# Vacuum considerations for ET

Henk Jan Bulten,
Nikhef Amsterdam,
for the ET-pathfinder collaboration

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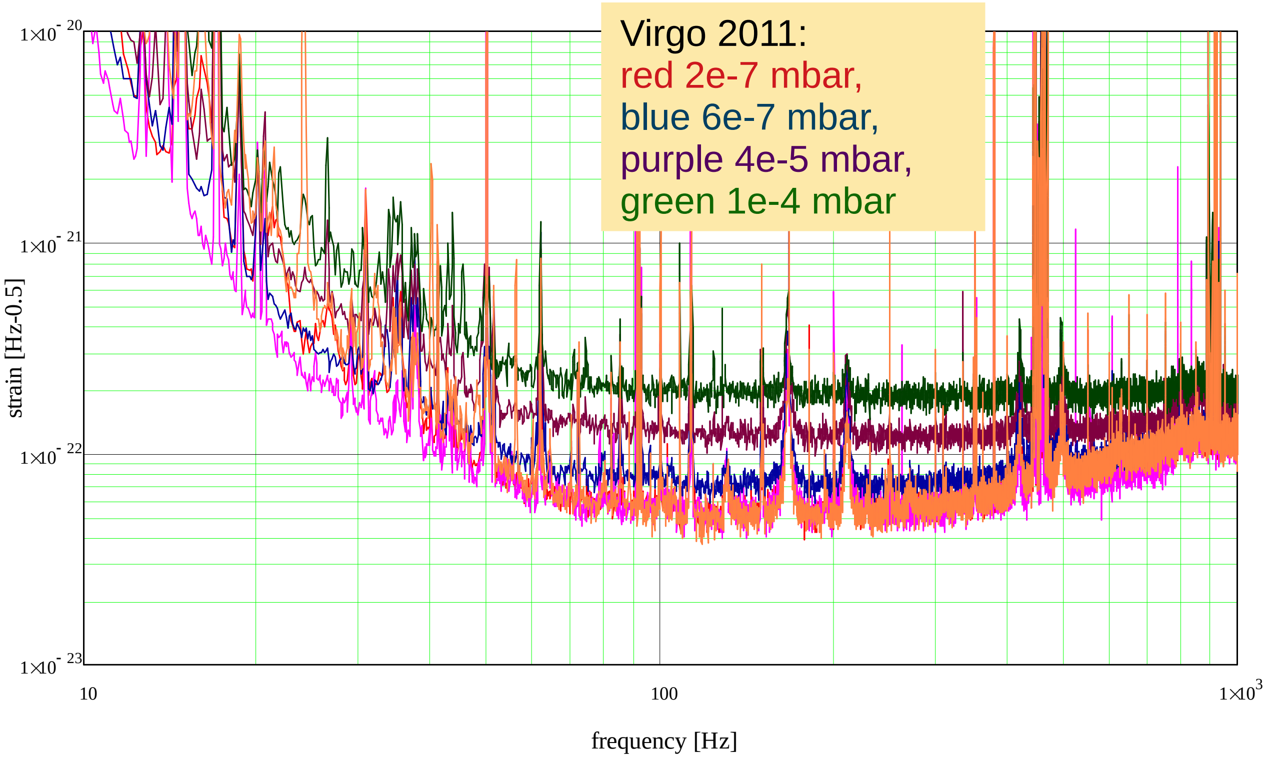
# Einstein telescope, CDR-2011, residual gas

Disclaimer: I am not involved with ET work package on vacuum (F. Ricci, E. Majorana,…); I give the perspective from ET-pathfinder facility; the Dutch-Belgian-German test facility for cryogenic techniques for future GW interferometers.

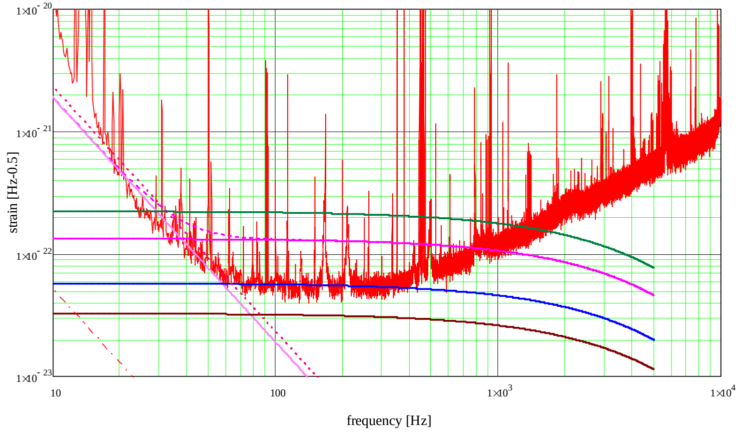
ET vacuum requirements, from CDR-2011, for residual gas pressure in arms:

- residual gas contributes to phase noise: optical path length changes aim for < $10^{-10}$ mbar total pressure ($H_2$ -dominated) in arms
- phase noise scales with square root pressure (measurements from LIGO and Virgo)




LIGO : S. Whitcomb and M. Zucker, “Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer,” 7th Marcel Grossman Meeting on General Relativity, July 1994, Stanford University, pp. 1434–1436, 1994.

Virgo: Pasqualeti, Cella, et al, TDS Vir-0667A-11



# ET vacuum requirements, FP mirrors

## FP end cavities, mirror surface

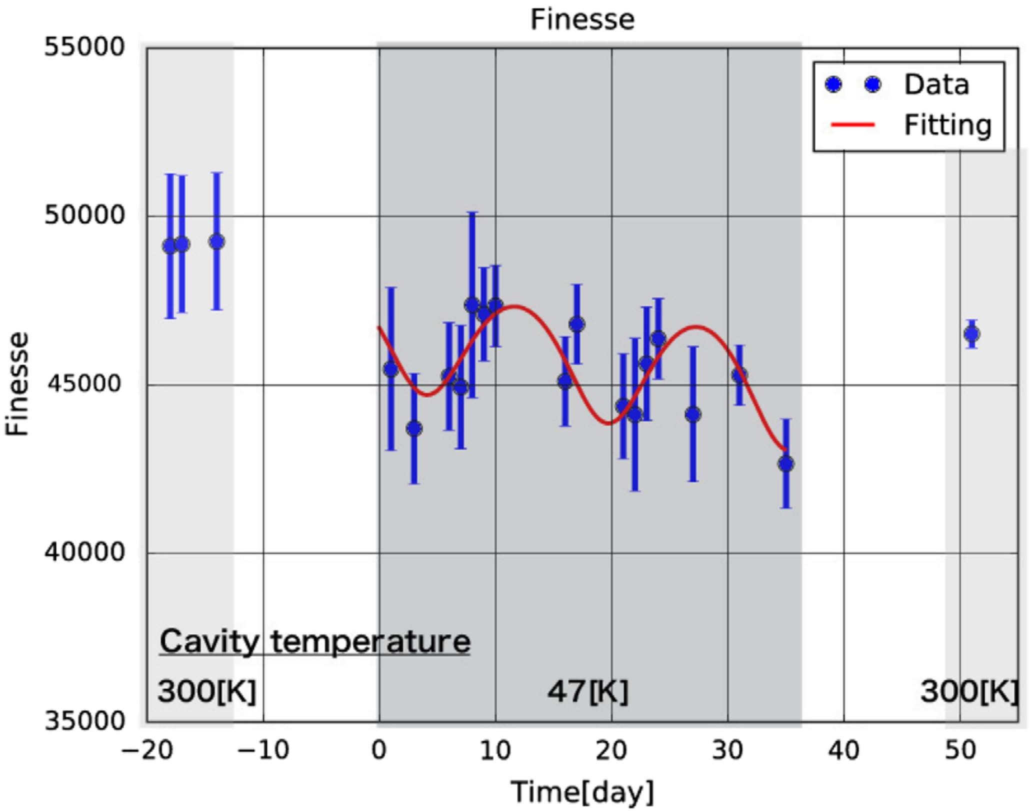
- Residual gas may impact mirror movement: small effect for ET due to large mirror mass
- Chemisorption of hydrocarbons on mirror surface: <10$^{-14}$ mbar for CH>100 amu
  - Avoid any lubricant as far as possible: dry forepumps are needed
  - avoid plastics as much as possible (MLI foils, teflon wire coatings, O-rings, etc)
- Cold interferometer: avoid freezing of gas on mirror surface
  - Need strategy to get rid of water in FP-endmirror towers.

