DN650/400 Valves to isolate the ‘towers’ from each other**

# TSPs pumps

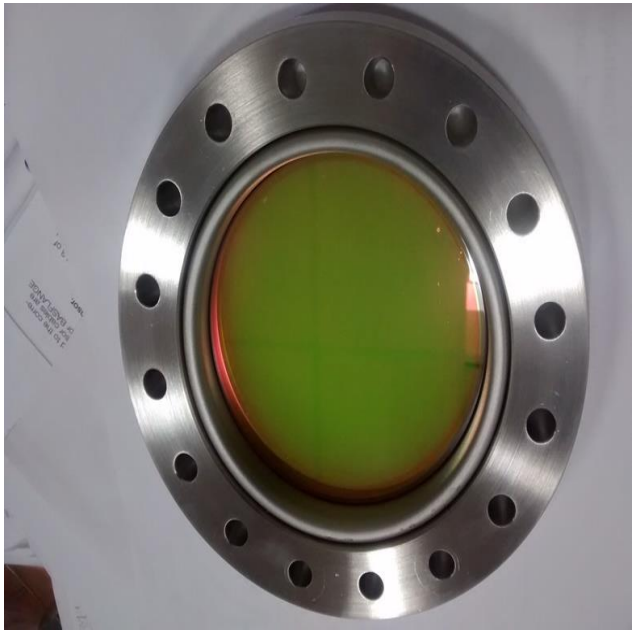
- 1 sublimation every 2 months or similar.
- Those near the towers saturate after a few days (all gas species) and are not used.
- The ones in the middle of the tube appear saturated with other species but still pump H2 (different sites?!).
- Unable to replicate this in the lab.
- Effects of gas release ?



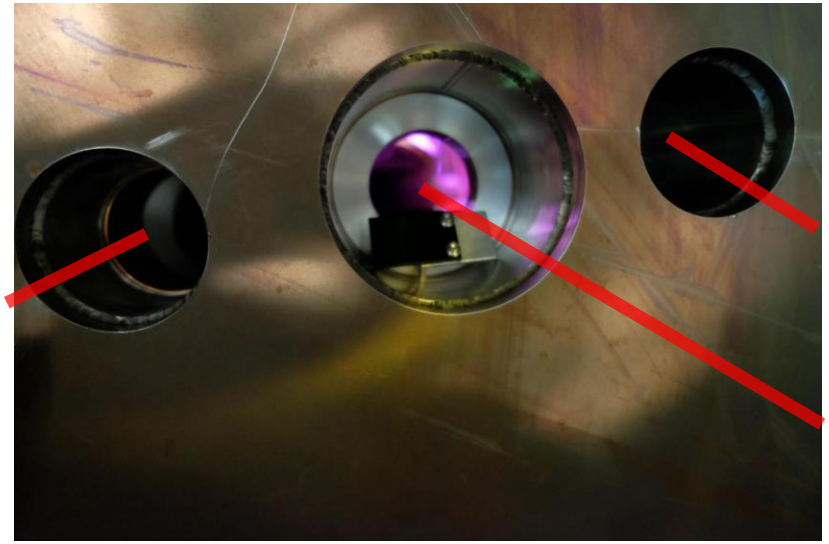

# Viewports

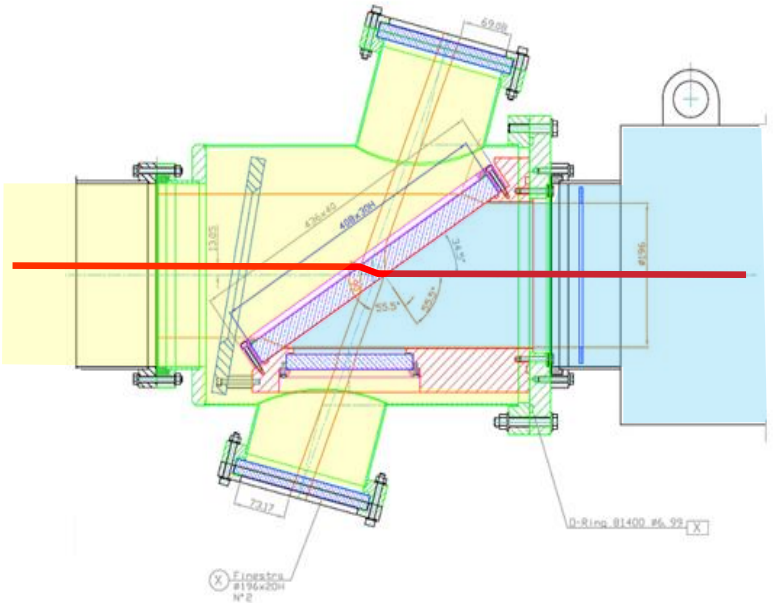
- Large number of viewports, e.g. 1000, large dimensions, of different base materials and possibly exposed to high power beams .
- Policy and solutions against breakage risks must be foreseen already during the design phase.
- *In addition, they are a possible source of disturbance for the ITF*

# ‘WINDOW’ SEPARATIONS

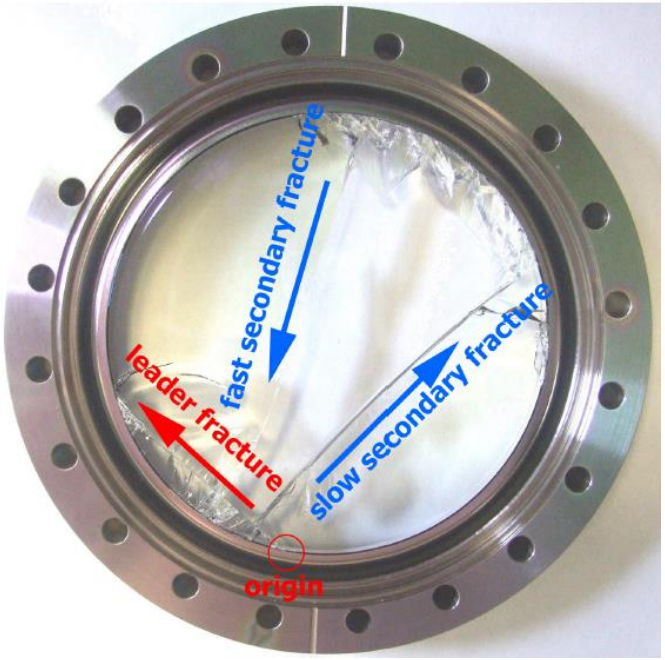
- Vacuum tight glass separation are in use to allow beam passage between chambers at different vacuum levels. May become limiting for the experiment (or for vacuum when removed). Not a valid solution for critical areas.

