Alternative designs for cryogenics

- ETpathfinder: research facility for cryogenic interferometry
  - Funded in 2019. No time to develop superfluid He-II link, monolithic silicon suspension, etc
  - However: goal to operate cryogenic interferometers with a noise budget that fulfills ET requirements:
    - Injected vibrational noise from cryogenics small enough (displacement < 1e-18 m/sqrt(Hz) for f>10 Hz and 15 cm (3.5kg) mirrors
    - Less than 1 nm/month ice growth (thus aiming for 1e-9 mbar pressure before cooling shields)
  - System designed, modeled and partly tested to full detail
    - e.g. vacuum/cryogenics simulations include all effects:
    - all radiative, conductive and convective heat flows between all installed objects,
    - hydrogen migration as a function of temperature and exposure time in the stainless steel
    - All gases in all polymers (cables, O-rings, feedthroughs) – simulated and measured
    - All adsorption and desorption from molecules at the vacuum surfaces (sublimation/evaporation, water monolayers, …)
  - Estimated 30 FTE-years of mechanical/cryogenic/vacuum engineering to arrive here; we make very mature predictions backed by measurements for vacuum and vibration.

- We concentrated on getting ETpathfinder to work and had no time to design the baseline for ET, we needed a working platform now (2025).

- In our design, we assumed (and calculated) that the base of the suspension chain needs to be supported from the floor – hence the thermal shields need to fit in between the inverted pendulum legs

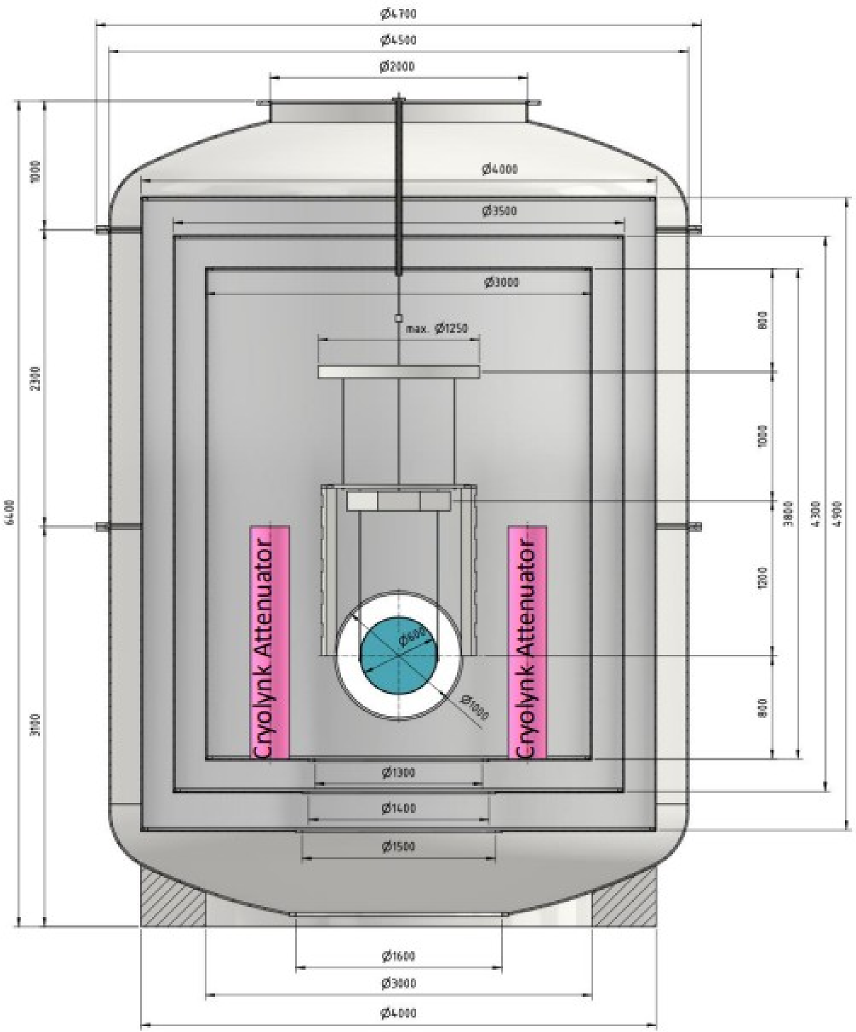
- In our design, we rely on pumping speed around the mirror when the system is at room temperature to get rid of water vapor before cooling down, and that we can cool down outer thermal shields and cryolinks while keeping the innermost shield and payload at room temperature.

