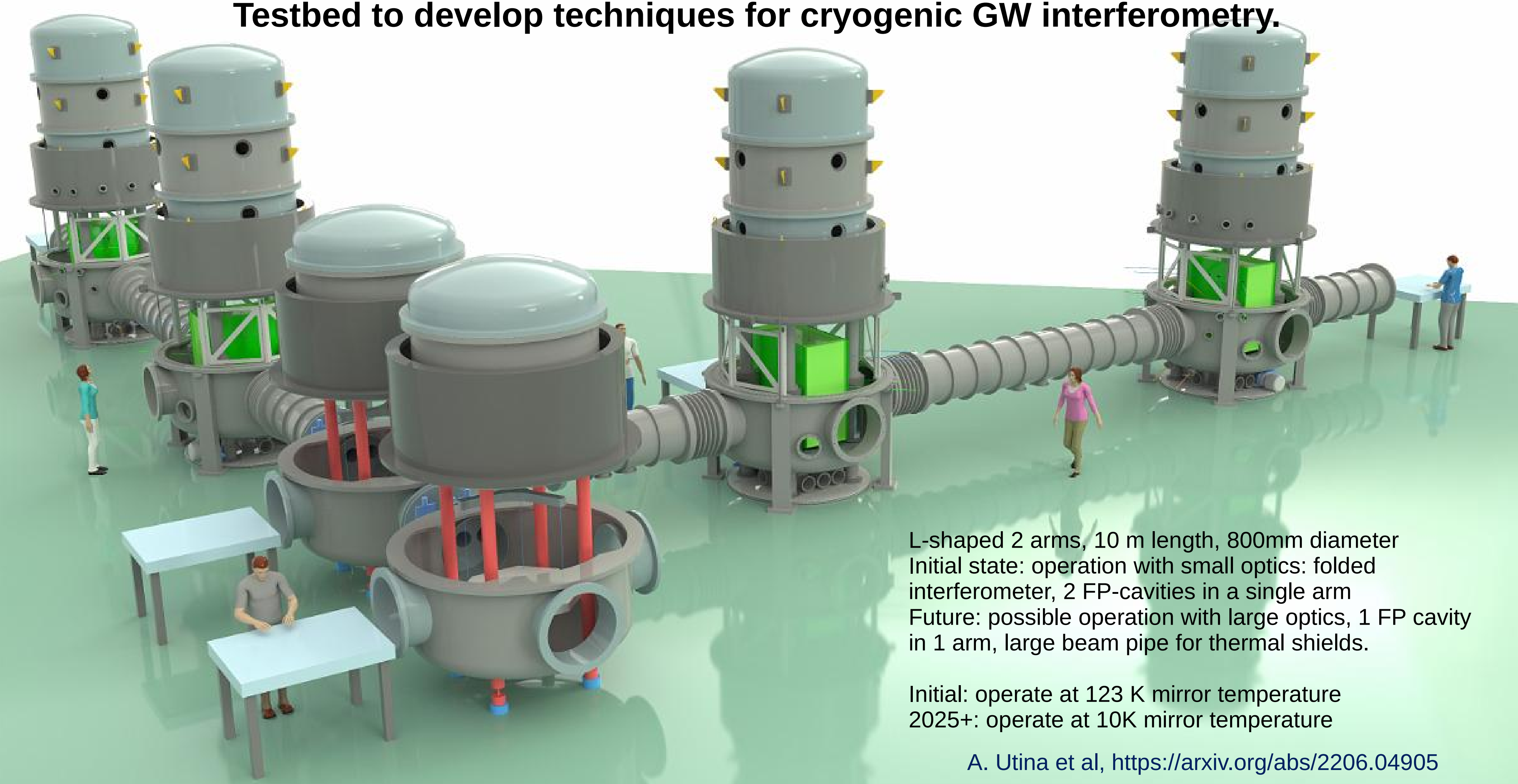
Vacuum, Cryogenics, and water vapor transport in ETpathfinder.

H.J. Bulten, for the ETpathfinder community

GWDVac’22, Elba, Sept 30, 2022

ETpathfinder project

Testbed to develop techniques for cryogenic GW interferometry.



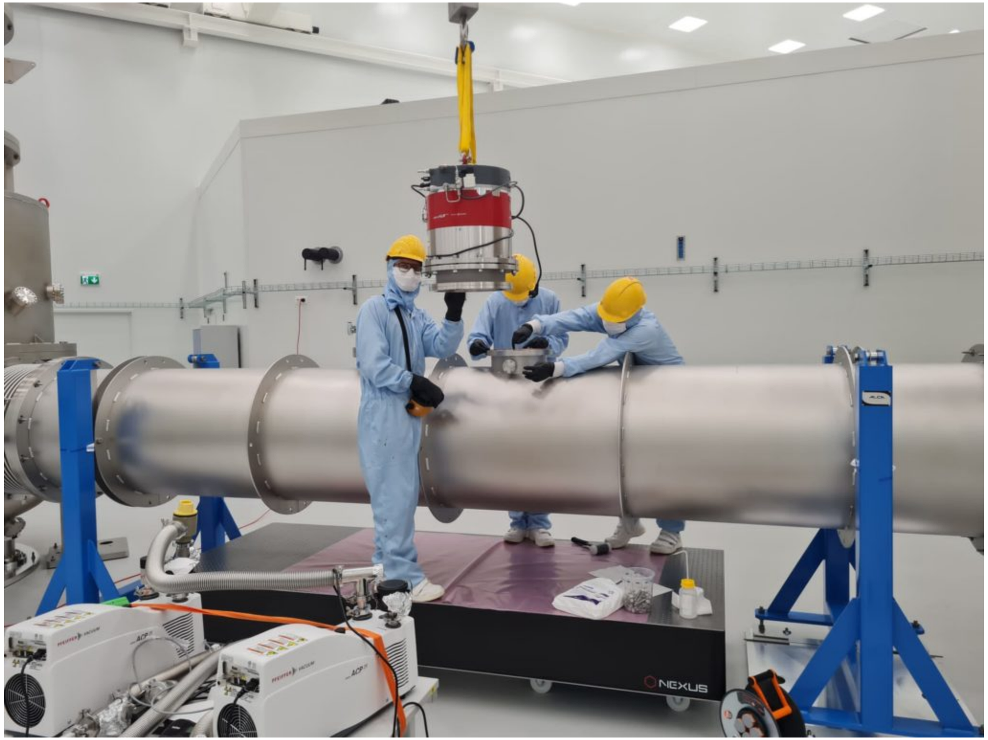
L-shaped 2 arms, 10 m length, 800mm diameter
Initial state: operation with small optics: folded interferometer, 2 FP-cavities in a single arm
Future: possible operation with large optics, 1 FP cavity in 1 arm, large beam pipe for thermal shields.

Initial: operate at 123 K mirror temperature
2025+: operate at 10K mirror temperature

A. Utina et al, https://arxiv.org/abs/2206.04905

ETpathfinder project

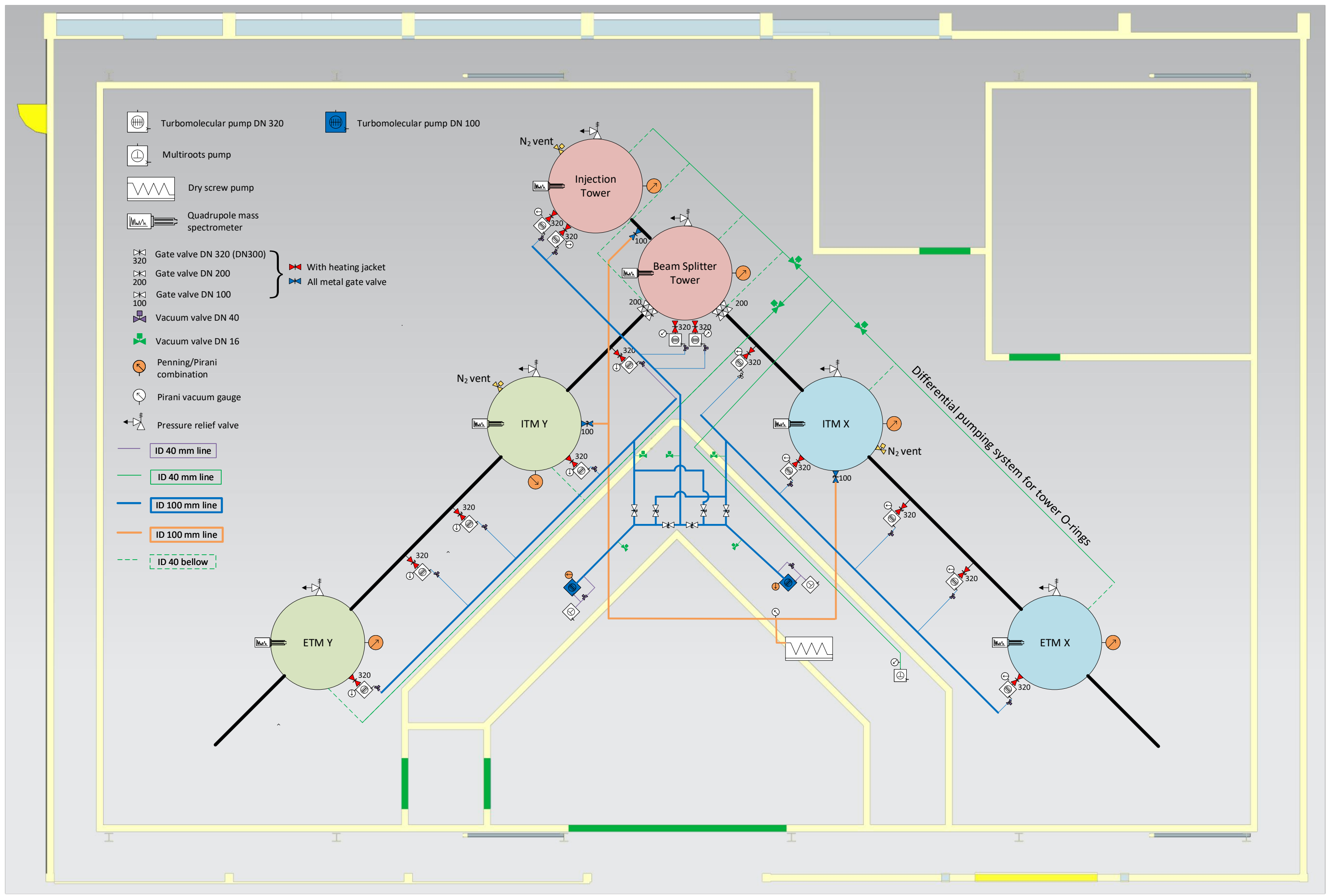
- Currently under construction – no scientific measurements yet
  - EU interreg funds (Dutch-Belgian border region) – three-year funding ending Dec 2022
  - Many partners from outside the region (vacuum-related: KIT vacuum, PLC controls, VDL/Tata Steel material properties, Univ. Twente, Demaco, Absolut Systems, Cryoworld for cryogenics, KIT possible future tests with He-II, Barcelona (cryogenic shields, coatings, instrumented baffles), Jansens precision technology (cryogenic actuators and seismic damping)
  - This presentation: modeling, vacuum and cryogenic set-up