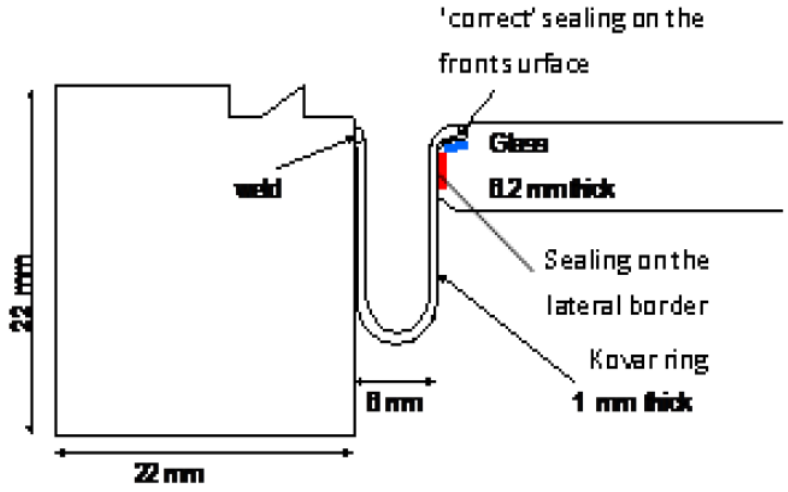




# VIEWPORT RISKS

Order of 90 viewports needed, mostly standard ones. Dedicated policy against breaking risks in force. Further mitigation actions shall be implemented (external screen).



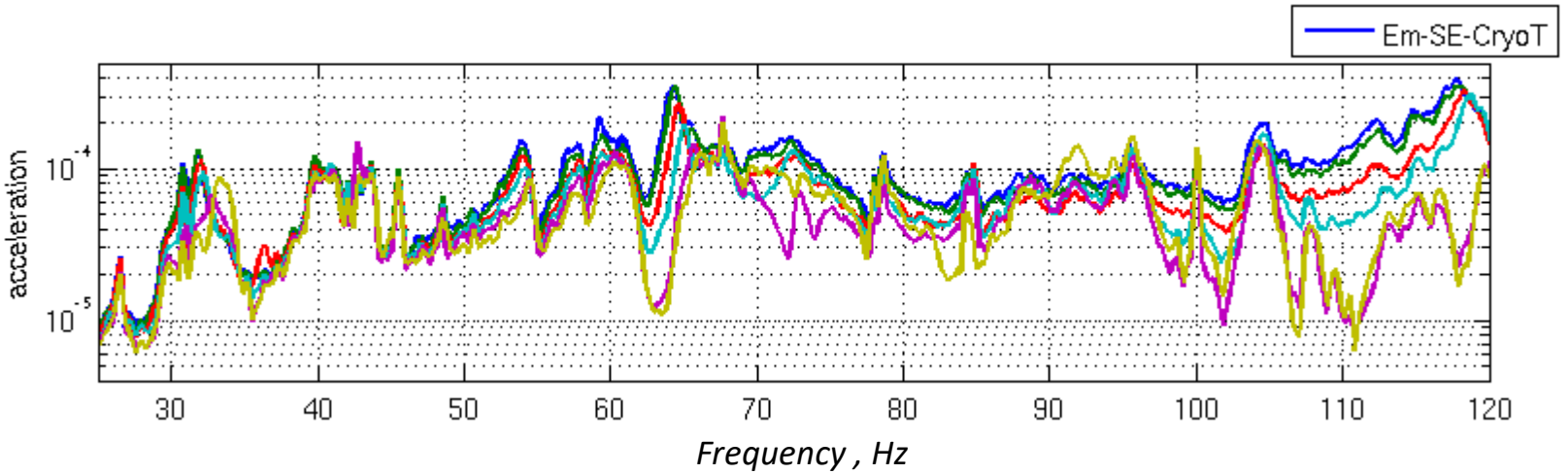

Breaking event of a viewport, 2008

**Risk = defect + stress x time**

Glass/KOVAR joint design was the origin of the stress (SSV)

# LN2 BUBBLING

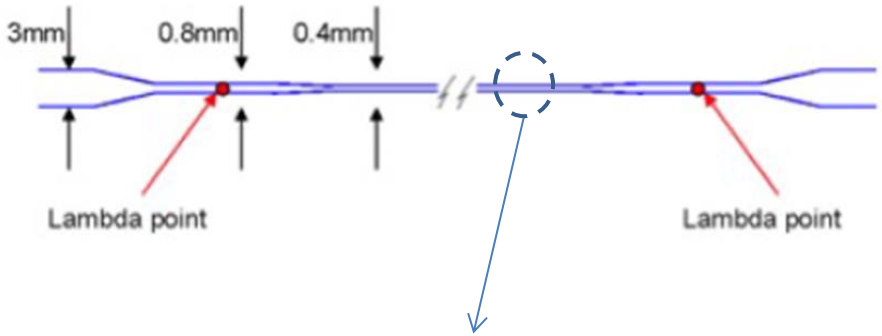
LN2 boiling inside cryostats is a possible source of noise (mechanical vibrations): *accurate design to avoid 'heat concentration spots' , seismic isolation of the cryostat, large walls opening.*