Impingement rate of molecules on a surface:

$$J = \frac{P}{\sqrt{2\pi m k_b T}} = (water, 300\,K)\, 3.6 x 10^{22} P [\#/Pa/m^2/s]$$

For water at room temperature at a pressure of 10$^{-6}$ mbar, a monolayer of water builds up in less than 10 seconds.

Partial water pressure around mirror should be far below 10$^{-9}$ mbar before cooling down the mirror




Kagra data, from Hasegawa et. Al, PRD 99, 022003 (2019).
The finesse in the arm changes periodically due to layers of water freezing on the mirrors (fitted rate: 42 nm/day)

# General vacuum, pumping

## Overview of pumps, and pressure regimes when pumping down a vacuum vessel

- Rouging pumps are needed to evacuate to ~ $10^{-3}$ mbar (roots pumps, screw pumps, etc).
- UHV pumps, types:
  - Oil-diffusion pumps: not very clean, no option for ET
  - (ET) Turbo-molecular pumps : fast, start at ~ 1mbar, end pressure ~ $10^{-9}$ mbar
  - Cryopumps – needs regeneration, needs better forevacuum at start, but better end pressure $10^{-10}$ mbar. Higher vibration levels.
  - (ET) Getter pumps: sputter material, best end pressure, but can pump relatively small anounts of gas; . Should not have direct line of sight of optical components.
  - NEG strips : non-evaporative getter material
    - Needs activation ~ 200 deg. C
    - Enormous pump speeds, best end pressures obtainable
    - Suitable when no vacuum breeches are needed (e.g. LHC beam line)

- Pump-down of vacuum vessel:
  - 1bar – $10^{-3}$, $10^{-4}$ mbar: membrane pump, screw pump, multi-stage roots pump,... (nitrogen and oxygen)
    - Laminar flow limit: pressure as function of time can be calculated by dividing the vacuum volume by the pump speed
  - 1 mbar – $10^{-9}$ mbar: turbo-drag pump (backed by rouging pump)
    - Removes residual gas from volume,  necessary for regenerating cryo/getter pumps and to remove initial gas load after venting.
    - Around $10^{-6}$ mbar, monolayer of water on the metalic surfaces will dominate the residual gas pressure
      - Residence time on surface depends on binding energy and temperature:

$$t_{res} \approx 10^{-13} e^{E_b / k_b T}$$

      - On SS and Al: binding energies of about 65-100 kJ/mole, sojourn times of minutes-days on surface (depending on surface treatment, shape)
        - Halves every 5-6 deg. of temperature increase: baking
        - Without baking, pumping down from $10^{-6}$ to $10^{-9}$ mbar in ET would take more than a century for the planned pump stages (1/t dependence)
      - Water on water ~ 25 kJ/mole (physisorption), sticking time around 1 microsecond – pumped away instantly
- around $10^{-10}$ mbar H, CO from chemisorption on SS dominate – baking to 250 deg. required to remove these
  - Assuming negligible contribution from leaks and outgassing of plastics (signal cables), O-rings, etc.

# ET strategy, CDR-2011

## Beam line high vacuum (no breeches), end towers lower vacuum

- HV ($10^{-7}$ mbar) in filter cavities and beam splitter/injection towers ~ few hundred meter beam lines
- HV sections will not be baked: lots of water vapor will be inside system.
- UHV in 10-km arm
  - Baked at start and never to be vented again
- Separation of arm (UHV) and end towers (HV) via cryolinks (also at Virgo, LIGO)
  - About 10m long section, 1m diameter, of liquid-nitrogen cooled screen around the beam
  - Residual water vapor from the towers freezes on it; should reduce water load by 4 orders of magnitude
  - Separated with “pseudo-valves” on both sides to be able to regenerate the cryotraps once per year.
- For the LF interferometer, also 4K-cryotraps are needed to shield test mass from thermal radiation; the 80-K section needs to be 50 m long and the 4-K section around 10 m.

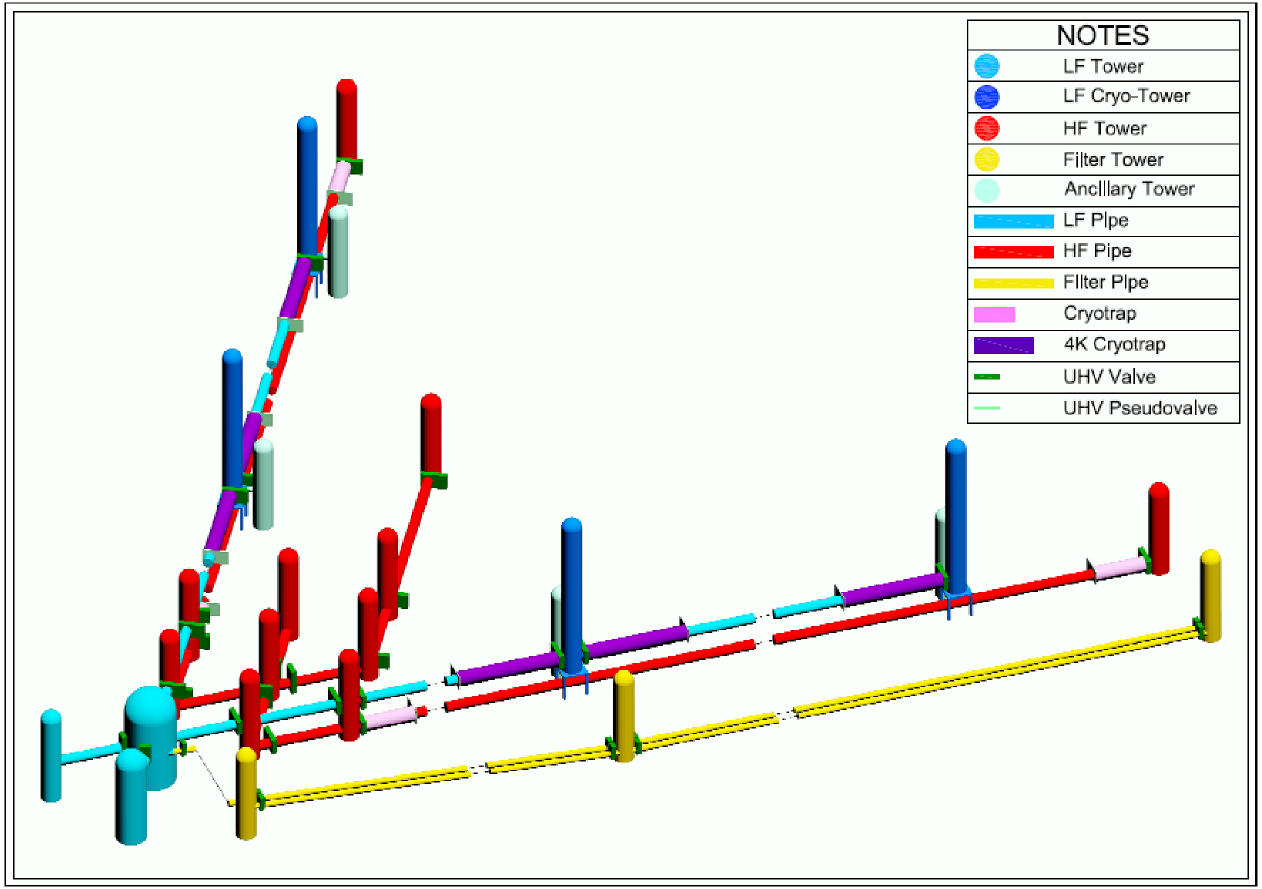



**Figure 88:** Schematic of the ET vacuum system lay-out, out of scale. Only one xylophone detector is shown, out of three.