Currently, initial pressures few microPa with half the turbopumps, no differential pumping, and only multi-roots forepumps.

Vacuum setup

P&I Diagram Vacuum System ET Pathfinder



v13 June 30, 2022

Munneke, Bulten, van Overbeek

Research facility: vent/evacuate quite often – turbo pumps chosen.

3 separate UHV-sections

- Central region vented most often; arms host the cryogenics
- About 130m^3 volume, 40m^3/s pumping speed below 1 mbar, 600m^3/h at 1 bar

Aim: 10^{-9} mbar base pressure

- Extremely challenging considering the cabling, coils and optics

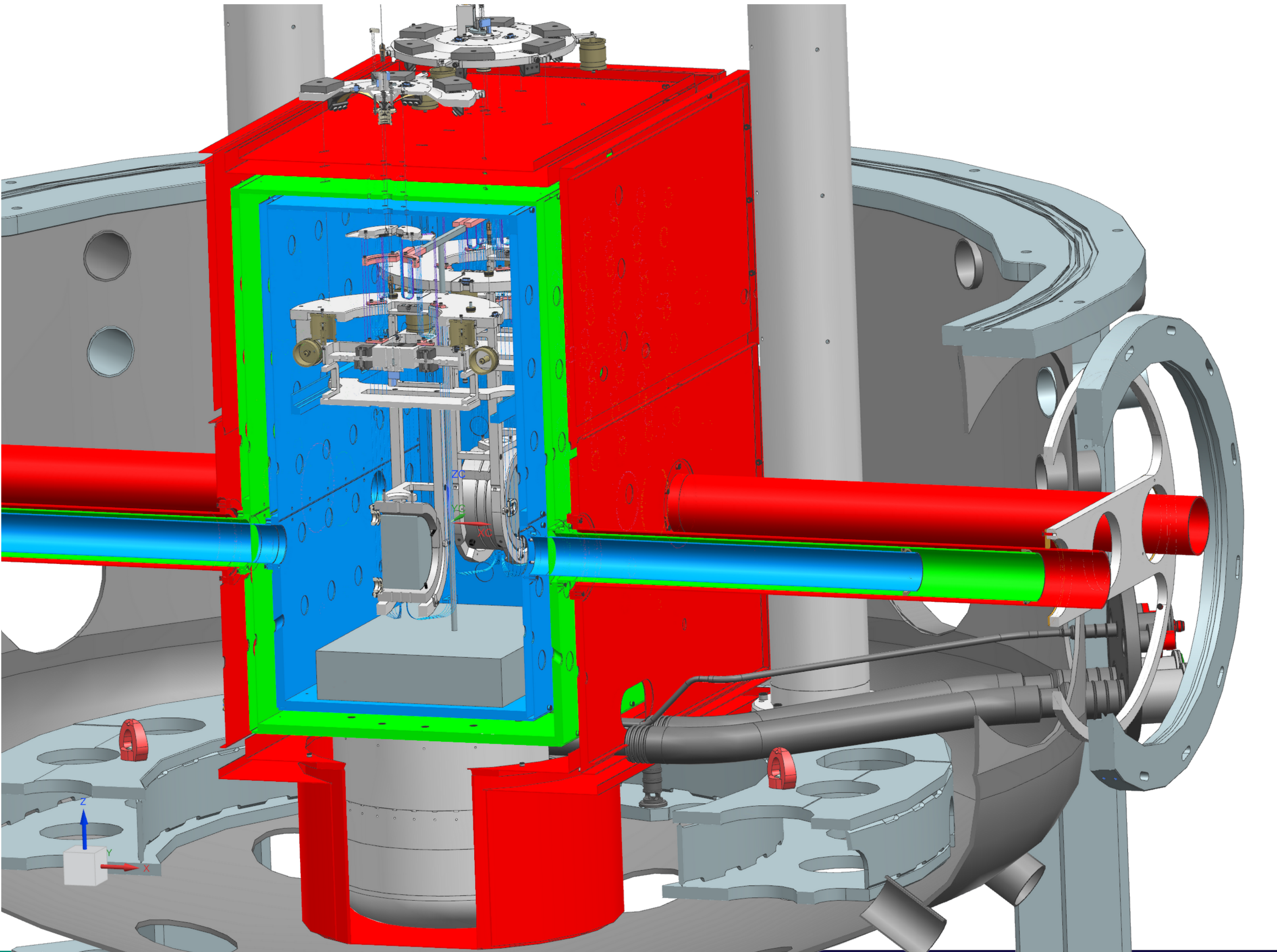
Tandems of turbo pumps for UHV, hydrogen compression, and ease of operation (venting)

Noisy-equipment area: triangular corridor: separate clean room, on separate floor, acoustic enclosure

- Houses the fore-vacuum system and the pumps/cryostats.

Mantle of tower can be lifted for access – we use Viton O-rings and differential pumping.

Cryogenic mirrors



Small optics: Si mirrors 150-mm diameter, 2 suspended mirrors per tower

Beam spot small (few mm): we can make a thermal shield with small apertures: 1 m long tubes, 20mm opening

Thermal shields:

red : passive shields with high emissivity (replace MLI foil; we only use aluminum).

green shields are liquid-nitrogen cooled with (reduces thermal load on inner shields with a factor of 100)

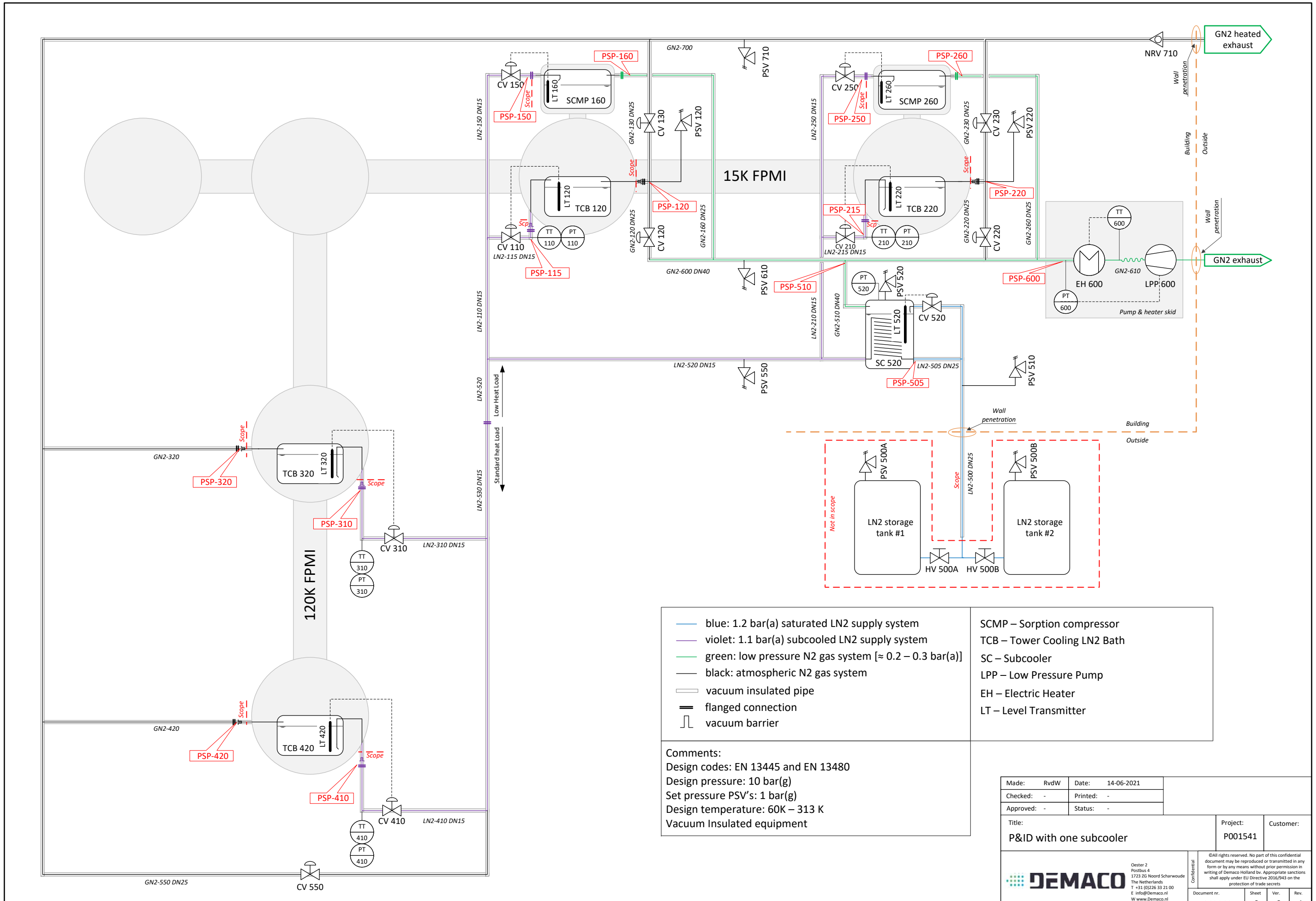
blue: inner shields – 30 K?

