NB. presentation done by pptx

Cryogenic sensing and actuation for Einstein Telescope

Joris van Heijningen

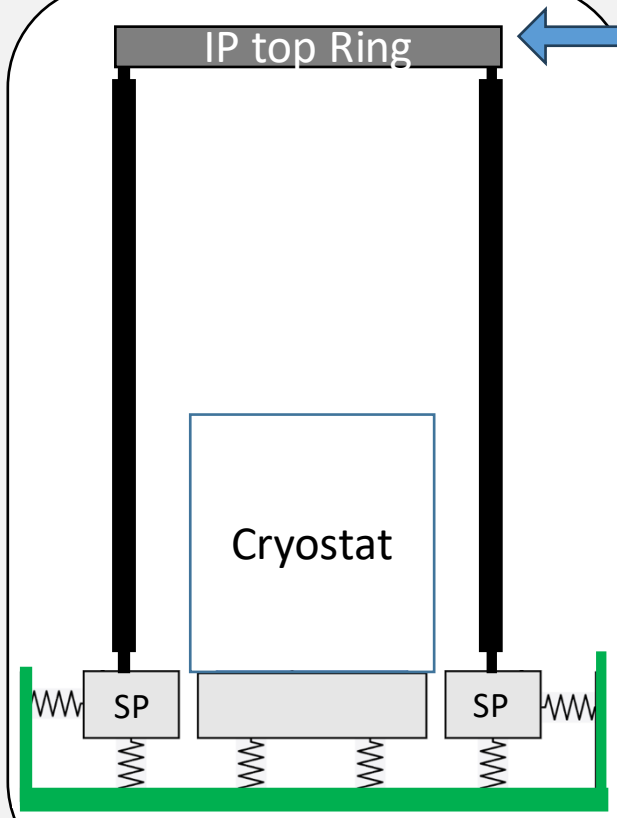
Cryogenic session 20 March 2026

4th ET-LF Tower Workshop | Pisa

VU Nikhef

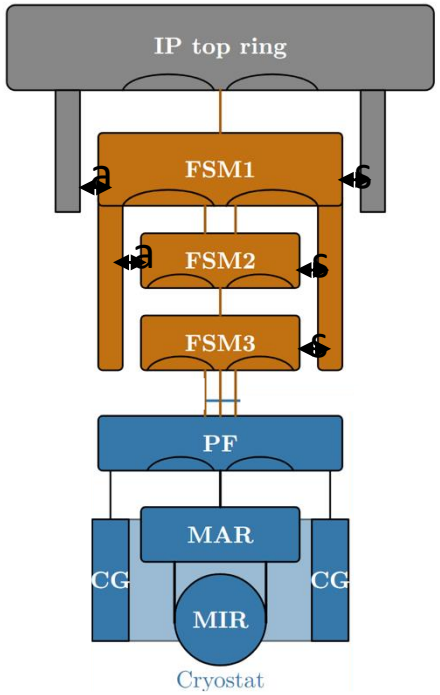
I use Nikhef 11-m tower design as model

As presented in 3rd ET-LF tower meeting (Elba)



Controls: Michele Valentini
GWADW Presentation

+

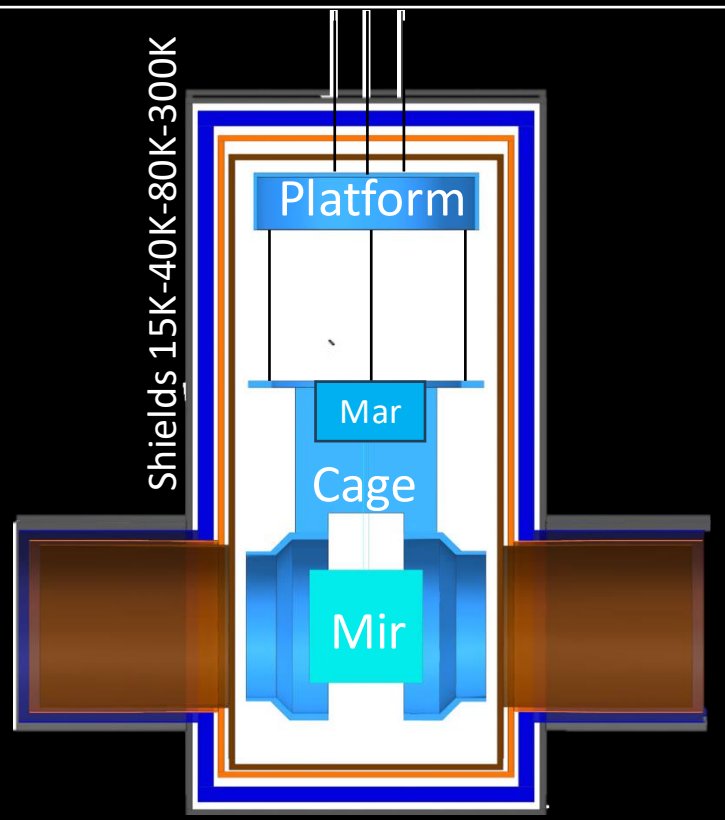


Damping Controls: Sander Sijtsma
Soon with optimal global control

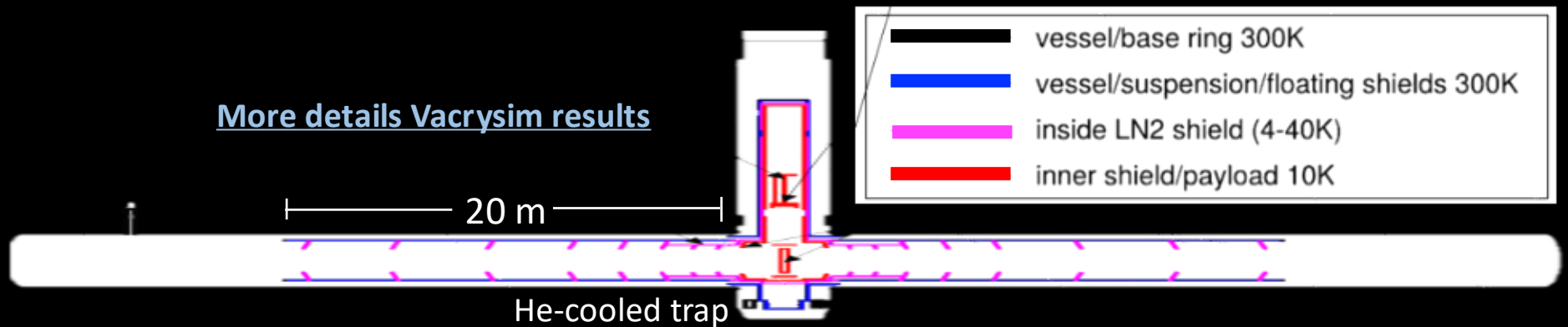
Mechanics Modelling (FEMTO):

Cryostat design in the Nikhef tower

- Based on **ETpathfinder** cryostat (to be tested later this year)
- Pumping via staggered holes
- Shield Design **for low-vibration sorption cooler**
  - *Helium-cooled up to 5m & LN2 cooled up to 22.5 m
- Modelled with **Vacrysim** (by Henk Jan Bulten)
  vacuum and cryogenic simulations, toolkit. (see supporting document for The ET Baseline Detector Layout Taskforce)
- Simplified but quite detailed, e.g.
  - 5000 cooling wires with diameter 0.15 mm
  - (outgassing) Includes $0.6\ \mathrm{m}^2$ Kapton for Cables in cryostat
  - **Including all required holes in shields**
- Some Suspension Discrepancies



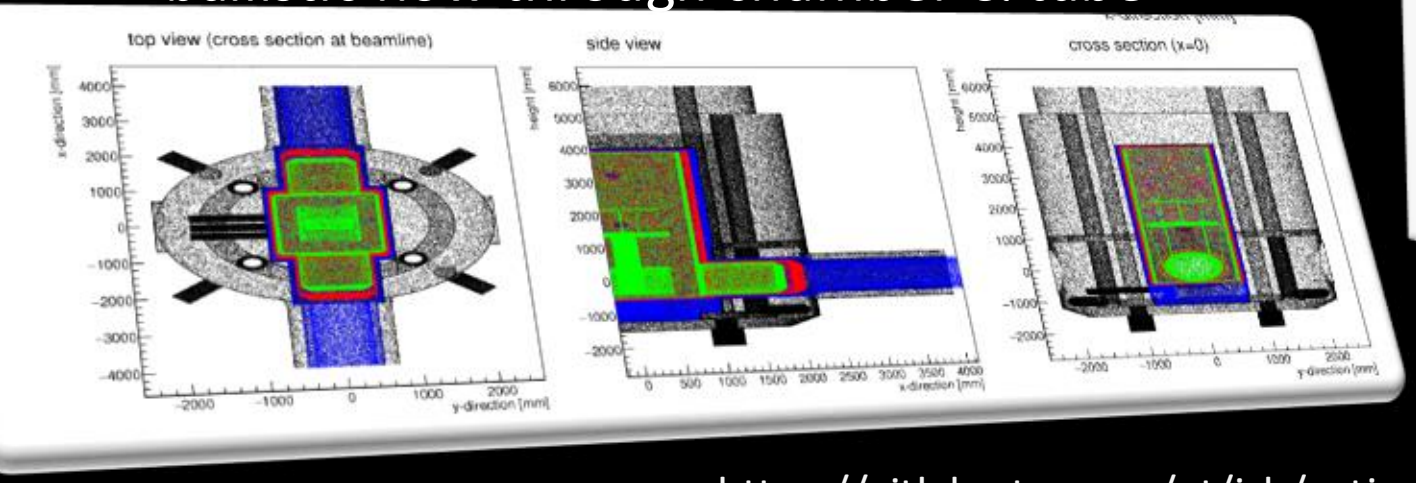
More details Vacrysim results

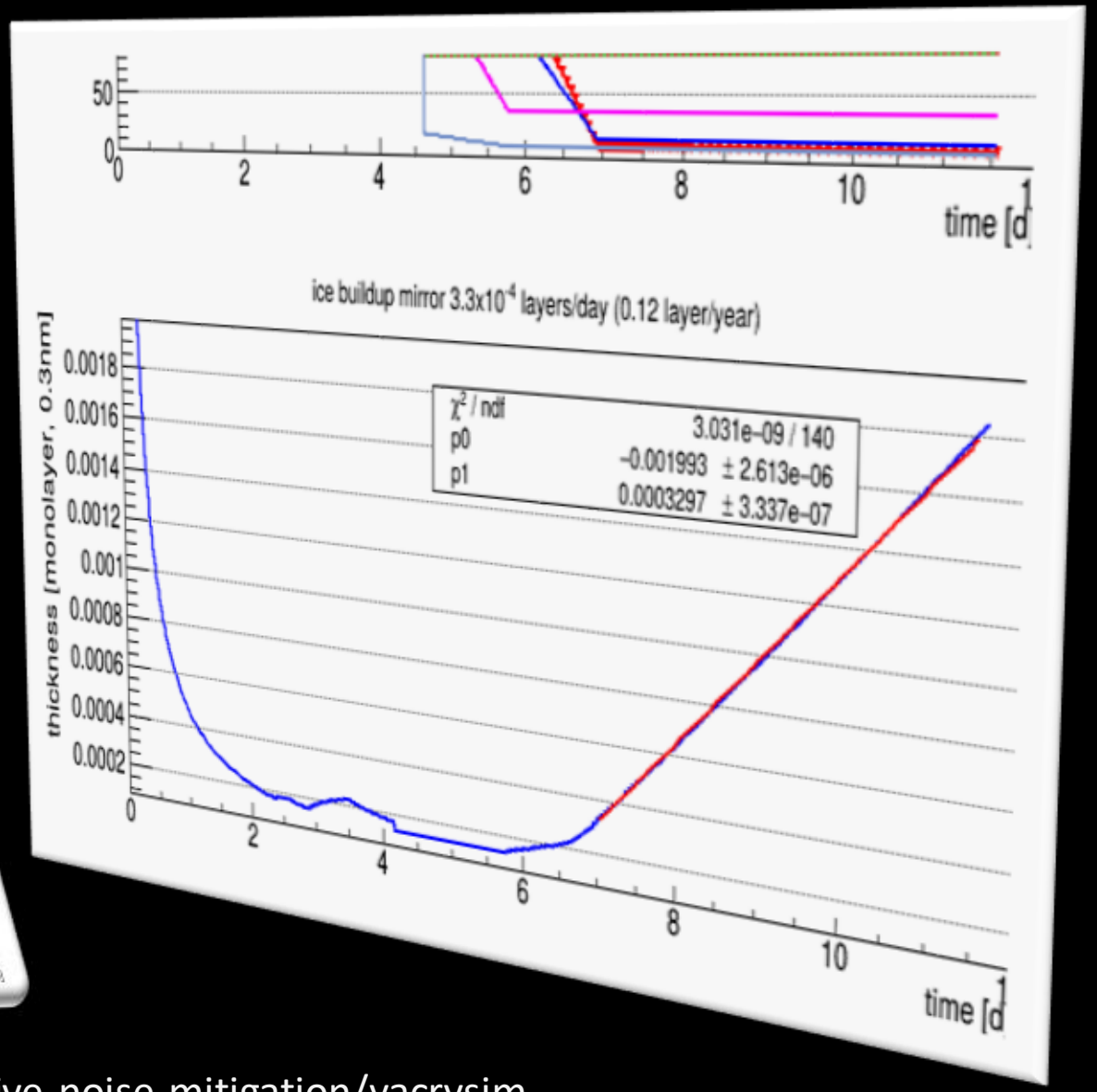


Reminder of vacryosim results

- Careful cool down strategy;
- H_2O vacuum goal yields realistic ice growth ;
- About 1 monolayer per 8 years;
- Rate dominated by ballistic flow from BS-pipe.

