# Trillingsvrij koelen
# Einstein Telescope/ET pathfinder

(Nikhef en TU Twente)

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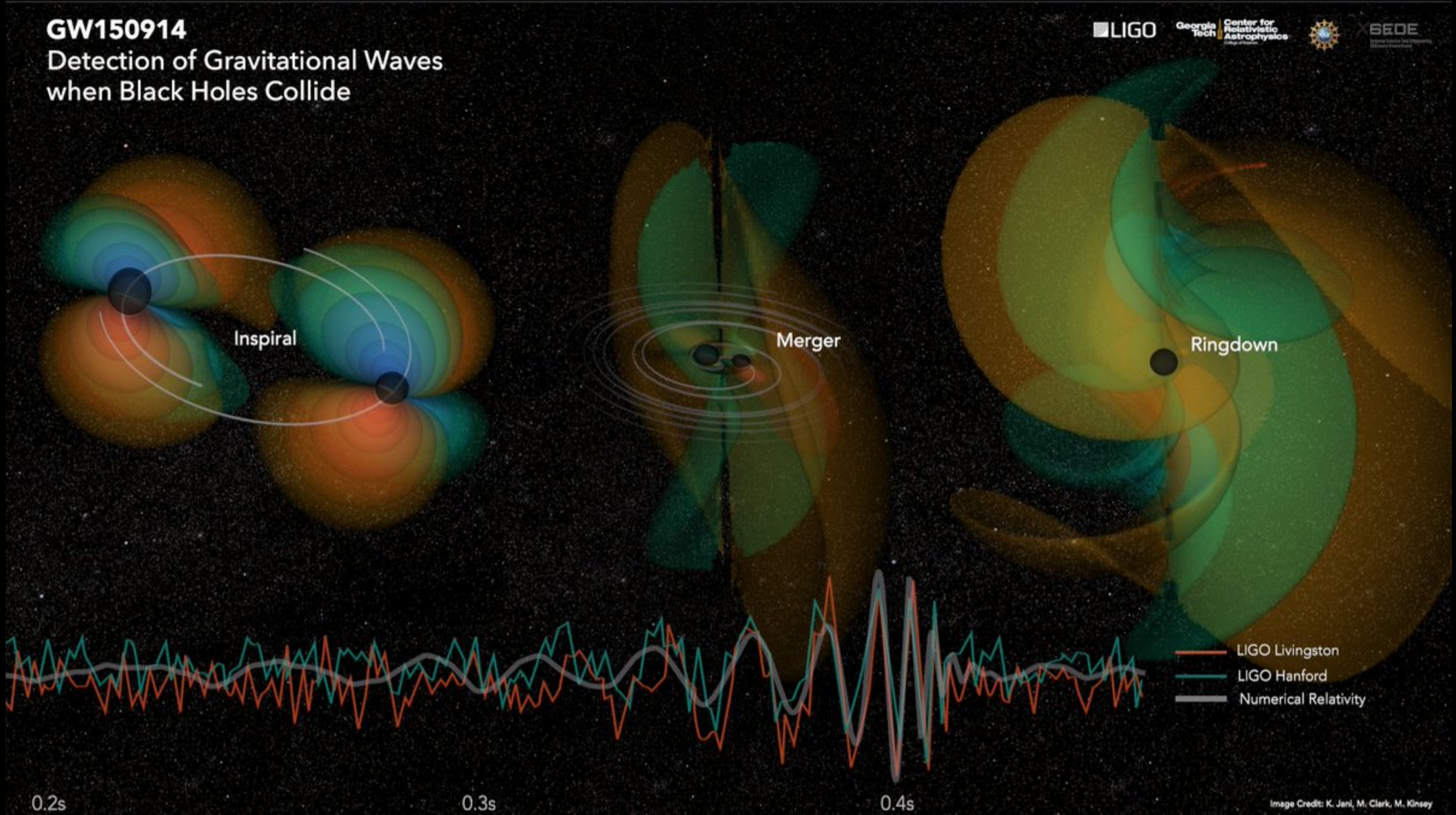
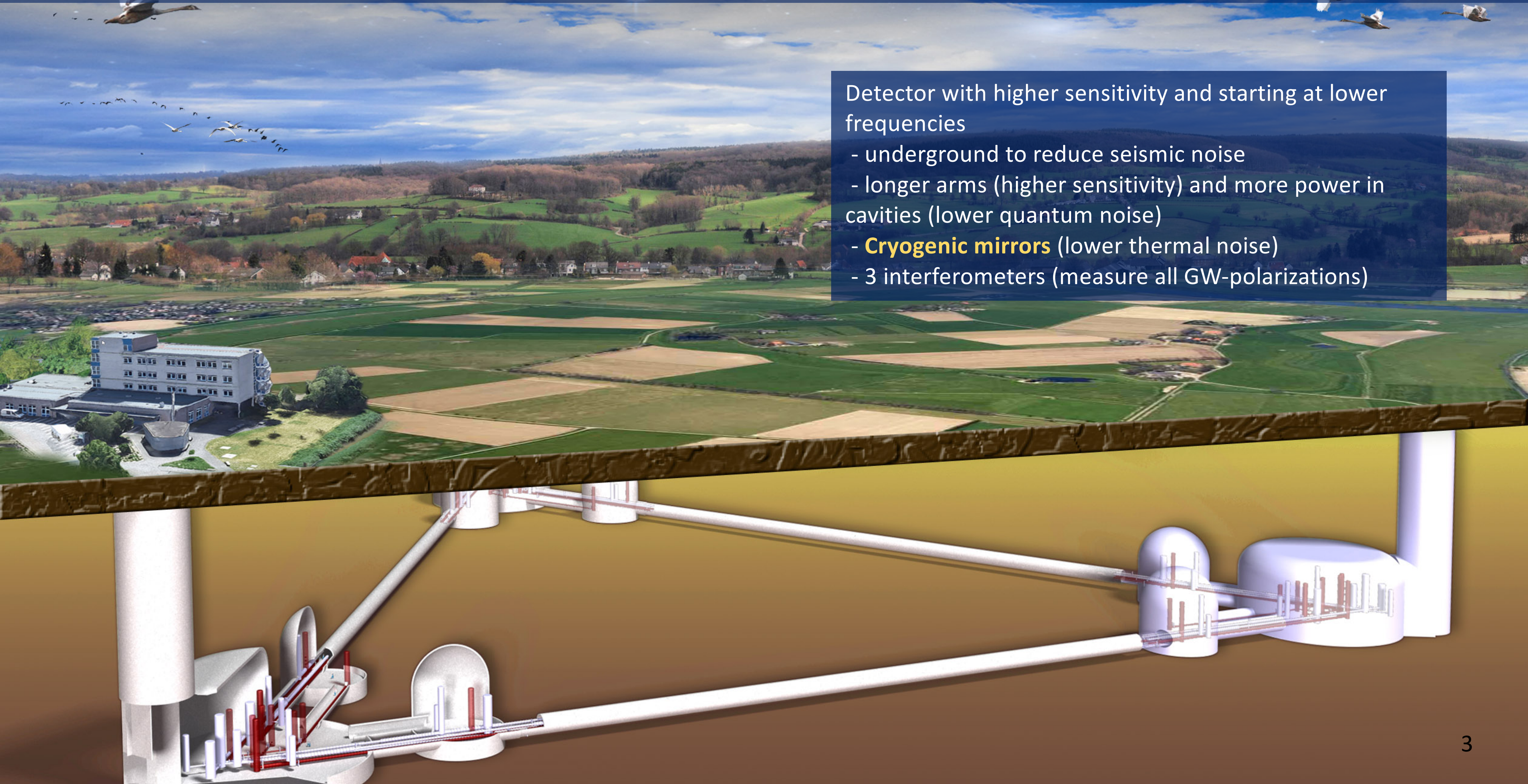
*Cryogenic Challenges worksop, Microcentrum Veldhoven (15-05-2019)*

# Gravitational wave interferometry

Dynamical structure of space-time. A new window to the universe. Tiny chages in distance, O($10^{-22}$)