grey box: placeholder for cold finger, heat exchangers

The bottom of the green LN2 shield is mounted on the base ring (with SS flextures); the inner shield is mounted on the bottom of the LN2 shield. No active seismic damping of the shields.

Sub-cooled LN2 (74K at entrance) is fed into the LN2 vessel: heat load below nucleate boiling. Gas return: laminar flow!

Sub-cooled LN2 supply (low noise) – good option for cryolinks ET?



Sub-cooled LN2 supply: outsourced to DEMACO.

15m^3 storage vessels outside building (Linde)

Blue line: LN2 from storage tank. Passes a subcooler unit: a bath of LN2 that is pumped down to 0.2 bar; 66 K

Purple lines: subcooled LN2: cooled to 67K (at towers still below 74K)
thermal shield needs about 1 – 2 gr/s of liquid nitrogen; this is filled continuously and evaporates below nucleate boiling in the tower.

Green lines: gas at 0.2 bar (from subcooler unit and from sorption cooler units, which are also cooled to 67K by the same system

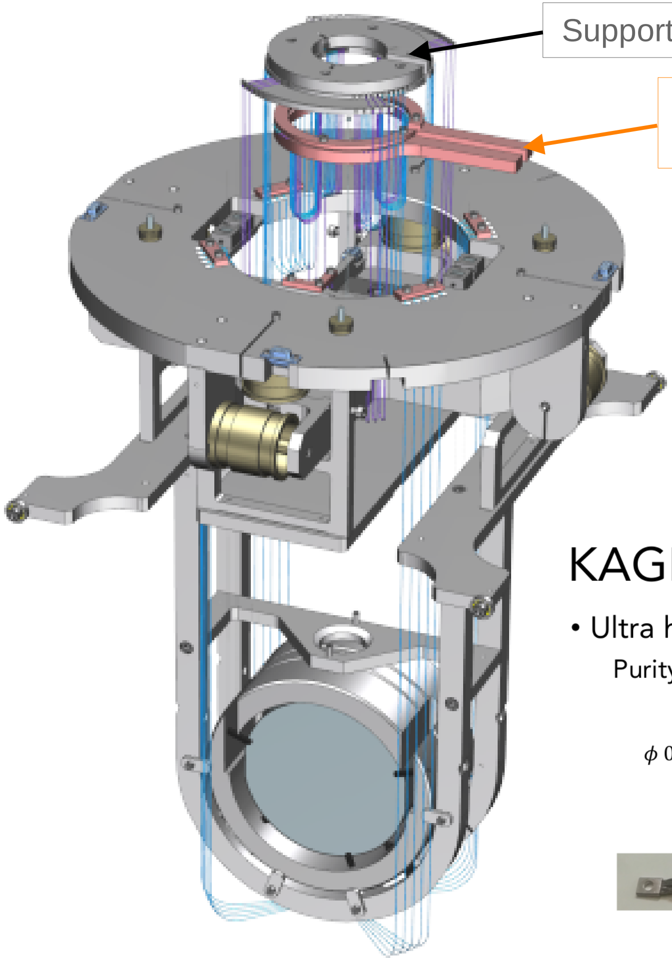
Black lines: Gas return at atmospheric pressure. All lines are vacuum-insulated.

Subcooler pump is in noisy corridor – no noise sources inside clean room.

Cryogenic mirrors, thermal links

- Operation at 123 K: the inner shield is heated to produce a homogeneous ambient temperature and keep the mirror at 123K in thermal equilibrium (about 10W of heat needed) – no conductive link to mirror needed.

- Operation at 10K:in development
  - Soft conductive links to marionette and reaction chain needed to extract the latent heat (~5 MJ/payload). Ultra-pure Al (KAGRA method, c ~ 20kW/mK)
  - Two-phase cold Helium loop for initial cooldown (>30W cooling power)
  - Ultra-quiet sorption coolers (3W@30K Neon, 0.5W@15K Hydrogen, 0.1W@6K He) to maintain equilibrium temperates
  - For operation at 10K we also have to develop a monolithic Si suspension for the mirror.



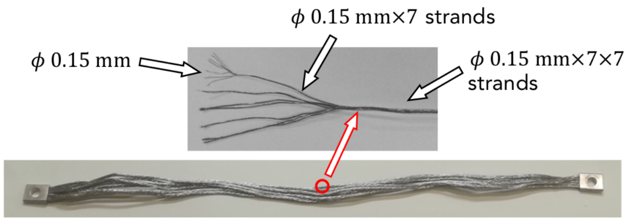
Ultra-pure Al (KAGRA)
32 wires 0.2mm diameter, guided via a distribution ring hanging from the last filter above the marionette.

heat load on mirror < 10 mW, heat load on support structure, reaction mass, marionette ~50 mW.
Transfer function tested in test setup.

KAGRA heat-links

- Ultra high-purity aluminum heat-links

  Purity: 99.9999%, 6N (Sumitomo Chemical Co., Ltd.)



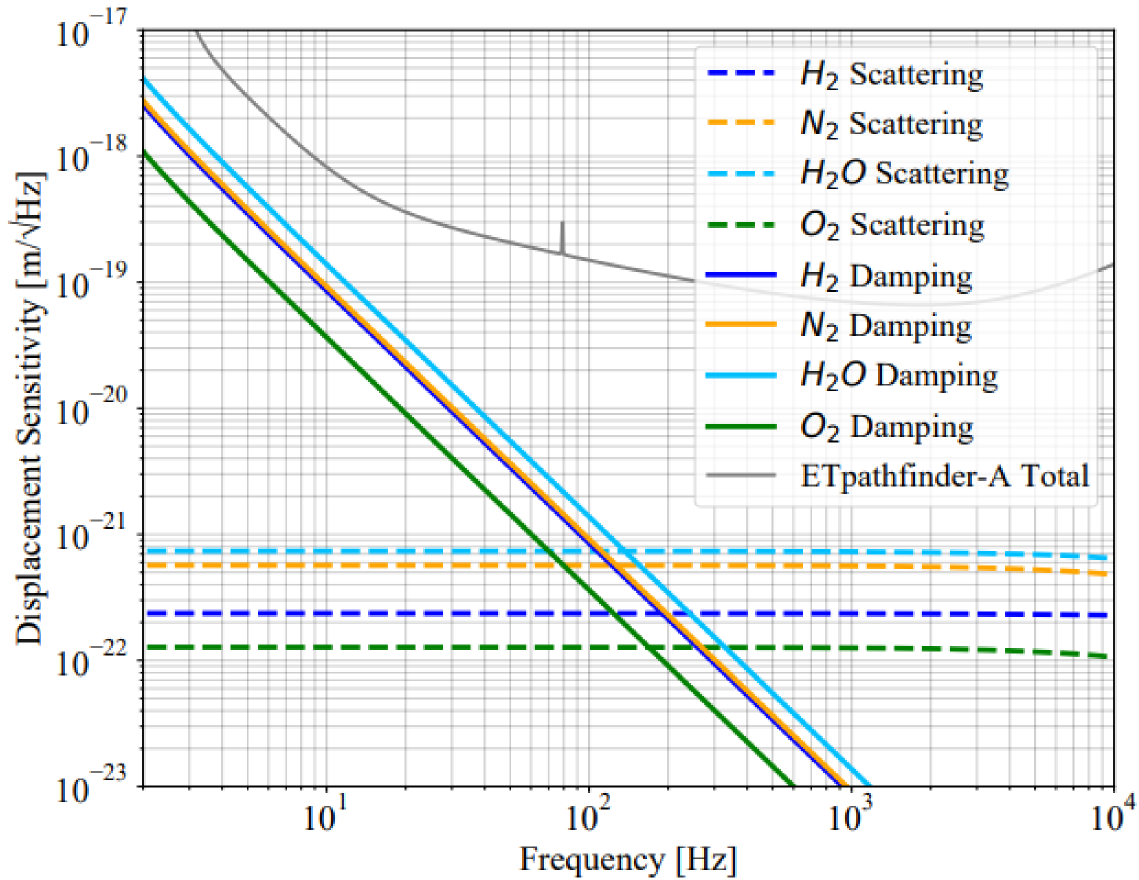
7 parallels of ϕ 0.15 mm×7×7 strands

high thermal conductivity and low spring constant(stiffness)

Residual gas noise sources

- Residual gas: optical path length differences in arm:
  - Depends on density, beam waist, polarizability of molecule
  - ET : 10 km arm, high power – pressures $<10^{-10}$ mbar needed
  - ETpathfinder: short arms, pressures $<10^{-8}$ mbar in arm are sufficient.