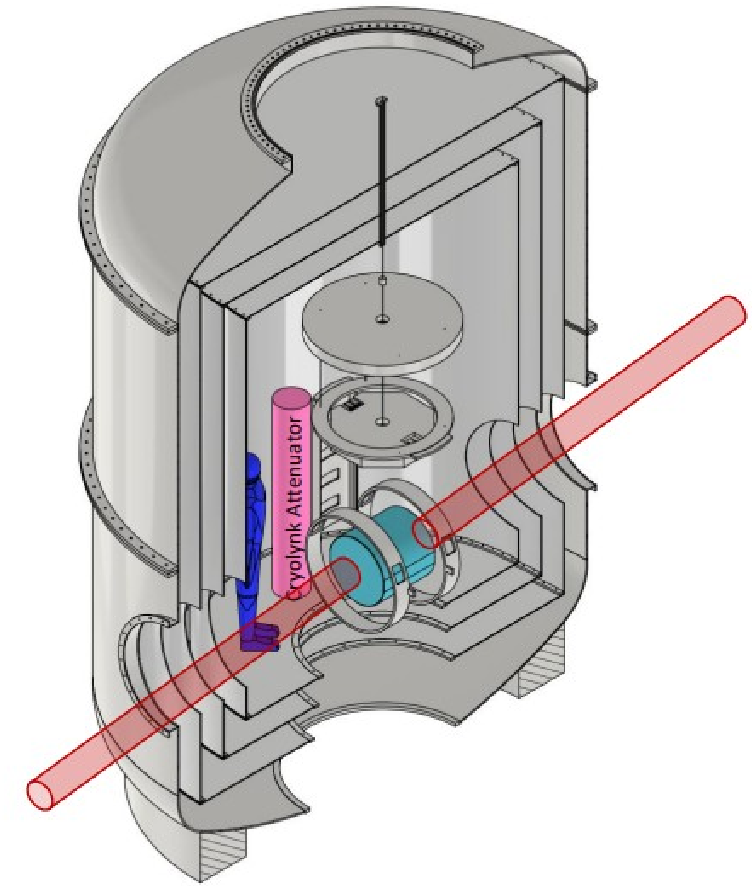
- Furthermore we anticipated the development of a monolithic silicon suspension. We hope for the solution proposed by Riccardo Desalvo (compressed flexures that support the mirror ears from below, thick silicon bar going up to marionette)
  - In our simulation toolkit we did not yet put sapphire as a material, so I do not have models for radiative cooldown of sapphire. We assume an aluminum marionette and silicon monolithic suspension (with flexures) in the cool-down calculations.

Baseline design

- Baseline cryostat concept places serious constraints:
- Full footprint of LF tower is claimed by the cryostat, leaving no floorspace for the suspension or other systems
- Underground access requires also that the tower is not supported from below (frame hanging over excavation)
- Currently only a conceptual design:
  - How to enter/reach the marionette? Walking platform?
  - How to provide clean air flow when inside shields?
  - How to pump around the mirror?
  - Cool-down and pump-down strategy.
  - How to install the cryostat in the vacuum tower? Lifting from top?
  - The cryogenic leads from outside towards the shields/payload?

Cryostat dimensions





Cryogenic shields: requirements

- The design of the cryostat has been chosen assuming that the allotted space is available and that there is no need to also provide a stable base for the suspension and the tower.

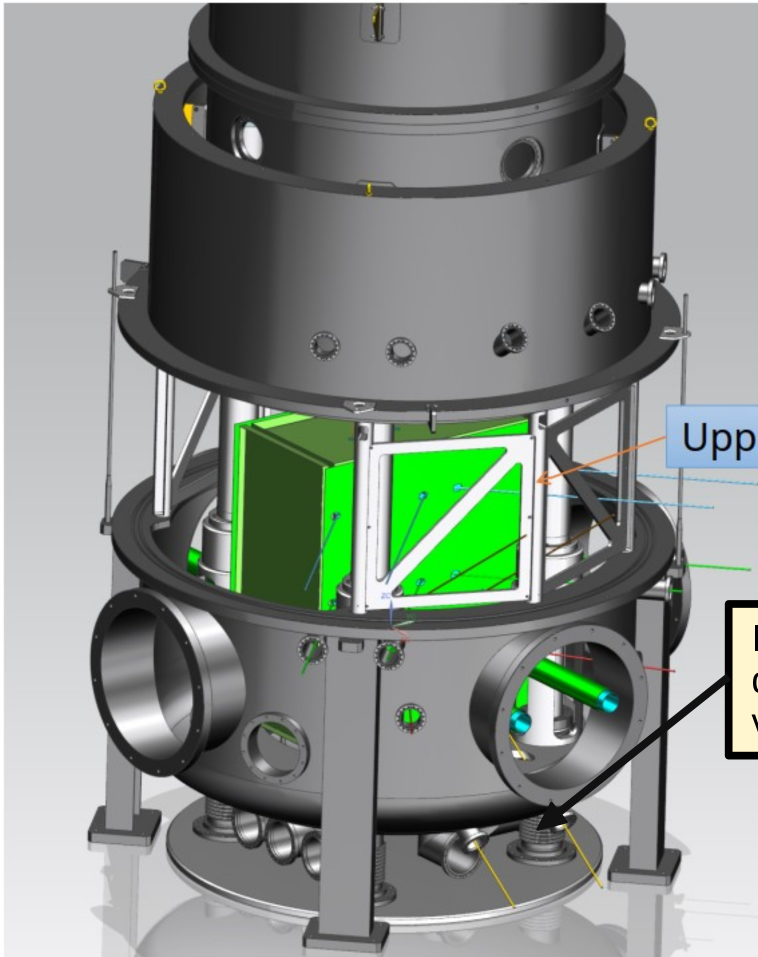
- For convenience, a lot of space is reserved inside the cryostat so personnel can walk around the payload