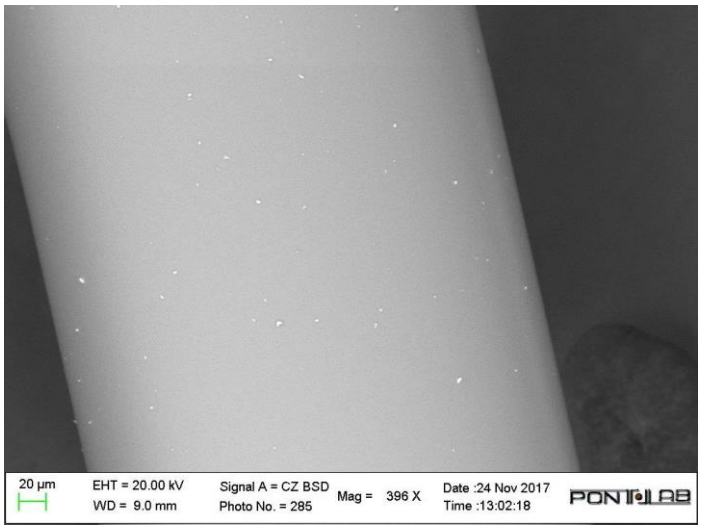



*Increase of the seismic vibrations of cryostat walls due to LN2 bubbling*

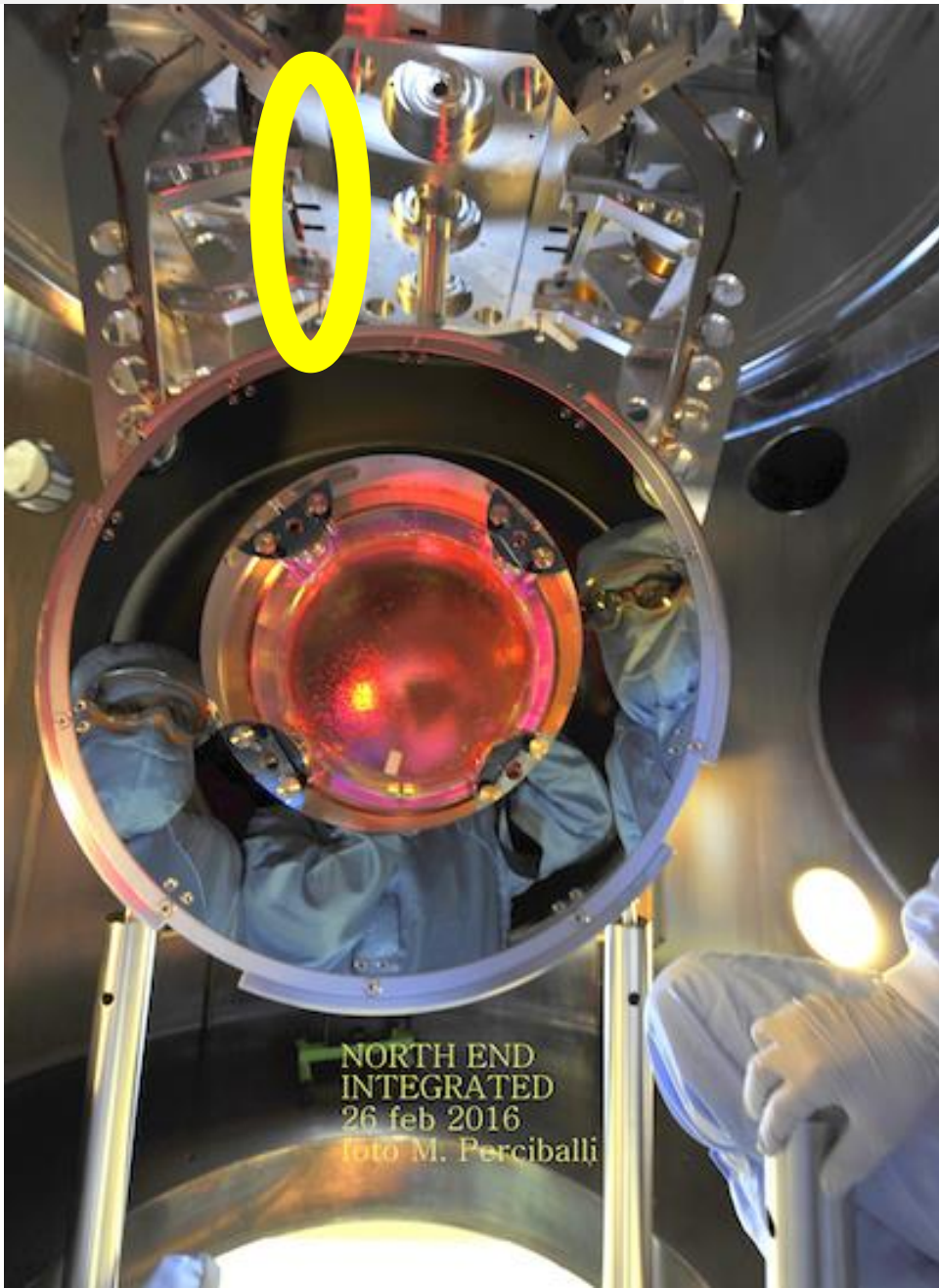
# DUST PARTICLES vs QUARTZ FIBERS

The last stage of seismic attenuator is realized with fibers made of fused silica (0.4 mm diameter).