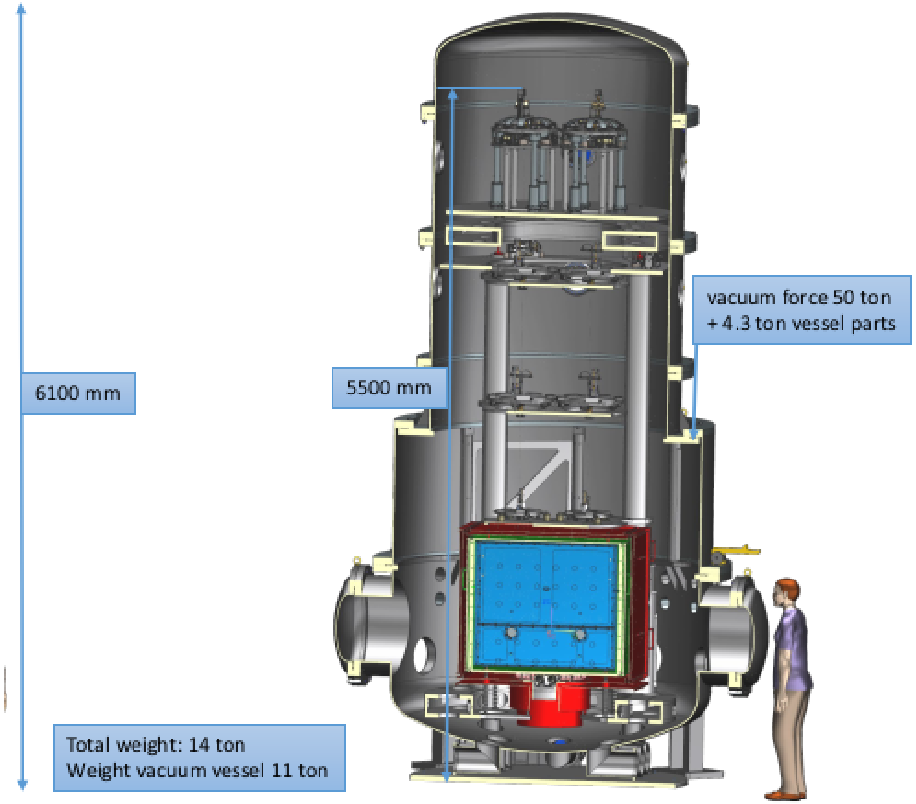
- Residual gas: Brownian motion, mirror
  - Scales with pressure, surface area, mirror mass as sqrt(p A)/m
  - ETpathfinder: mirror diameter 15 cm, mass 3.5 kg – about 20 times larger than for ET
    - Noise dominated by Brownian motion mirror for ETpathfinder, water contributes most.
  - Calculation based on Energy fluctuation dissipation theorem: Cavalleri et al., Phys. Lett. A374, 4465 (2010)
    - Cylinder in free space
  - Effects from trapped molecules: scattering between mirror and reaction mass may significantly enhance this noise. - Can be studied in numerical simulations.



Residual gas noise from path length change (dashed) and Brownian motion (solid) for the ETpathfinder facility, using initial partial pressure spectra.
A. Utina et al, https://arxiv.org/pdf/2206.04905.pdf

Residual gas noise: ice build-up on mirror

- Under cryogenic conditions, rest gas will freeze on the mirror
  - Mainly water, already at 123K
  - At 10K mirror temperatures everything except He freezes.
  - Gas kinetic theory: Impingement rate: J=p/sqrt(2m kbT) – $3x10^{24}$ collisions/m^2 at 1 mbar for water. A monolayer builds up in 3 seconds at 10^{-6} mbar pressure.
  - The additional ice layer affects the optics: see Hasegawa et al. for the KAGRA experiment
  - At temperatures below 10K, also hydrogen may freeze.



Gas sources:
Hydrogen dissolved in the steel : total amount about 300 bar liter (>10 mole) per tower
 - results in constant base pressure

Water adsorbed on metal surfaces: about 0.01 mole, 170 mbar l.
 - 1/t pressure decay

Water dissolved in PEEK, vespel, Kapton – to be studied
 - 1/sqrt(t) pressure decay

When does the gas come off? Where does it go?

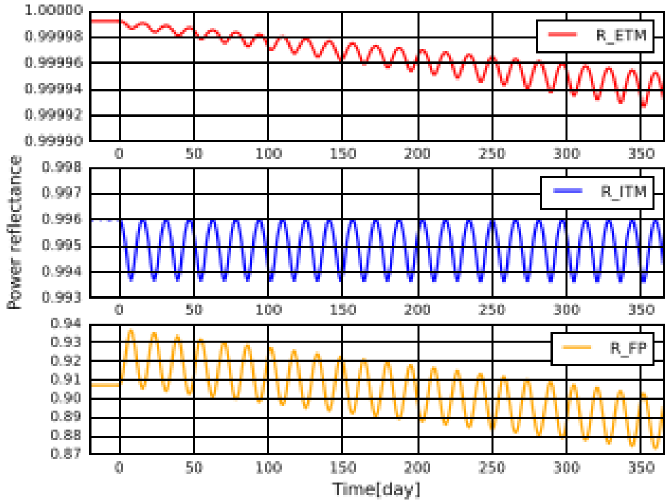


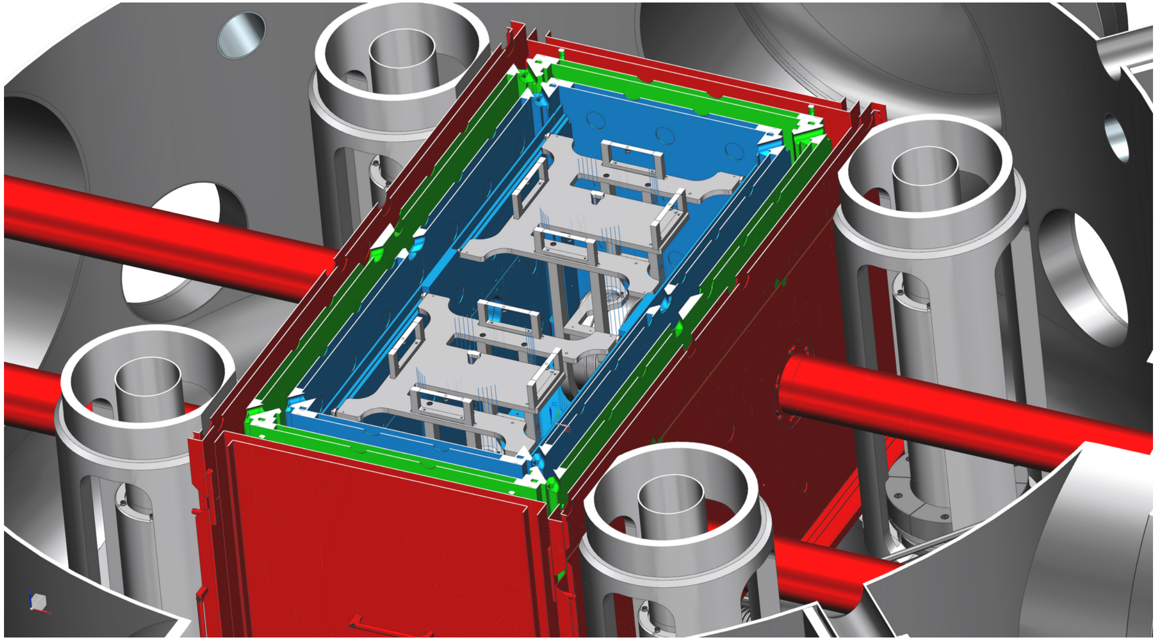
FIG. 9. Reflectance oscillations of the ITM (top), ETM (middle), and the arm FP cavity (bottom) of KAGRA due to the molecular adlayer by using the parameters in Table II. In this calculation, the formations of a molecular adlayer for the ETM and ITM start at the same time. Because the original reflectance of the ETM is higher than that of the ITM, the amplitude of reflectance oscillation of the ITM is larger than that of the ETM. The reflectance of the ETM decreases over time due to the optical absorption inside the adlayer. On the other hand, the reflectance of the ITM does not decrease. This is because the ITM reflectance is lower than the ETM reflectance, and the absorption of the adlayer is not large enough to significantly reduce the ITM reflectance. The reflectance of the arm cavities increases when the reflectance of the ITM decreases because the reflectance of the ETM is higher than that of the ITM.