# ET arms

## Production of beam line arms (CDR-2011)

- Vacuum pressure should be better than $10^{-10}$ mbar and will be dominated by hydrogen atoms, diffusing out of the stainless steel (from dissociative chemisorption)
- In order to lower the hydrogen and CO outgassing rate, 20-m arm sections will be pre-baked to 250 deg. C for a week, and sealed with inert gas, before transported down in the tunnel and installed into ET.
- 20-m segments of beam pipe with bellows on 1 end will be lowered inside the tunnel, 500-m sections will be welded in place and leak-tested. Welding complicated – cannot access inside of pipe. Welds and bellows required of very high quality. Also, no easy way to remove a faulty segment.
- The 500-m sections are baked to 150 deg. C for 10 days to get rid of all water: needs 10-15 cm thick thermal isolation and 50 kW of DC electrical power running through a 250-m section of the beam
- every 500 m there will be a pumping station, 5000l/s :
  - 3 times 2500l/s Ti sublimation and 300l/s ion-getter), 2x2000l/s turbo, for regeneration and initial evacuation.
  - To be considered: NEG coating of beampipe (Requires higher temperature to activate; makes thermal isolation more costly).
  - In my opinion NEG coating along the beam should be used to obtain enough pumping speed as security; a pumping station every 500 m cannot cope with higher outgassing/larger leak rate than foreseen or with more water load from the HV beam lines.

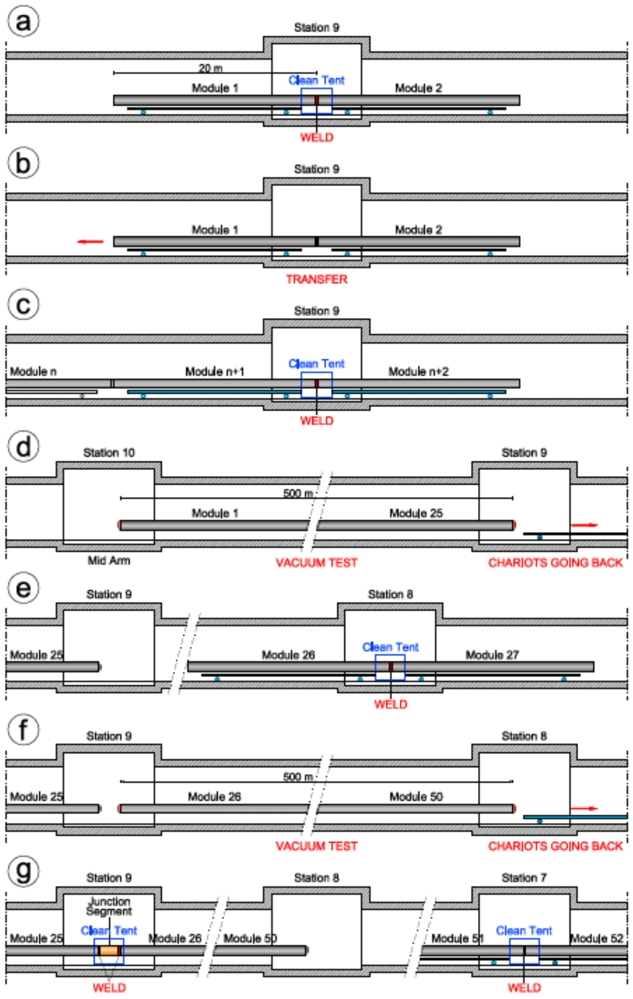



**Figure 94:** The assembly sequence of one vacuum pipe.

# Cryotraps

## Should stop all water from HV end

- Cryotraps: 10-m long tubes around beam line cooled with liquid Nitrogen.
- Should capture almost all water vapor from HV towers to protect beam line: water passing the cryotrap is not pumped out any more (physisorption, pump-down time of many centuries at room temperature).
- Beam load with proposed cryotrap will be around $10^{-6}$ mbar l/s from ballistic flow, assuming that all water hitting the cylindrical trap is frozen on contact.
  - This may be optimistic; binding on ice is not as strong as on metal – some water may come off the walls or pass the trap
  - With this gas load, the partial water pressure in the beam line will raise with about $2\text{x}10^{-12}$ mbar/year, assuming that only 1ppm of the water resides inside the vacuum volume, the remainder sticks to the wall of the beampipe.
- Scattered light: trap should vibrate minimally
  - At ETpathfinder, we want to test a method to strongly reduce vibrations from boiling liquid Nitrogen

Proposed length around 10 m.
Pseudo-valves to be able to regenerate.
20 m away from mirrors to avoid condensation.
Ballistic flow: about 0.02% of water passes through – about $10^{-6}$ mbar l/s

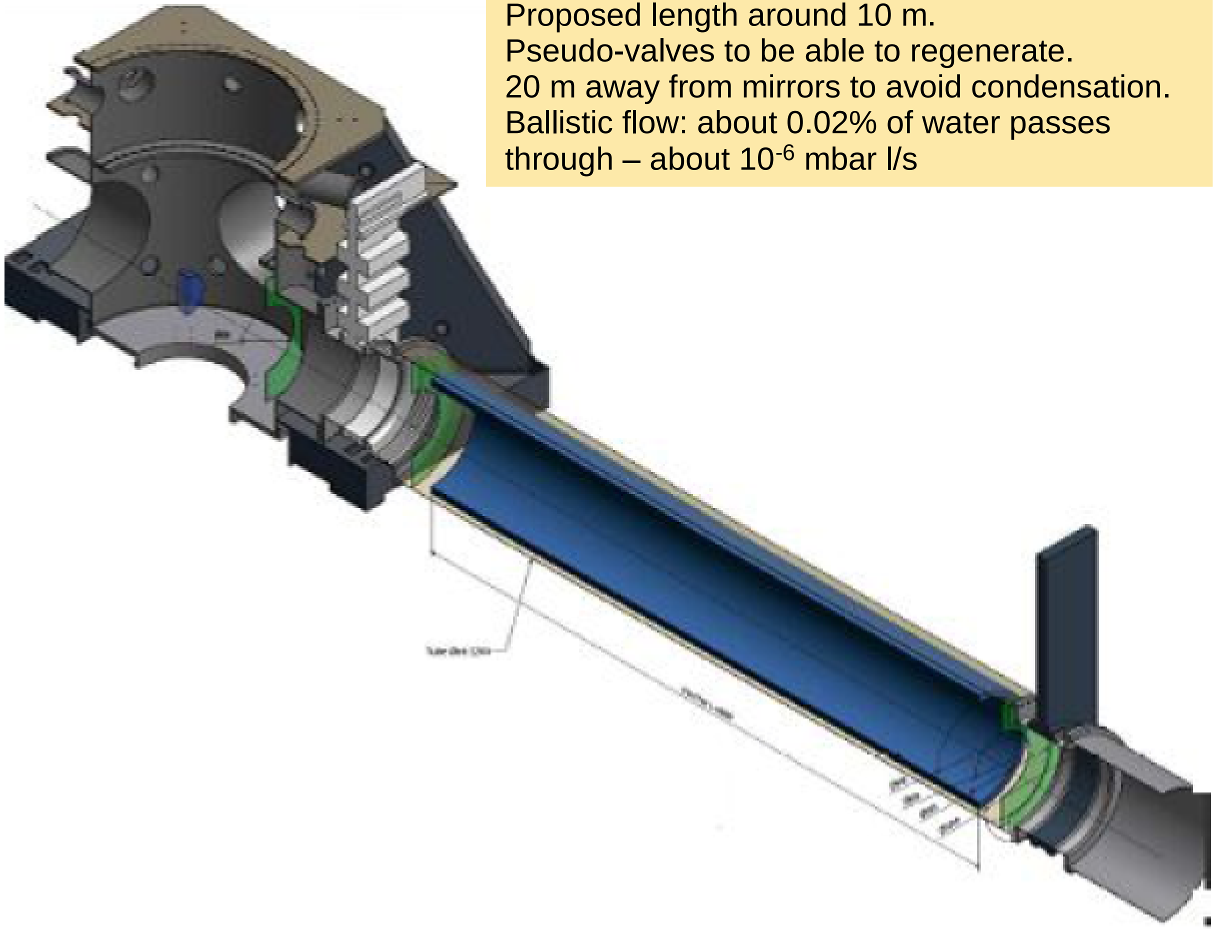


Figure 95: A liquid nitrogen cryotrap.