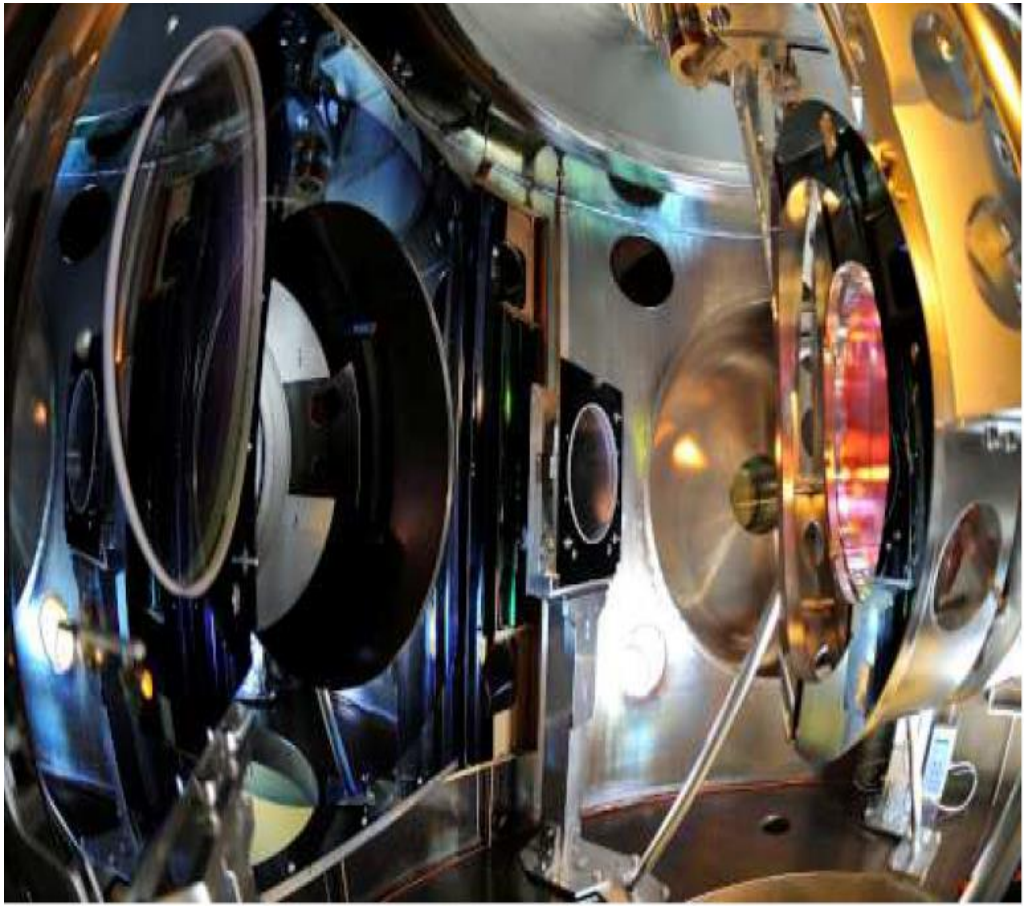



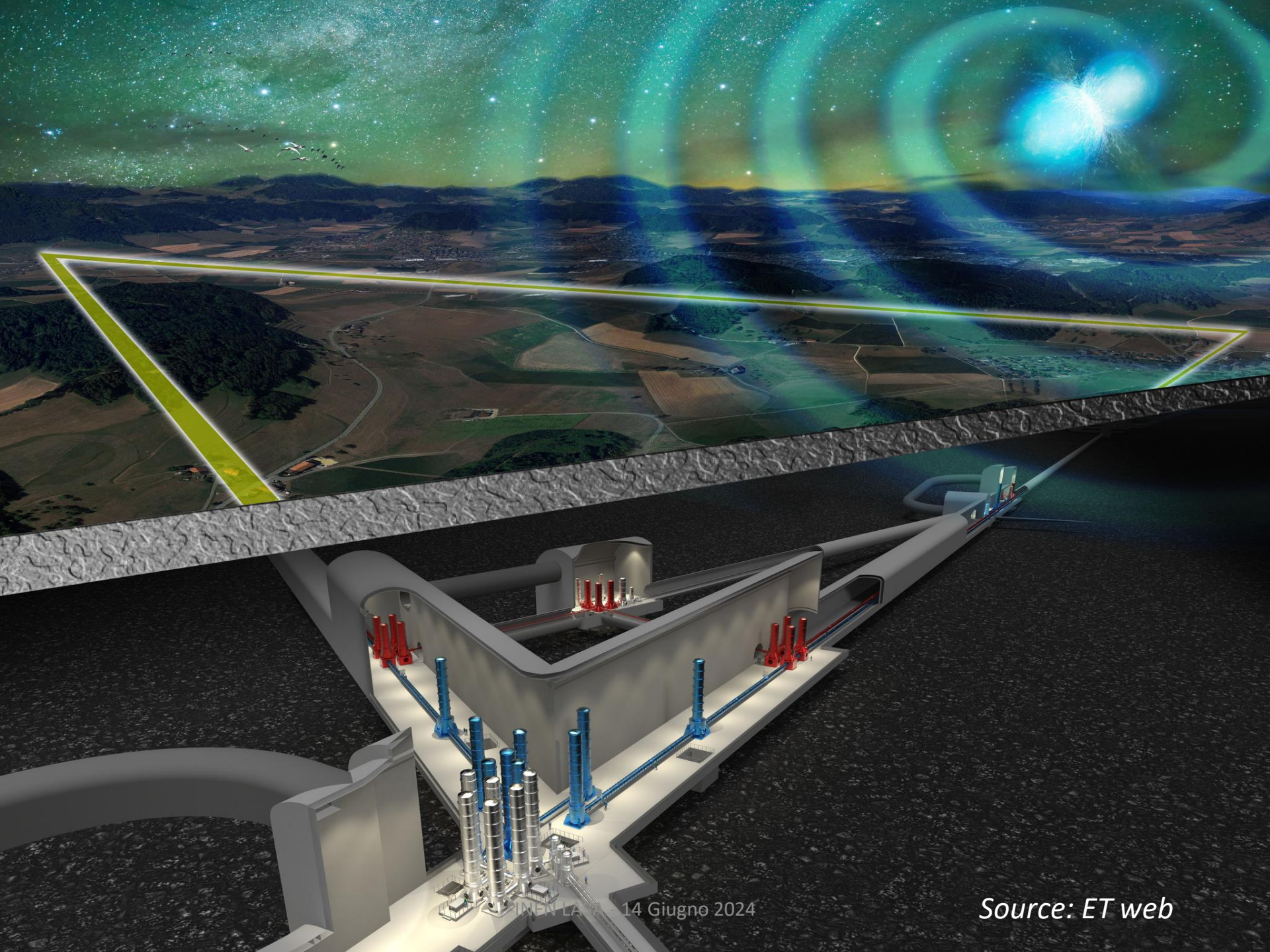

*Electrostatic forces may play a role…*



# CHARGES ACCUMULATION

- Static charge can build-up on TMs after months of service under vacuum (in Virgo estimated at level of E-9 C) = neutralization device needed.







*Source: ET web*

# ET PROJECT VACUUM SYSTEM

*Six independent (nested) systems of 10 kilometer-scale*

Huge **Pipes** (volume, length, surface) for the circulation of the laser beam: **world-largest UHV !**