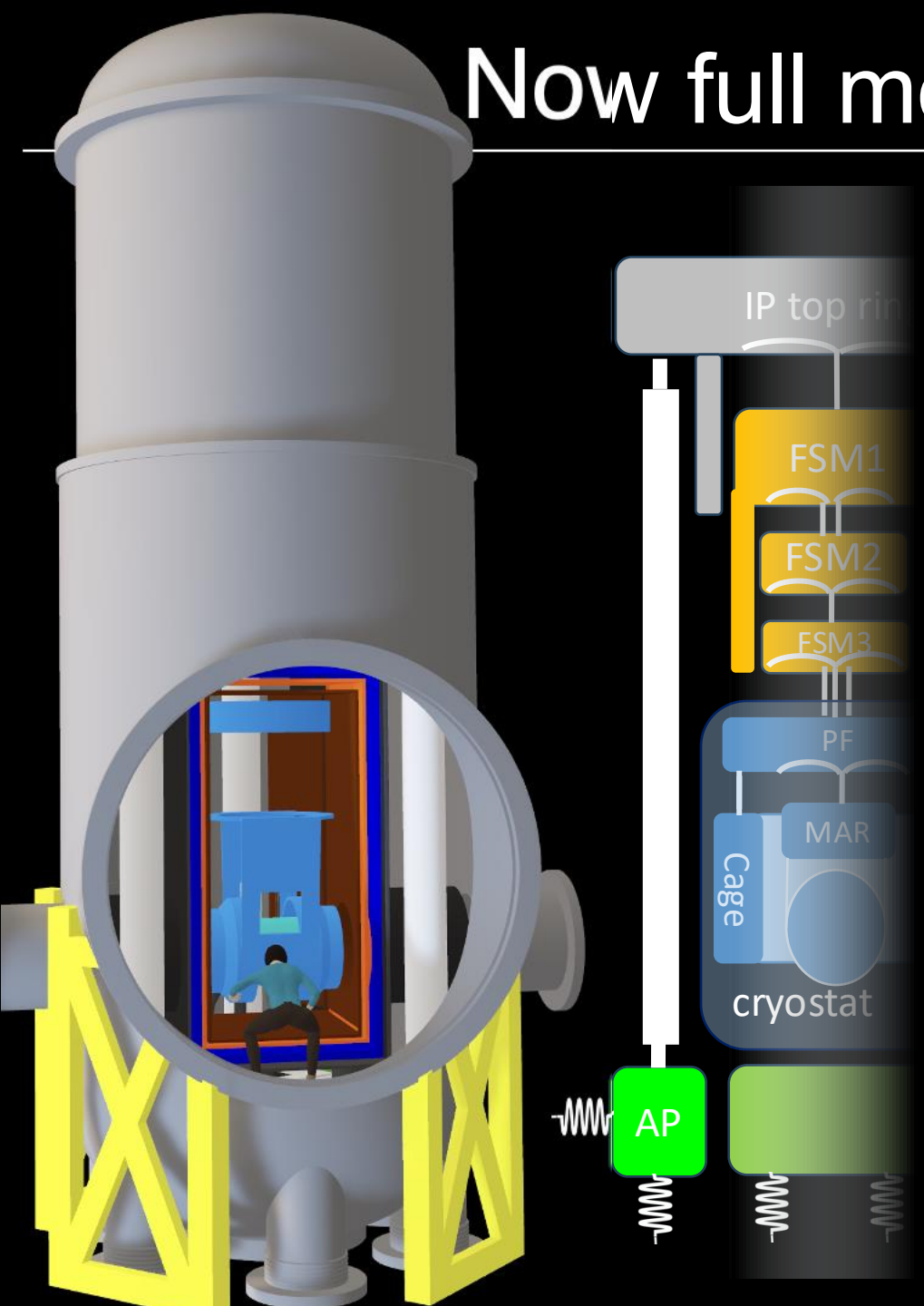
ballistic flow through chamber & tube

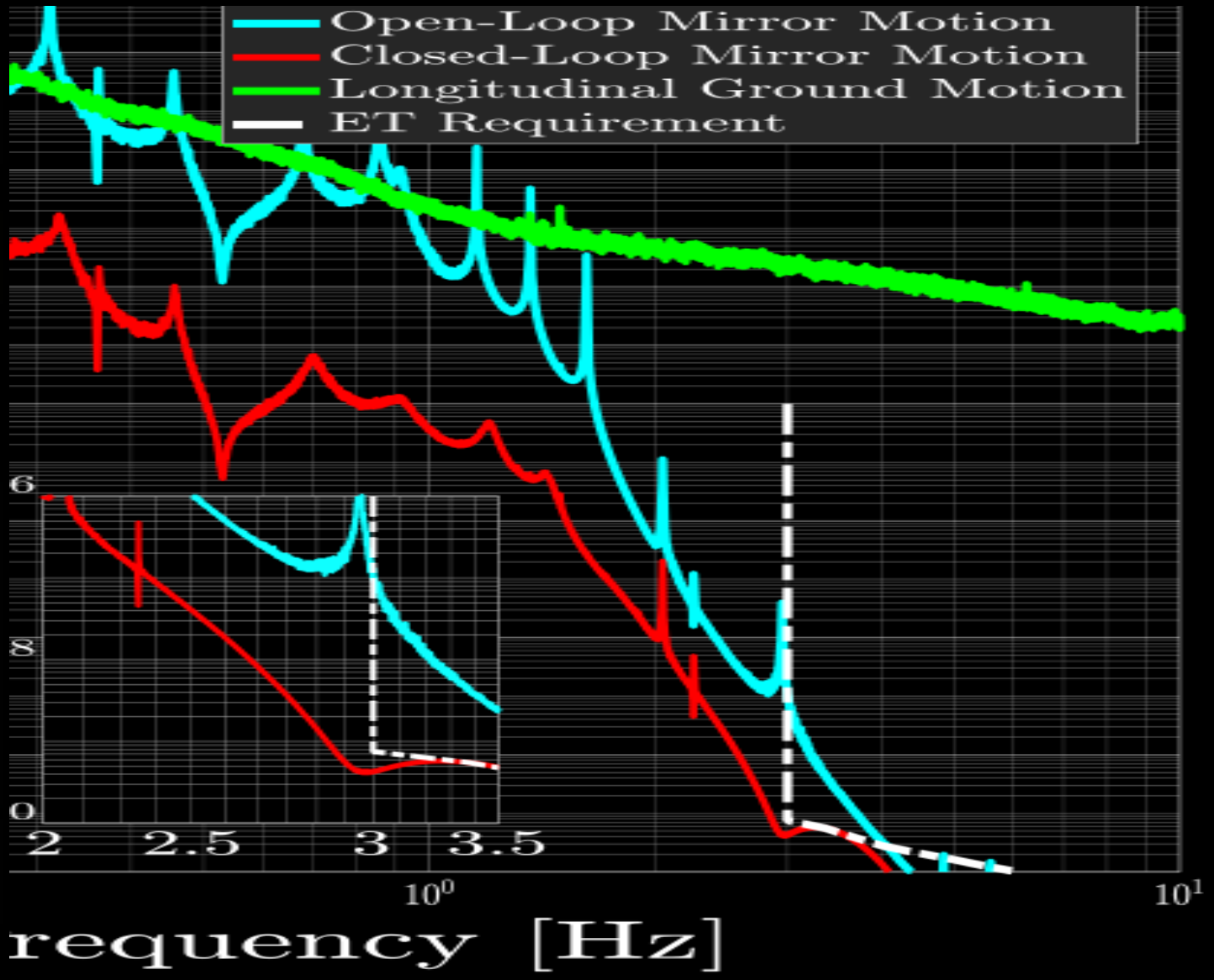


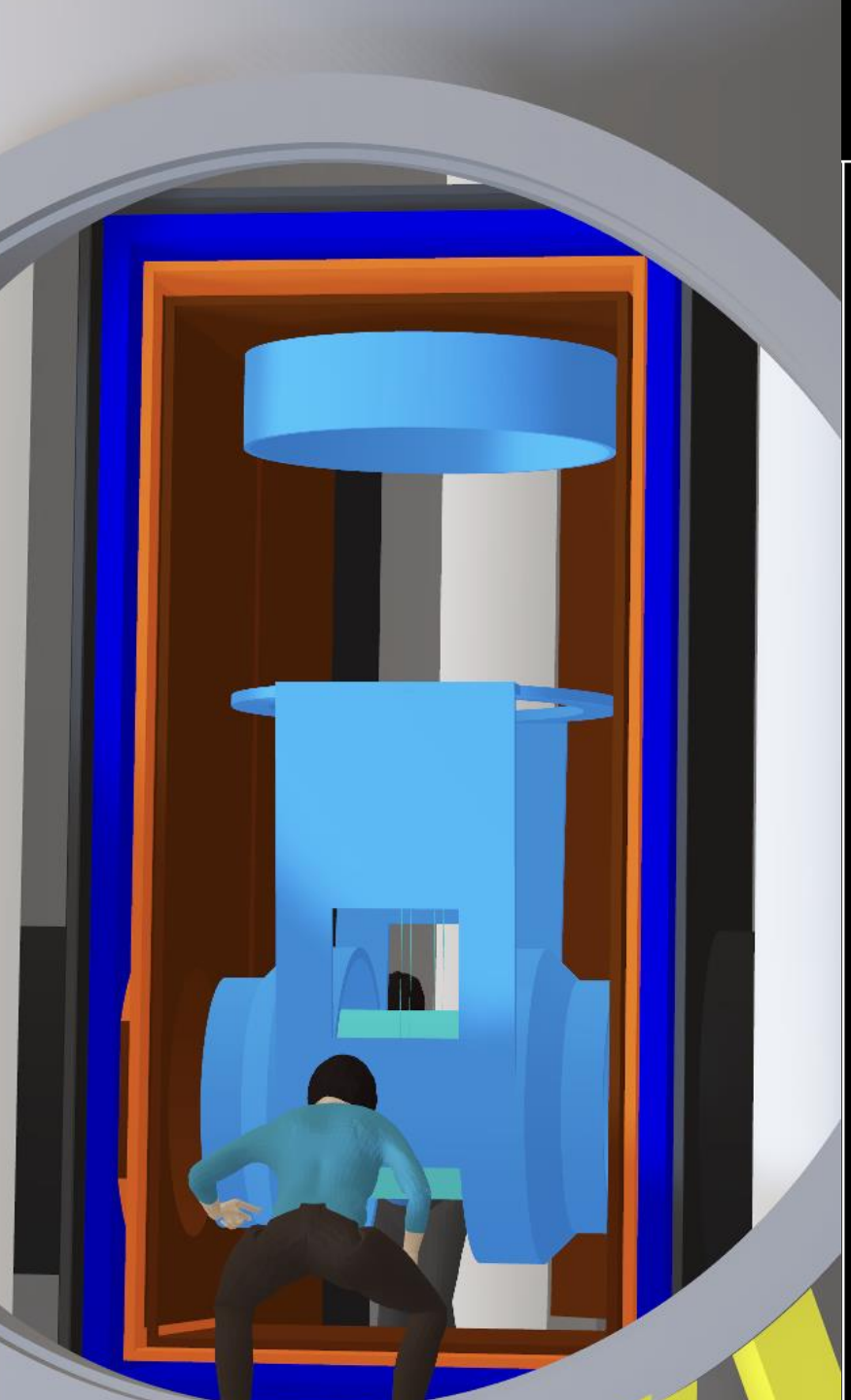


https://gitlab.et-gw.eu/et/isb/active-noise-mitigation/vacrysim

Now full mechanics and controls model

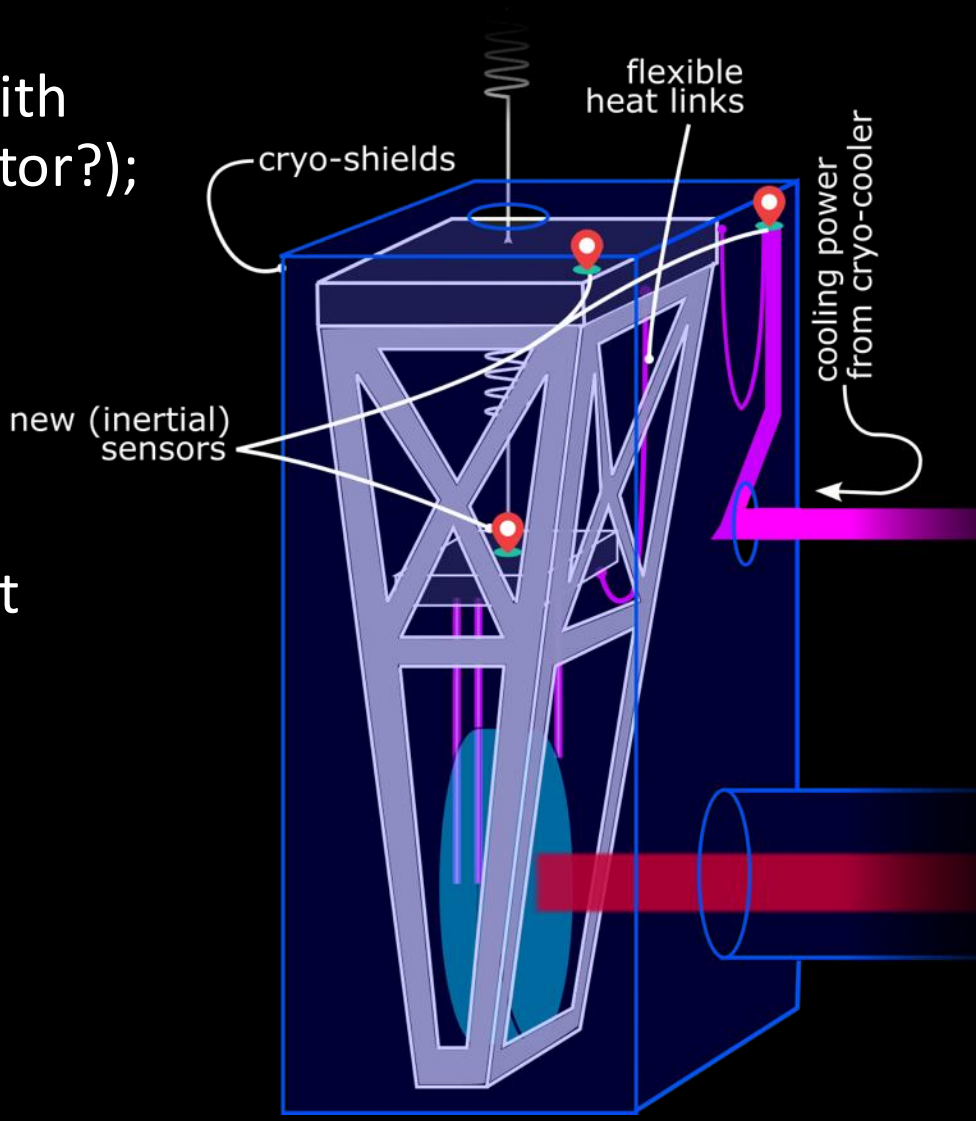




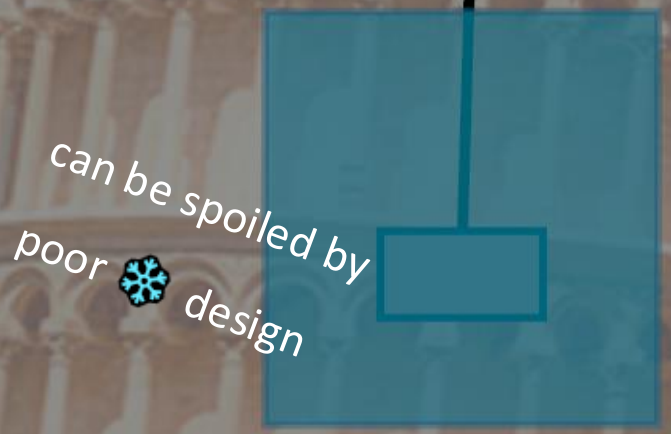


Where cryo-sens/acts helpful?

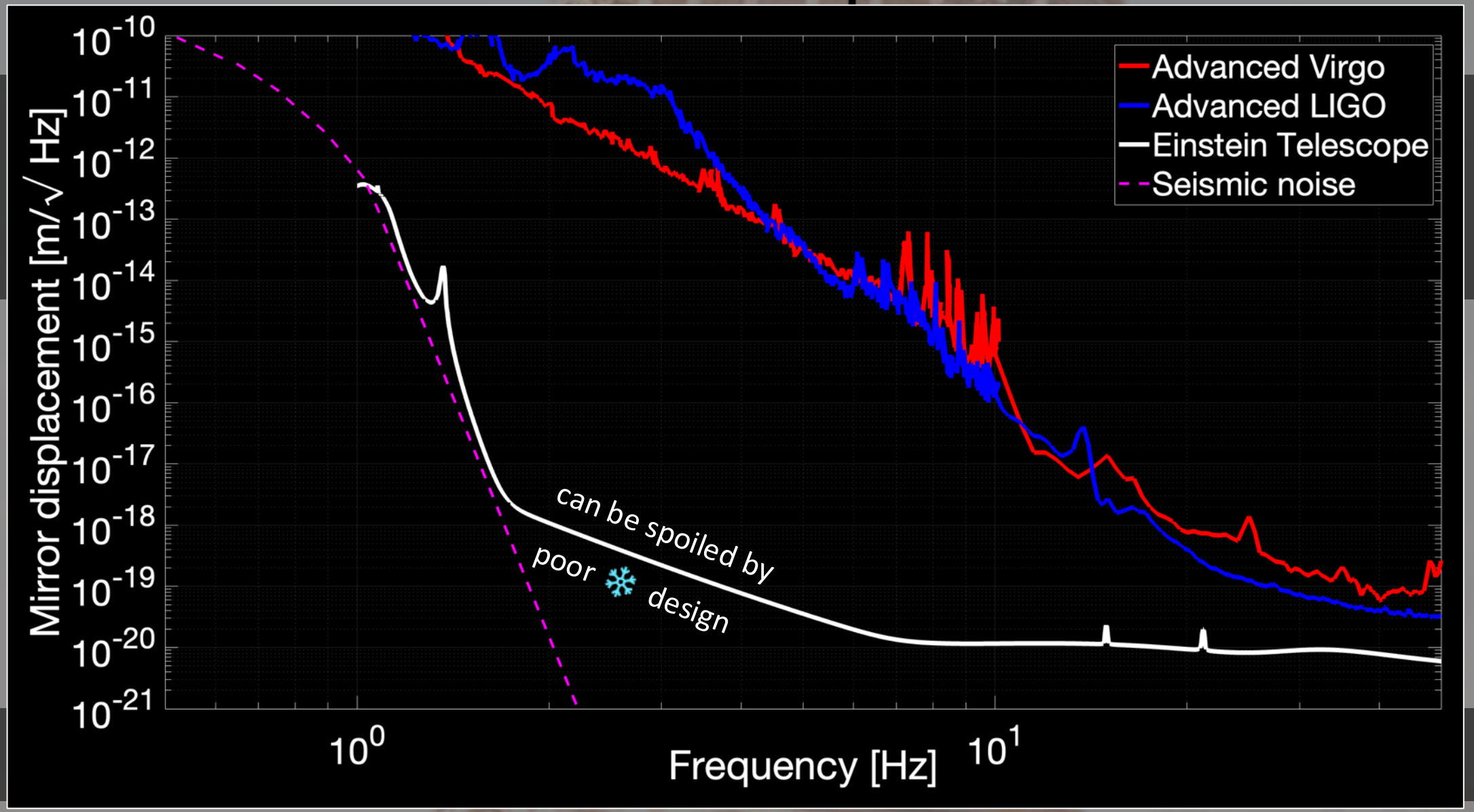
- Actuators at mirror (with different superconductor?);
- Damp angular modes of the marionette;
- Active isolation of heat link from cryocooler;