# Einstein telescope, next generation detector

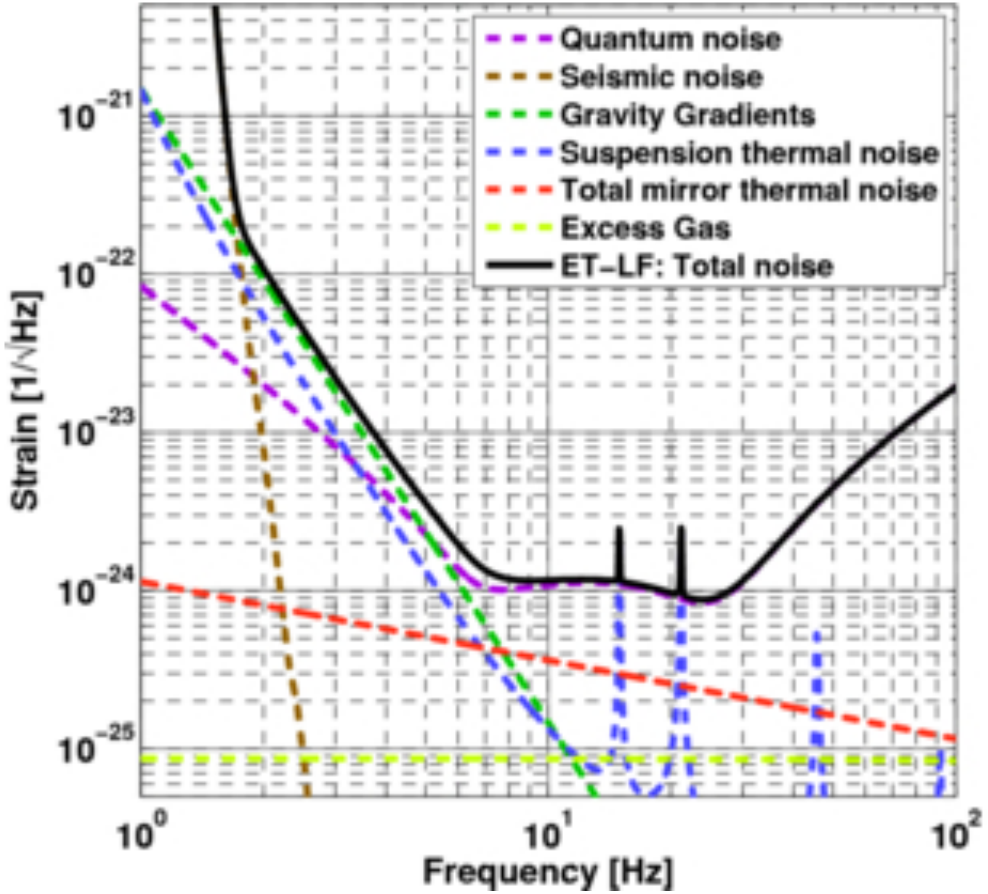


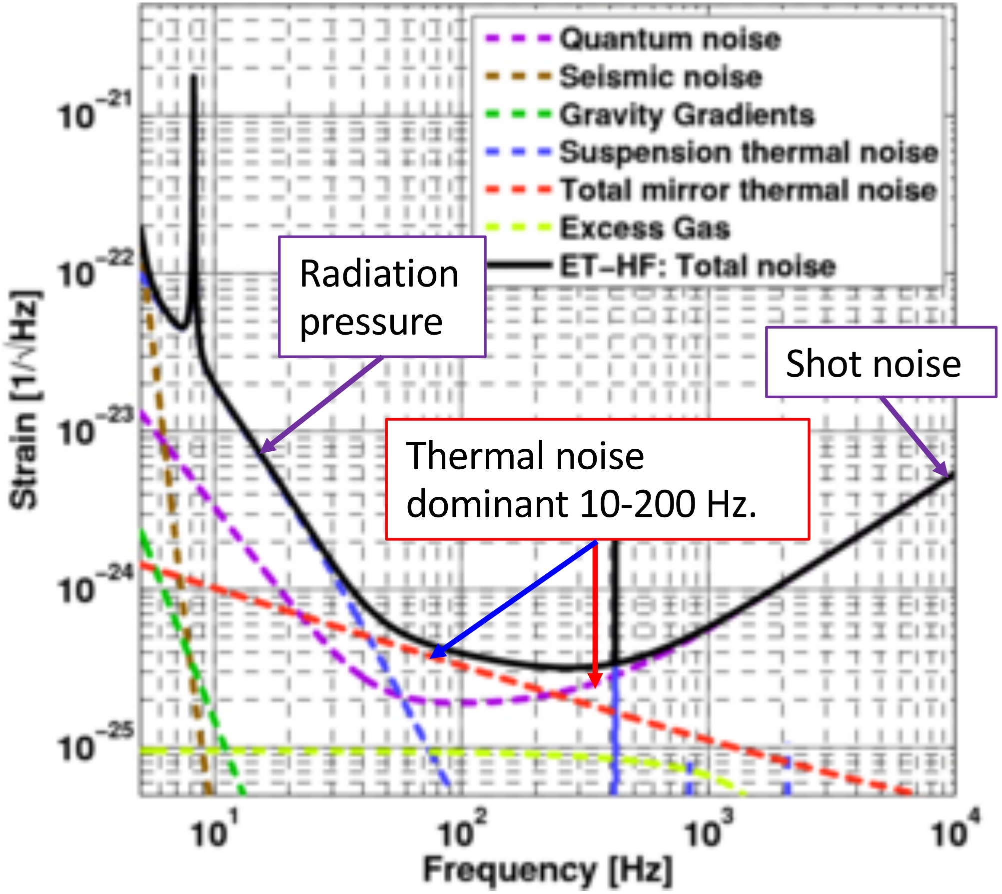
Detector with higher sensitivity and starting at lower frequencies

- underground to reduce seismic noise
- longer arms (higher sensitivity) and more power in cavities (lower quantum noise)
- **Cryogenic mirrors** (lower thermal noise)
- 3 interferometers (measure all GW-polarizations)

# Einstein telescope noise limits

Thermal noise limits the sensitivity in mid-frequency range.





Radiation pressure

Shot noise

Thermal noise dominant 10-200 Hz.

Low frequencies:

Quantum noise: heavy mirrors, 18 kW beam power, squeezing.

Seismic noise: underground. Thermal noise: cryogenic.

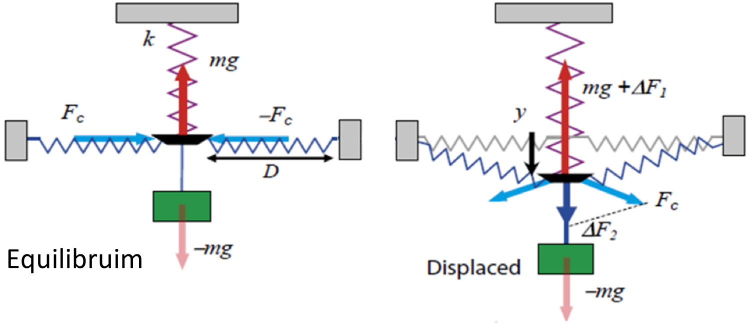
High-frequencies:

shot noise limited. Room temperature, 3 MW beam power in arms.

# Cryogenic Mirrors: suspension

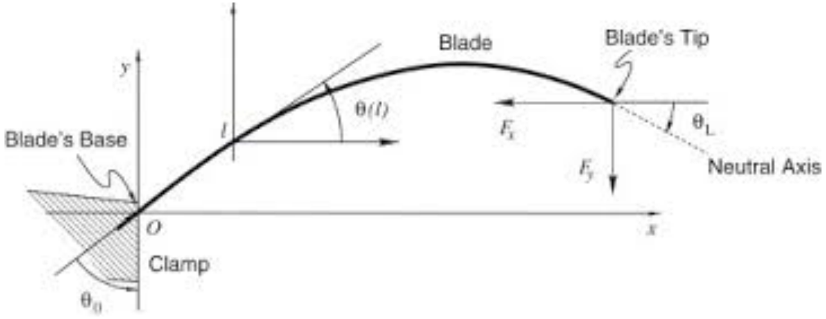
## Mirror surface should be defined to < $10^{-20}$ m/sqrt(Hz)

- Horizontal isolation: (inverted) pendula. Vertical isolation: geometric anti-springs. Horizontal compression leads to negative spring constant.

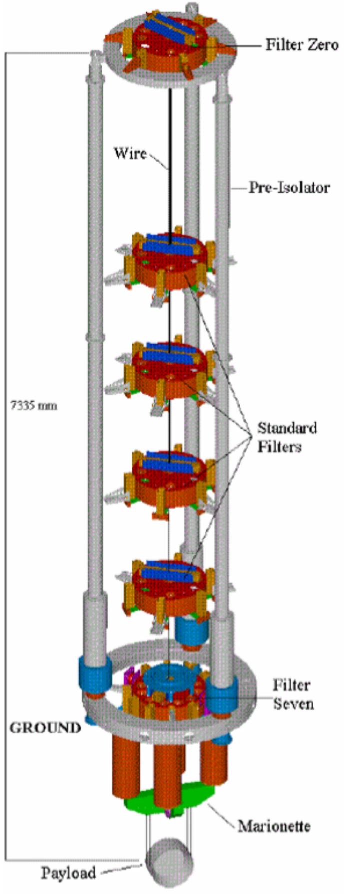


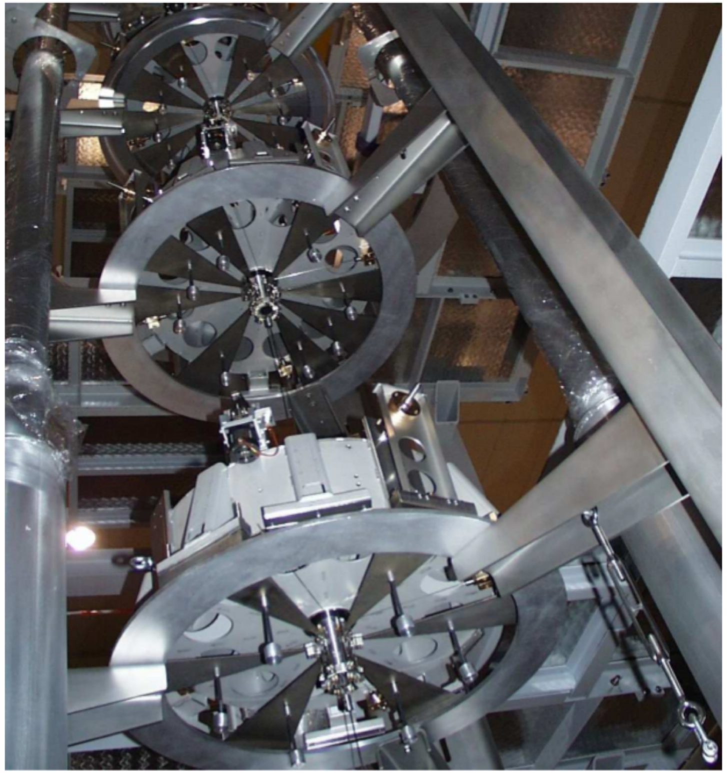
Equilibruim

Displaced



- Geometric Anti-Spring (GAS) filter stages need to stay at room temperature!
- Eliminate external forces on mirror – vacuum better than $10^{-10}$ mbar, low acoustic noise in surroundings, jellyfish connections of wires for actuators and cooling.

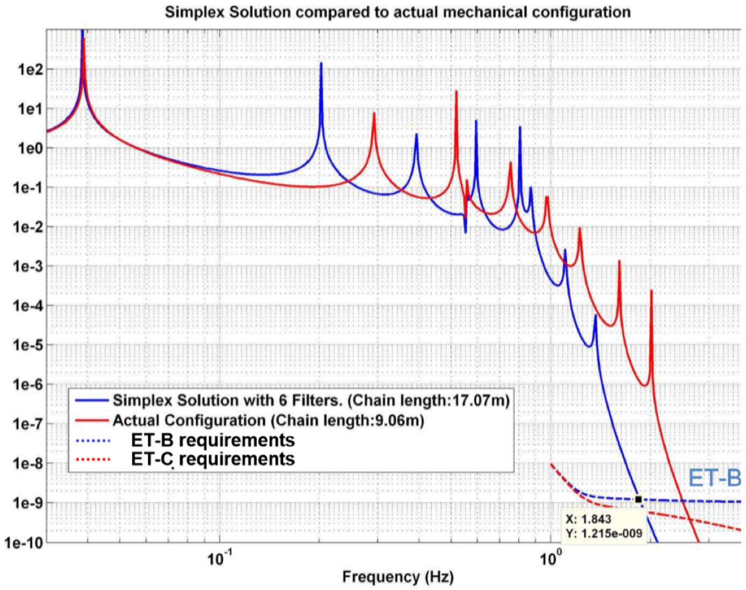




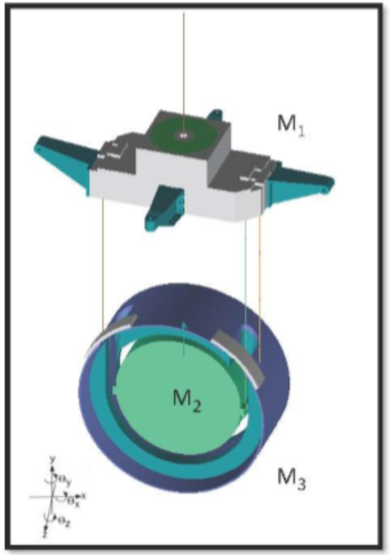
The Virgo super-attenuator suspension. Pendula for horizontal/angular d.o.f. and GAS filters for vertical isolation.

# Einstein telescope mirror suspension

Suspension chain of 17 m limits seismic noise above 2 Hz. Thermal noise is critical in last elements of the chain.