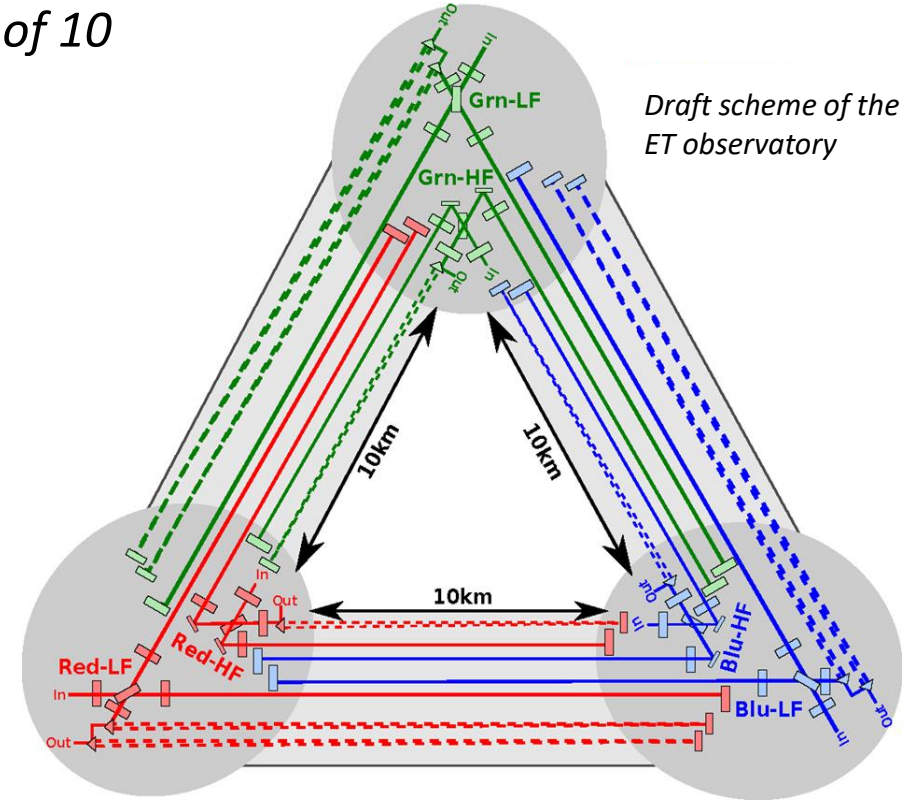
**Towers** chambers, hosting the scientific equipment.

Combined together by very large **cryogenic pumps**.

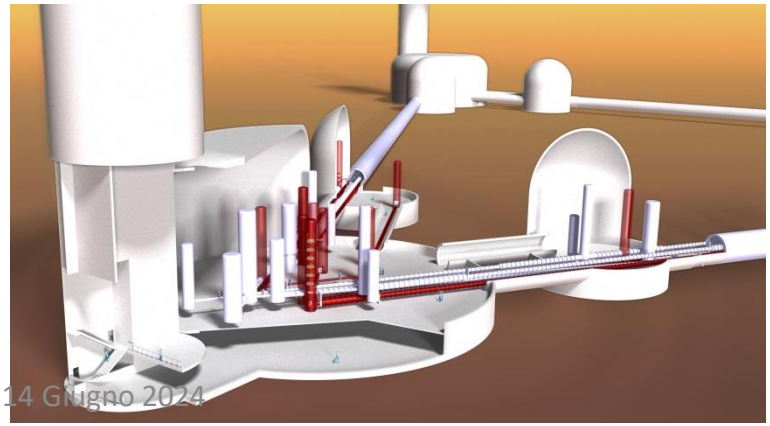
***Cryostats*** *housing 10K mirrors and cryogenic payloads .*

To be realized **underground** (bake-out, installation, operation).

**Size (Costs):** a primary challenge.

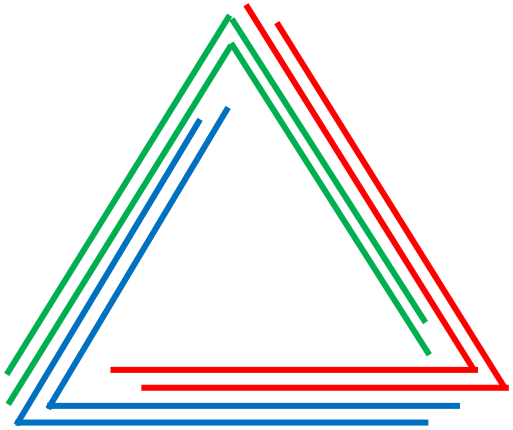



*Draft scheme of the ET observatory*



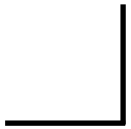
# ET LAYOUT

- Two different layouts:



**ET Conceptual Design**
3 x (HF+LF)  10 km arms
(+ filter cavities)

*120+ km long UHV tubes*



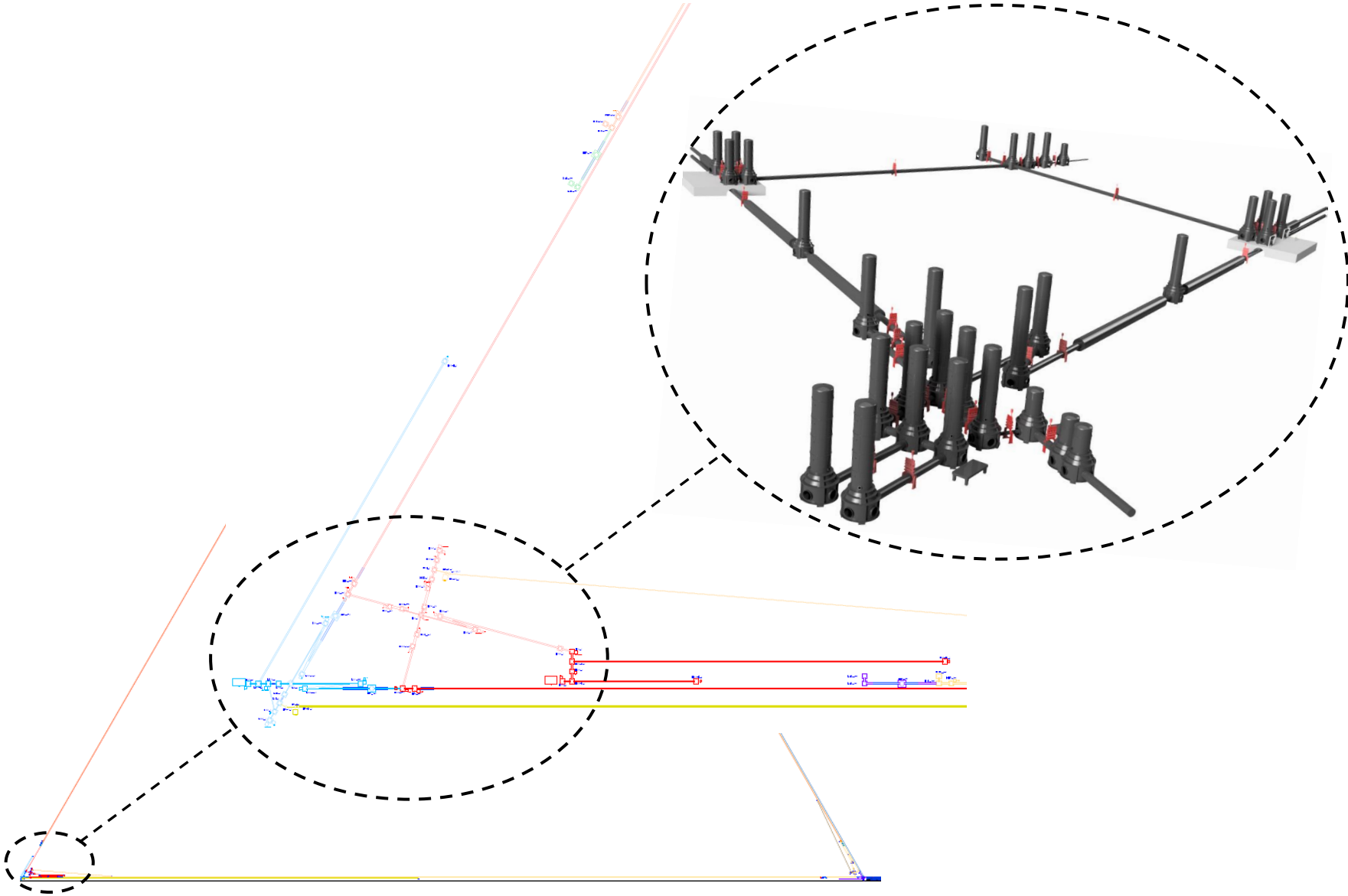
**Virgo**
3 km arms
(+ 300m FC)

*6 km long UHV tubes*

**ET  L_case**
1 x (HF+LF)  15 km arms
(+ filter cavities)

*60+ km long UHV tubes*

# ET PROJECT VACUUM SYSTEM



# VACUUM CHALLENGES

- **Chambers realization costs**
- **Chambers realization schedule**
- **Vacuum Systems installation schedule**
- **Vacuum Systems performances**