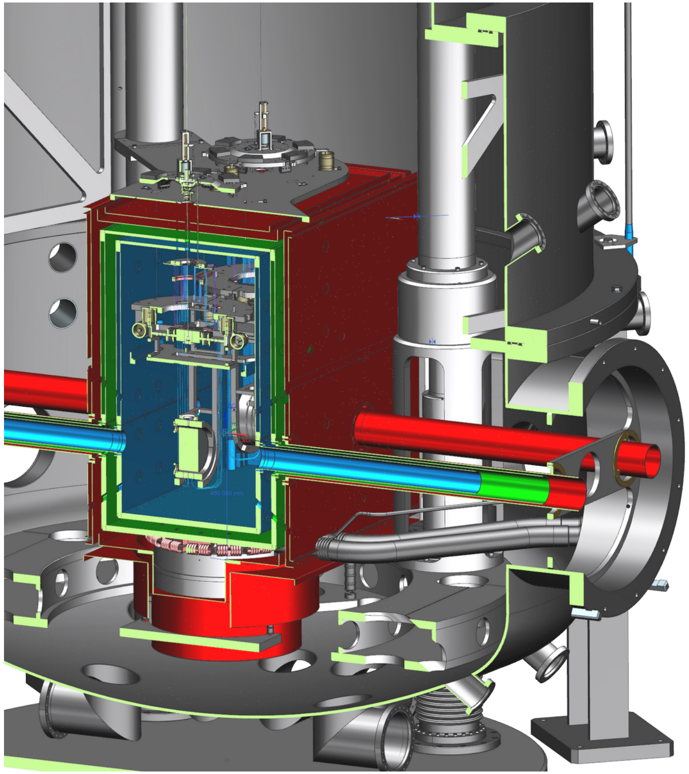
Hasegawa et al., PRD 99, 022003 (2019)

Simulation of residual gas noise and cryogenic operations

Modeling Cryogenic shields: heat flow depends on thermal radiation.
- double-walled with staggered holes to allow conductance for vacuum.
- holes needed for the laser beam, the suspension wires and cabling, the optical levers.
- What is the thermal radiation heat load on the inner shield? The suspension chain? The mirror? What should the emissivities be? The cooling power? The conductive heat flows?
- OK for scattered light noise?
- What is the vacuum conductance? Where do the water molecules go? Do they freeze on the shields or on the cryogenic payload? Ballistic flow? Evaporation?

A good design requires input from models capable of tracking radiation and rest gas, and of describing the interactions with the surfaces and the sources (EM emissivity, laser beam, outgassing).





Simulation of residual gas noise in cryogenic environment

- Both residual gas and thermal radiation originate from the surfaces inside the vacuum system. Model to track!

- First step: build tracking matrix
  - molecules/radiation are generated homogeneously from all surfaces. They are scattered towards other surfaces until they are absorbed:
  - EM radiation: depending on the emissivity of the surface
  - Molecules: when they encounter the aperture of a pump.

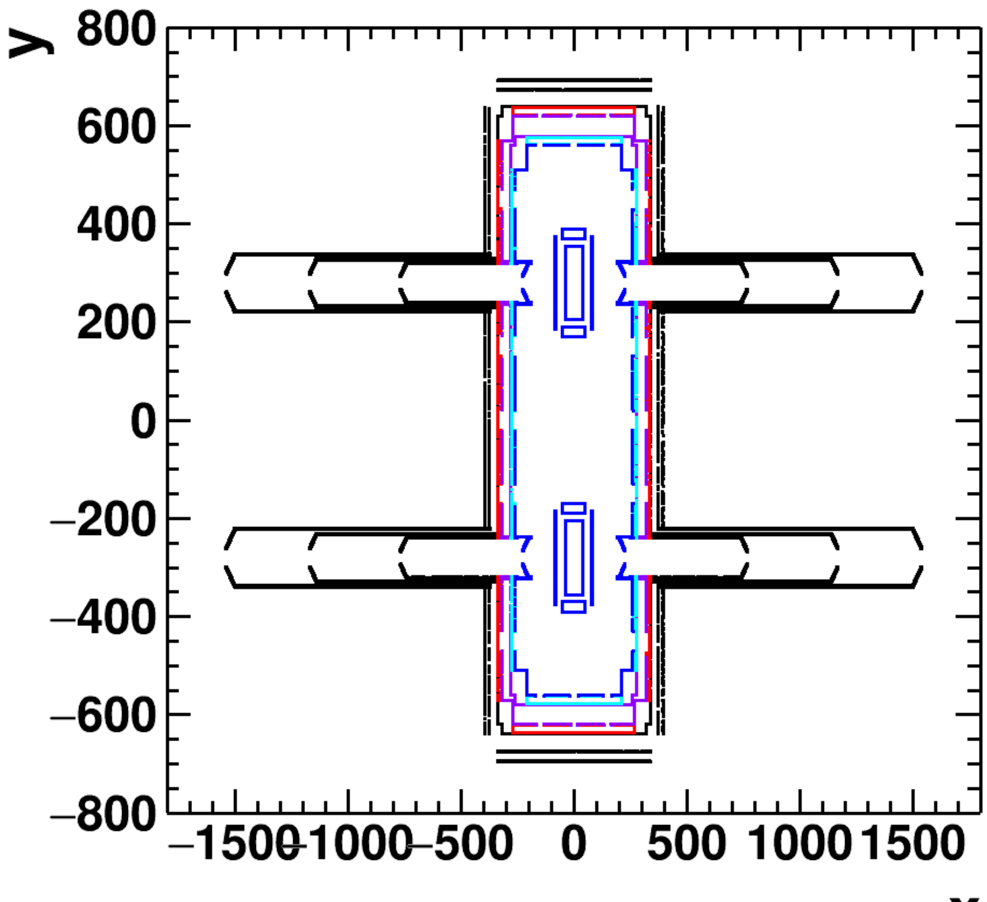
- Next step: store tracking parameters
  - All particles are tracked: the amount of bounces per surface and the total distance traveled per volume is stored for each trial.
  - Volumes are fully enclosed by surfaces (with holes to reach one volume from the other volume. This to keep track of pressures inside a volume – needed for vacuum simulation.
  - We keep track of the surfaces from which the particles originate and against which a particle bounces

- Scattering: specular or isotropic (for molecules only isotropic).

- We have only a limited amount of shapes from which we build bodies: blocks (with cylindrical holes), cylinders (with cylindrical holes in the side), cones (for baffles: the base of the cone is flat, the top of the cone is perpendicularly shaped), and half-spheres (for a dome).

- Complicated shapes are built from these basic shapes.

- Using the tracking parameters, one can then numerically integrate the coupled equations that describe time-dependent heat flow, vacuum pressure, etc.



Cross section of the shields, mirror and reaction mass at beam height. Volume around the mirror dark-blue, between the walls of inner shield light blue, LN2 shield purple/red, passive shields and baffles black.An almost exact replica of the shields is reconstructed using 172 basic shapes.

Thermal simulations

- A few billion of particles are tracked (~ a day on an icore7). For each surface, the view angle is calculated: a full list of the amount of tracks that are emitted from the surface and absorbded on each other surface (NxN matrix), and vice versa, with weights of surface area and emissivity included.

- Thermal radiation power towards surface i follows then easily from (constant) a_ij:

$$dQ_i/dt = \sum_j \alpha_{ij}\left(T_i^4 - T_j^4\right)$$

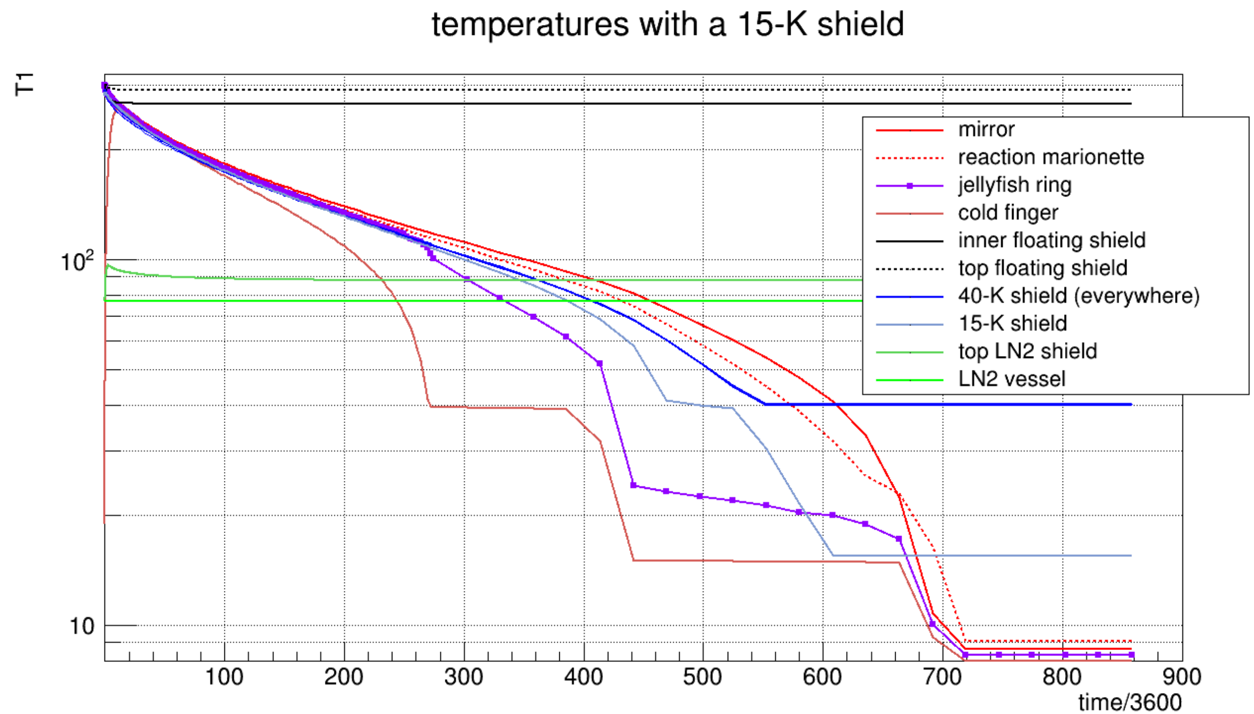
- The conductivity as a function of temperature is tabulated for the materials we use. Bodies can be labeled a heat sink (constant temperature, e.g. the LN2 vessel and the towers).