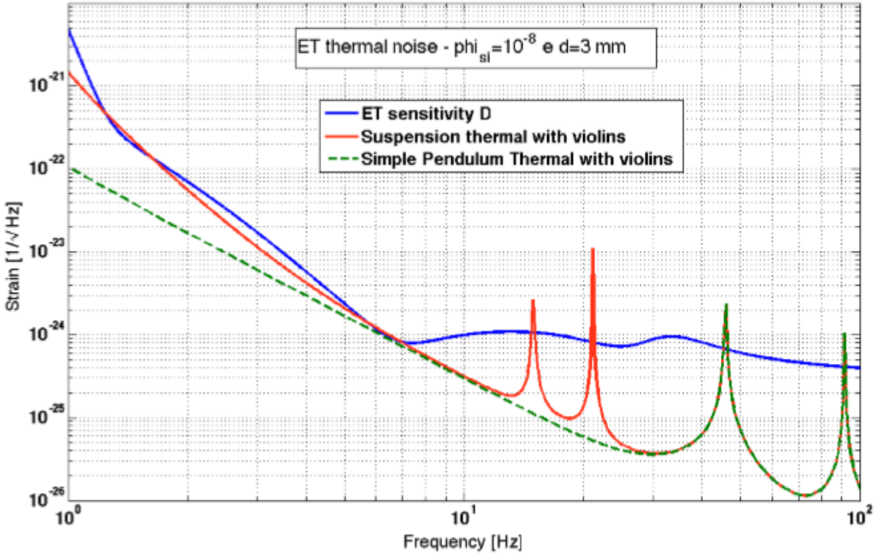


Transfer function of the proposed super attenuator chain for ET (ET design report 2011), a 17-m long chain. Red shows the performance of the current Virgo SA (9 m chain).
Seismic motion is reduced with 9 orders of magnitude above 2 Hz.



Last stage suspension:

422 kg Marionette with 211 kg Silicon mirror (M2) and 211 kg reaction mass (M3). Monolithic suspension (crystalline Si) wires/bondings are required to obtain small loss factors.

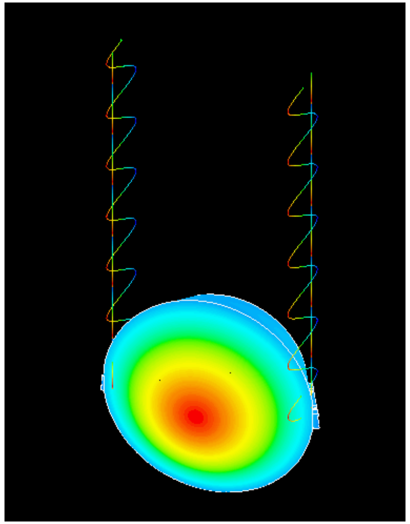


Thermal noise of the suspension calculated for ET, assuming monolithic suspension (Si with loss factor $10^{-8}$, marionette from TiAlV alloy ($10^{-5}$), mirror at 10 K and marionette at 2K, 2 m wires 3mm diameter, ET design report)

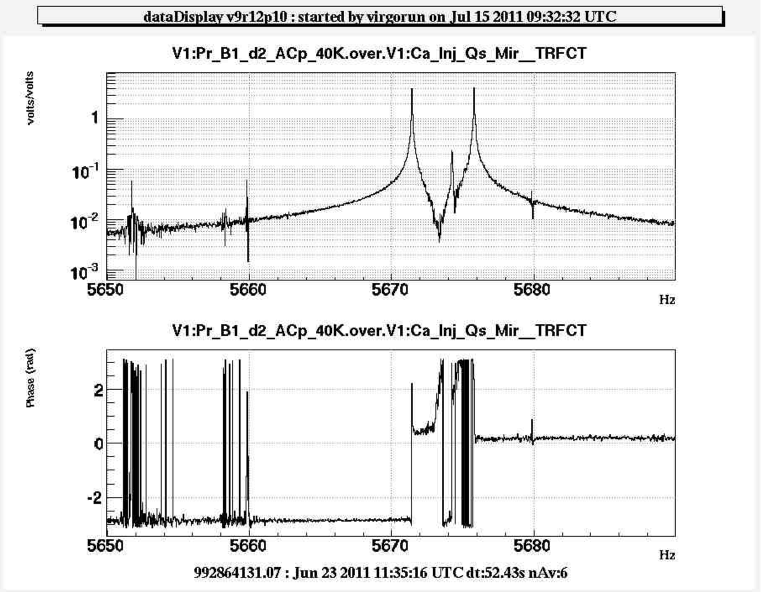
# Thermal noise contributions

## Noise coatings is dominant (1/f)

- Thermal noise in the cryogenic interferometers limit the performance in several ways:
  - Bulk mass mirror, Brownian and thermo-elastic. Fluctuation-dissipation theorem couples the induced movement of the test mass by Brownian noise to the quality factor of the dissipation. Silicon has a very high quality factor exceeding $10^8$
  - Suspension
    - Above the frequencies of interest, the suspensions filter seismic motion to below detection limit. The noise of the last stage is the dominant one; this is the noise in the wires between marionette and reaction mass/mirror. Using monolithic suspensions (pure Si wires), bonded to the mirror, the quality factor can be chosen such that also this noise is concentrated in sharp lines
  - Mirror coating
    - To obtain high enough reflectivity and small absorption, mirror coatings need to be applied (also with sub-nanometer thickness fluctuations: atomically flat!) The thermal noise in these coatings is the dominant thermal noise source, since a) there will be some laser light absorbed in the coating (< 1ppm), heating it and b) quality factor of the coating, with alternate layers of different materials with different breaking indices is limiting (currently $\phi \sim 10^{-4}$ for the layers)

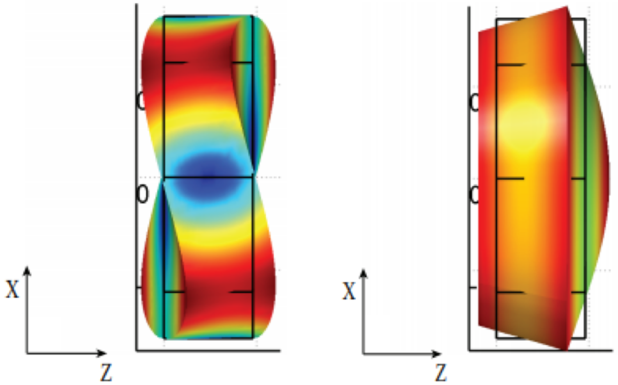


Drum mode mirror and 13th violin mode wires, low Q



dataDisplay v9r12p10 : started by virgorun on Jul 15 2011 09:32:32 UTC

992864131.07 : Jun 23 2011 11:35:16 UTC dt:52.43s nAv:6

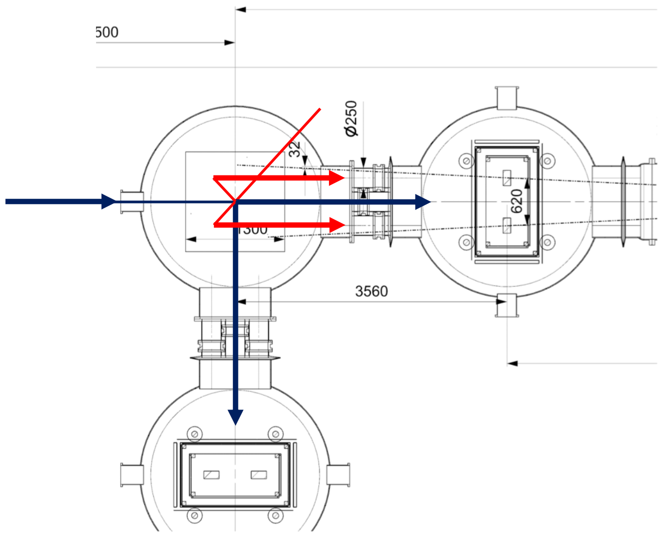


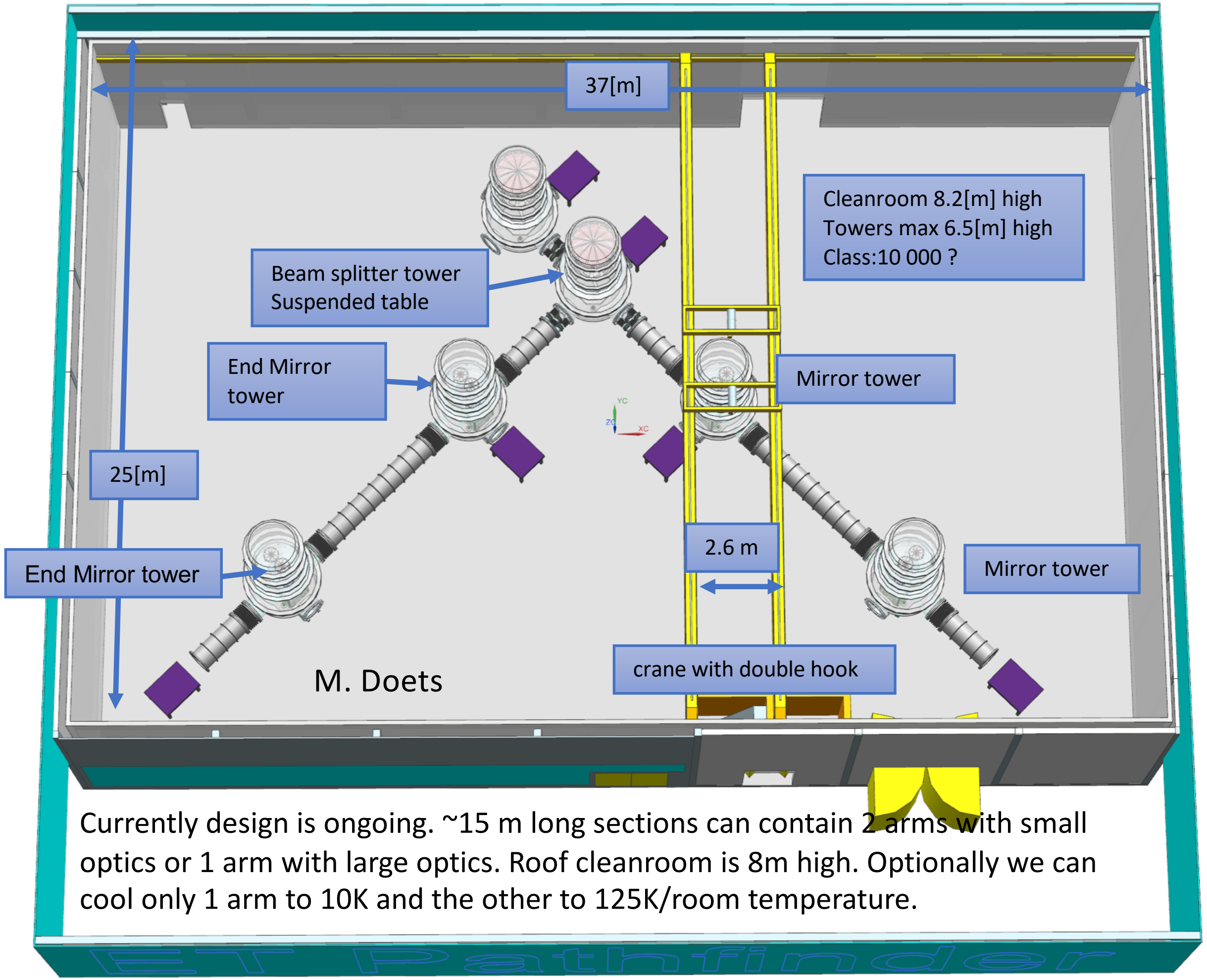
Bulk modes mirror disappear for Si at 123K, 10K