# ET LF end mirror towers

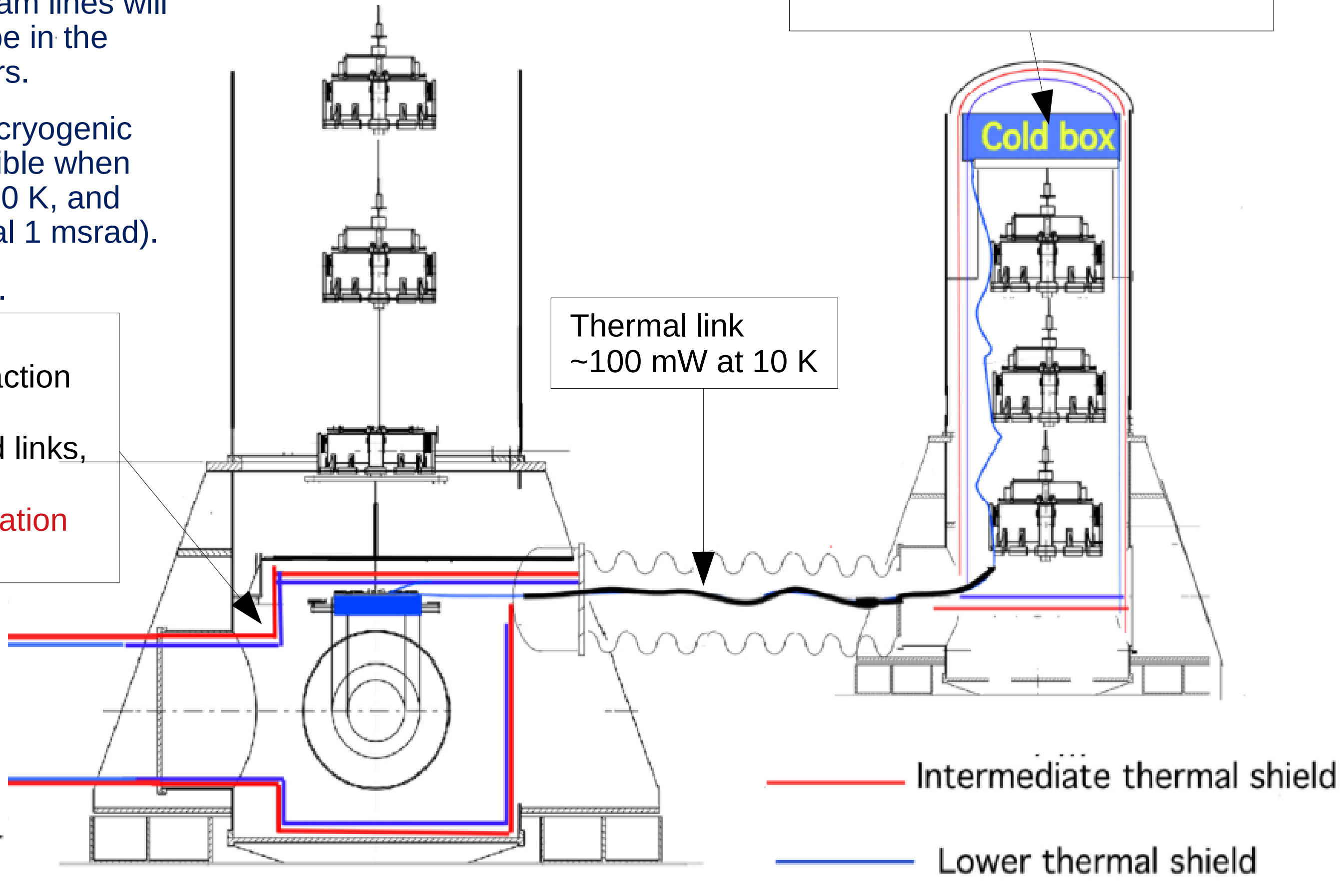
## Water vapor residual pressure may spoil LF sensitivity

- In ET: no baking of towers. The surface of the towers, suspensions, thermal shields, mirrors, beam lines will be saturated with water. Outgassing will be in the order of $10^{-5}$ mbar l/s /m$^2$ of water for years.
- ET strategy: capture all this water on the cryogenic shields surrounding the mirror. Only possible when screens are <100 K while mirror still at 300 K, and when aperture solid angles are small (total 1 msrad).
- Complicated, not yet studied in any detail.

4K cryostat – seismically isolated (no mature design yet)

Thermal shields, ~10 K and 80 K.
Surround cold payloads (mirror, marionette, reaction mass, total ~ 2000 kg.
Opening for viewports beam, suspensions, cold links, optical levers.
Surrounded by 50-100 layers of MLI superinsulation to reduce thermal radiation load.

Thermal link
~100 mW at 10 K



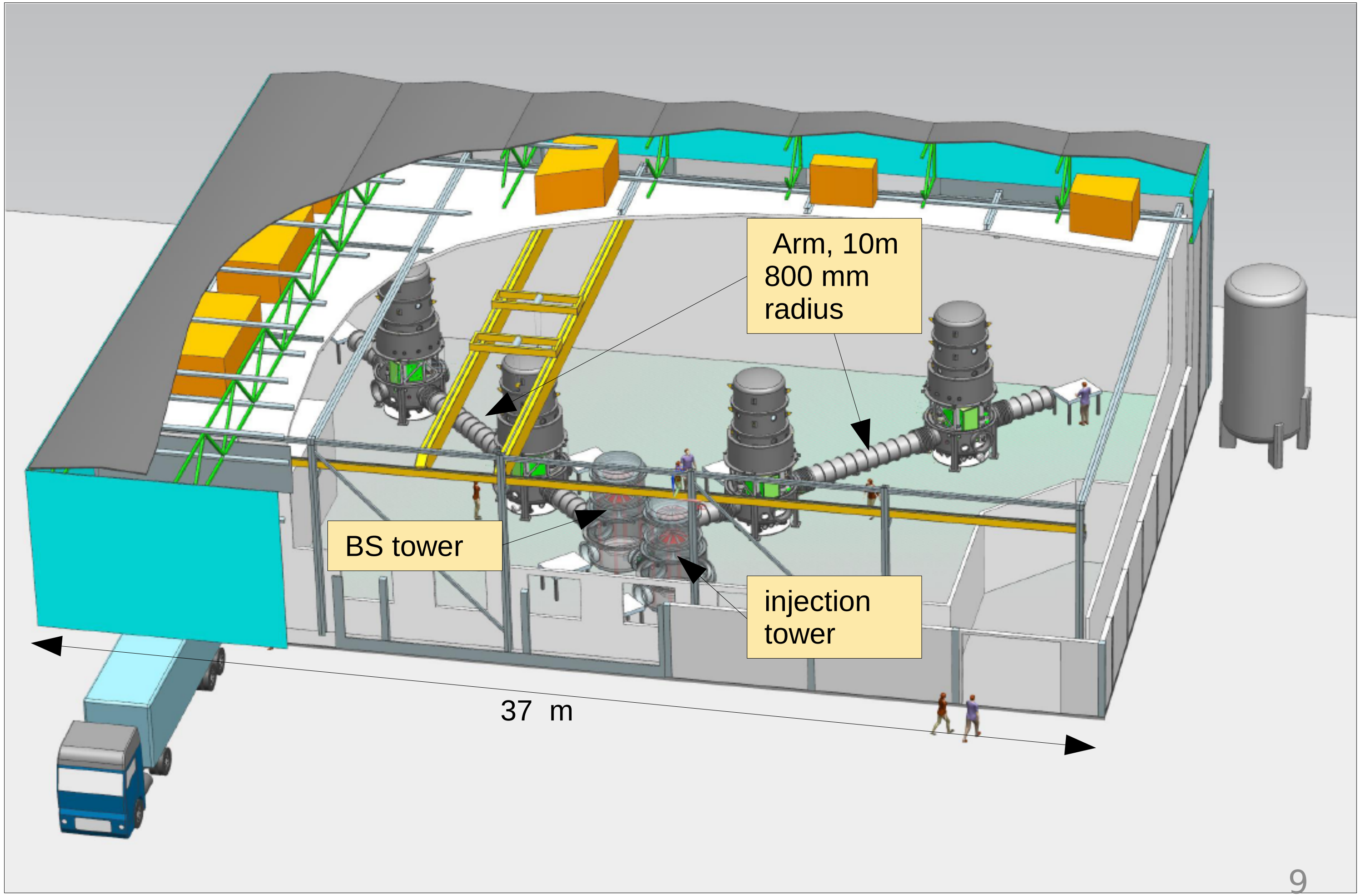

- *ET cold mass: about 400 MJ heat needs to be extracted in initial cooldown to 10K. Probably contact gas is needed: mirrors should be enclosed vacuum-tight then in some way.*