- Inertial sensing on platform/cage.



Zooming in

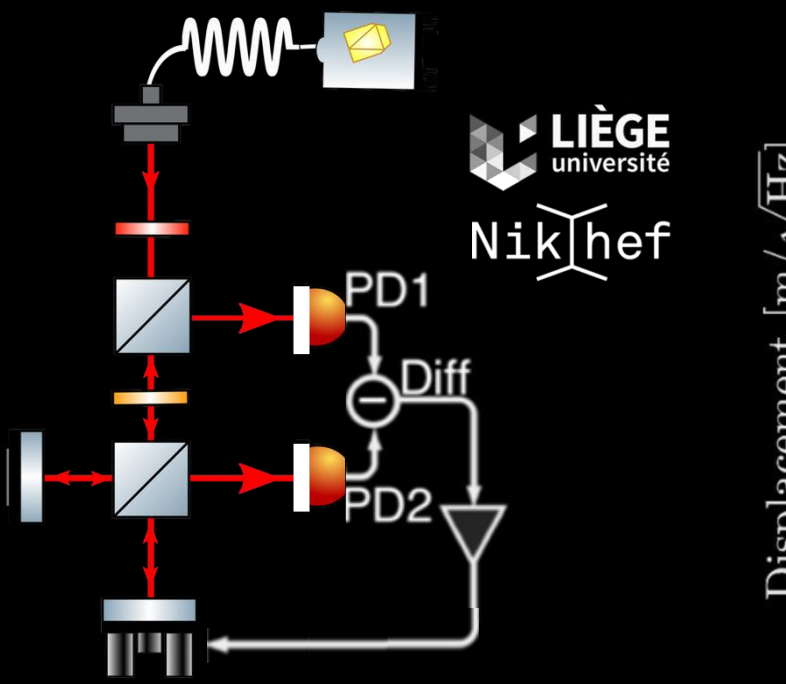


Cryogenic superconducting sensing and actuation


Advanced Virgo
Advanced LIGO
Einstein Telescope
Seismic noise
Mirror displacement [m/√ Hz]
Frequency [Hz]
can be spoiled by
poor design

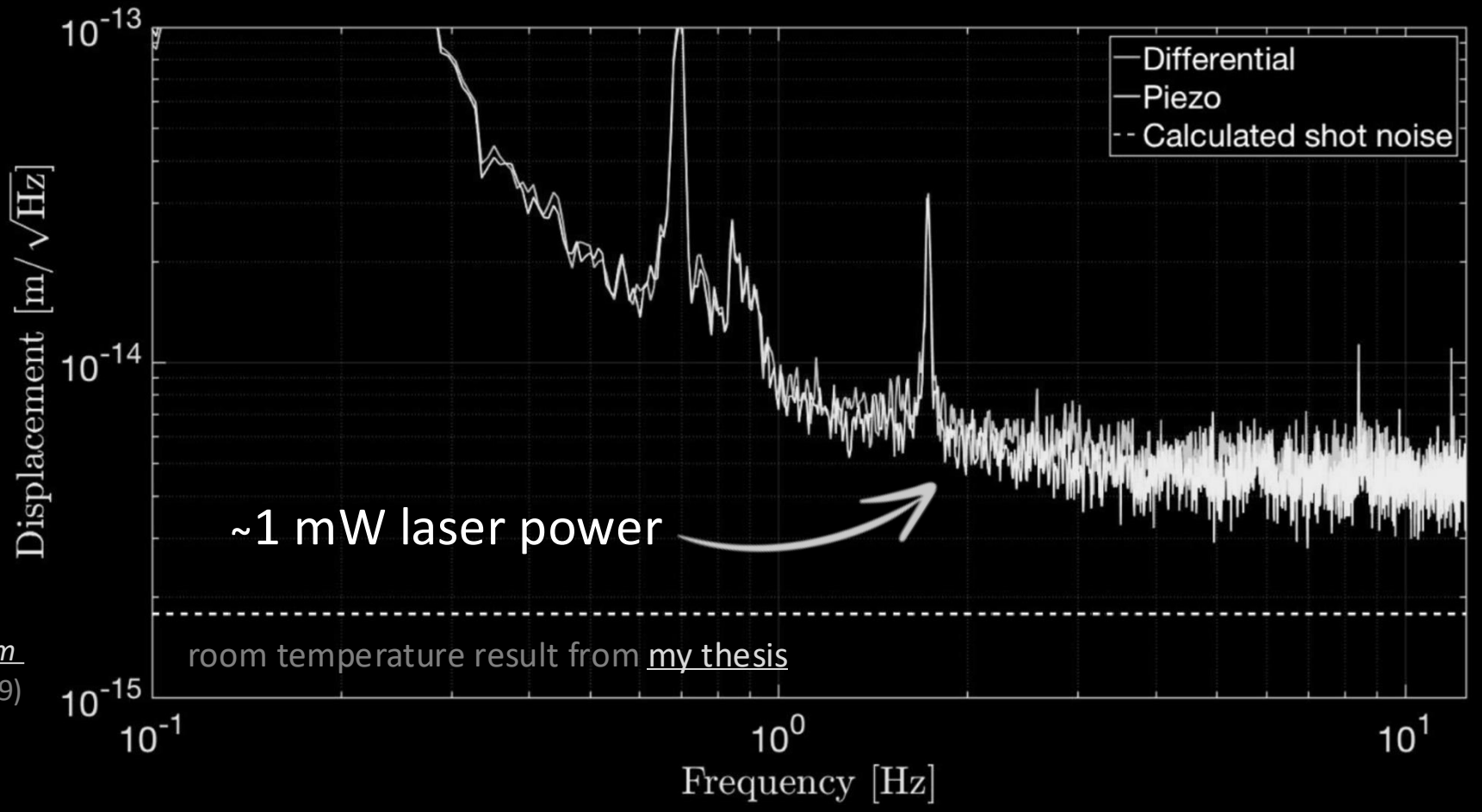
Cryogenic version of M.B. Gray readout

M. Zeoli found the right components for the cold environment: Kuhlbusch, Zeoli+, Cryogenics 142, 103895 (2024)



original: *Optical and Quantum Electronics* **31**, 571–582 (1999)