# ET pathfinder

## ETpathfinder facility (Limburg) to study cryogenic optics, under design

- Cryogenic option for ET: silicon mirrors at 1.550 micrometer
    - Optical properties of Silicon at cryogenic temperatures
    - Development of optical coatings need study
    - Thermal lensing: depends on thermal properties of the coating.
    - Cryogenic operation needs to be explored.
    - Monolithic suspension.
- Test facility in Limburg, under design

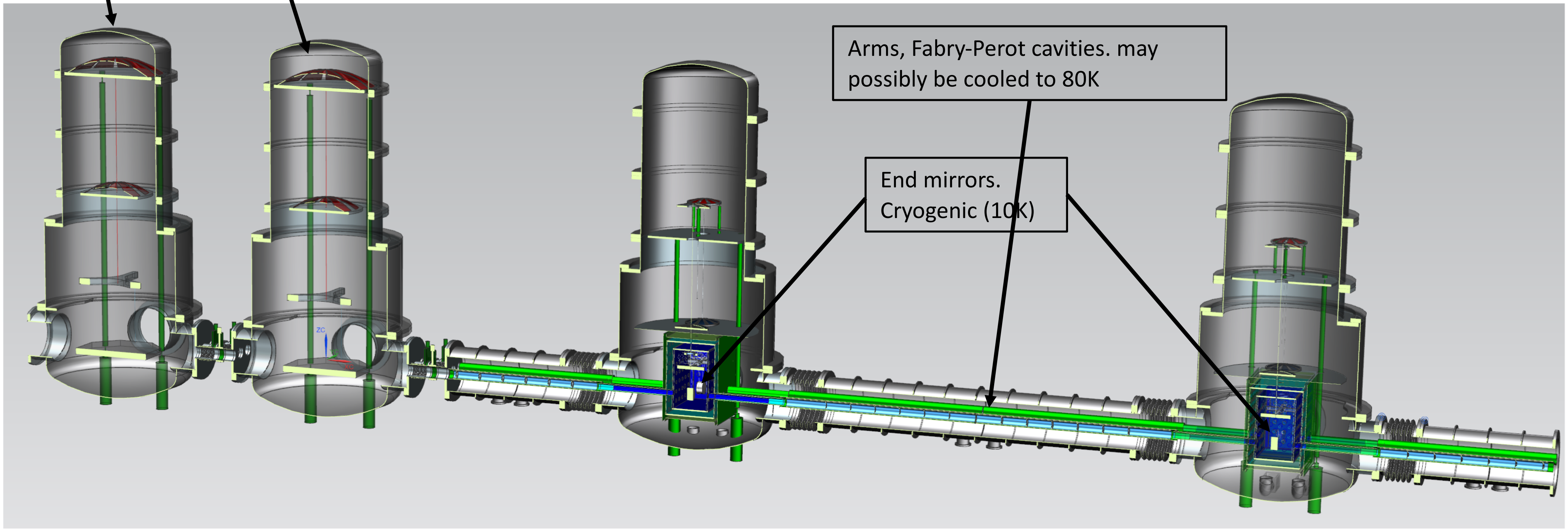




Currently design is ongoing. ~15 m long sections can contain 2 arms with small optics or 1 arm with large optics. Roof cleanroom is 8m high. Optionally we can cool only 1 arm to 10K and the other to 125K/room temperature.

# ET (pathfinder) cryogenic challenges

1) Cool mirrors in the Fabry-Perot arms to about 10 K
    1) Without introducing vibrations (< $10^{-18}$ m/sqrt(Hz)
    2) Without freezing water on the monolithic suspension and mirror surface
    3) With thermal shields with openings for laser beam and optical levers
    4) Without use of MLI superinsulation in the primary vacuum (CH partial pressure should be minimal)
2) Maintain good vacuum in arm (ET: < $10^{-11}$ mbar) (cryolinks needed)
3) Be able to operate at room temperature and at cryogenic temperature (displacement control)
4) Control temperature-dependent changes in optical path length



Injection tower/laser bench. warm

Beam splitter tower, warm

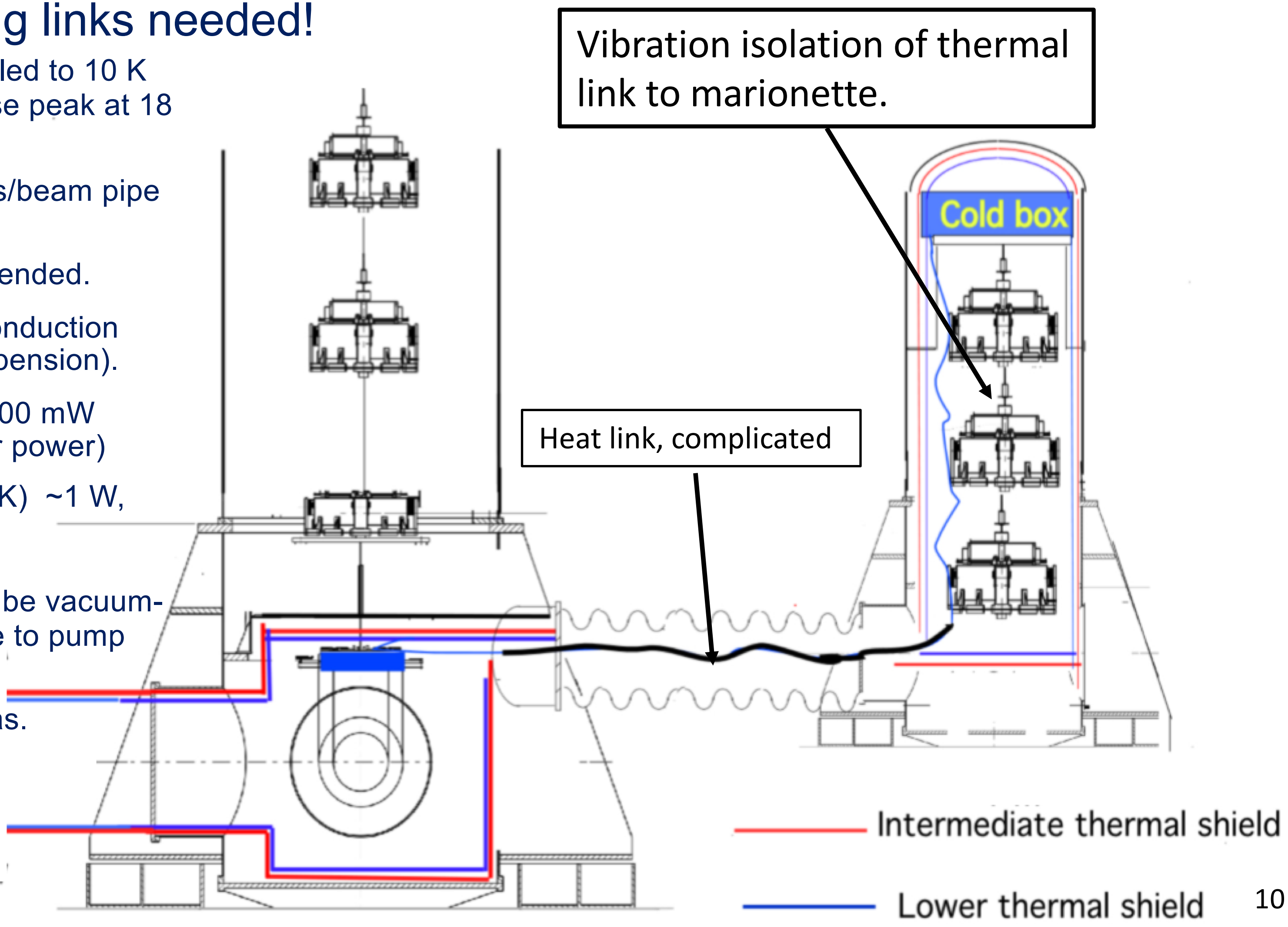
Arms, Fabry-Perot cavities. may possibly be cooled to 80K

End mirrors. Cryogenic (10K)

# ET cooling (conceptual design 2011)

## Vibration-free cooling links needed!

- End mirrors need to be cooled to 10 K (mirror coating thermal noise peak at 18 K)
- Separate cooling for shields/beam pipe and marionette
- Marionette cold link is suspended.
- Mirror cooled to 10 K via conduction (monolithic silicon wire suspension).
- Mirror heat input load ~ <100 mW (thermal radiation and laser power)
- Thermal load cold shield (4K) ~1 W,
- Intermediate shield ~ 50W
- Cold shield (blue) needs to be vacuum-tight and need conductance to pump before cooling.
- Initial cooling via contact gas.



Vibration isolation of thermal link to marionette.

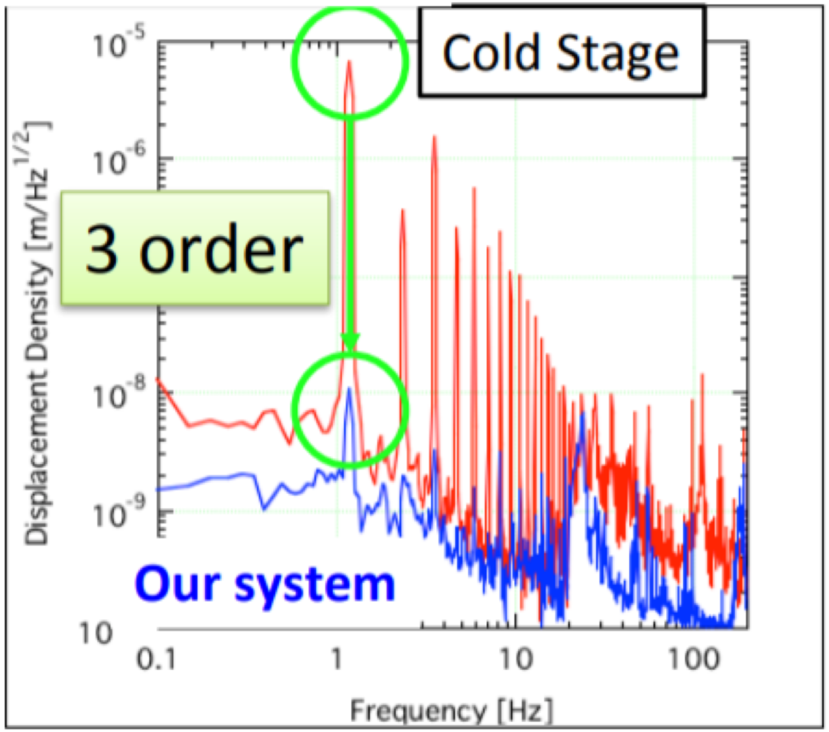
Heat link, complicated

# Pulse-tube cooler (Kagra)

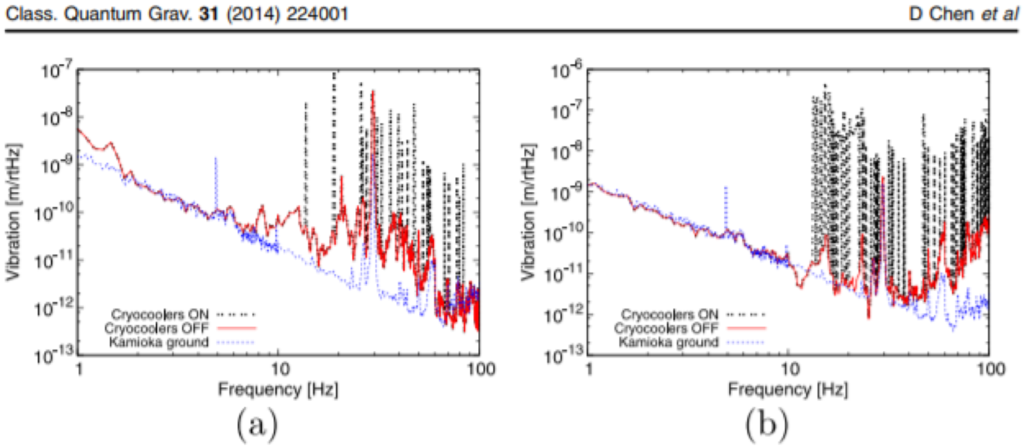
Gas injection at JT restriction of a pulse-tube cooler lead to vibrations