**Figure 96:** Scheme of the cryostats needed for cooling a test-mass of the LF-interferometer.

# ET pathfinder facility – test of ET technology

## Aims to test and develop techniques of cryogenic interferometry with Si mirrors

- German-Dutch-Belgium border region, EU-interreg funding
- Proposed fall 2018, funded April 2019
- Hosted by Univ. Maastricht, near Aachen and Liege
- 2 10-m long arms; a single arm can host 2 FP-cavities with small optics (3.5 kg end mirrors)  or 1 FP cavity for large optics (ET  scale, 220 kg mirrors)
- Want to study cryogenic operations, mirror temperatures at room temperature, at ~123 K (silicon expansion coefficient 0), and around 10 K (lowest thermal noise from coatings, suspensions, etc).
- Vacuum interwoven with cryogenics: main vacuum challenge is avoiding contamination of the mirror surface (i.e. water freezing on it) In Etpathfinder: single work package (WP-4)
  - Main cryogenic challenge is to cool the mirror to 10K without introducing vibrations



# ET pathfinder facility – vacuum system

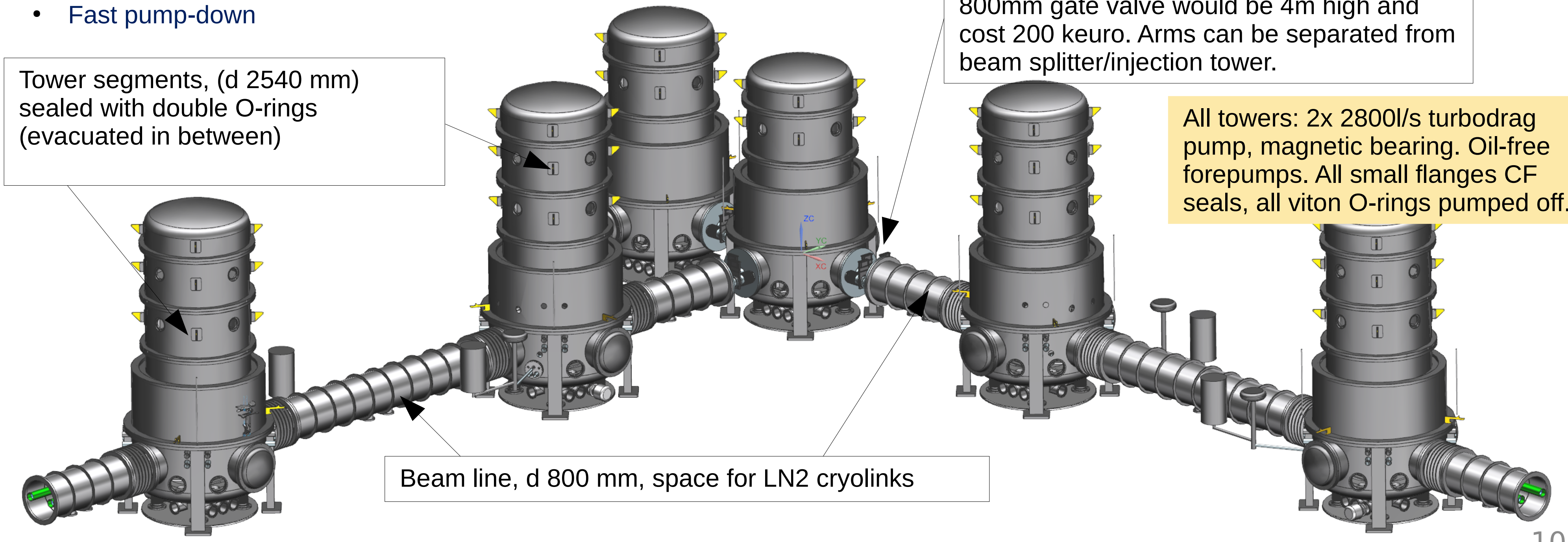
## Requirements

- ETpathfinder: $10^{-18}$ m/sqrt(Hz) at 10 Hz and above.
- Residual gas introduces phase noise from optical path length changes and from Brownian noise FP mirrors
  - Required vacuum in beam line <$10^{-7}$ mbar (shorter arms, less sensitivity than in ET)
  - Required pressure around mirror <$10^{-7}$ mbar (all temperatures, Brownian noise mirror scales with $1/D^2$, larger than for ET)
- Research facility: we need to be able to open the BS/injection tower regularly
  - Fast pump-down

Manifold, 3 200mm gate valves (staggered). 800mm gate valve would be 4m high and cost 200 keuro. Arms can be separated from beam splitter/injection tower.

Tower segments, (d 2540 mm) sealed with double O-rings (evacuated in between)

All towers: 2x 2800l/s turbodrag pump, magnetic bearing. Oil-free forepumps. All small flanges CF seals, all viton O-rings pumped off.