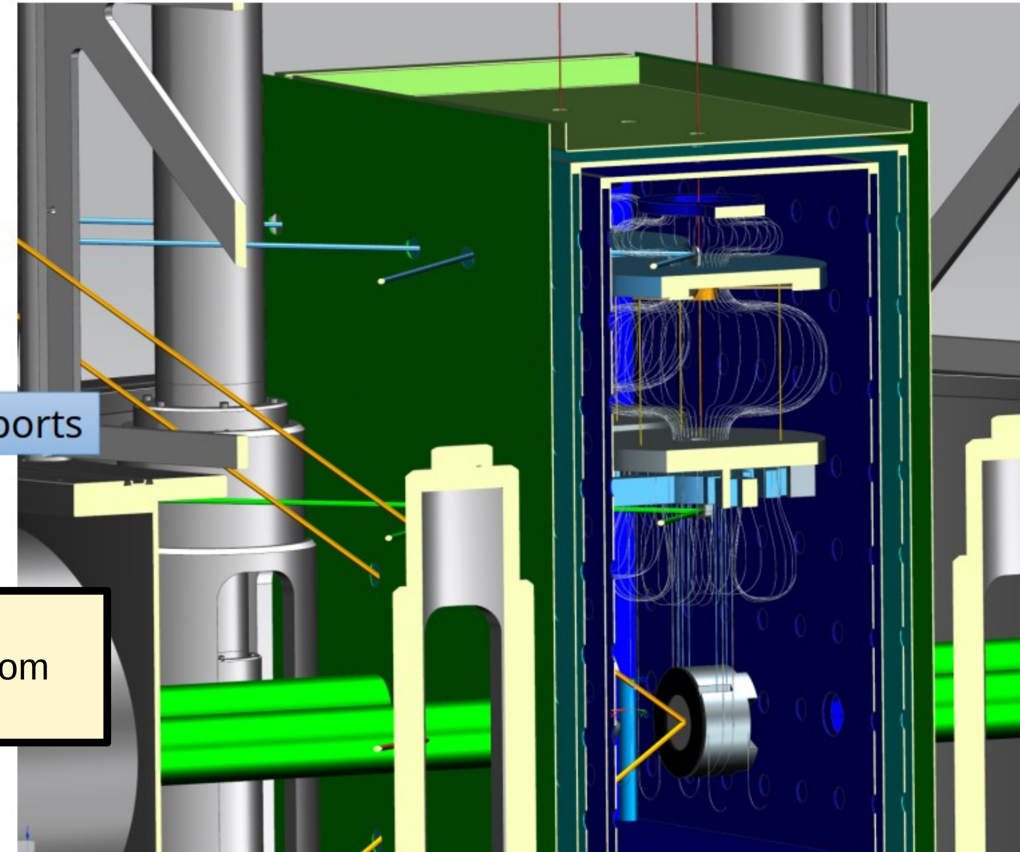
- The cryogenic shields should shield the payload from thermal radiation and from ice buildup – dimension of shields irrelevant, only solid angle/view angle matters. However, one needs a strategy for pumpdown after venting: about 1 kg of water vapor will be present inside the inner shield (multilayers of water on all metal surfaces). You want to pump down to reasonable level (<1e-8 mbar residual water pressure, possibly requiring a mild bake to ~ 60-80 deg. C in situ of the tower and cryolinks around it), cool the intermediate shield while keeping the inner shield above room temperature, freeze the water on the intermediate shield and then cool down the inner shield and the payload after that. That strategy only works if there are large enough venting holes between the inner and intermediate shield (and between the intermediate shield and the tower). Also the pressure in the tower base should be lower than 1e-8 mbar before cooldown.