- Coupled equations are solved: the temperature and heat per body is calculated as a function of time. For the conductive flow, use

$$\frac{dQ_{12}}{dt} = \frac{A}{L}\int_{T_1}^{T_2} c(T)\,dT$$

To simulate a cryogenic arm, about 400 bodies were needed (mirror-symmetric system) and a 400x400 set of differentially coupled equations needed to be evolved in time.

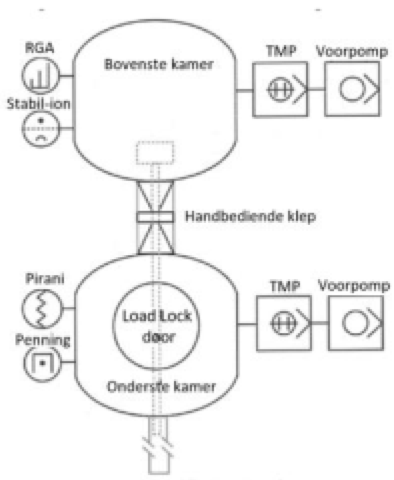
Stiff equations (derivatives that span 12 orders of magnitude) pose a numerically challenging task: 6th-order adaptive Runge-Kutta to integrate the coupled differential equations, smart grouping of bodies needed. Multi-threading. Tests with implicit differencing. The results below took 5 days on an iCore7 to compute.

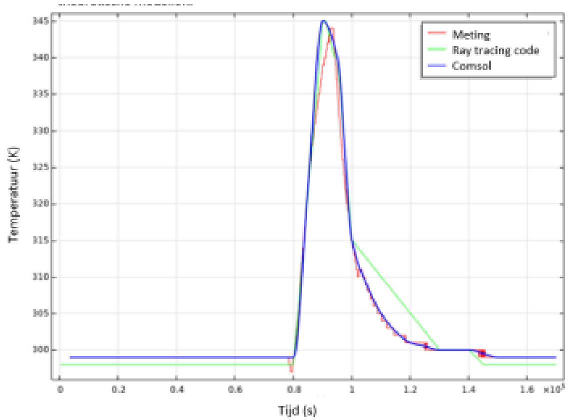


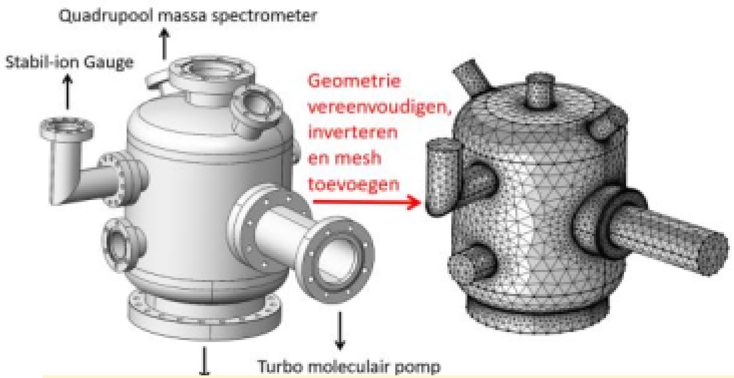
Example calculation of cool-down of the mirror with the use of a sorption cooler with 3 temperature plateaus,an adittional thermal screen at 15K, and a Helium loop system.

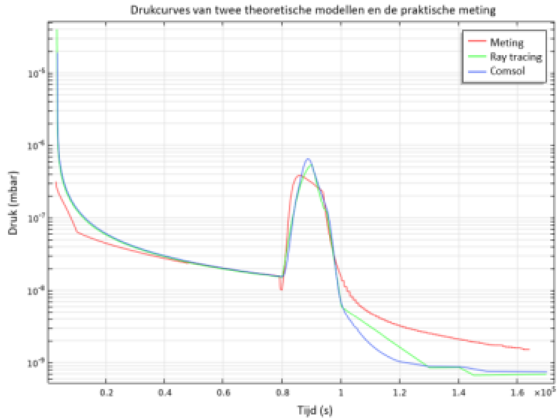
Vacuum simulations

- Coupled equations:
  - Impingement rate per surface. Particle flow between volumes. Surface-dependent adsorption and desorption.
- Initial tests: comparison for our outgas chamber with Molflow (CERN vacuum software) and COMSOL (molecular flow package) (minor thesis Vera Erends)
  - **Molflow**: the vacuum part is used as volume. Pumping speeds/impingement rates at different points in space can be calculated, effective pumping speeds for the full system can be obtained.
  - **Comsol**: we could program a time-dependent adsorption rate by tracking the outgassing history here and have an occupancy-dependent sticking probability. We subdivided the surface in small parts with different activation energies for water to simulate the Temkin isotherm.
  - **Our code**: the occupancy of the monolayer is tracked, and the hydrogen profile in the steel. Therefore we can simulate time-dependent and history-dependent adsorptions and desorptions, in contrast to Molflow and Comsol.
  - We can also easily introduce different models for e.g. surface coatings.









Verification of our code for a simple testcase with Comsol and Molflow;
Vera Erends, Nevac Nov. 2021 https://nevac.nl/archief_pdf/pdf_208.pdf
https://www.comsol.com/blogs/simulating-the-pressure-in-an-ultrahigh-vacuum-system/

Vacuum simulations: hydrogen outgassing

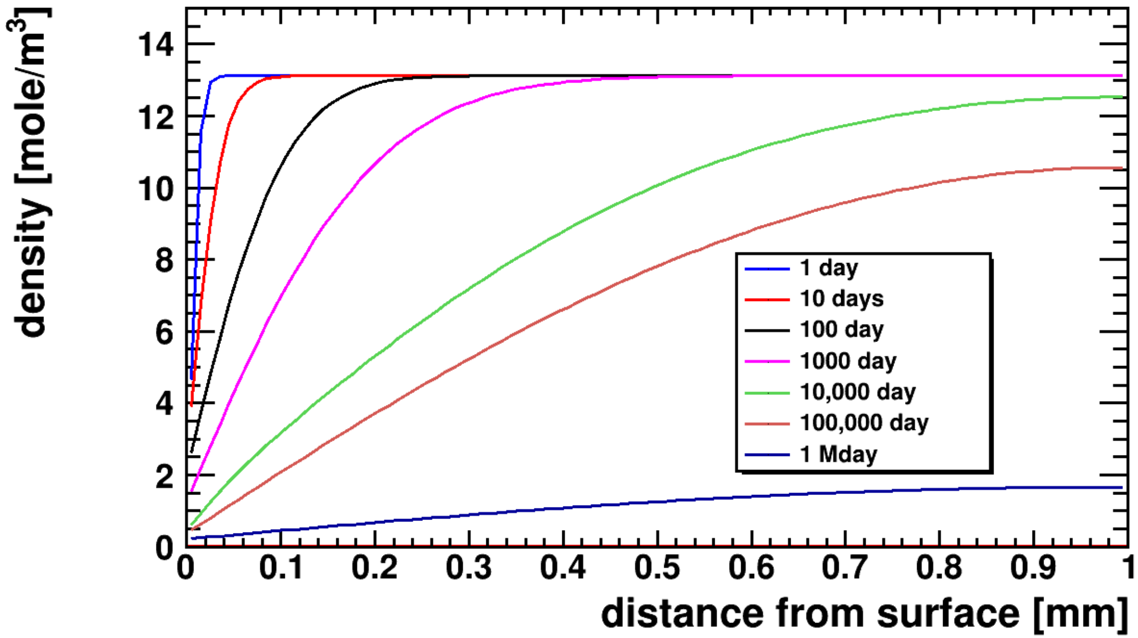
- Hydrogen: dissolved in the bulk of steel during production.
  - Mild steel (low Carbon) or ferritic steel (BCC roster) : relatively high diffusion speeds, low dissolved densities (~0.01 weight ppm)
  - Stainless (austenetic) steel: FCC roster. Low diffusion speed. SS304: concentrations of 1-2 ppm weight
  - Diffusion towards surface: Fick's Law (temperature-dependent, material dependent):

$$J = D \nabla \phi \ ; \ \frac{d\phi}{dt} = D(\nabla \cdot \nabla)\phi$$

  - At surface, you need to recombine two hydrogen atoms into a molecule to leave the surface.
  - Recombination-limited desorption: depends on surface properties and the hydrogen-density at the surface squared

$$J_{des} = K_{rec} \phi_{surf}^2$$

  - Outgassing of hydrogen: time-dependence driven by a combination of both. Diffusion process is very slow, a profile builds up over years.