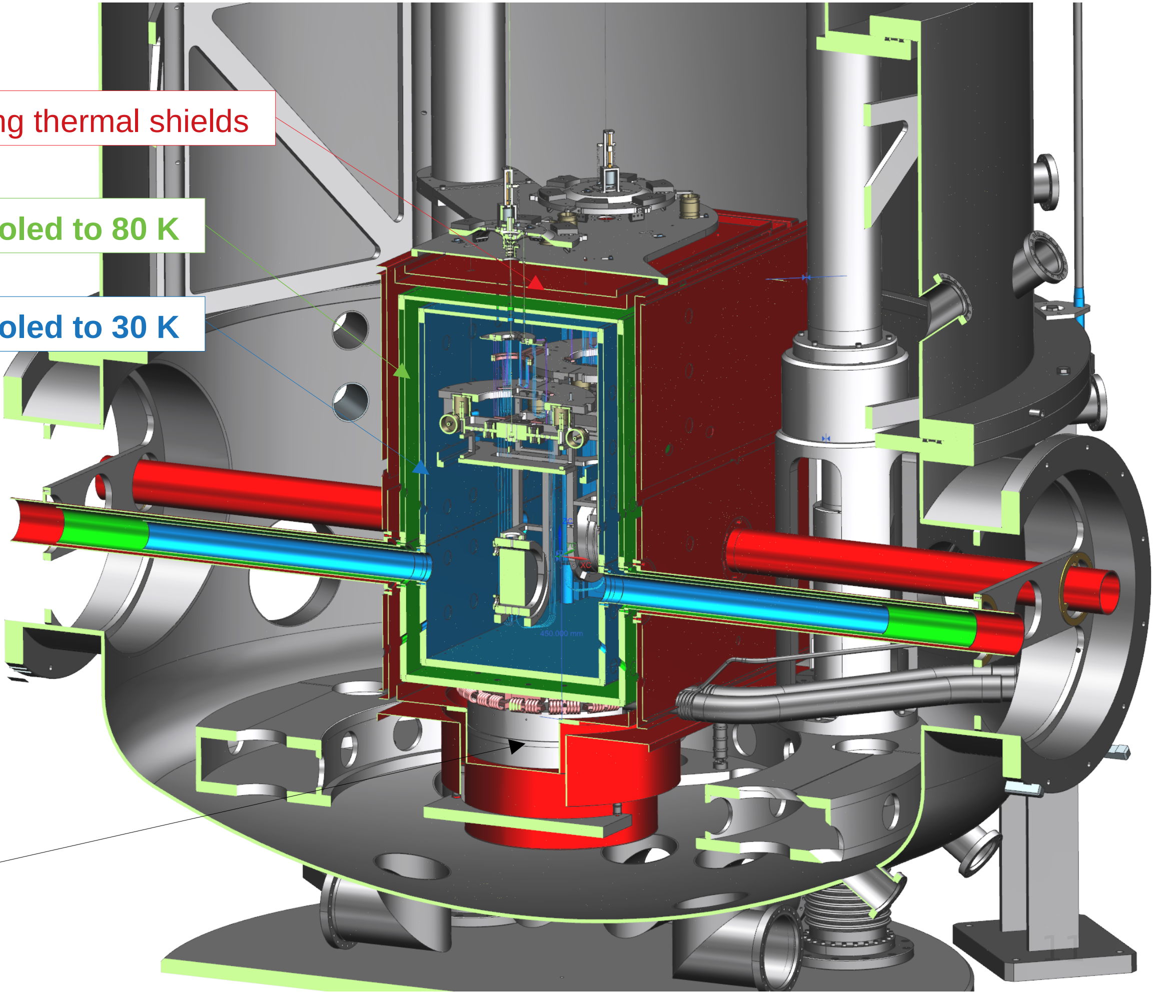


Beam line, d 800 mm, space for LN2 cryolinks

# ET pathfinder, thermal shields

## Allows to reduce thermal radiation and acts as cryopump

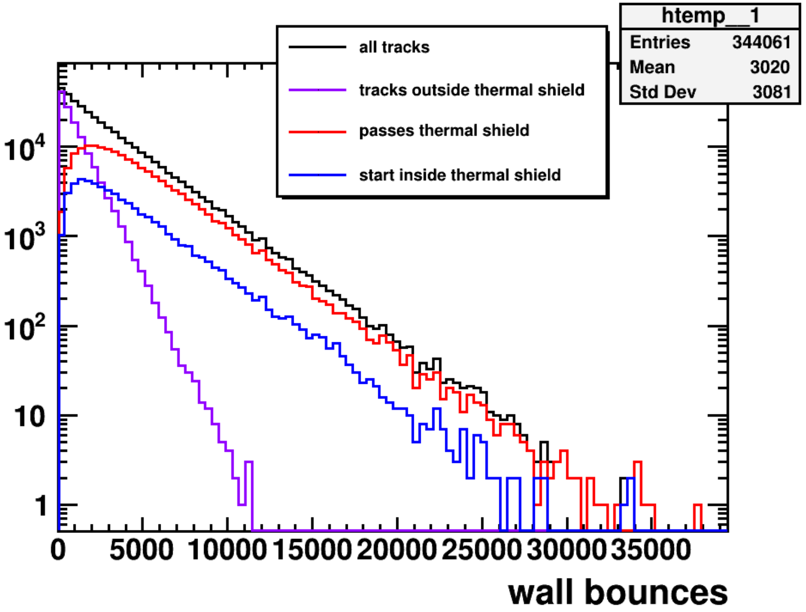
- 1) we need many direct line-of-sight openings to the mirrors, with 2 suspended mirrors per tower. Therefore, we do not want to use MLI superinsulation; that would require very complicated shields. Thus, we need comparatively more cooling power at 80 K for the thermal shields since radiation load less reduced by passive means.
- 2) the 80-K shield is cooled by liquid Nitrogen, and gets about 300W heatload in equilibrium. We will try a technique to reduce vibrations of the evaporating LN2 inside the shield.
- 3) we do not aim to isolate the thermal shields from seismic noise: they are not suspended, as in ET conceptual design. Rather, the shields are further outside the acceptance of the beam than the thermal links and beam pipes at Virgo/Ligo
- 4) For the inner cryogenic payload, we will try a sorption-based cooling scheme that introduces about 100,000 times less vibration as a pulse tube cooler.

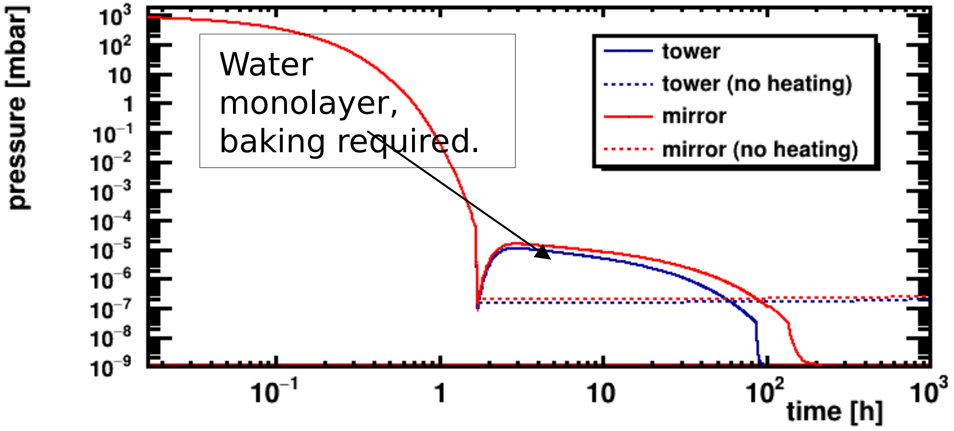


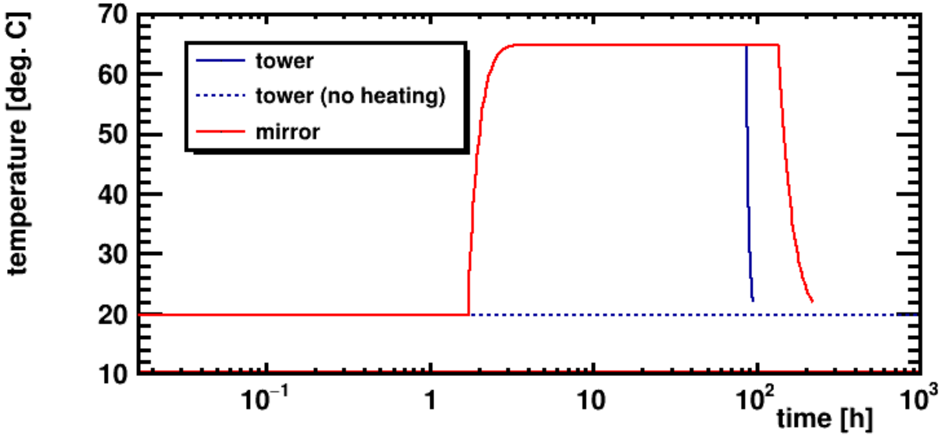
# Shield modeling, vacuum

## Raytracing code to calculate vacuum performance, scattered-light absorption, and temperature gradients

- Also for ET, it is crucial to determine how much water vapor reaches the mirror and how much water vapor can pass the cryotraps into the beam line.
- For ETpathfinder, we developed a ray-tracing code that can follow the path of the molecules from any part of the surface until it reaches a pump aperture. With this code, and a model for the sticking coefficients and binding energies of water on the metal surfaces, one can model pump-down curves and also grow rates of ice on mirror surfaces.
- As an example, pump-down curve for 1 arm with heating to 65 deg. C is demonstrated here. Similar studies are needed for ET.