- Shields should not vibrate too much. Shields should allow for pumping around mirror (else you do not get rid of the watervapor after venting). Middle shield should conduct a lot of heat (initial cooling via thermal radiation).

- Avoid polymers, avoid MLI foils. Impossible to reach long-term UHV after venting.
  - Our proposal: make a fixed frame with removable panels. Due to piping towards the shield, use lateral access (more handy than bottom access. If you do not have vibration-free cooling (like subcooled LN2) and the shields vibrate more than the ground, you can consider an active platform below the shields.
  - Inner shield can be very thin: in equilibrium it experiences only a few Watt radiative heat load so no thermal gradients over the shield. Middle shields (40-80 K) need more conductance (kW heat load).
  - Side panels: fix with high-conductive leads (e.g. KAGRA ultrapure Al) to frame; you can then just hang them from the frame without need for semi-permanent connection (indium, bolting).

ETpathfinder towers





ETpathfinder design, **M. Doets 2019**. Mantle-lifting system for sideways access. Shields in between the inverted pendulum frame and the frame for the upper part of the tower. Inverted pendulum feet connected to stable floor through bellows; tower and suspension are mechanically discoupled so that tower modes do not influence the suspension.

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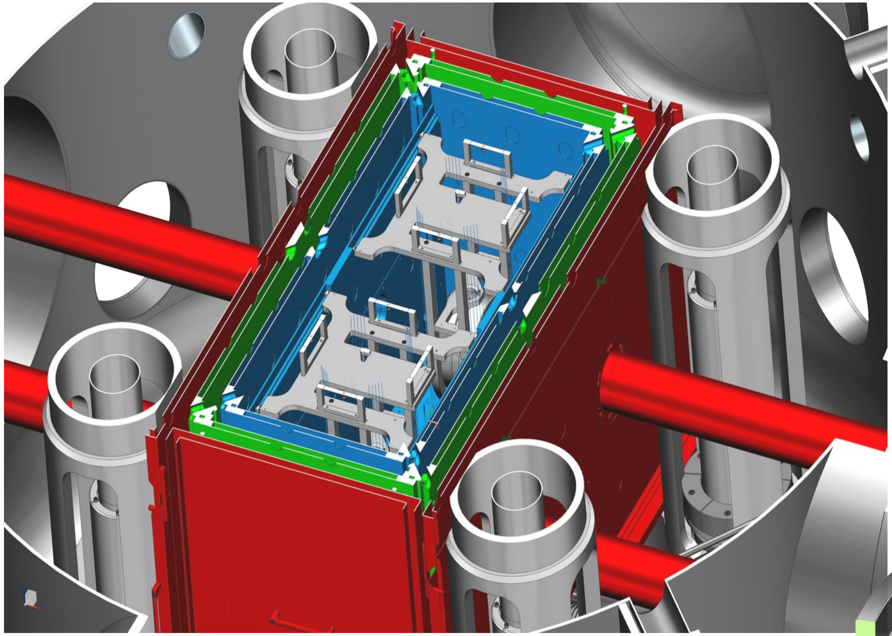
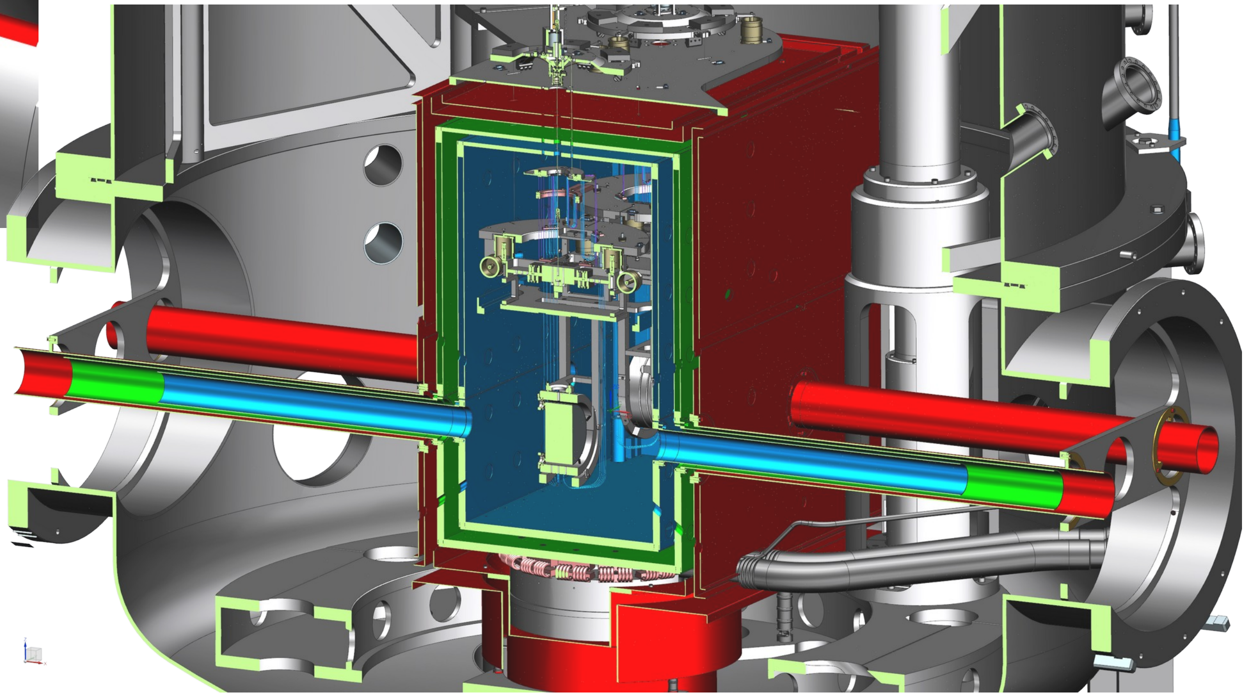
ETpathfinder test mass tower (design 2019, M. Doets)