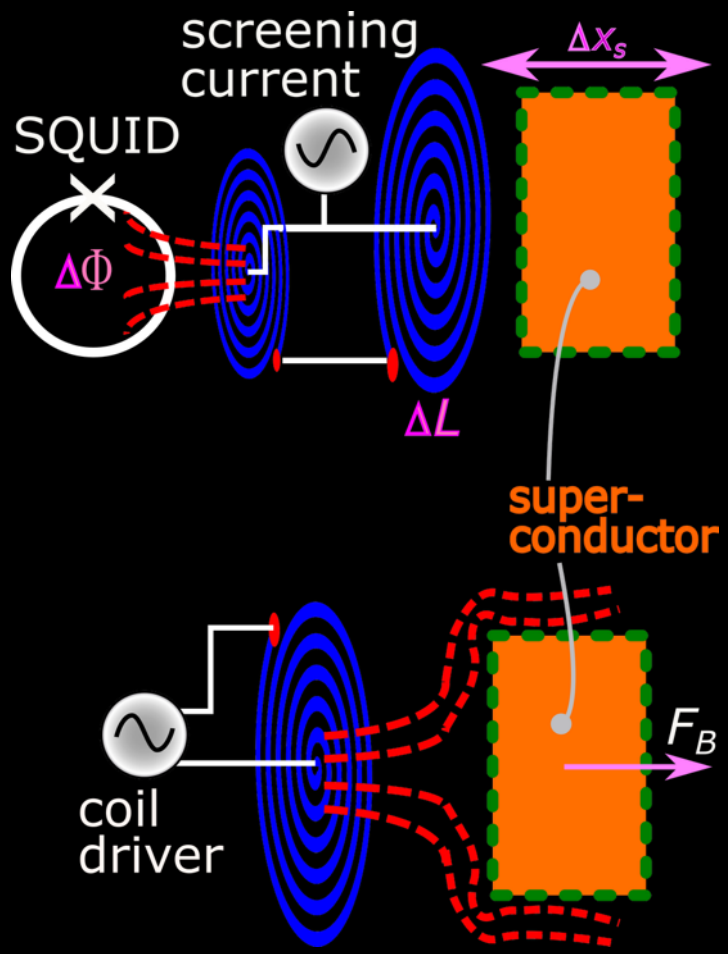
Polarizing optics allow for all light to go to the photodiodes



see implementation in inertial sensors in M. Zeoli's LVK Pisa contribution

Superconducting coils for readout and push

basic circuit, e.g. quadruple coil for back-action evasion not shown.

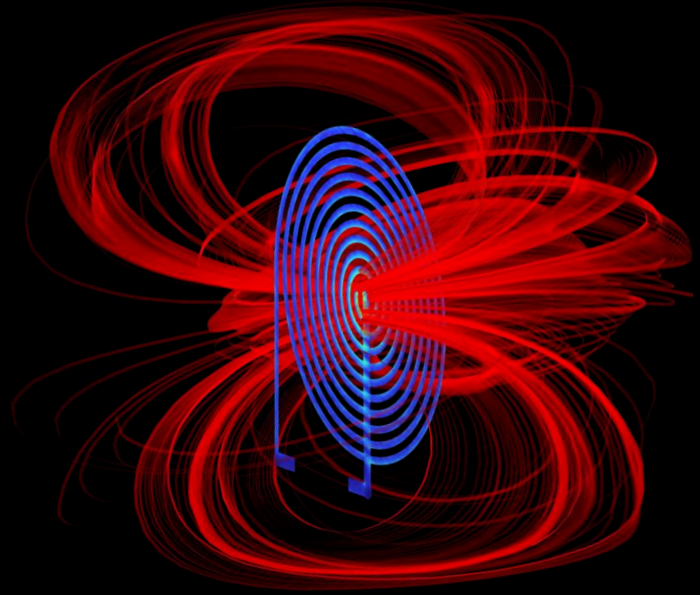


JVvH+, J. Appl. Phys. 133, 244501 (2023)

- Sensing and actuation using the Meissner effect.

  JVvH, JINST 15 P06034 (2020)

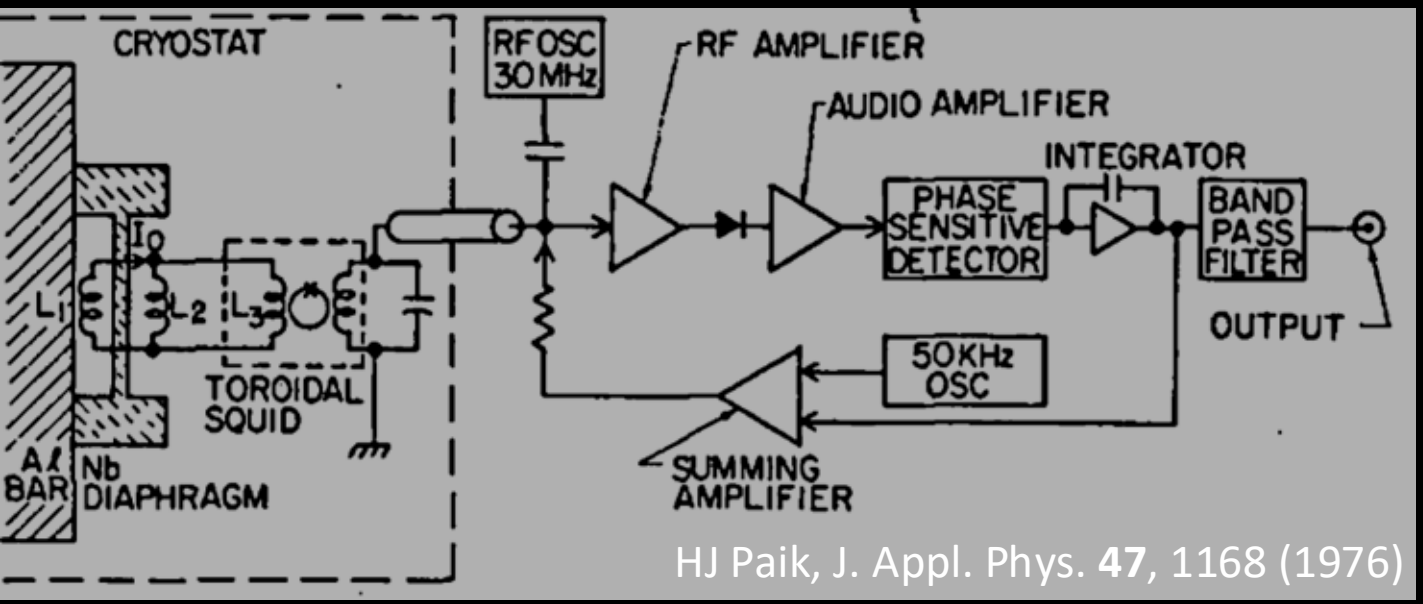
- Preliminary work to understand typical dimensions, forces, currents.



from Ferreira+, J. Phys.: Conf. Ser. 2156 012080 (2021)

Is this new? Partially.

Nautilus, cryogenic bar detector

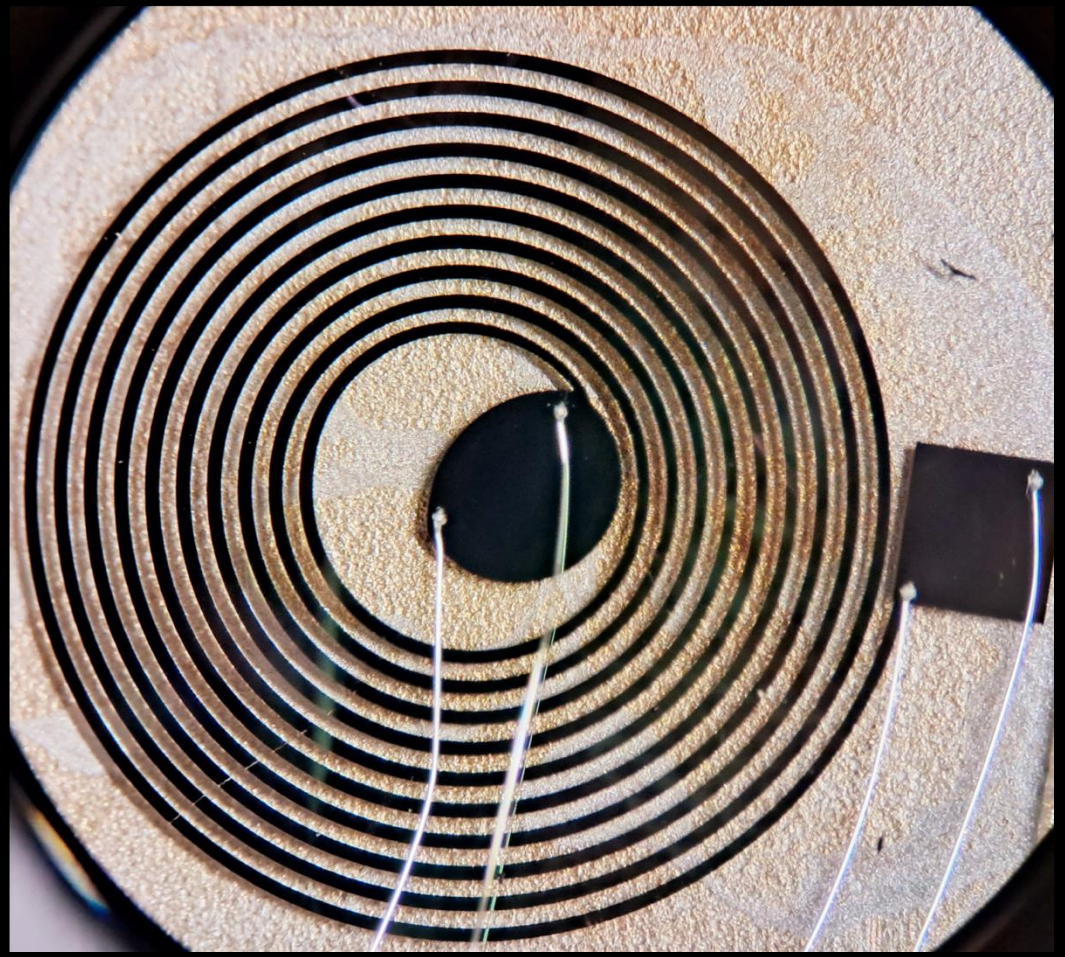


HJ Paik, J. Appl. Phys. **47**, 1168 (1976)

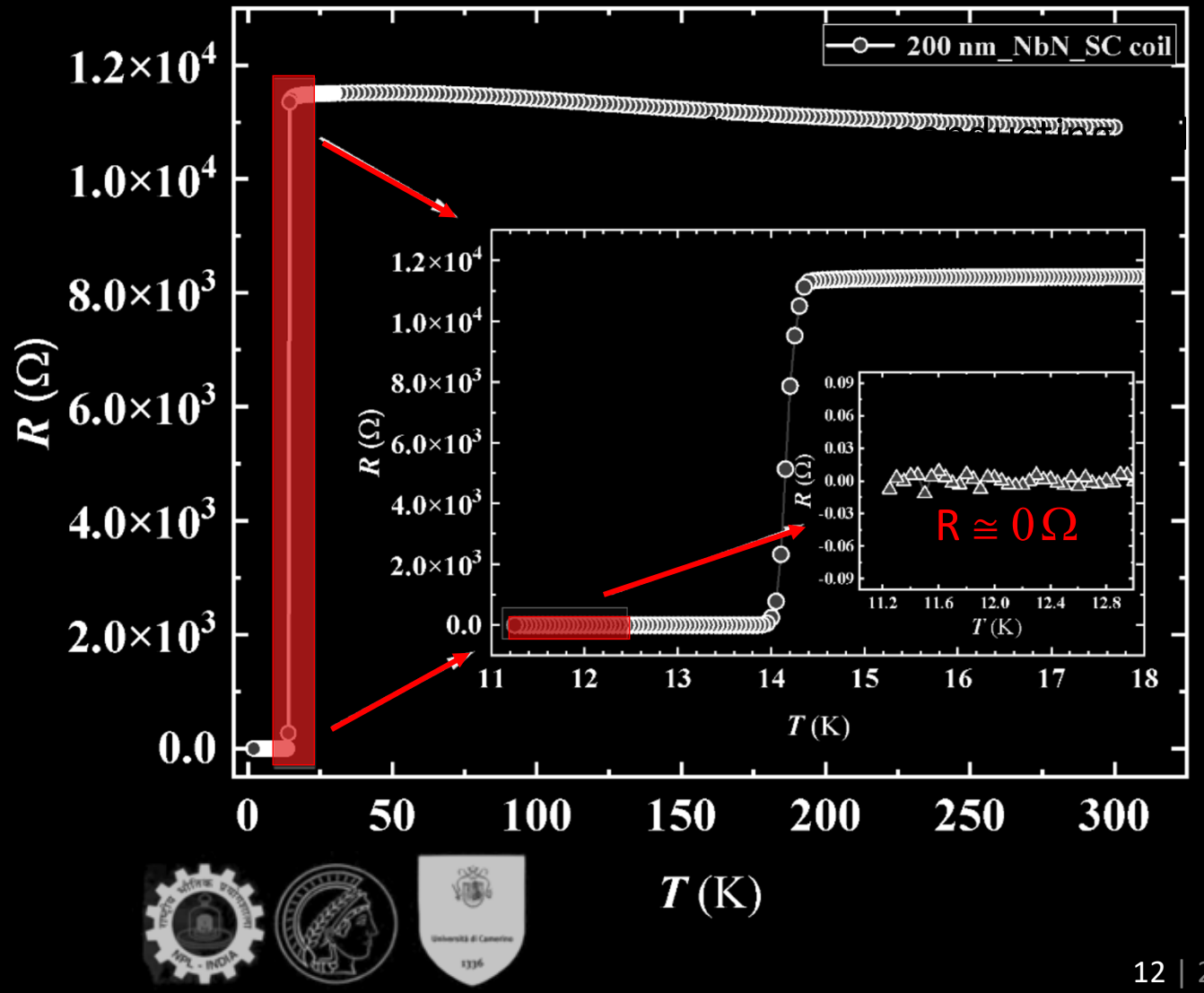
- Bar detectors developed from 1960s-2010s;
- Cryogenic operation <1K enabled (mostly Nb) superconductive readout;
- Einstein Telescope operates at >5-10 K, so other superconductors are needed.
- Deposited thin film superconductors, such as Niobium Nitride (NbN)