# VACUUM CHALLENGES

**Not to mention cryogenics:**

***Cryopumps*** *up to ≈ 30 m x Ø 1m at 4K or below*

## Outgassing database

Buildup & maintenance requires a wide effort

*Possibly useful for the whole vacuum community*

| Component | | | | Optical measurements | | Vacuum measurements | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Item | Manufacturer | Main material | History | Optical check | Optical losses (ppm) | Test procedure | mbar-l/s | | | | | | Q_HC (peaks N>44) (m/z) | Preparation (highlight) | Pre-baking | | | Notes | Installation scenario | Reference |
| | | | | | | | | Q_H2O @24h | Q_H2O @100H | Q_H2O @1000H | Q_H2 | Q_N2+OTHERS @24h | Q_N2+OTHERS @100h | Q_HC (level>44) | | | Done? | Temperature (°C) | Hours | | |
| | Baffle PCB#10-21 | IFAE | Pyralux AP | | Absolute losses @LMA | 0.50 | throughput method | 1.02e-8 | 5.43e-9 | 1.94e-9 | | | 3.31e-11 | 5.00e-13 | | IPA cleaning | Yes | 70 | 160 | After pre-baking, one day in a clean room ISO5. | Mirror compartment | IMC Instrumented Baffle, Ref. IFAE-PCB#10-21 |
| | Al EN AW-6061 | N.A. | Al EN AW-6061 | | No | | throughput method | 4.86e-10 | 1.17e-10 | 1.17e-11 | 5.50e-14 | | | | | Factory Cleaning | No | | | Q_H2O : Q=Qo*t^-alpha, with Qo=4.2e-3(Pa L s-1 cm-2) and alpha=1 | Lower compartment | NIST: DOI: 10.1116/6.0000657 |
| | AISI 316L Vacuum Fried | N.A. | AISI 316L | | No | | throughput method | 8.64e-11 | 2.40e-11 | 3.21e-12 | 5.10e-14 | | | | | Factory Cleaning | No | | | Vacuum fire process: 950°C for 24h Q_H2O : Q=Qo*t^-alpha, with Qo=3.30e-4(Pa L s-1 cm-2) and alpha=0.91 | Lower compartment | NIST: DOI: 10.1116/6.0000657 |
| | AISI 316L | N.A. | AISI 316L | | No | | throughput method | 1.20e-10 | 3.09e-11 | 3.48e-12 | 1.00e-12 | | | | | Factory Cleaning | No | | | Q_H2 : conventional outgassing rate Q_H2O : Q=Qo*t^-alpha, with Qo=7.25e-4(Pa L s-1 cm-2) and alpha=0.95 | Lower compartment | NIST: DOI: 10.1116/6.0000657 |
| | AISI 304L | N.A. | AISI 304L | | No | | throughput method | 2.68e-10 | 4.19e-11 | 2.10e-12 | 1.00e-12 | | | | | Factory Cleaning | No | | | Q_H2 : conventional outgassing rate Q_H2O : Q=Qo*t^-alpha, with Qo=7.00e-2(Pa L s-1 cm-2) and alpha=1.3 | Lower compartment | NIST: DOI: 10.1116/6.0000657 |

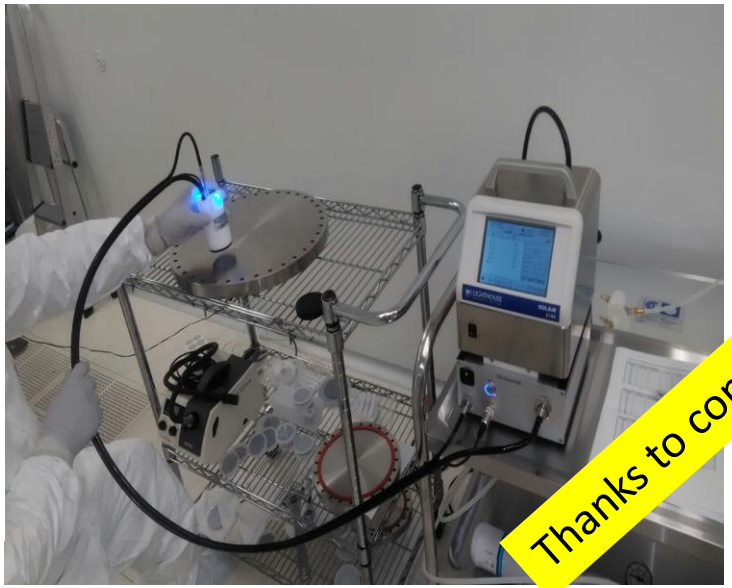
ET Outgassing database: https://apps.et-gw.eu/et_outgassing_db/

# Chambers realization

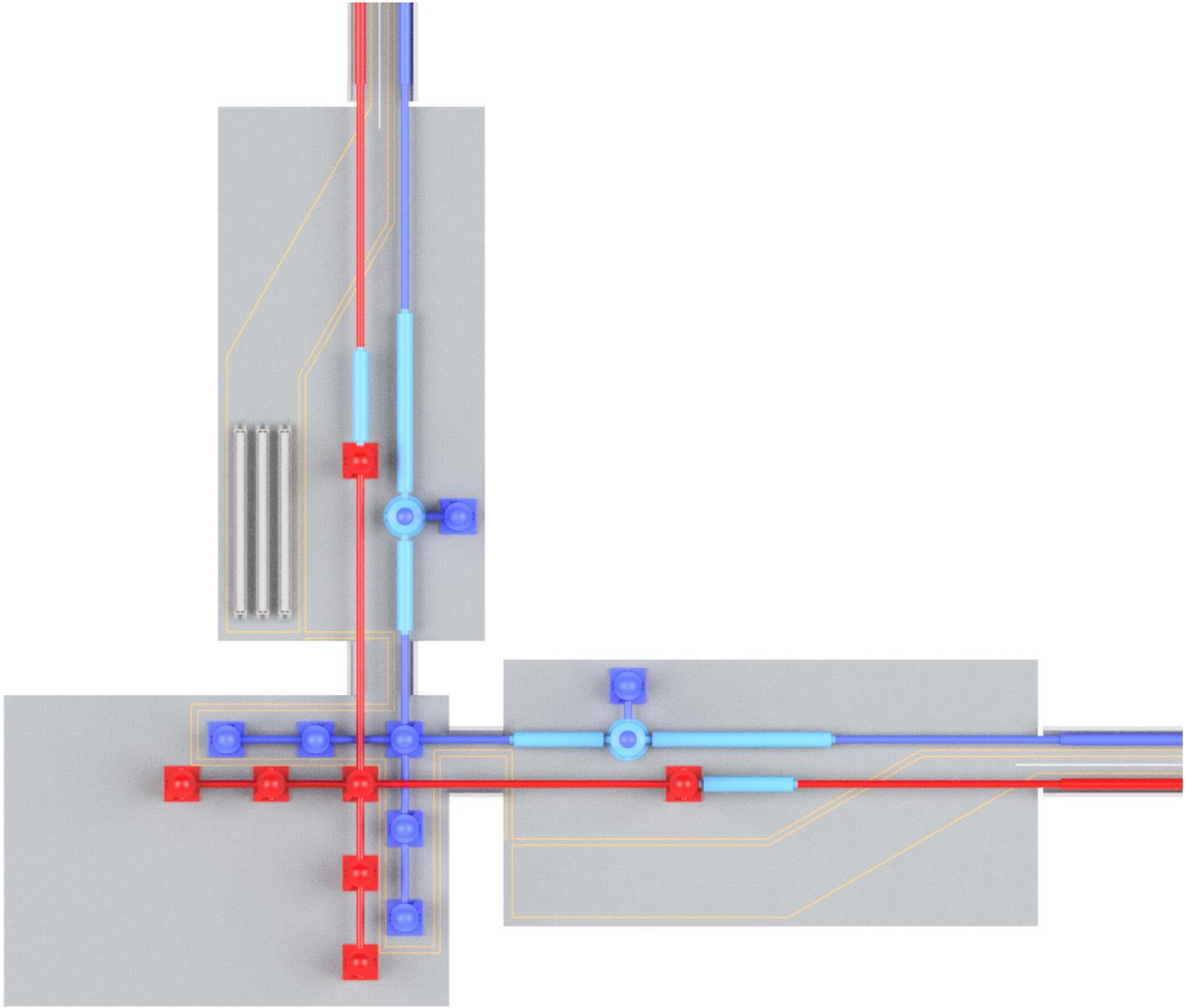
## A new specification for GW vacuum chambers:

- limits for particle concentration on walls to be included for chambers realization
- A standard to refer -> ISO 14644-9:2022
- Need to define wanted limits and measurement tools

*Solutions are to be found both to control the surfaces during the fabrication process and to monitor the tower chambers when in service*



Thanks to contributions by LASA and DESY experts

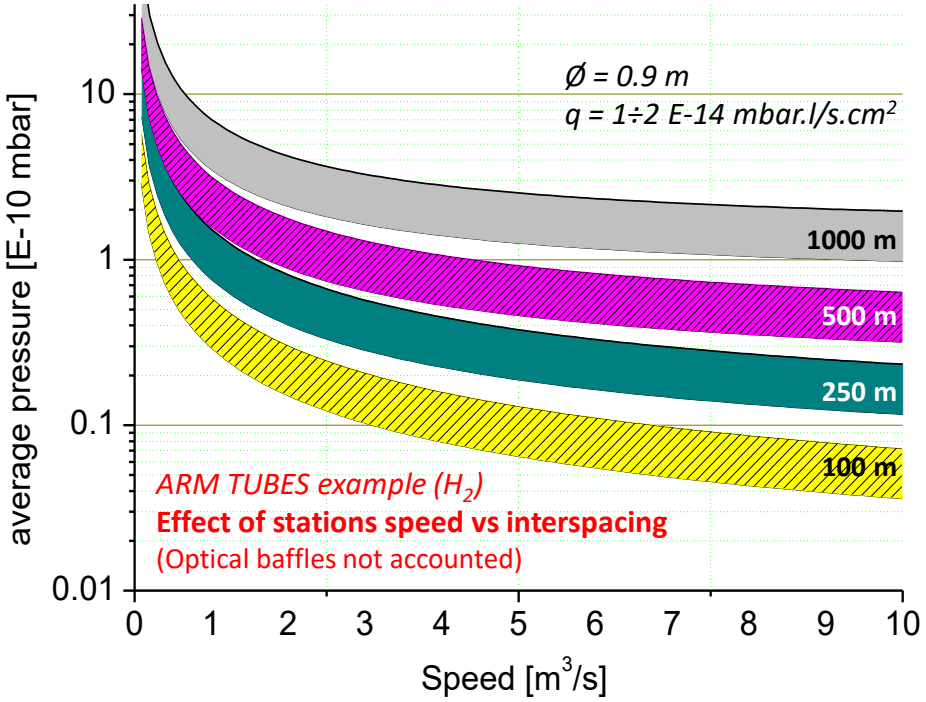


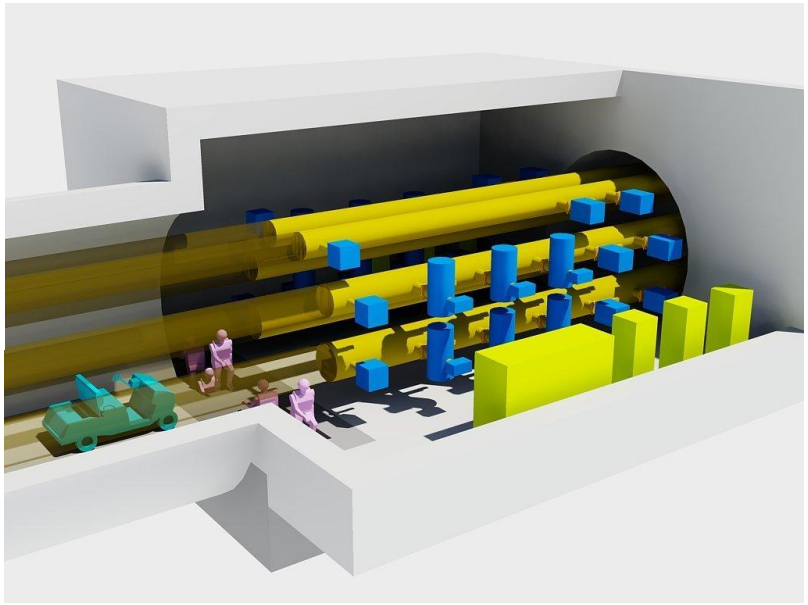
# ET – Arm tubes: pumping stations

**Concentrated pumping stations is the 2G solution. Enough?**

**Distributed pumping: is an option to be explored:**

- **normally needed to push the vacuum limits.**
- **implementation in a 'big' GW pipe is to be studied.**



***Design linked to civil infrastructure***

**Option 1: dedicated 'enlargements' @ 500 m (spares every 250 m)**

**Option 2: a larger tunnel (or a better arranged space and good environment) .**