ETpathfinder cooling scheme

- Use of sub-cooled LN2
  - Advantages:
    - 1) the enthalpy of evacuating liquid nitrogen is used: 200 kW/kg at 77K 1 atm. Since you can cool away 200kW at fixed temperature, you can cool using only laminar flow, thus avoiding all turbulence.
    - 2) >99% of the cooling power needed to cope for the total heat load can be provided with liquid Nitrogen
    - 3) the vacuum-insulated LN2 lines in the building are at 70K; this is much easier to obtain than liquid He which requires 4K.
    - 4) per cryogenic corner we do not need the underground power for a He liquefier (about 1 MW of electricity and then also 1 MW of water cooling, which is a substantial load for an underground tunnel)
  - Disadvantages:
    - LN2 supply need to be refilled, LN2 consumption of about 50kW → 1000 liter/h

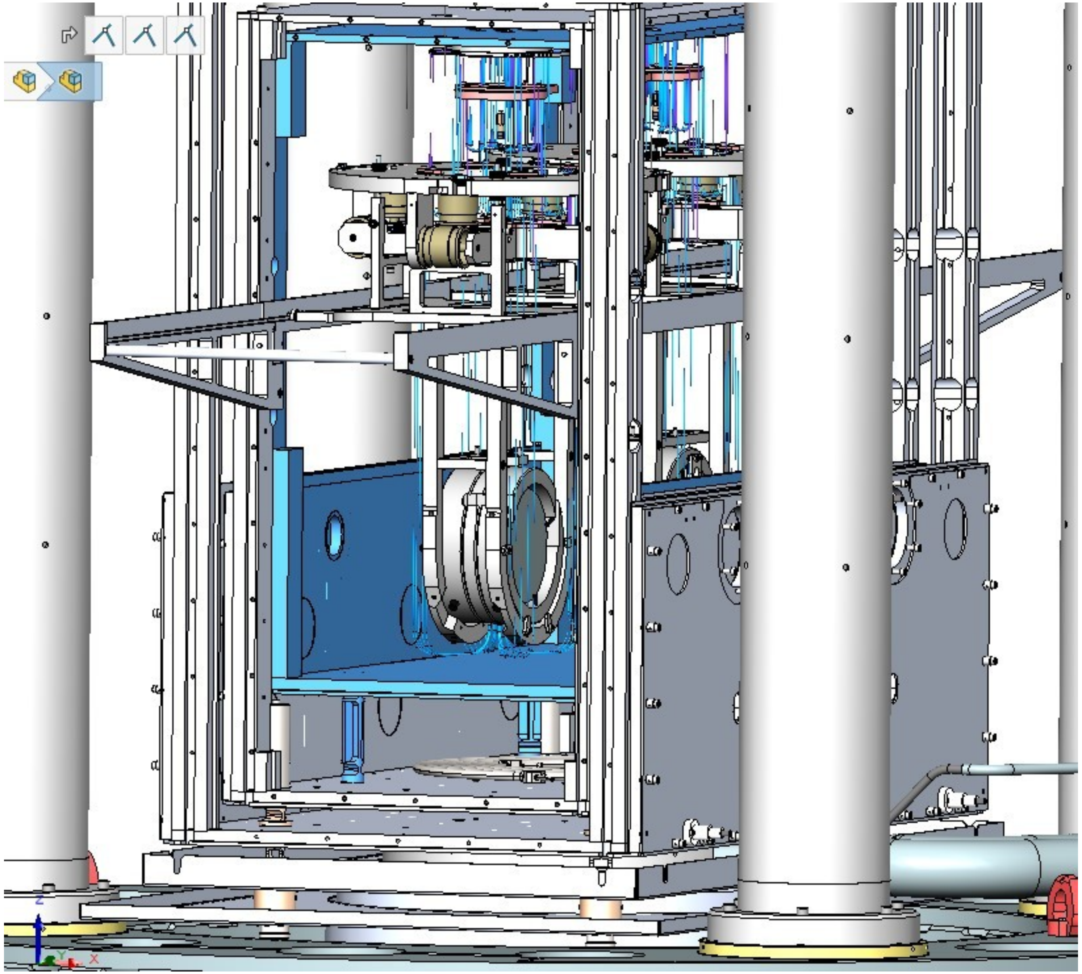
- Use of sorption coolers
  - Advantages:
    - 1) extremely low vibrations
    - 2) with counter-flow heat exchangers, the gas outside the tower passes at room temperature. Thus it is far easier to make feed-throughs through the tower walls, and the piping is very small (order ¼”)
    - 3) LN2 pre-cooling: no watercooling power needed, temperature hall constant. little electrical power needed (much less than for e.g. a pulsetube cooler) and this is dumped inside the pumping cycle)
  - Disadvantages
    - 1) relatively inefficient
    - 2) 3 drive gases/mixtures needed (Ne/H/He)
    - 3) more complex heat exchangers on the shields