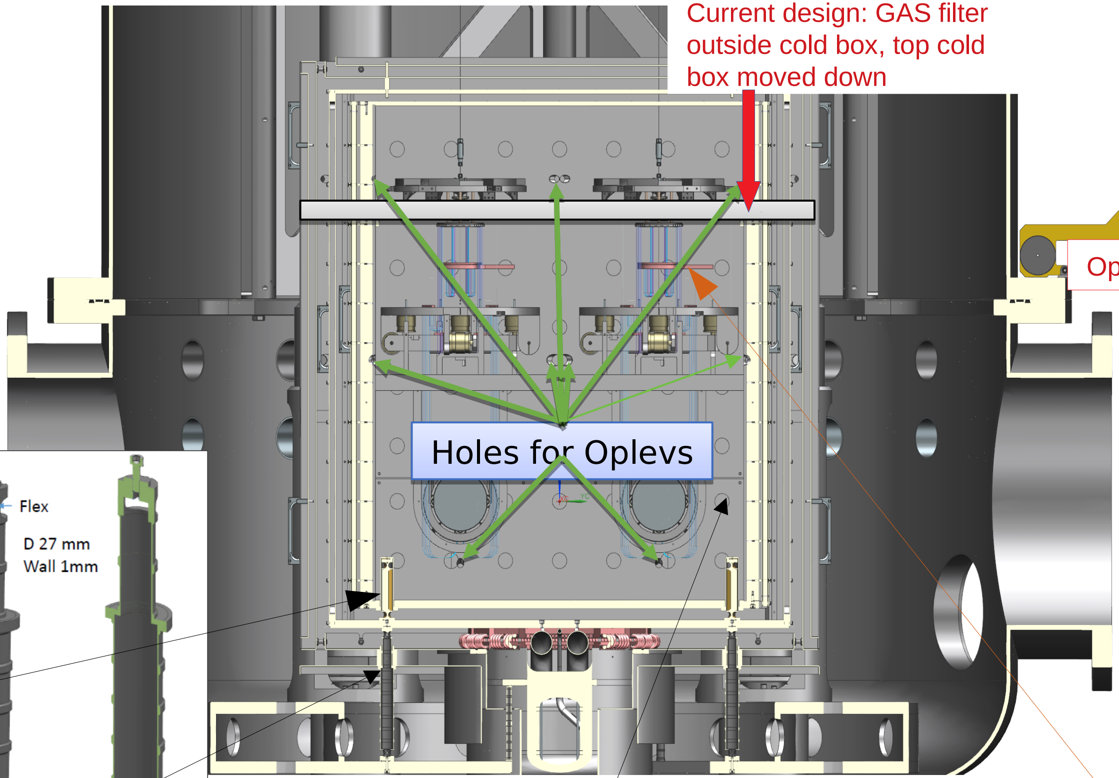



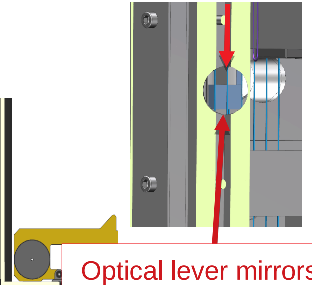
# ET pathfinder, thermal shield support

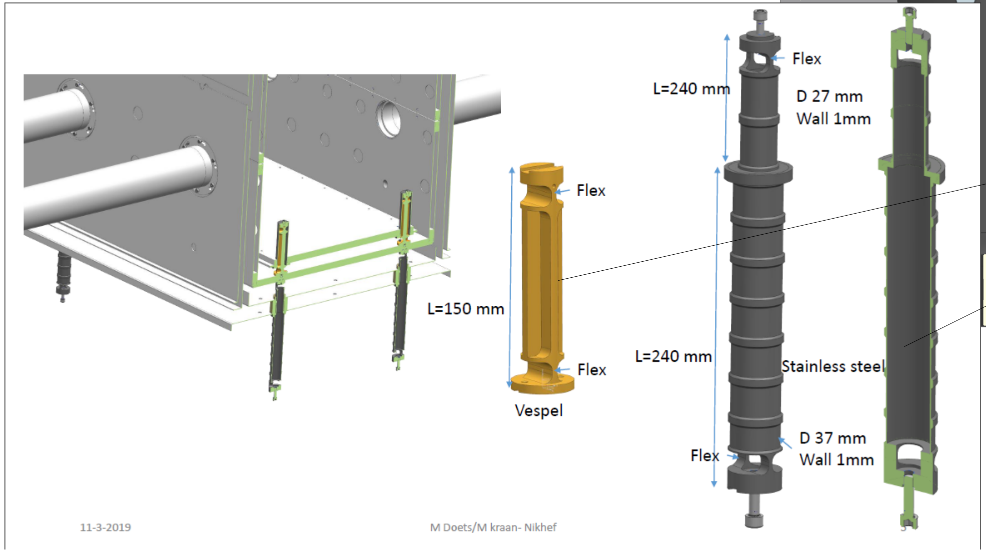
## Supports, apertures

Many holes for pump-down (staggered) and optical levers. Jellyfish wires should bend around optical lever path

LN2 and inner thermal shields rests on tower, via SS bellows and and Vespel flextures (to allow shrinking when cooling down the shields)
Shields shrink about 3 mm