**Commercial**

**Pulse-Tube Cryocooler**



From Ushiba(KAGRA), GW workshop Taiwan(2015)


Class. Quantum Grav. **31** (2014) 224001 D Chen *et al*

Kagra, CQG 31.
Projected vibrations due to pulsetube cooler
KAGRA (red: off, black: on)

Pulse-tube cryocooler: typically pressure spikes (5-10 bar difference, repetition rate ~1.5Hz)

Liquid He: complicated and vibrations from boiling

# Sorption cooling (see presentation ter Brake)

Collaboration with EMS-Twente (group ter Brake) to develop a *sorption-cooling* strategy for ET

- Sorption cooling: pressure ripple several orders of magnitude below that of a pulse-tube cooler. Accelerations due to gas in feedline are at least 10,000 times smaller!

Sorption cooling also gives excellent temperature control!

Y. Wu et al. / Cryogenics 84 (2017) 37–52

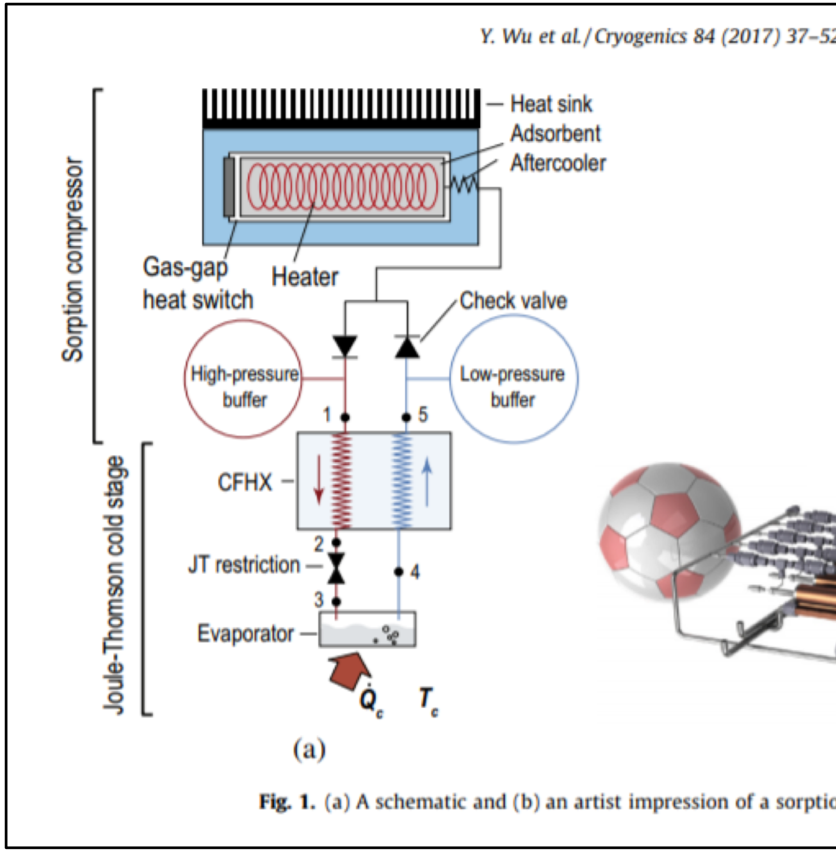


Fig. 1. (a) A schematic and (b) an artist impression of a sorption Joule-Thomson cooler.

Y. Wu et al. / Cryogenics 84 (2017) 37–52

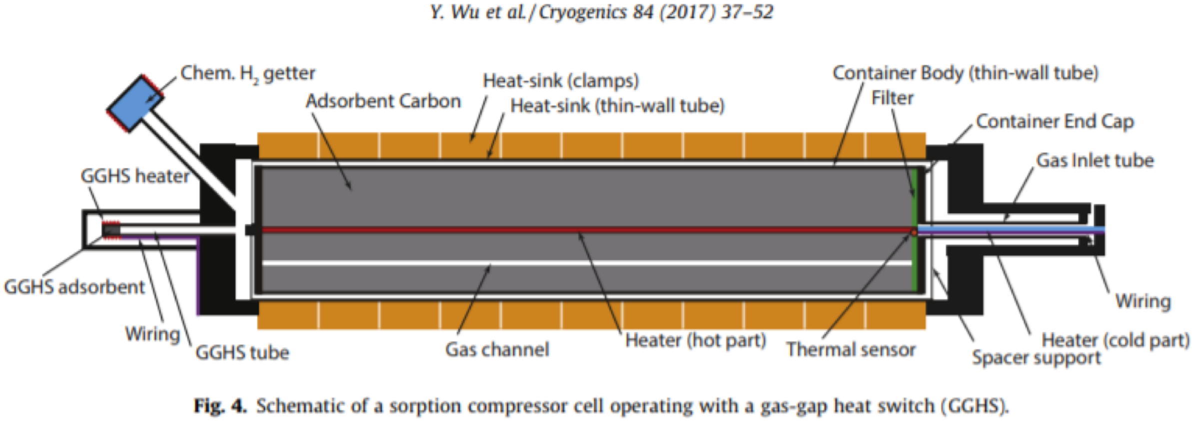
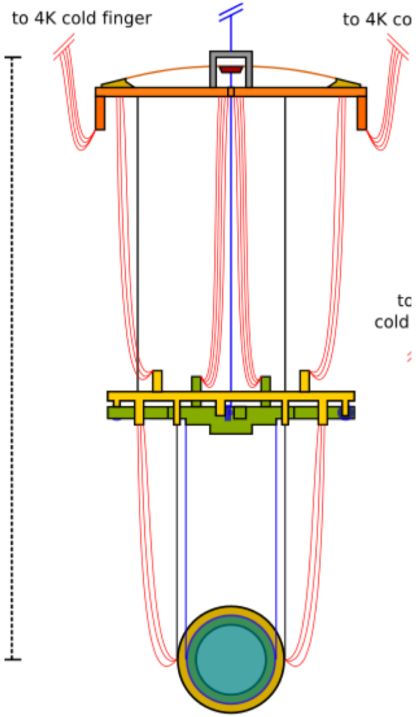


Fig. 4. Schematic of a sorption compressor cell operating with a gas-gap heat switch (GGHS).

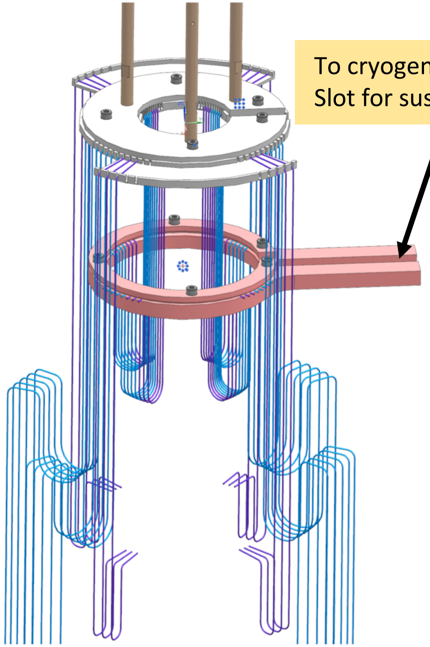
Technique developed in Twente and demonstrated in the METIS instrument of the ELT telescope.
Wu et al., Physics Procedia 67 ( 2015 ) 411 – 416, Cryogenics 84 (2017)
Tzabar & ter Brake, Adsorption 24 (2018) p325-332

# Link between cryogenic coldhead and mirror suspension

- Jellyfish connections: introduce minimal vibrations
- Ultrapure Al : up to 15000 W/m/K at 10 K
- Monolithic silicon: flexible, up to 20000 W/m/K

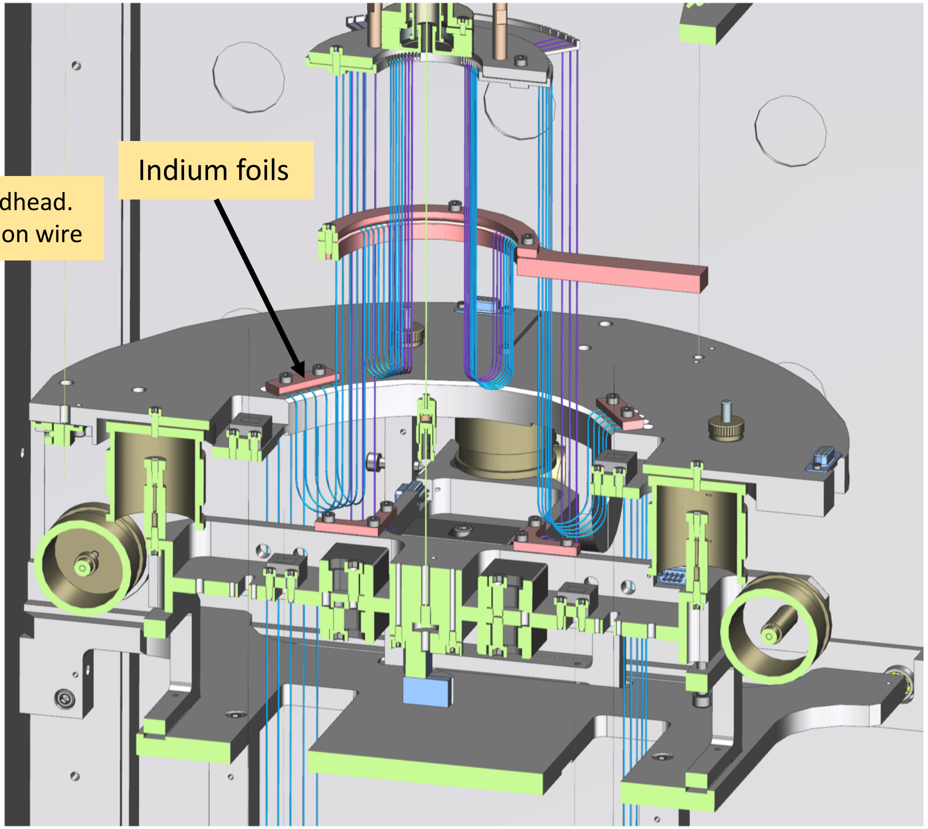


low vibrations cold finger case



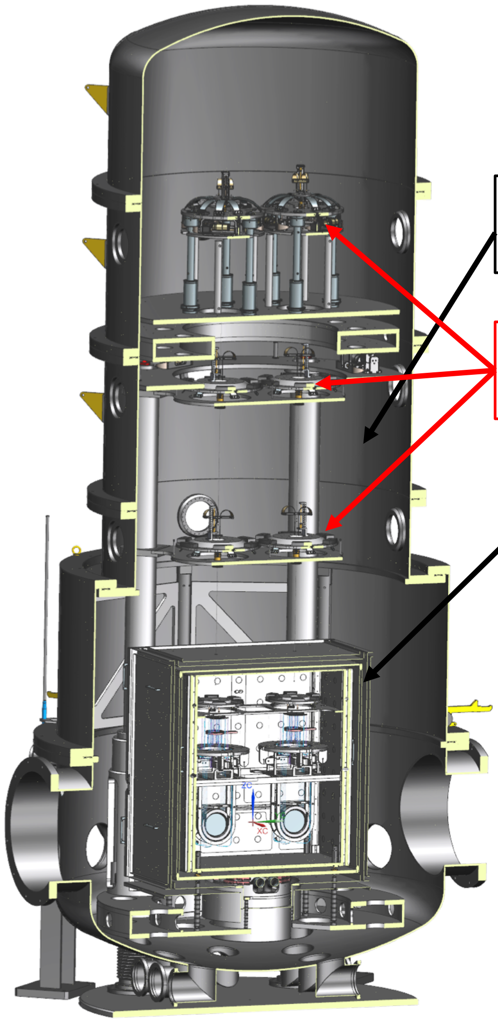
To cryogenic coldhead. Slot for suspension wire