Our first coils fabricated at MPI CPfS (Dresden)

image credit: Meenakshi Sharma (CPfS Dresden)



1 cm



Coil design for thin film superconductors

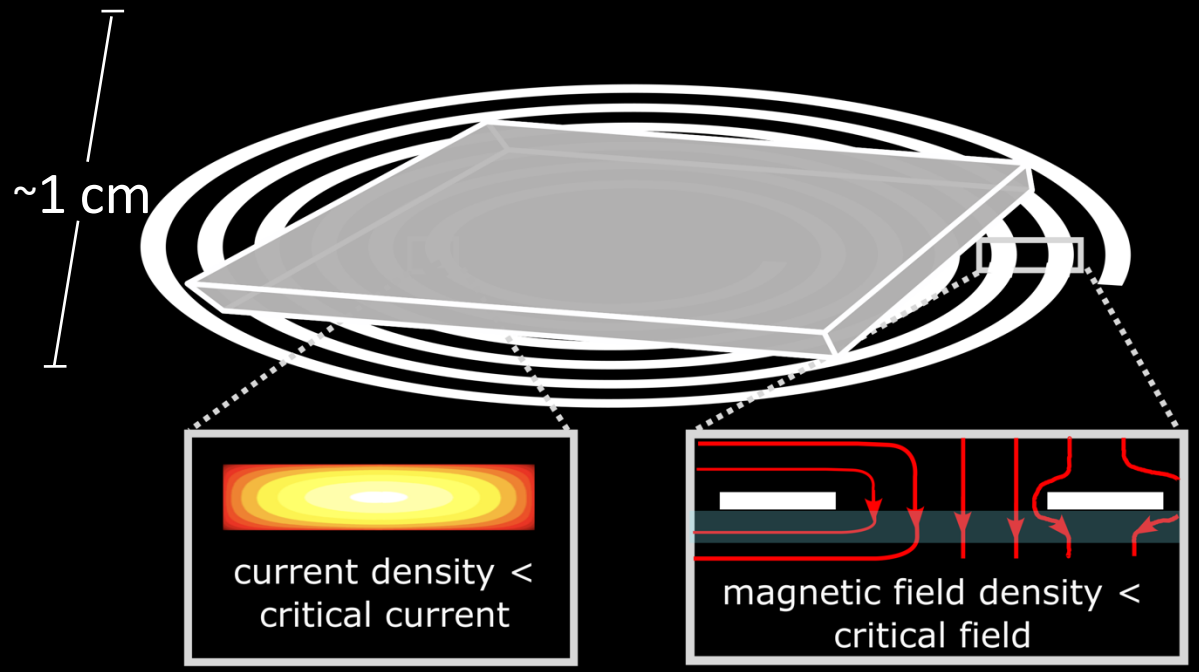
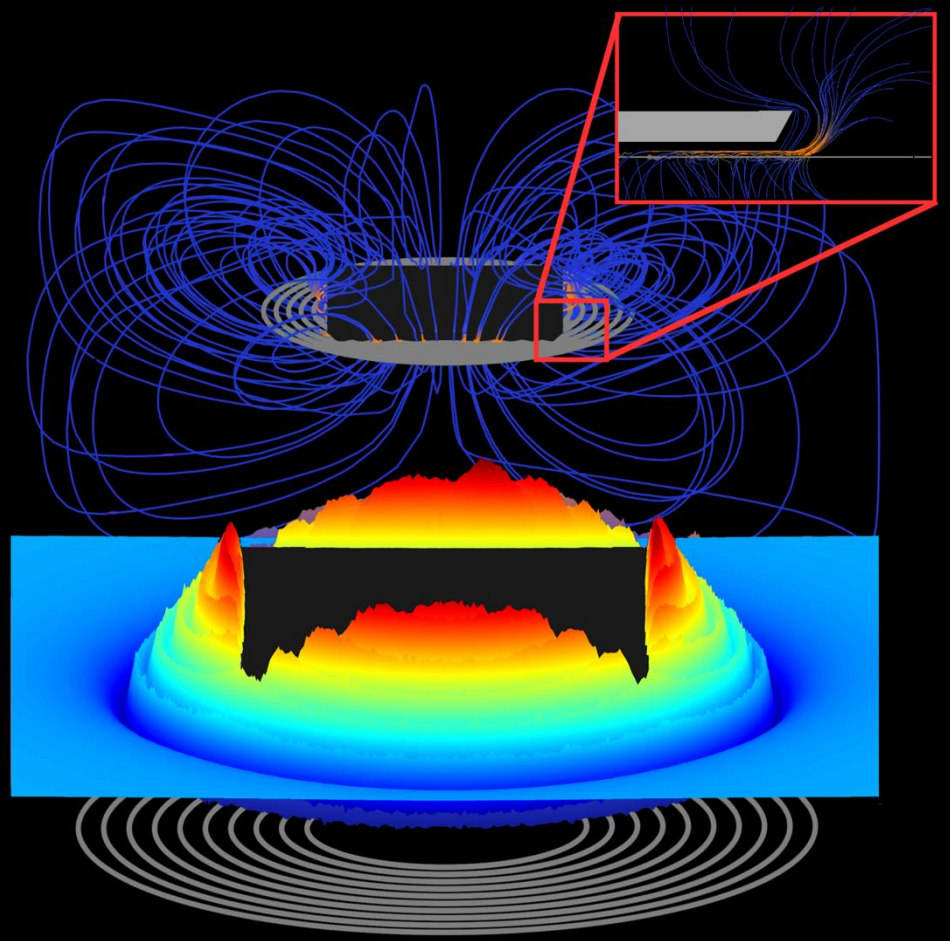


image credit: Veerle Ellenbroek



- Besides $T < T_c$, the superconducting coil should stay below critical field and current density.

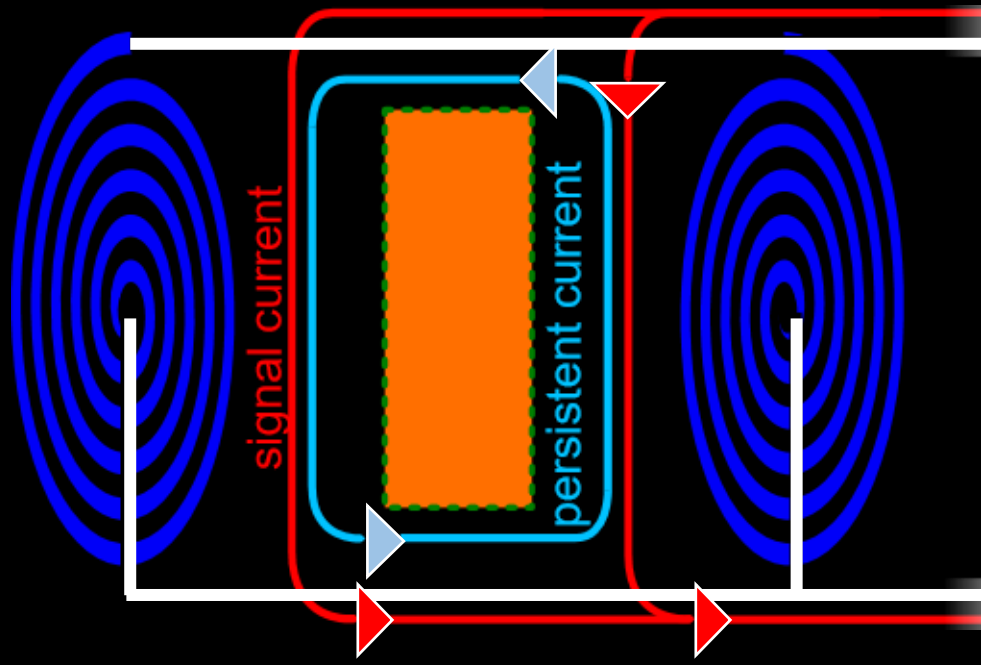
Persistent current amplification

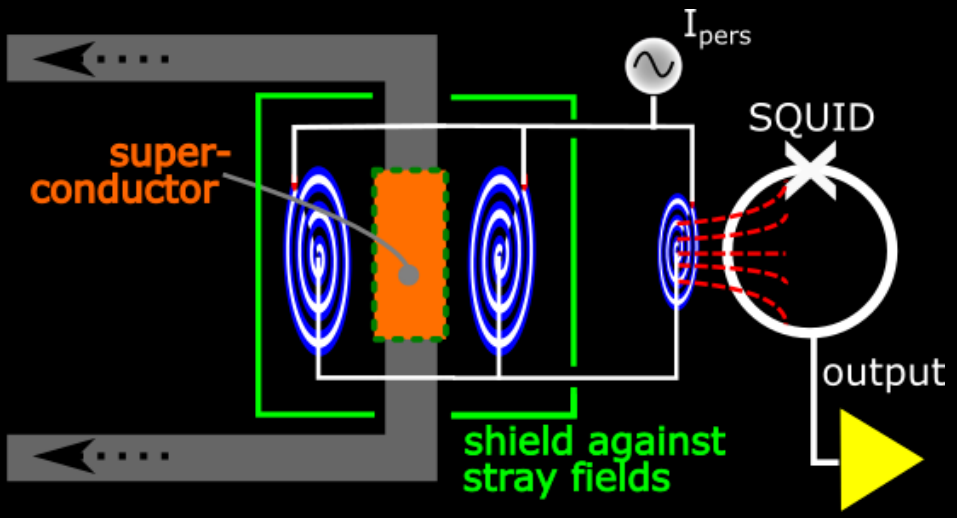
- Dual coil sandwich configuration
- $F \sim B^2 \rightarrow \left(B_{\text{pers}} \pm B_{\text{sign}}\right)^2 =$

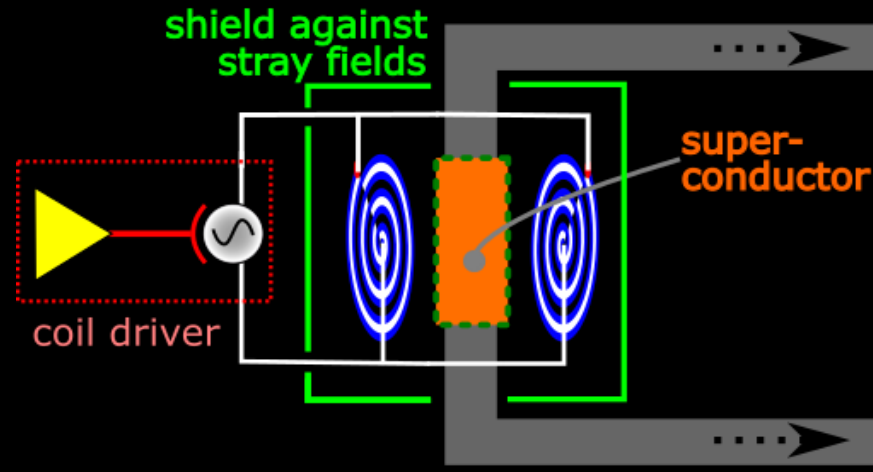
$$B_{\text{pers}}{}^2 \pm 2B_{\text{pers}}B_{\text{sign}} + B_{\text{sign}}{}^2$$

DC push — amplified — small

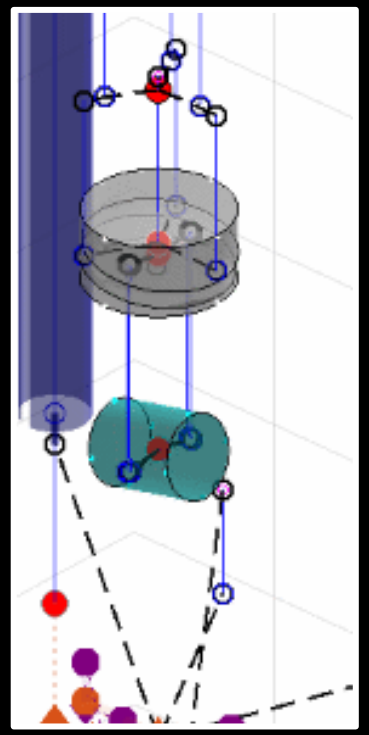
- Linear position sensor signal, with amplification