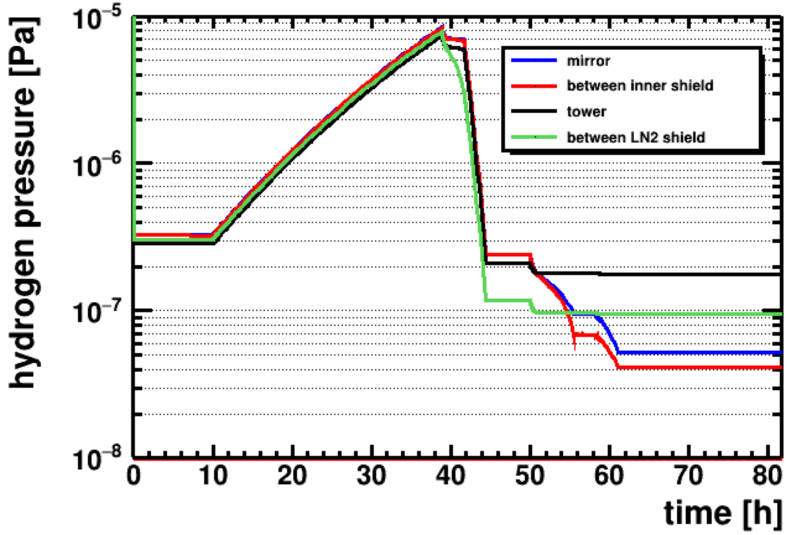


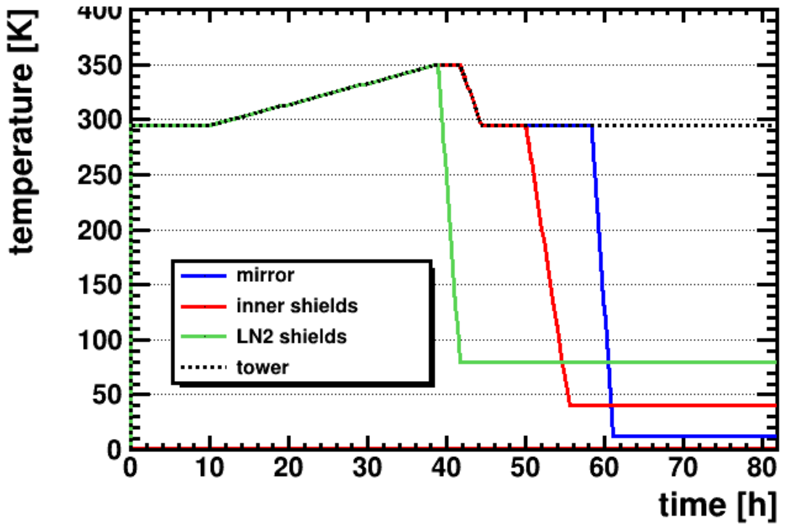
Hydrogen density profile in a 2-mm thick sheet of SS-304 as a function of time since production. Fick's laws for diffusion describe the transport of H to the surface, and the recombination cross section is used to calculate the outgas rate. Model, Diffusion coefficient, and recombination cross section from [Moore, Journal of Vacuum Science & Technology A 13, 545 (1995)]
Density assumed to be 1.64 ppm weight [Park, J. Vac. Sci. Technol. A 34, 021601 (2016)]

A very extensive study of outgassing rates, including traps and surface barriers, has been published by [Berg; Journal of Vacuum Science & Technology A 32, 031604 (2014)] Our model can accommodate his parameters.

Vacuum simulations: pumpdown, hydrogen

- Example: 1 ET pathfinder arm
  - In this example, all materials were analyzed with the properties of Stainless steel.
  - 1.64 ppm initial concentration, ½ year after production, no pre-baking
  - Water: Temkin isotherm, occupancy-dependent sticking. Water-on-Water binding energy 0.47eV (for ice build-up)
    - Refinements needed: Al should be used. Binding of water on Al is similar as on SS304, but much less H outgassing
  - Study: different surfaces at different temperatures.
    - Pressure depends on outgassing and pumpspeed.
    - Concentration at the surface and outgassing complicated history





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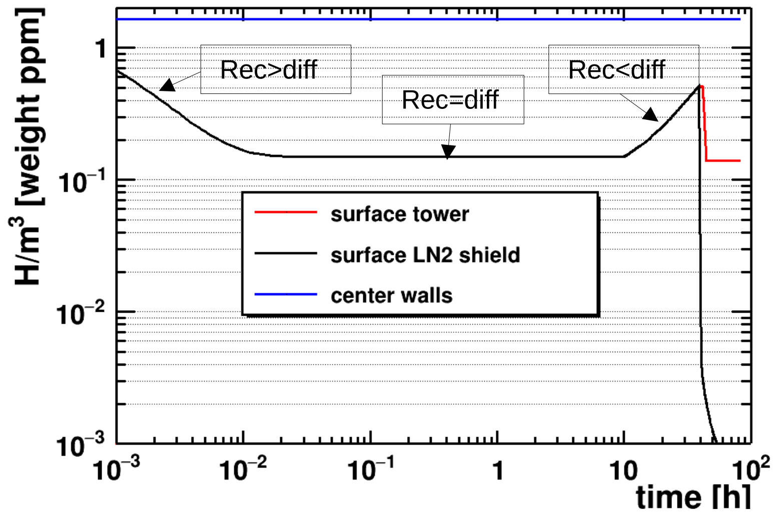
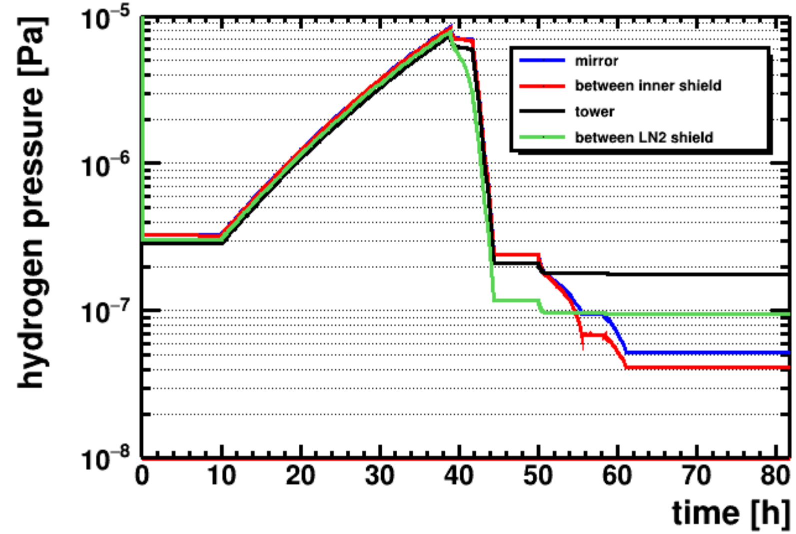
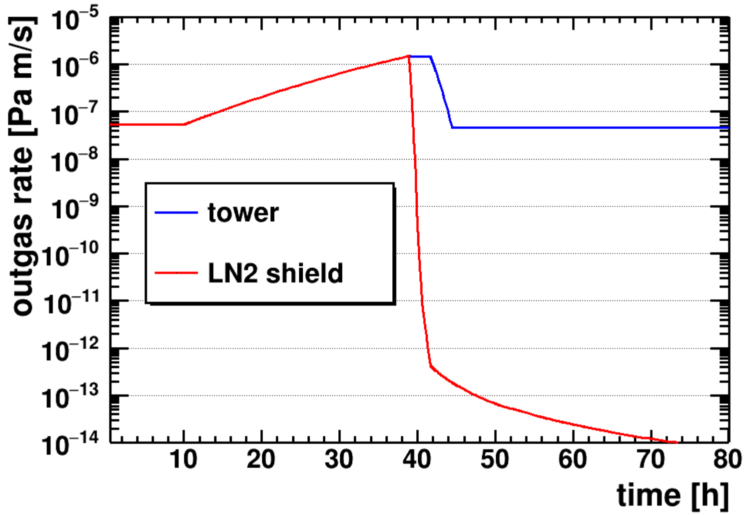
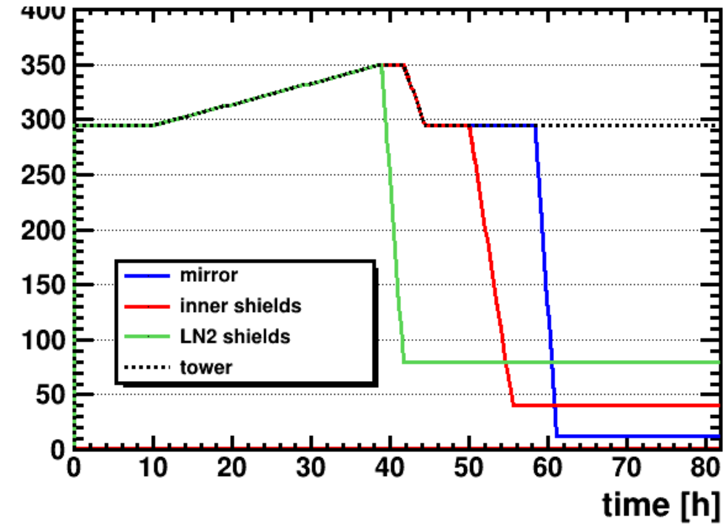
  - Refinements needed: Al should be used. Binding of water on Al i similar as on SS304, but much less H outgassing
  - Study: different surfaces at different temperatures.
    - Pressure depends on outgassing and pumpspeed
    - With cold shields, the local H2 pressure around the mirror is 5 times lower than in the tower.
  - Concentration at the surface and outgassing complicated history
  - Initial concentration decreases rapidly (1 minute) to establish equilibrium between equilibrium between recombination and diffusion processes.
  - At low temperatures, it takes a long time to reach this equilibrium.