Purple wires to marionette, blue to reaction chain



Indium foils

# End mirror towers



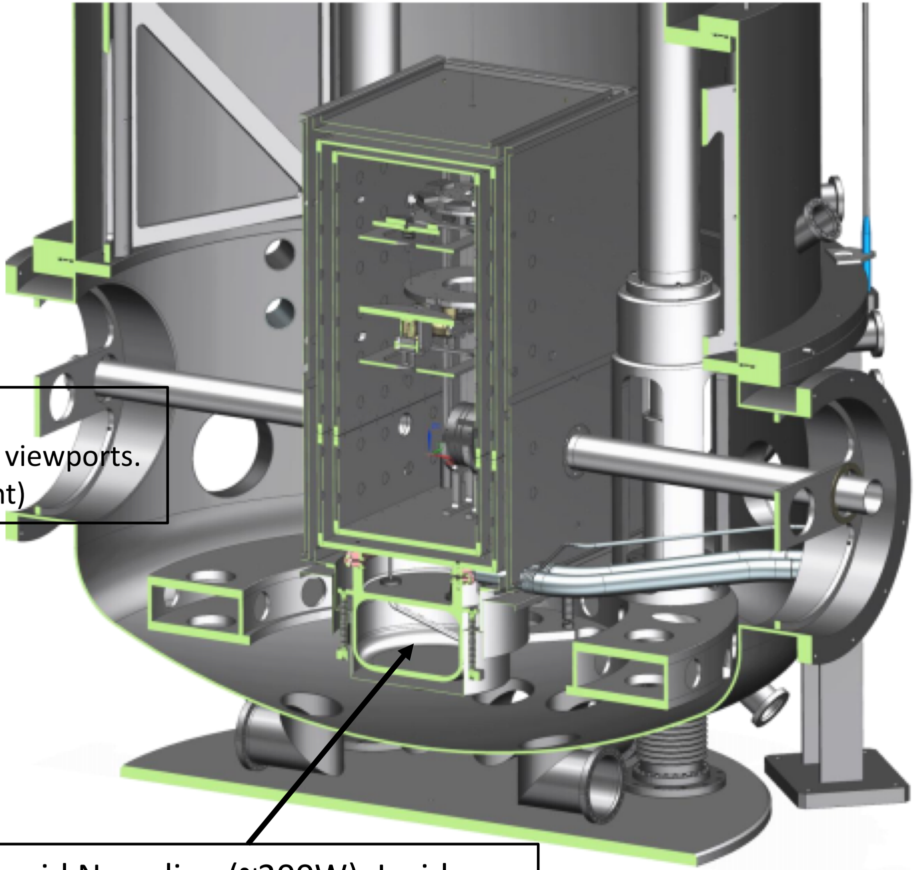
Start configuration:
2 FB cavities in 1 arm.

Primary vacuum: < $10^{-8}$ mbar required

suspension filters: constant temperature!

Thermal shields
Double-walled with holes for pumping and viewports.
Should not vibrate too much (scattered light)

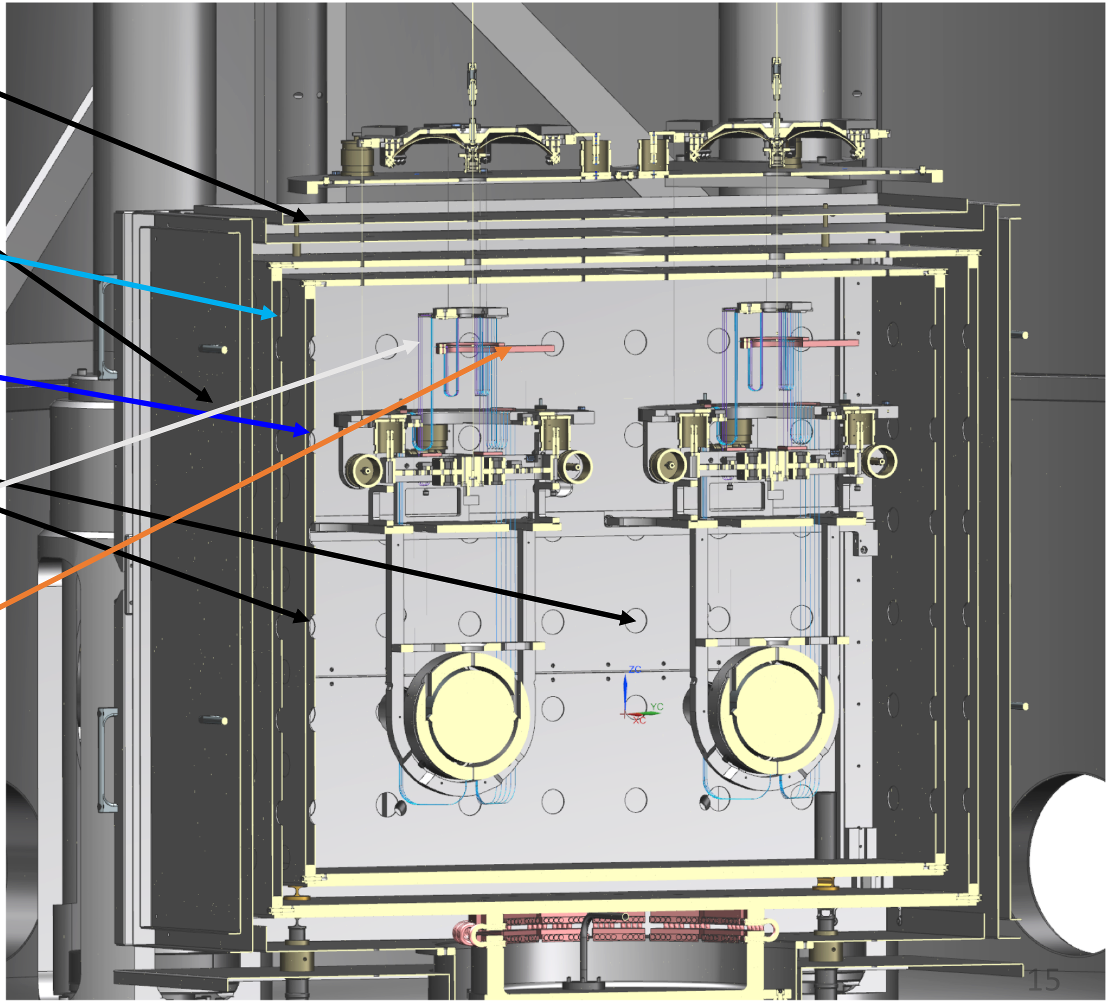
Mass cryogenic payload ~ 50 kg (Etpathfinder), 2000 kg (ET).
Mass inner cryogenic shield ~200 kg
Mass liquid Nitrogen shields ~ 300 kg.
Area shields ~ 5-10 $m^2$ so incident radiation kW level.



Liquid N cooling (~200W). Inside primary vacuum

# Cryogenic shields around mirror

## (Preliminary) design study for the cryogenic cooling of the optics (M. Doets)



300-K shield, stabilize filter temperature

Passive reflective shield to reduce radiation load on first shield.

Outer (80 K) shield (liquid nitrogen)?

Inner thermal shield, < 10 K.

Holes for pumping

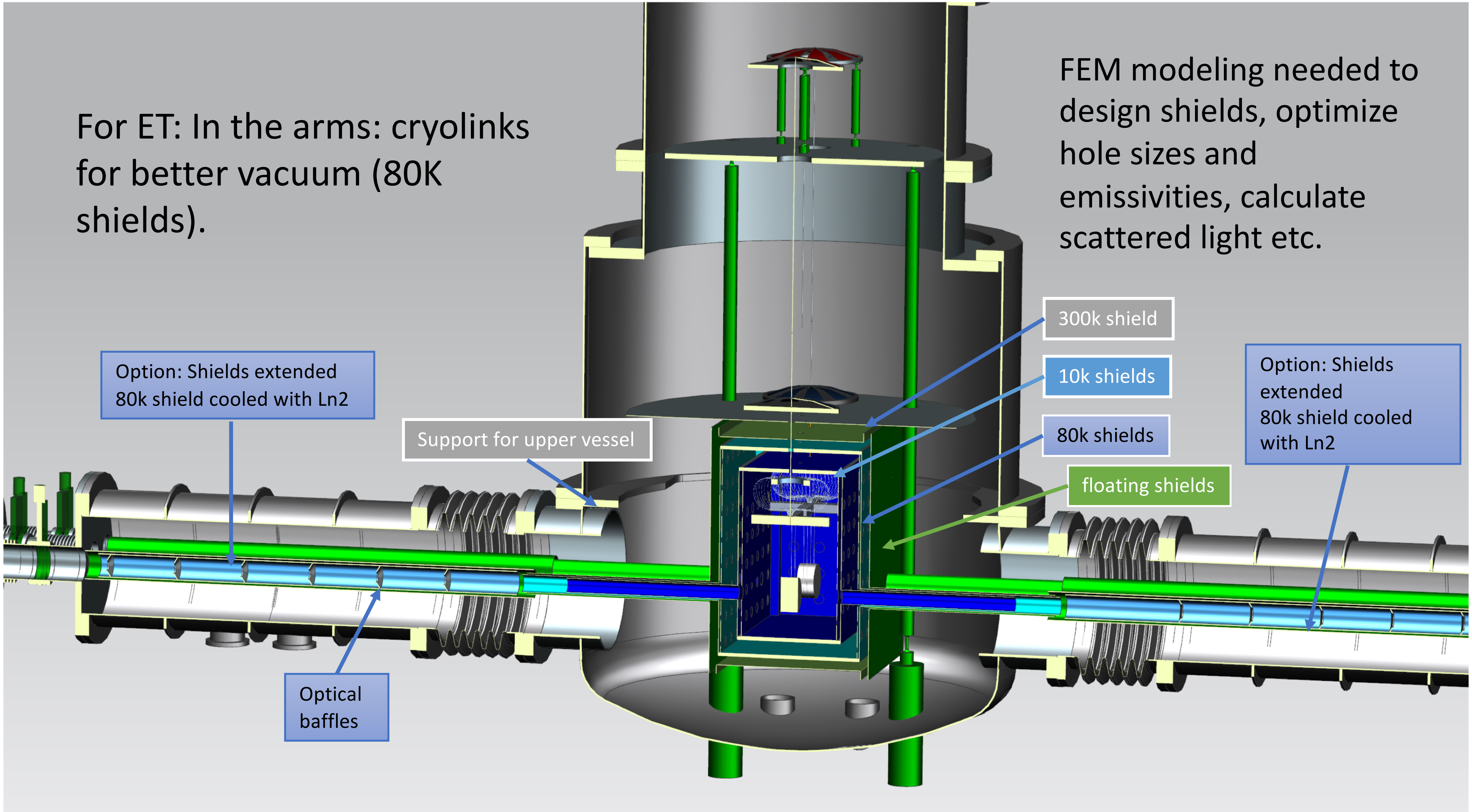
Jellyfish wires (ultra-pure aluminum) to cool marionetta and limit vibrations