ETpathfinder design: cryogenic shields

- mirror/marionette combination transported inside cryogenic shields via rail system that can be mounted on the frame of the cryogenic shields: side panels need to be taken off. (also necessary for ET)

- Space needed for cryogenic cooling lines/counter-flow heat exchangers/cold platforms etc; about 10 cm between sets of shields should be sufficient (in ETpathfinder we have only 4 cm between 40K and 80K platform and between 80K and passive shields); shields should give clearance of about 30 cm above/around marionette (for support platform to fix cryogenic link and have caternary shape link).

- ETpathfinder: total weight shields ~ 500 kg, frame contains corner bars of 50x50 mm. For ET I expect 100x100 mm corner bars on the LN2 shield for conductance.



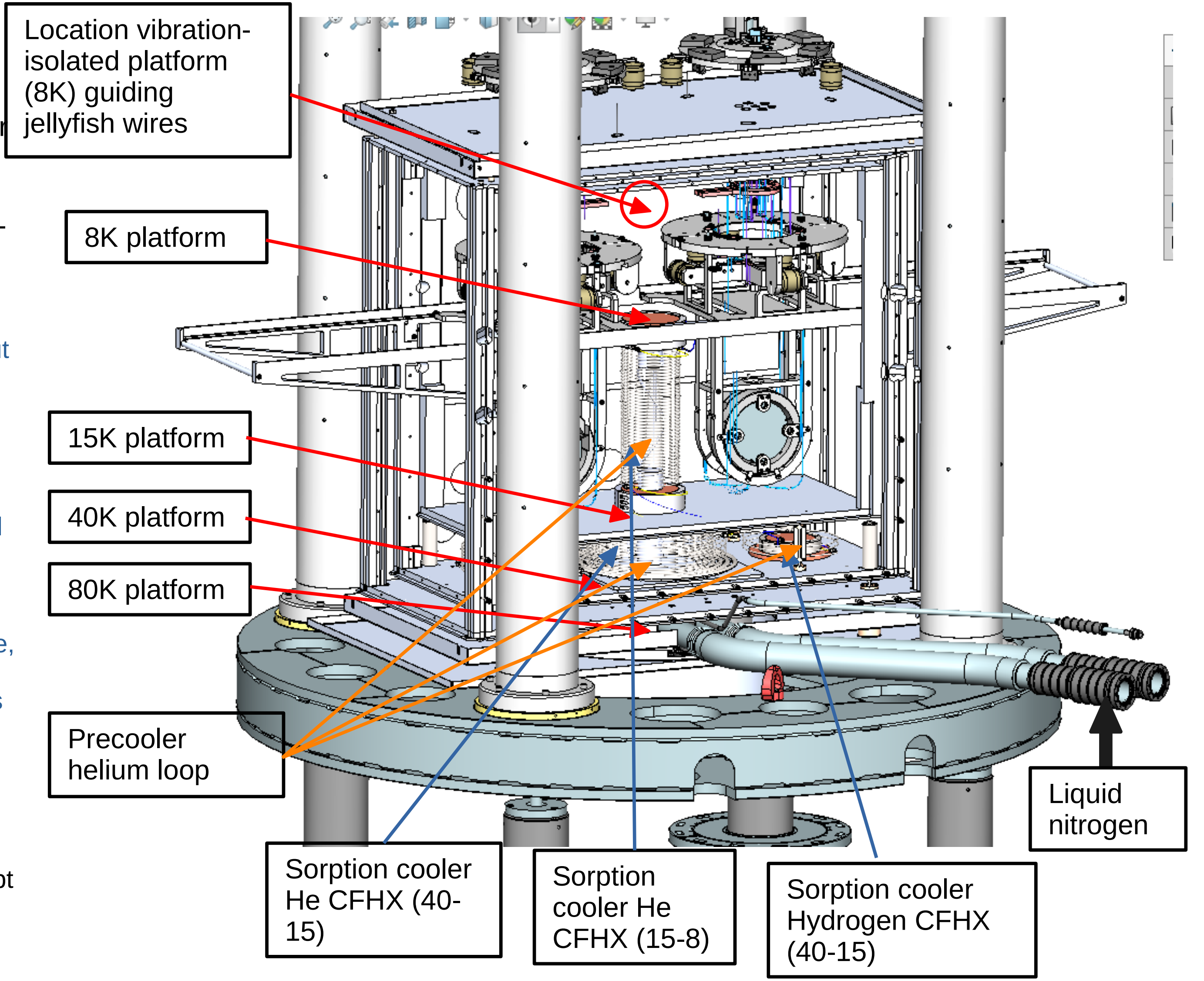
ETpathfinder cryogenic shields: in blue the innermost shield, a 15-K platform, with the mounting rails to transport the cryogenic payloads. All shield panels are omitted here. Design engineering: R. Garcia (IFAE Barcelona), M.Doets, K.Lam, M. Baars (Nikhef), H.J.M. ter Brake, C. Vermeer, M. van Limbeek (EMS Twente), R. Kunst (Demcon)