Vacuum simulations: pumpdown, water

- Example: 1 ET pathfinder arm
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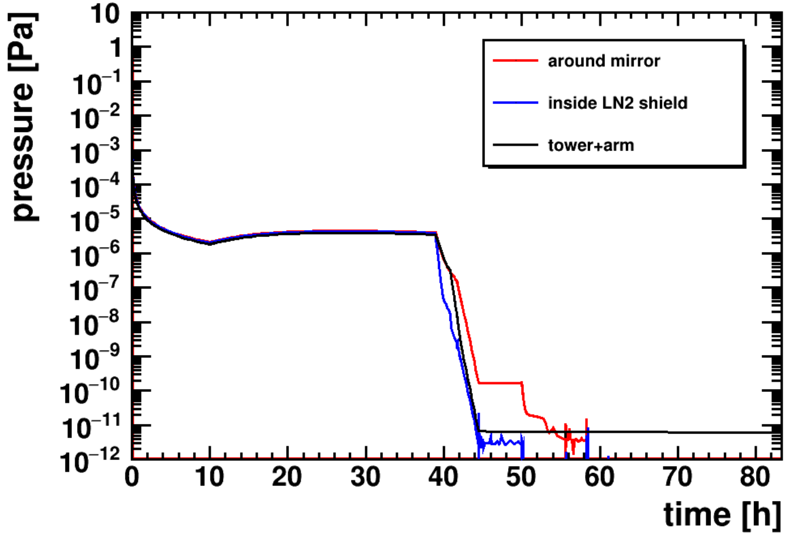
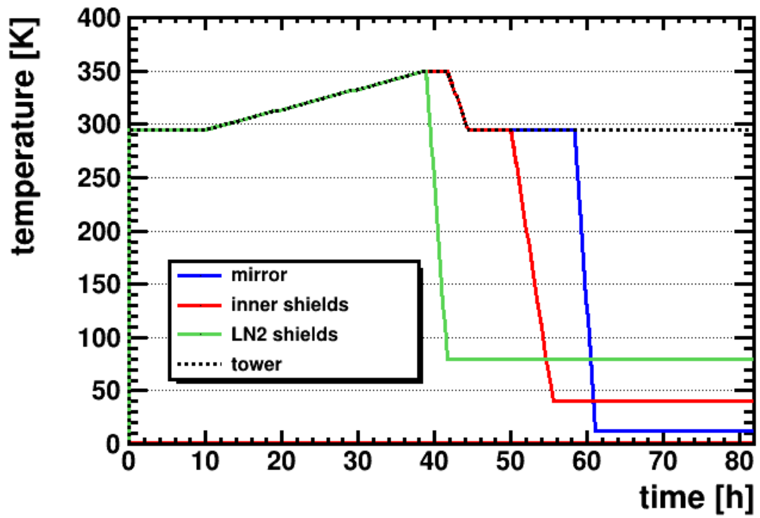
  - Start: 10Pa water vapor, full monolayers, 10-6 mbarl/s outgassing from kapton cables.
  - Adsorption: depending on monolayer occupancy and gas impingement rate.
    - All walls act as a pump, water will stick a long time
  - Desorption: Temkin isotherm.
    - SS-304 parameters used – literature outgassing is reproduced.
  - Adsorption and Desorption in equilibrium – when you stop pumping the water pressure does not increase notably.
    - Numerical inaccuracies around 10^-12 Pa: at that pressure, the adsorption constant is enormous and any H2O entering from outside is adsorbed within 1 bounce → this leads to undershoots of the pressure in nanoseconds
    - This leads to the fluctuatuions below 10-11 Pa for the small volumes (between the shields) – in this code anything below 10-8 Pa is considered negligible and small terms like recombination of H and O to H2O is not modeled accurately – work in progress





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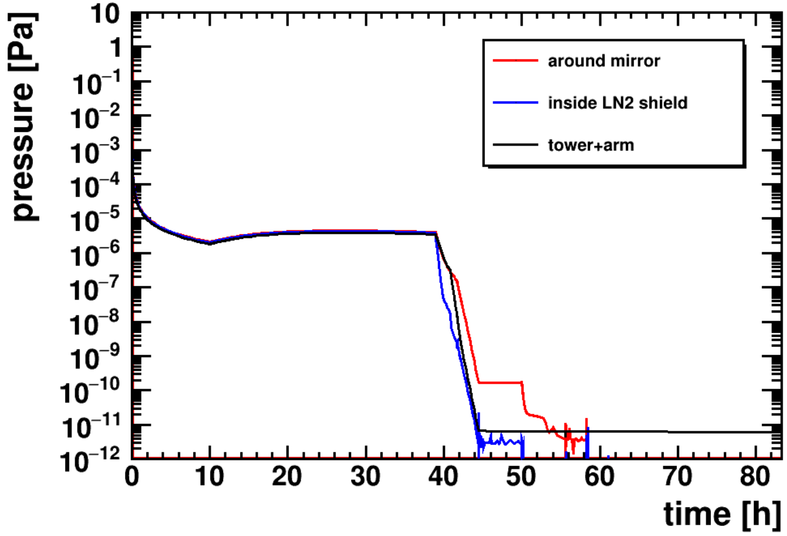
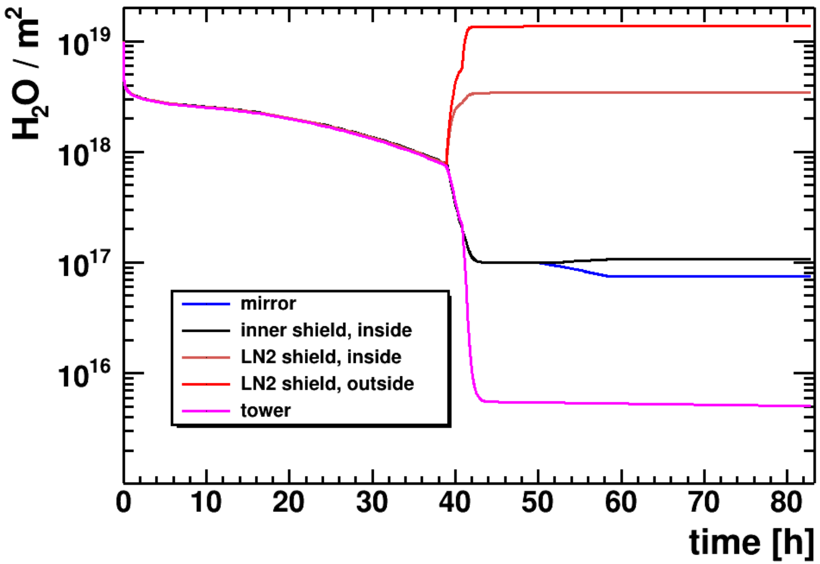
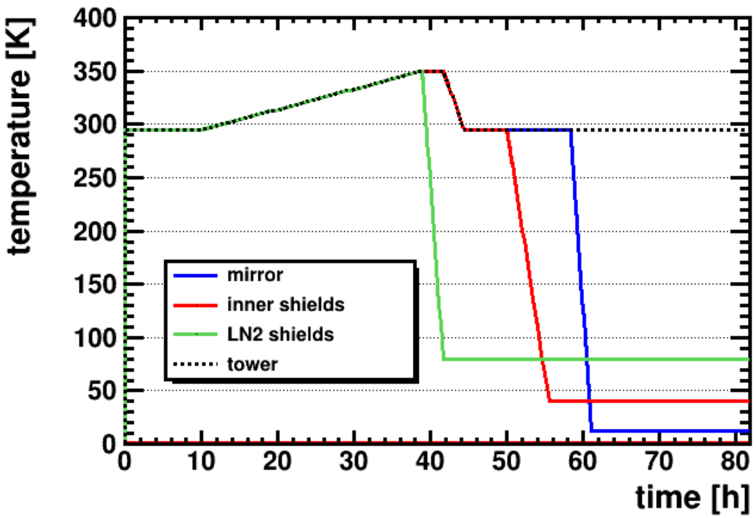
  - Desorption: Temkin isotherm.
    - SS-304 parameters used – literature outgassing is reproduced.
  - Adsorption and Desorption in equilibrium – when you stop pumping the water pressure does not increase notably.
  - Occupancy: outside LN2 shield collects water from tower walls (quickly), inside LN2 shield from mirrors – slowly due to lower conductance through inner shield







Summary

- ETpathfinder: a research facility for cryogenic GW interferometry
  - Rich research program for Silicon at 123K (Cosmic Explorer) and ~10K (ET)
  - Cryogenic handling, vacuum and cryogenic noise, interferometry at Si wavelengths (1550, 2050 micrometer)
  - Large towers and beam pipe – suitable for testing large-scale optics and devices
- Design and Construction: based on cryogenic and vacuum modeling
  - Code that can simulate in great detail heat flows, thermal loads, cool-down curves
  - Code that can simulate in great detail pressure, vacuum conductances, water migration, ice build-up, Brownian noise, residual gas noise
    - Different and time-dependent surface materials/temperatures/properties, tracking of all the gas (dissolved and adsorbed) in the system
  - Relevant for ET design as well
    - Ballistic flow, water desorption from thermal shields, enhancement of Brownian noise for realistic geometries, gas noise and pressures for different types of steel/Al for the beam pipe, water migration and ice buiild-up, etc.
- Sub-cooled liquid Nitrogen
  - We believe that sub-cooled LN2 should be used for outer thermal shields – we think the vibrational noise based on this system is far superior to any alternative
    - This will be extensively tested in our research. Acoustic noise in gas return lines, vibrations in inlet and vessel, ice build-up, water desorption from LN2 shields, emissivity as a function of ice layer, etc
- Currently under construction
  - Vacuum system being installed; LN2 system is being built, Mirrors, electronics, optics, DAQ, ordered and delivered this year
- Open to collaboration – if you want to develop a relevant technique, improve our set-up and test it for future interferometers - lets discuss!
  - Especially if you are interested in developing a monolithic suspension for cryogenic Si mirrors!