Vibration-free cold finger for cooling mirror (JT restriction sorption cooler)

Shields should reduce thermal radiation, but have holes to be pumped out. Holes through all 6 shields for optical levers and for the laser beam (shielded with pipes). Scattered light and thermal radiation must be absorbed somewhere.

For ET: In the arms: cryolinks for better vacuum (80K shields).

FEM modeling needed to design shields, optimize hole sizes and emissivities, calculate scattered light etc.



300k shield

10k shields

80k shields

floating shields

Option: Shields extended 80k shield cooled with Ln2

Support for upper vessel

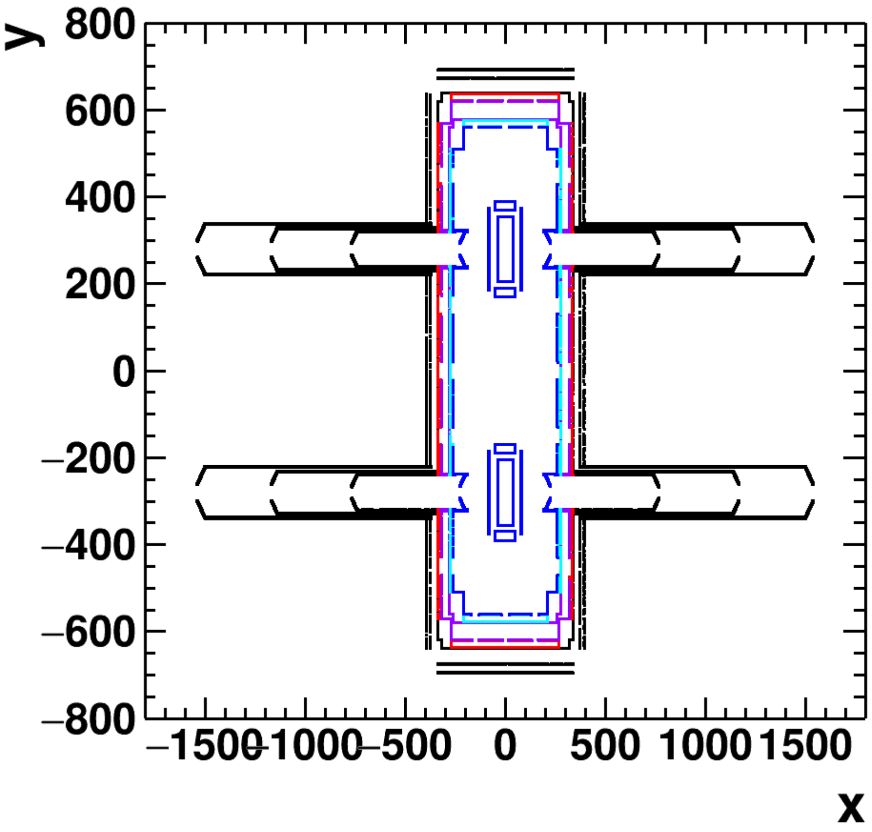
Option: Shields extended 80k shield cooled with Ln2

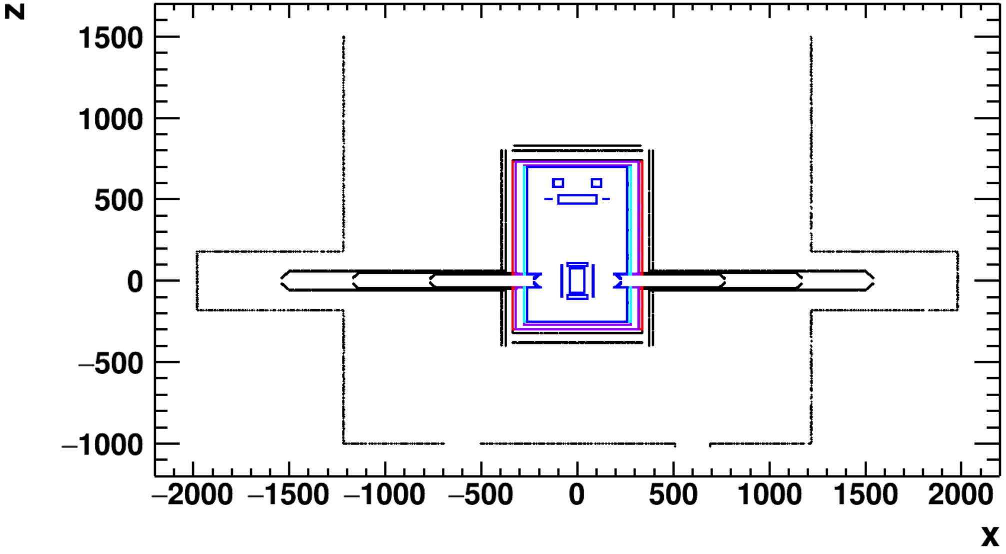
Optical baffles

# Shield modeling

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

Produces input for the sorption cooler design.



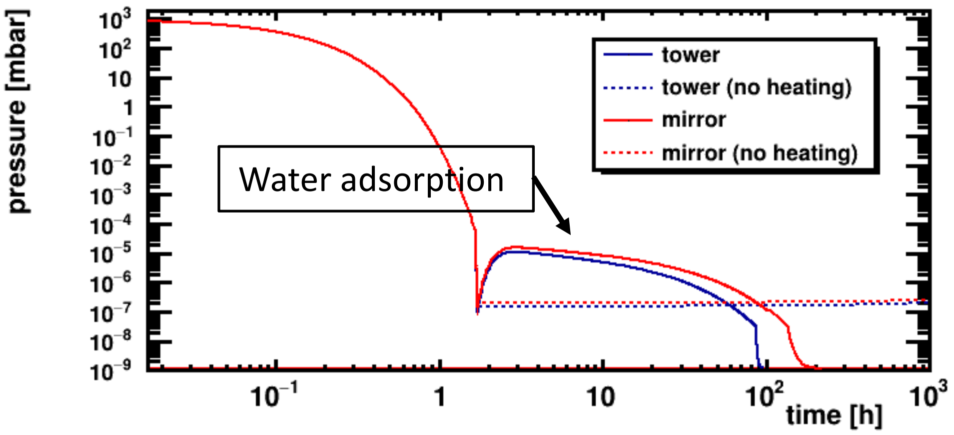


Top view and side view of the vacuum system around the end mirrors in 1 tower. The color codes indicate the temperature of the volume to which the surfaces point: inside inner thermal shield in dark blue, between inner shield and liquid nitrogen shield in magenta, towards room temperature in black.

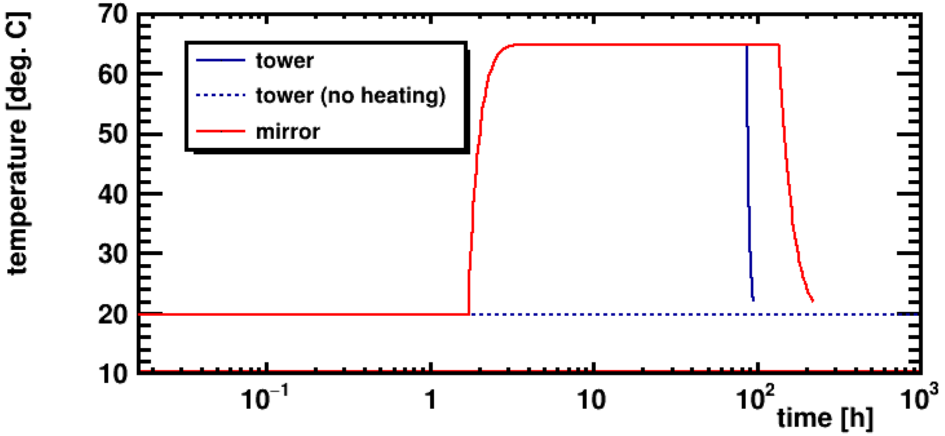
Several billion atoms or photons are tracked to calculate pump-down times, scattered-light absorption, and thermal radiation transfers.