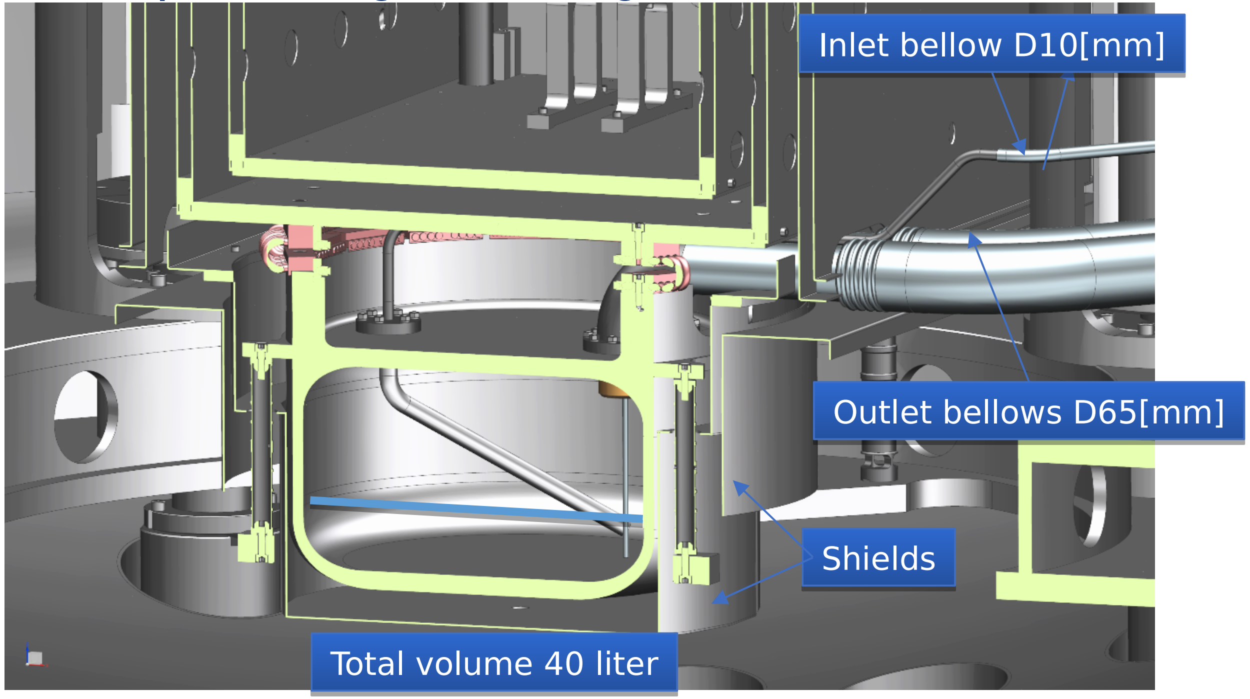



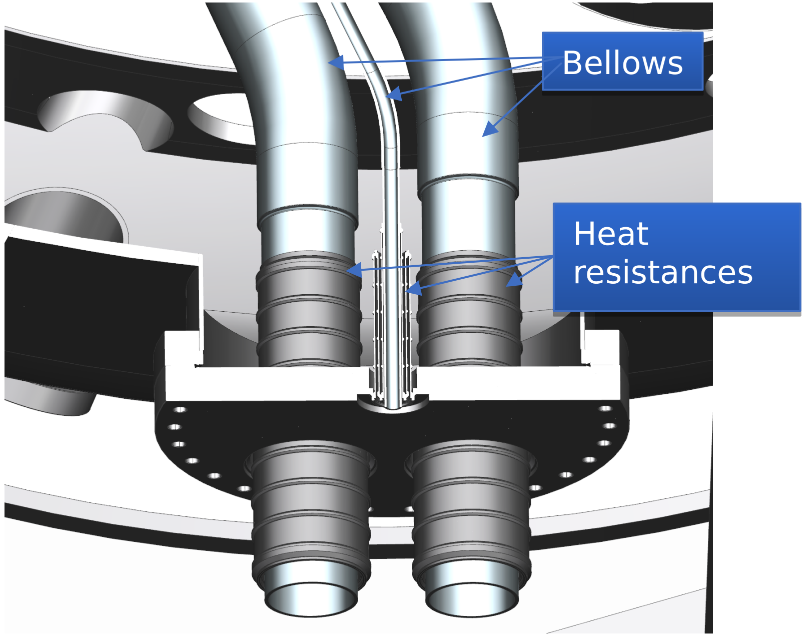




10-K cold finger cooled with *sorption cooler:* pressure ripple in coldhead at 10 Hz is ~ 100,000 times smaller than in pulse tube cooler

# Liquid Nitrogen cooling

## Liquid Nitrogen cooling




Double-walled bellows to transport cryogenic fluids. In case of He, the return gas cools the high-pressure inlet

The LN2 interface is mounted on a CF-300 flange.

- Slotted inlet pipes to avoid bubbles in inlet.
- Wide vessel to reduce vibrations from boiling.
- Lowering vibrations: coat inside vessel with Teflon
- or use spiral with capillary , pumped to 0.5 bar, immersed in the liquid Nitrogen to cool the Liquid nitrogen below boiling point – no vibrations at all! This innovation (ter Brake, EMS group TU Twente) will be tried and could be applied in ET cryotraps as well.
- Full-scale prototype needed for testing.

# Link between 10-K cold finger and mirror suspension

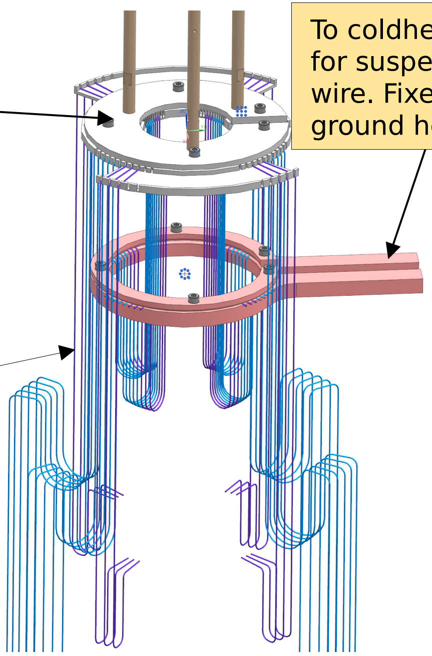
ETpathfinder intend to produce a jellyfish connection and measure the transfer function.

- Jellyfish connections: introduce minimal vibrations
- Ultrapure Al : up to 20 kW/m/K at 10 K (bulk)
- Monolithic silicon suspension: flexible, >2 kW/m/K

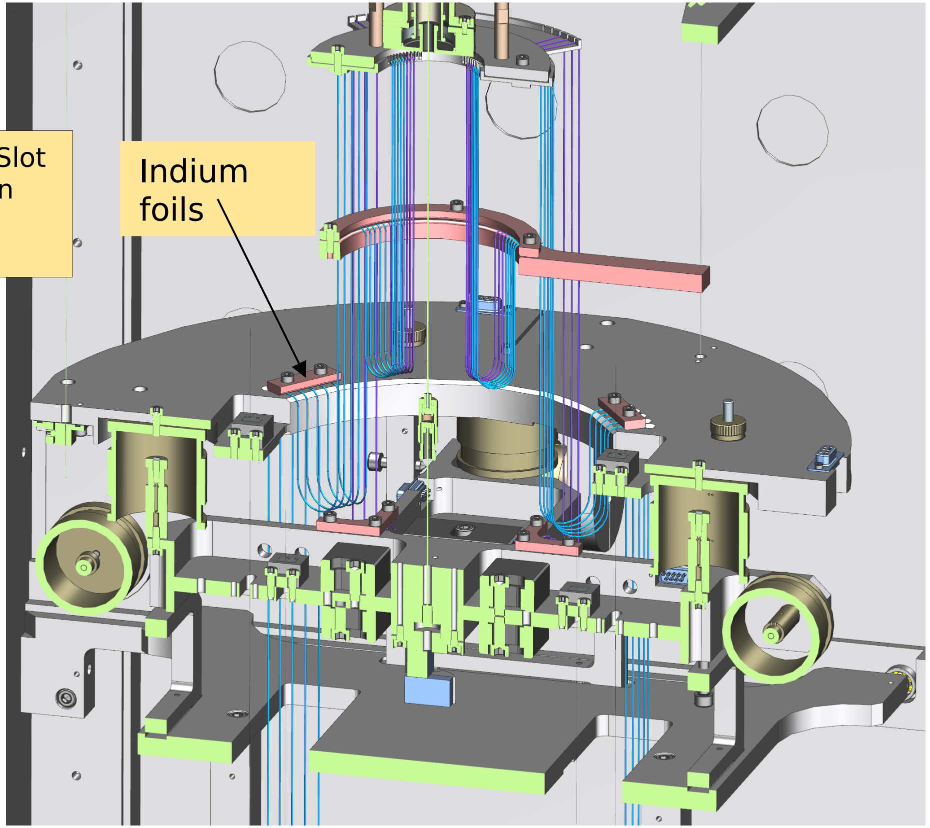
Cold platform (may be chosen isolator). Suspended from base GAS filter

20 wires, 0.15 mm diameter, 1.5 m long to reaction masses. Thermal current about 50 mW for temperature gradient of 300-10 K.

12 wires 0.75 m long to marionette




Purple wires to marionette, blue to reaction chain




**No MLI passive shields of cold finger needed: much less vacuum problems**

# Summary

## ET current design for vacuum system seems OK but contains some risks/challenges

- Beam pipe welded and baked in situ, pumping station every 500 m
  - 5000l/s pump speed, outgassing beam pipe wall should be below ~ $10^{-15}$ mbar l/s/cm$^2$
  - bellows/welding should be extremely good – leak rate below $10^{-9}$ mbar l/s for all welds
  - HV beam lines and all towers are not baked: walls will be saturated with water ~ $10^{-7}$ mbar pressure level (expected, but this will already be challenging. At KAGRA/Virgo the tower vacuum is ten times worse before cryolinks are on)
  - The cryotraps should capture more than 99.9 percent of that water load to avoid spoiling the beamline vacuum within a year of operation.
    - Modeling and testing required of cryotrap vacuum performance – water leakage needed
    - cryotrap/baffle vibration levels should be minimal – further design is recommended
    - ETpathfinder will try out an improved design for LN2 cryogenic shields.

In my opinion would be safer to also include 50 m of NEG-coated beamline behind the cryotraps: extra pumping speed of > 10,000,000 l/s also for water

- LV interferometer: water vapor can freeze on the mirrors.
  - At the moment a huge problem for KAGRA. ET should limit the amount of water reaching the mirrors by at least a factor of 10,000 compared to KAGRA, which operates at similar partial water pressures in the tower
    - Either water can be removed via a baking strategy (ETpathfinder will bake to 65 deg for 1-2 weeks),
    - Or a strategy has to be developed that proves that 99.99 percent of the water freezes on the cryogenic shields before reaching the mirror (ETpathfinder will try a strategy in which the shields can be cooled while the mirror stays hot)

In my opinion, the complicated cooling strategy as sketched in ET CDR 2011 is incompatible with the vacuum requirements: too much material with too many holes are needed around the mirror to be able to remove water.