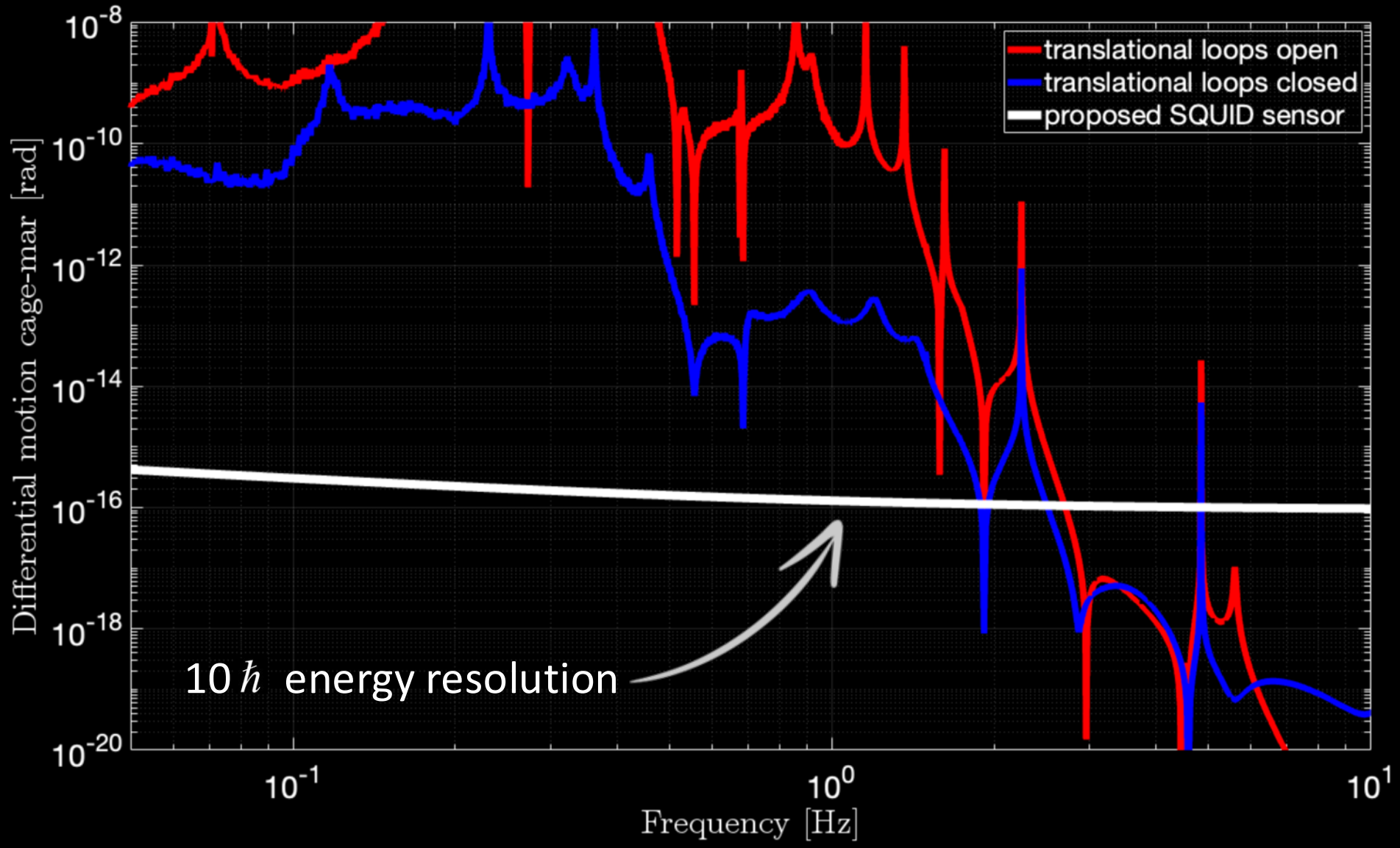




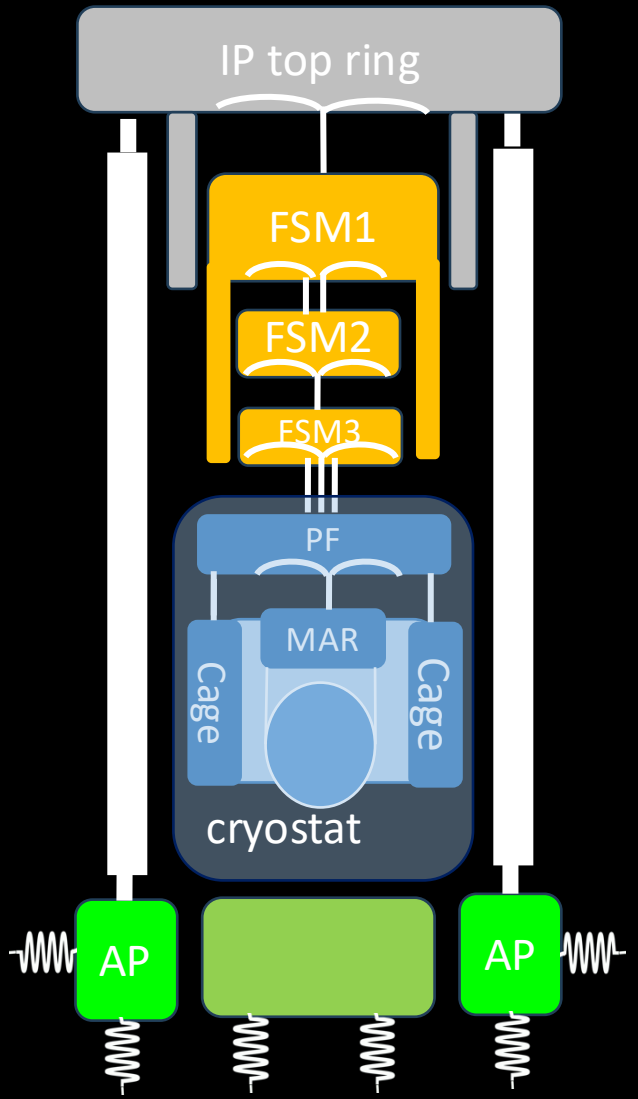
Can cryogenic SQUID sensors see anything?

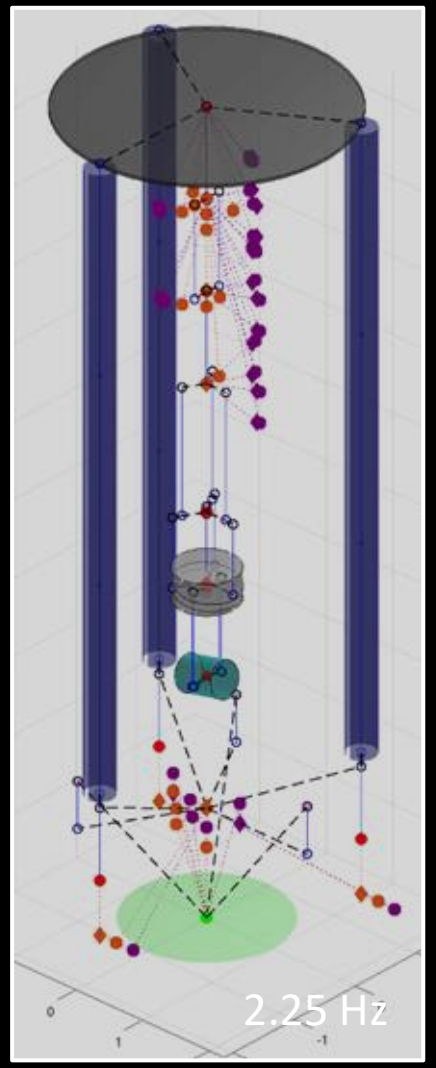


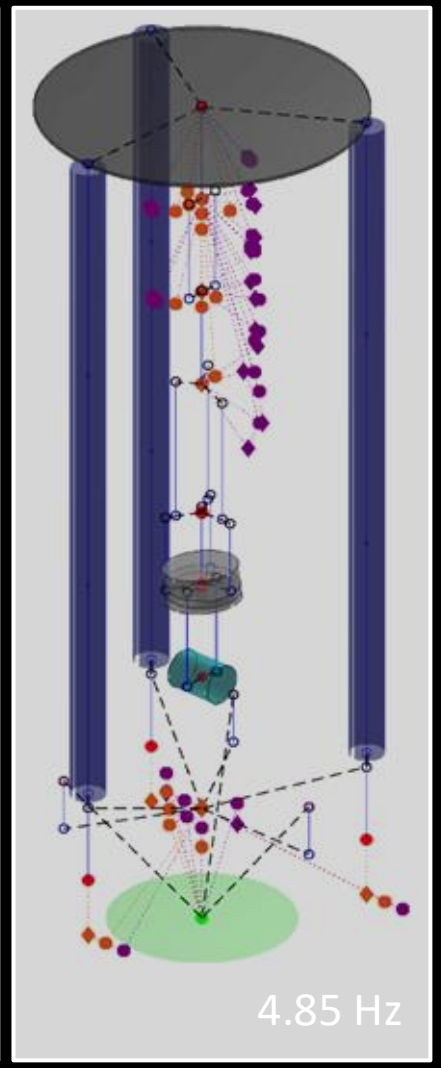
credit: Robin Cornelissen
https://git.ligo.org/robin.cornelissen/femto

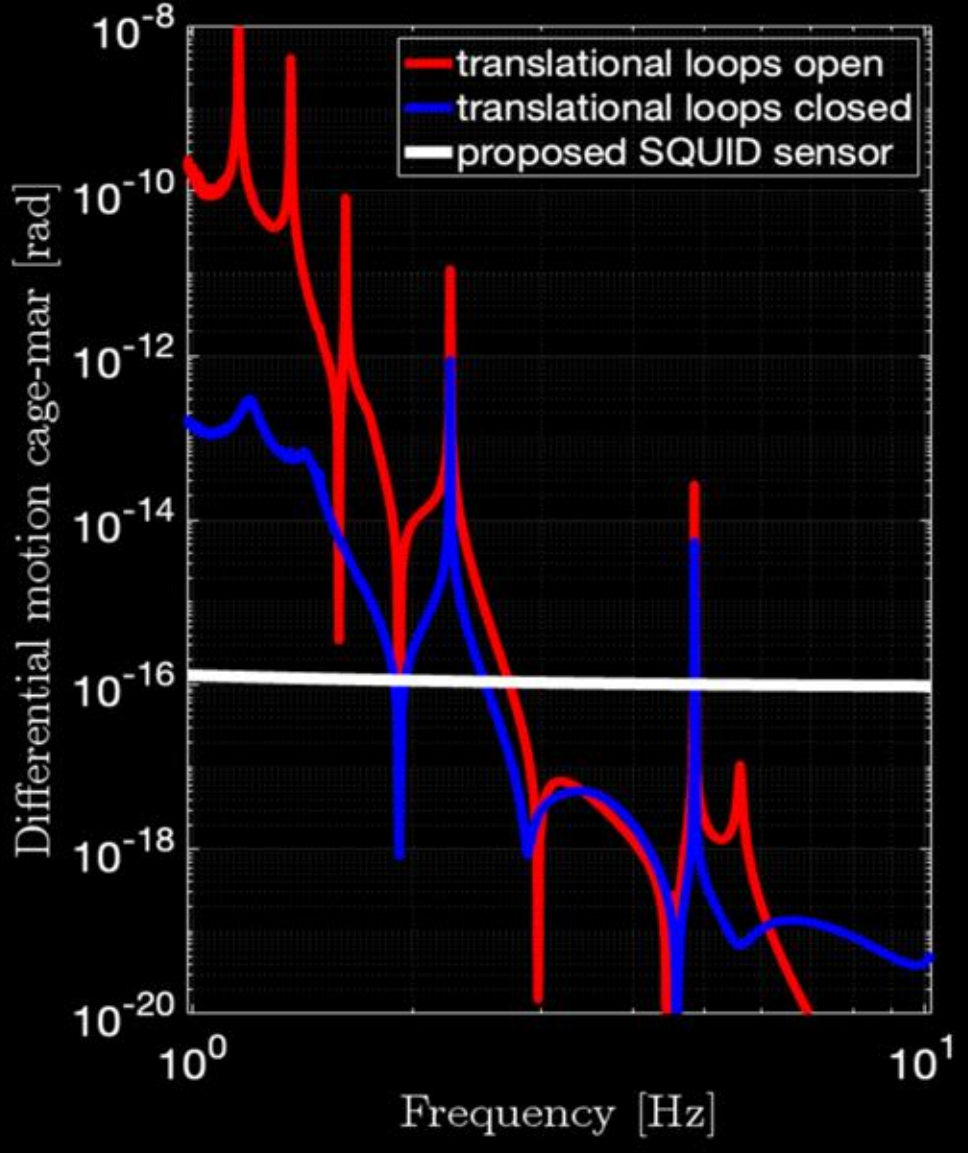


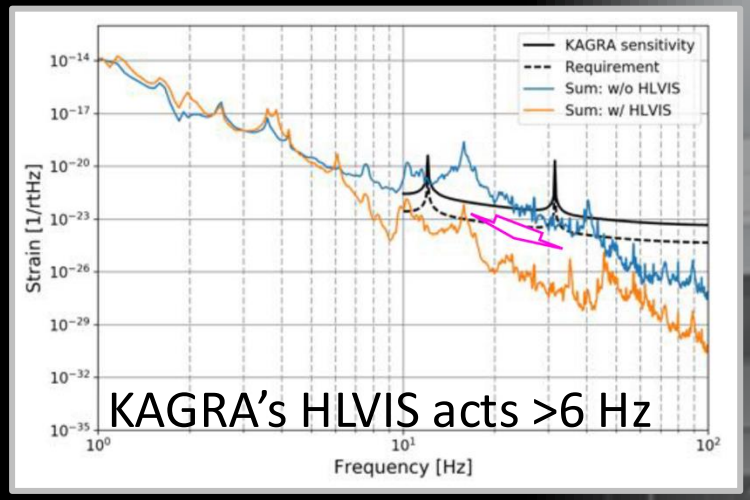
Can see undamped 2.25 Hz and 4.85 Hz mode