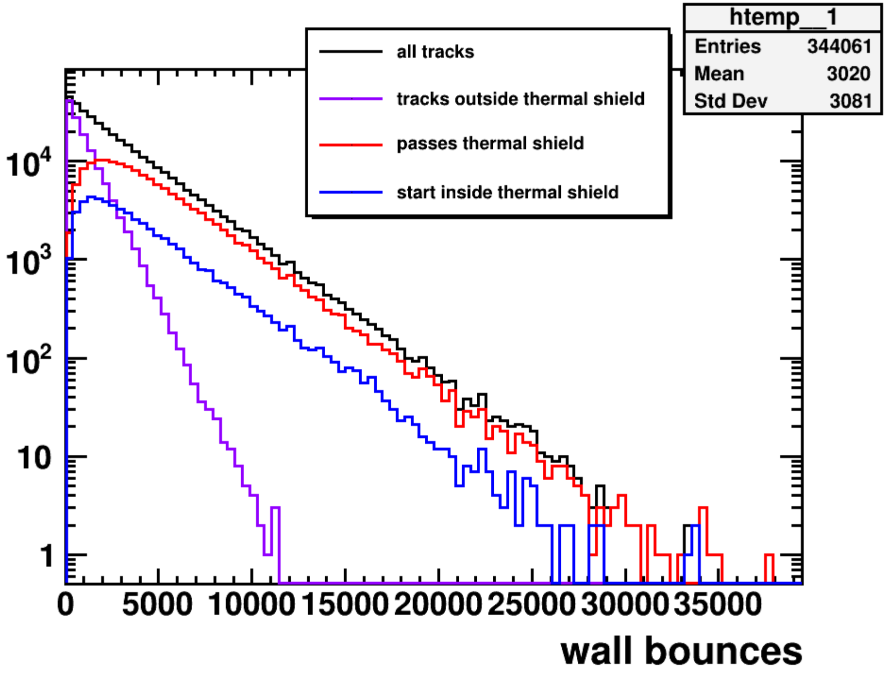
# First results, vacuum performance

Assumed 2800 l/s magnetic turbo pump and 1000 m^3/h roughing pump



Water adsorption



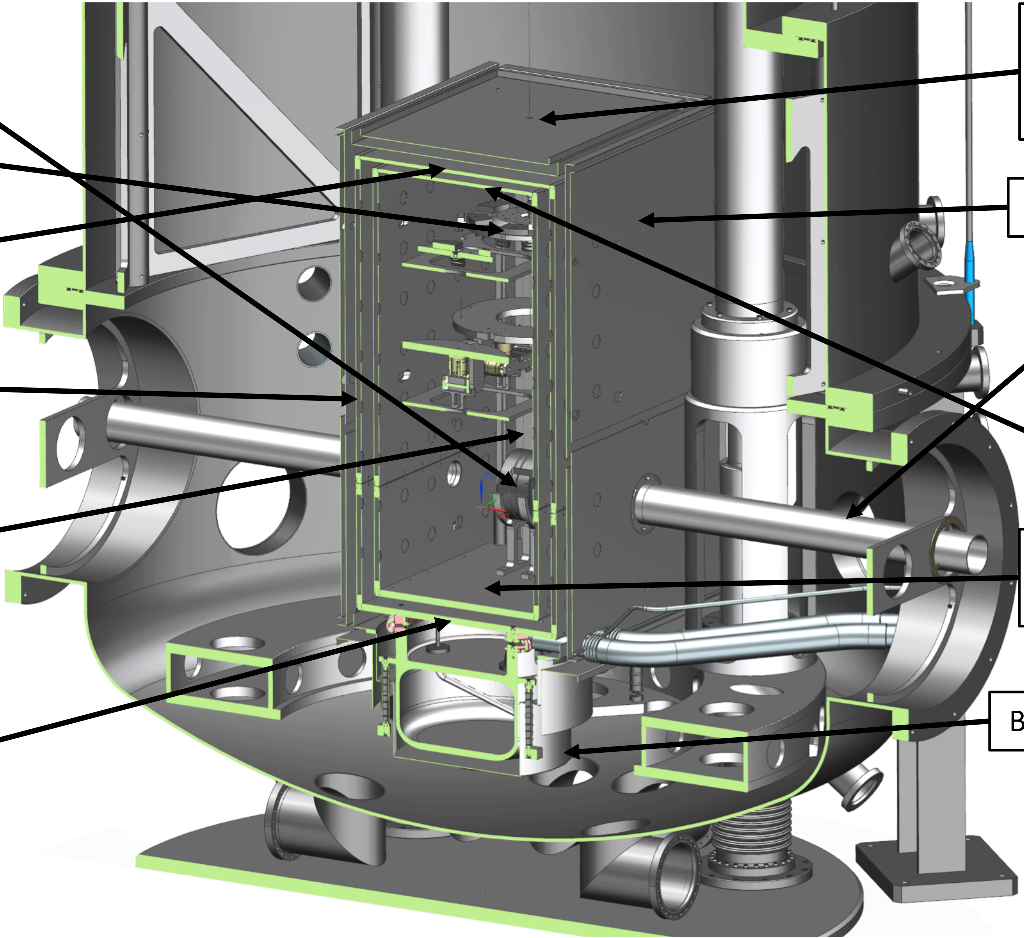


At room temperature, the pressure reaches $2x10^{-7}$ mbar before the monolayer of water dominates. Heating to 65 deg. C allows to pump down in 1 week time.

We need to be able to cool the 80-K shield and keep the mirror warm in order to prevent water freezing on the mirror (and freeze it on the 80-K shield instead).

# First results, thermal equilibrium

Shields all low-emissivity (0.1) except for baffles. Detailed studies must fix shield layout.



Mirror 12.8K, 1.7mW
Baffles 15.5K 9 mW

Coldheads 12 K, 40mW

Top liquid N center 120K, 20W

Front panel liquid N 123K (out), 118K (in), 23 W radiation, 13 W from guide and baffles (138K)

Side panels liquid N 114 K (out), 111K (in), 12 W

Bottom liquid Nitrogen 85K, sinks 180 W

Top floating shield out 292 K, in 270K (outshield must be heated)

Side floating shields out 291K, in 266 K

Floating guidepipe 287K, baffle end 286K (cooled by 80-K pipe)

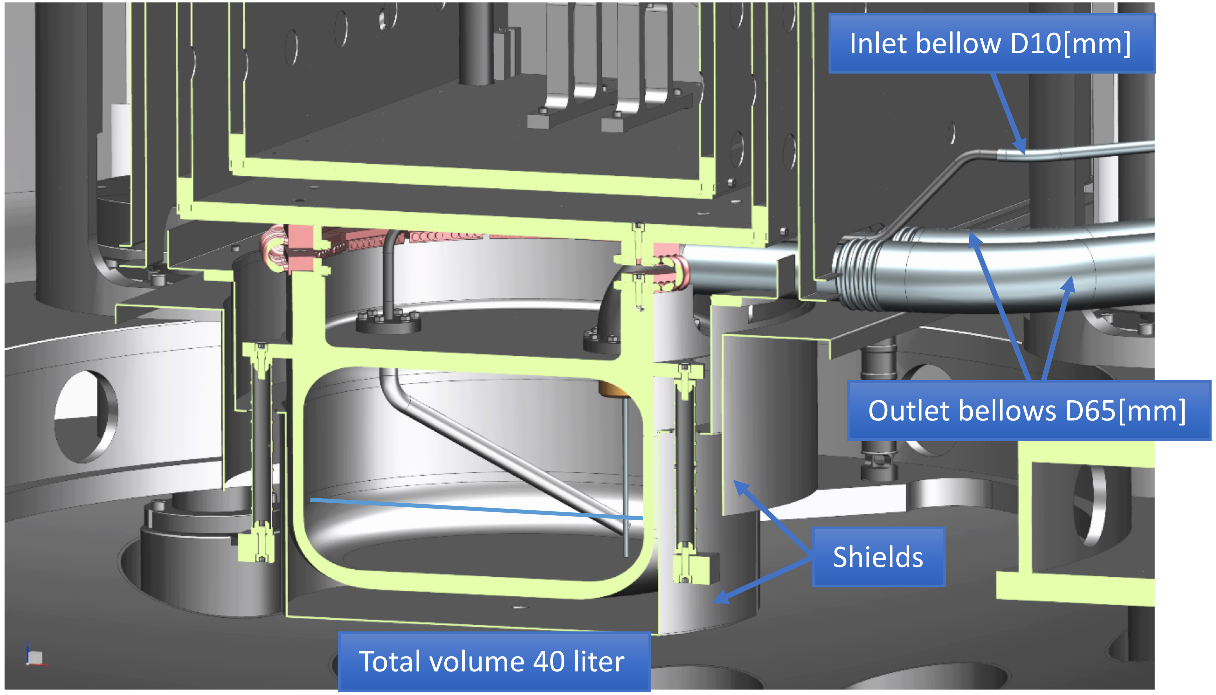
Top inner shield 30.8K, 0.3W

Bottom inner shield 30K, 5W (when black), 30K, 3W (when shiny)

Bottom floating shield 280K

# Liquid Nitrogen cooling

## Liquid Nitrogen cooling, mature design

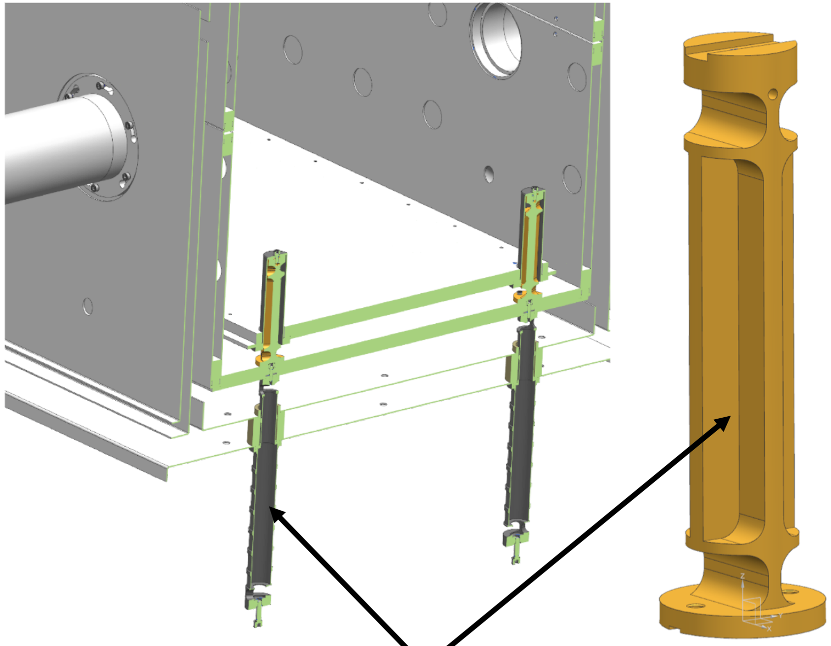


Inlet bellow D10[mm]

Outlet bellows D65[mm]

Shields

Total volume 40 liter



SS and Kapton flexures to accommodate shrinkage when cooling

- Slotted inlet pipes to avoid bubbles in inlet.
- Wide vessel to reduce vibrations from boiling.
- Vessel decoupled from 80-K shield with 192 litze braids (8mm diameter, 60mm length – may be replaced).
- Outer thermal shields support the inner thermal shield. Flexible joints to accommodate shrinkage when cooling down.

# Design sorption cooling

## Baseline requirements for design sorption cooler are being studied

- First simulations done: a liquid N shield needs about 200W cooling power in the current design configuration. Thermal gradients lead to a difference of about 30K between top/front and bottom of this shield (2mm thick shields, 50mm sidebars).
  - Heat link from outside tower is impractical: 1 ton of copper needed to bridge 2 m and have less than 10K gradient. Liquid nitrogen must be brought inside tower
  - Temperature inner shield can be chosen almost freely: radiation load on mirror is dominated by thermal radiation from outside/80K shield. Range of 15-40K fine for inner shield.
- Heat load on cryogenic mirrors/suspension/baffle about 80 mW. Temperature gradient very small when using ultrapure Al links.
- Heat load on inner cryogenic shield about 3W (5W when bottom is black). Mainly from radiation liquid nitrogen shield. Can be reduced by having smaller openings and lower LN2 temperatures ?
- Total mass cryogenic payload ~ 40 kg per mirror, inner shields ~ 150 kg: cooling down from 300 K may be problematic.
  - Contact gas? High-temperature cooler? At 300 K, about 150W thermal radiation from inner shield to 80K shield.
- Sorption cooler: in its own vacuum tower. Inlet/outlet gas in double-walled pipes inside a bellows to pass mirror tower walls.
- Next steps :
  - Optimize heat shields to get lowest loads on cryogenic masses
  - Calculate optimal heat reservoir temperatures, gas mixtures, pressures, cycles
  - Design the sorption cooler
  - Build a prototype: Test performance : vibration, temperature stability, etc