Heat exchangers (ETpathfinder)

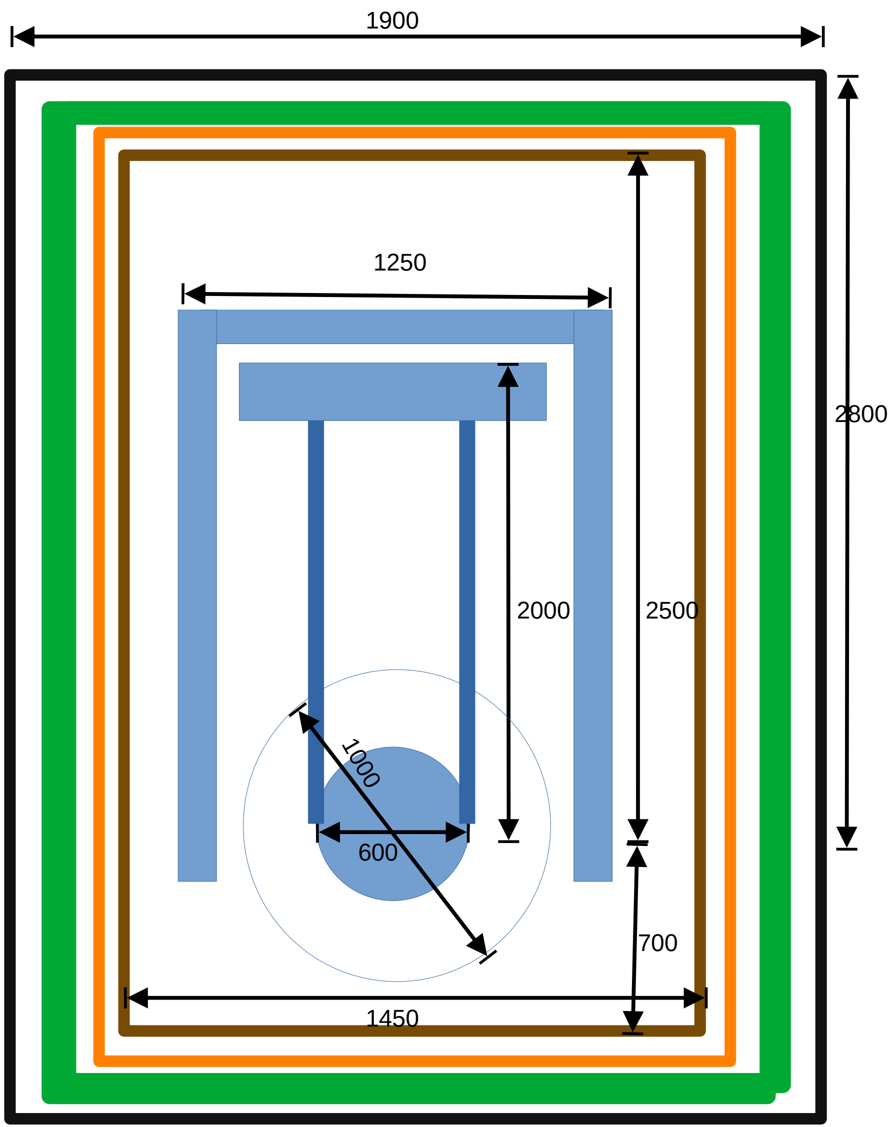
- For ETpathfinder we decided to go for sorption coolers since we considered that the most mature technology for low-vibration cooling. Disadvantage is that the efficiency of the cooler is low; especially at higher temperatures.