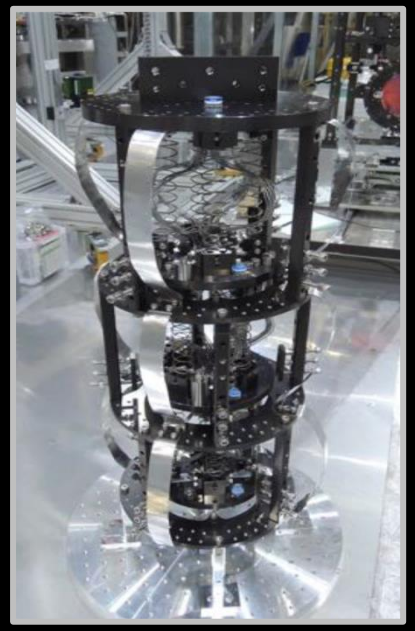




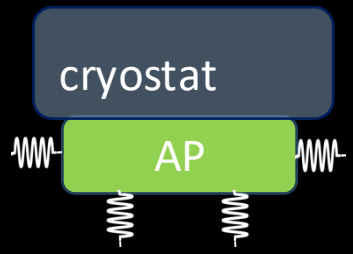




- KAGRA's heat link vibration isolation system (HLVIS) is 0.7 meter tall;



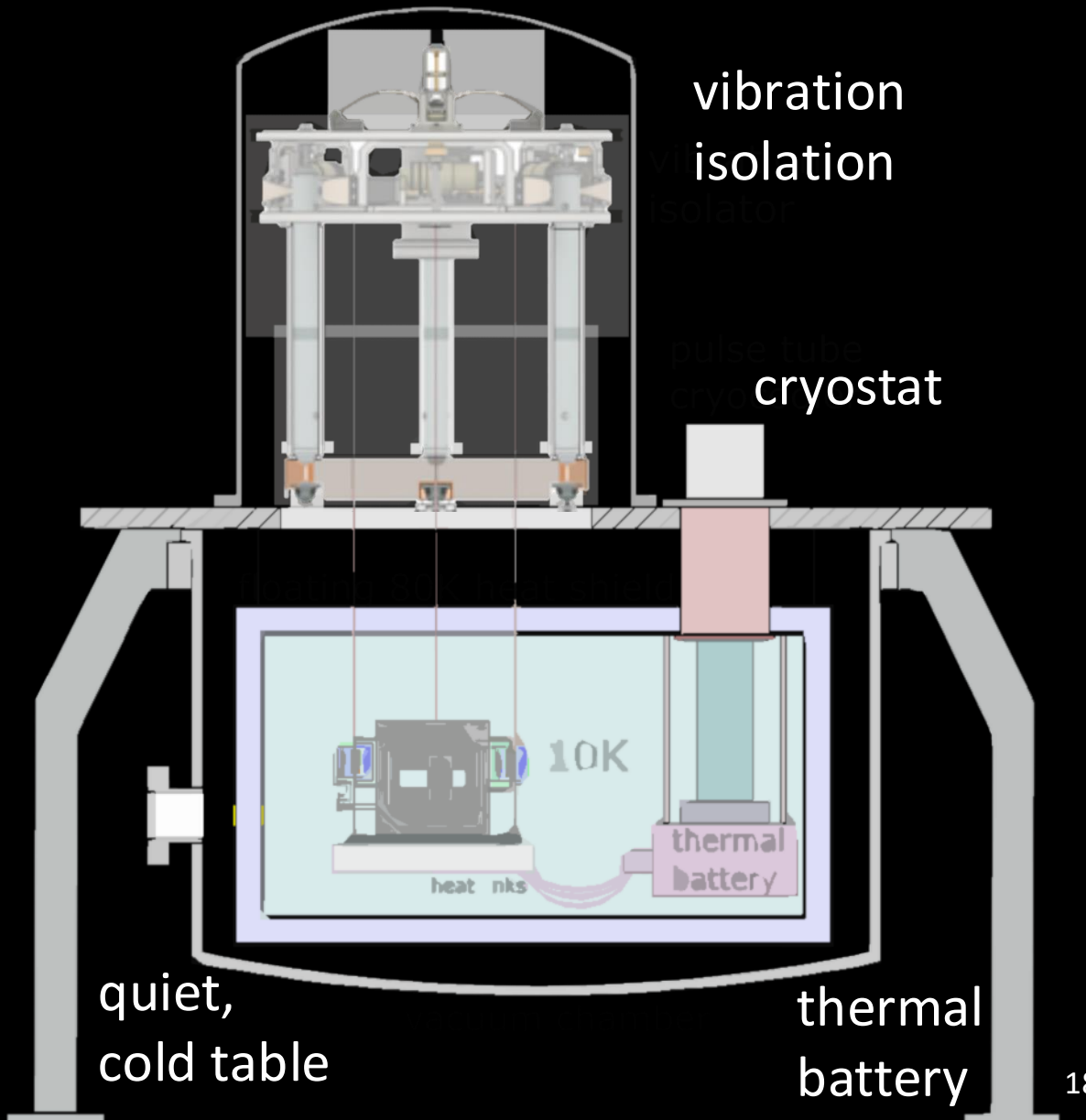
- Using the same technology, horizontal ($f_0 \sim \sqrt{(1/L)}$ length needs 11-fold increase for 1.8 Hz (60% $f_{low,BW}$) cut-off;
- Actively isolated stages in (and under!) cryostat are needed using our superconducting sensors/actuators;



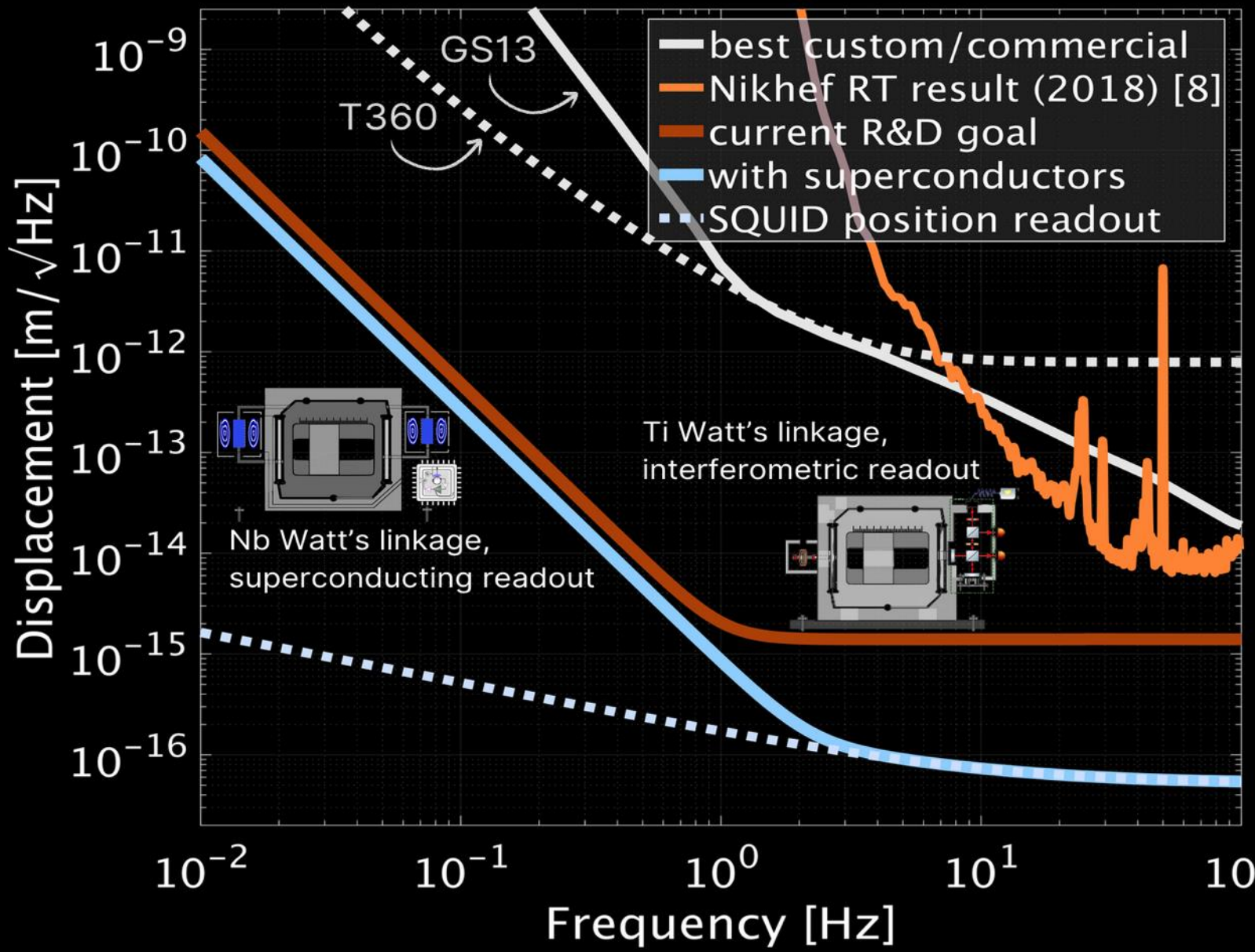
- Next step in modelling is to attach such stage to the cage via HL in our 11-meter tower.

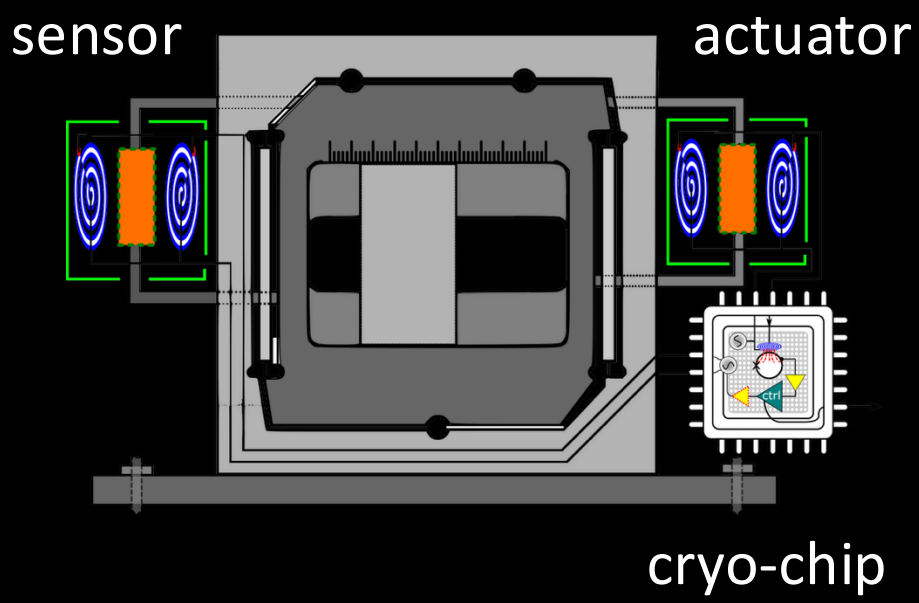
Sensor and actuator can be tested at Nikhef

- Cryogenic V-cavity experiment funds have realized this facility;
- Instead of V-cavity experiment, we place a Watt's linkage with actuator and sensor;
- A quiet and cold table allows performance tests at the sub-fm/√Hz level > 5-10 Hz.