- We need a more powerful cooler for initial cool-down that can be switched off when thermal equilibrium is reached
  - ETpathfinder mirrors: 4 kg. Majority of cooling above 40K is obtained by radiative transfer. About a week needed
  - Also a problem for ET; in order to cool a 200kg Silicon mirror from 300K to 10 K one needs more than 30 MJ of cooling. Difficult to transport that heat through thermal links.
  - In ETpathfinder we apply a cold He loop for initial cooldown; this loop is switched off in equilibrium (and the lines evacuated)
  - In ET baseline design a solution is found by making the mirror, the inner part of the marionette, and the connection to an extra cold stage above the marionette monolithic sapphire. This provides relatively more conductive cooling power to the mirror at the cost of having a stiffer link than foreseen in ETpathfinder.

- Drawing of the necessary heat exchangers and cryogenic lines for the ETpathfinder cooling concept may give an impression of the space needed.



Rough estimate minimum footprint for ET



From baseline (see Fulvio contribution 18-02-2025) : assume a mirror diameter of 600 mm (is that really an option in the future?), and 1000mm diameter for the reaction cage/baffle around the mirror; I assume that that is also the diameter for the cold cryolink around the beam.
From baseline: 1250 mm for reaction cage/safety cage around mirror (assumed suspended from filter above); 2000 mm for monolithic suspension. (Here also: is that needed? I would think that we can gain at least 1 meter in height and 25cm in diameter here?)

In this picture I skip the intermediate cold platform (consuming 2 m in the baseline design); if it is needed in the full size of the payload, then the shield should be extended in height. I assume that the connection between marionette and reaction mass can be made with jellyfishwires, hanging in caternary path (tbc).

All shields : double-walled with staggered holes to allow for pumping on the mirror and for feedthroughs of thermal sensors/heaters on the shields.

Black: outside passive shields; 1900 mm needed. Supported from 80K platform.
Green: LN2 shields; 80K platform. (Extra width needed for possible larger diameter gas return exhausts. Could be more compact when cooled with He?) Supported from (possibly) actively-controlled vibration damping frame from ground (so one can track the superattenuator low-frequency movement if necessary). Heat load in equilibrium about 2kW? To be calculated/confirmed.
Orange: intermediate temperature platform (30K? 30W?)
Brown: intermediate temperature platform (10-15 K? 1W).
Blue: hanging from suspension system (the filter above the shields. Links via ultra-pure aluminum; a light-weight suspension stage is needed (0.5W, load on mirror)

Cryogenic cooling lines and heat exchangers (going through tower walls) are connected to the bottom of the shields in Etpathfinder (and also in this concept): bottom access is ruled out then.

Design for ET

- In my opinion the design of the shield is just an engineering challenge; one should develop a solution with a more reasonable space limit. (2 m diameter should by ample sufficient).
  - Same holds for lateral access. Ligo has no bottom access either. In ETpathfinder, the hall is better than class-5 even during cleaning (particle counts measured during vacuuming the cable trays in Feb 2025). We bring in the payload doubly-wrapped and open the tower (Better than class 5), install the payload and remove wrapping.
  - If for ET higher-class is needed for servicing, one can modify the shields to allow for installation of temporary air blow system from top of shields that could be mounted before opening the shields.

- Vacuum: if you have completely closed shields you do not pump much on the mirror/marionette. After venting, you introduce a monolayer of water in the volume enclosed in the inner shield, as well as dissolving water on the cables (at the reaction mass, and for temperature sensors/heaters). Preferably you pump this water away before cooling, else it will be difficult to avoid freezing on the mirror

- Vacuum inside tower should also be good. Consider e.g. KATRIN neutrino mass experiment (KIT):
  - Volume vessel about 8000 m^3, at 18 kV high voltage
  - Tritium beam decays in flight; beam steered to 0 velocity and decay products detected 4pi around decay path
  - Large amount of sensors and actuators needed in the vacuum system, many more cables than for ET LF tower
  - Still, vacuum level is 2e-12 mbar while injecting tritium beam!
  - Thanks to NEG coating walls (about half the surface). We could also be much more strict with material choice and apply large NEG pumps on upper part tower/