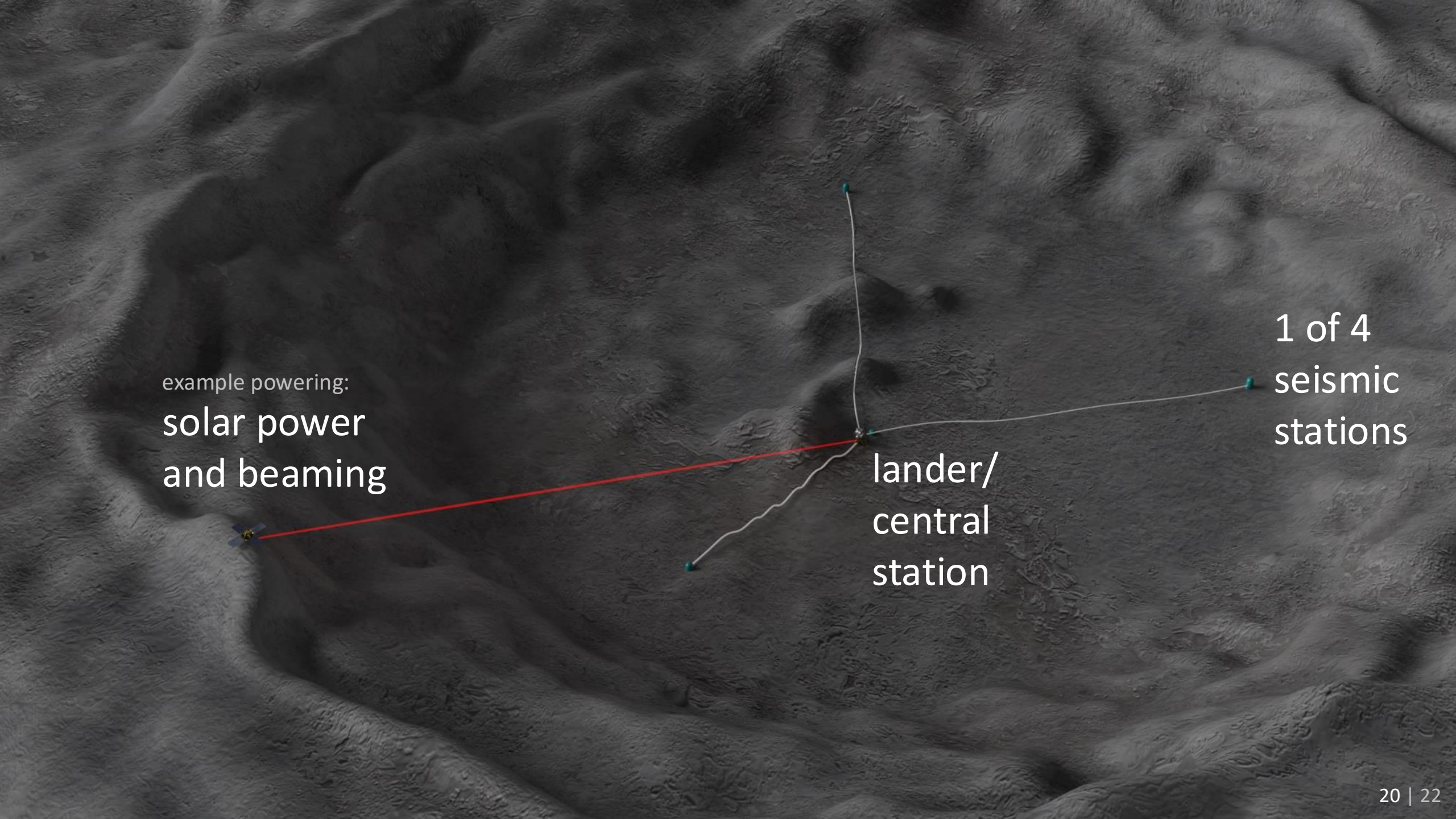


Sensor and actuator on inertial sensor

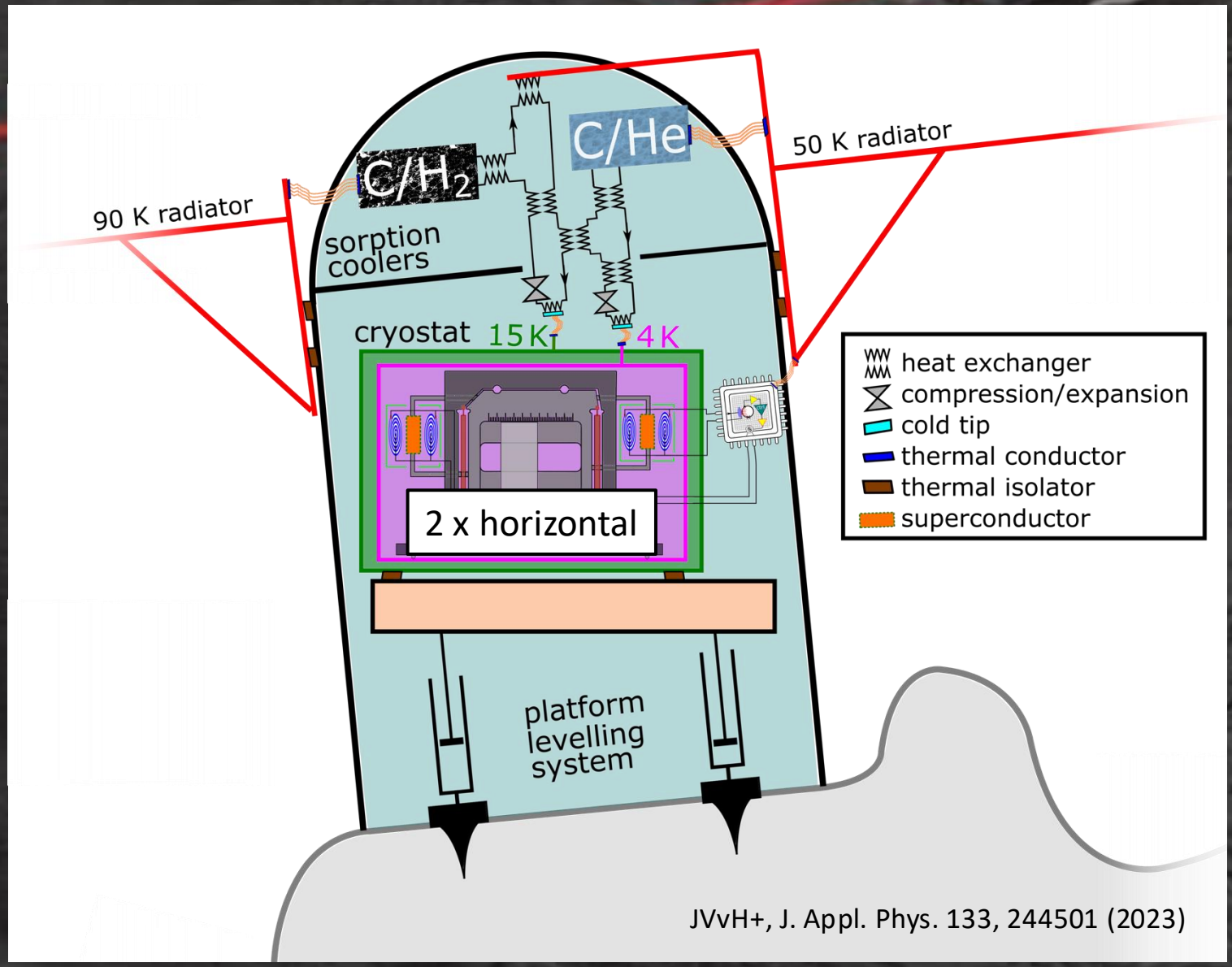




- Test setup can also act as inertial sensor;
- Can be deployed in ET cryostat and on the Moon.

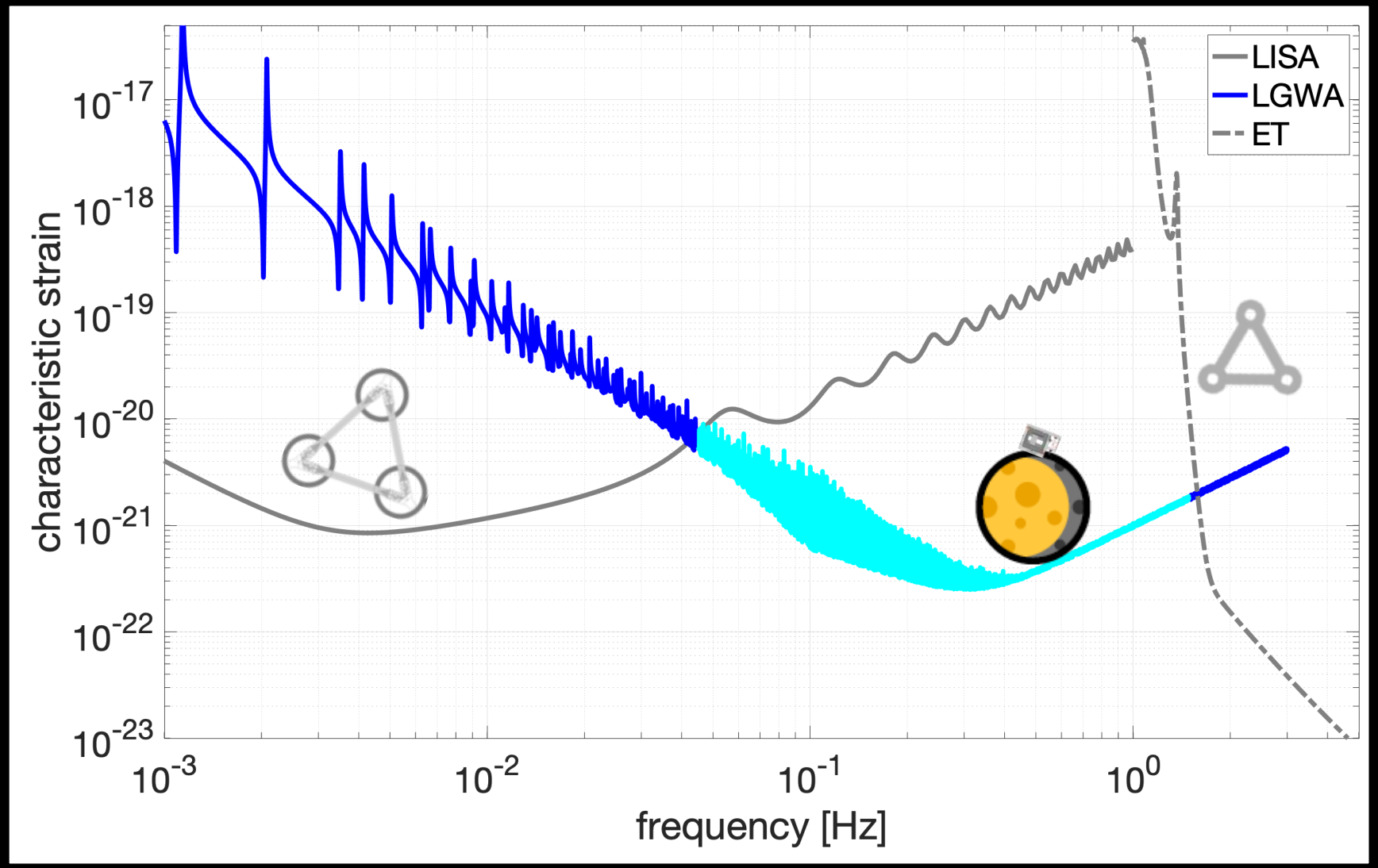

example powering:
solar power
and beaming
lander/
central
station
1 of 4
seismic
stations

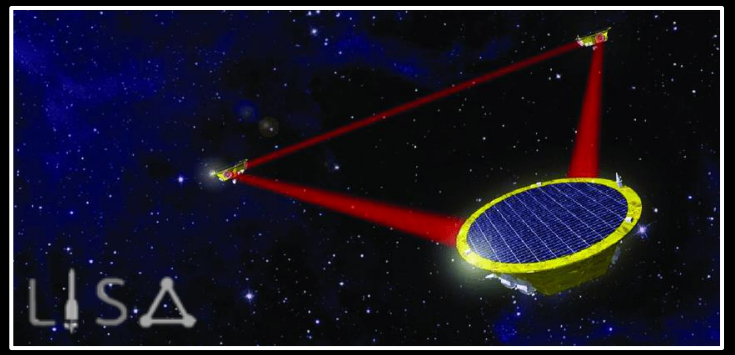
What would we deploy in the < 40K environment?

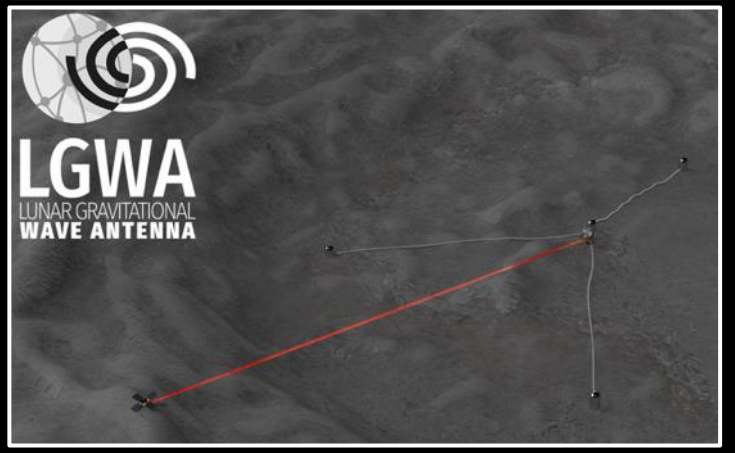


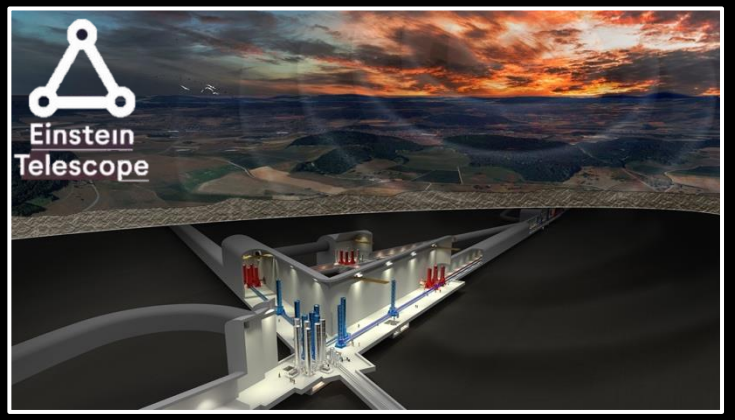
JVvH+, J. Appl. Phys. 133, 244501 (2023)

Bridging the gap between LISA and ET







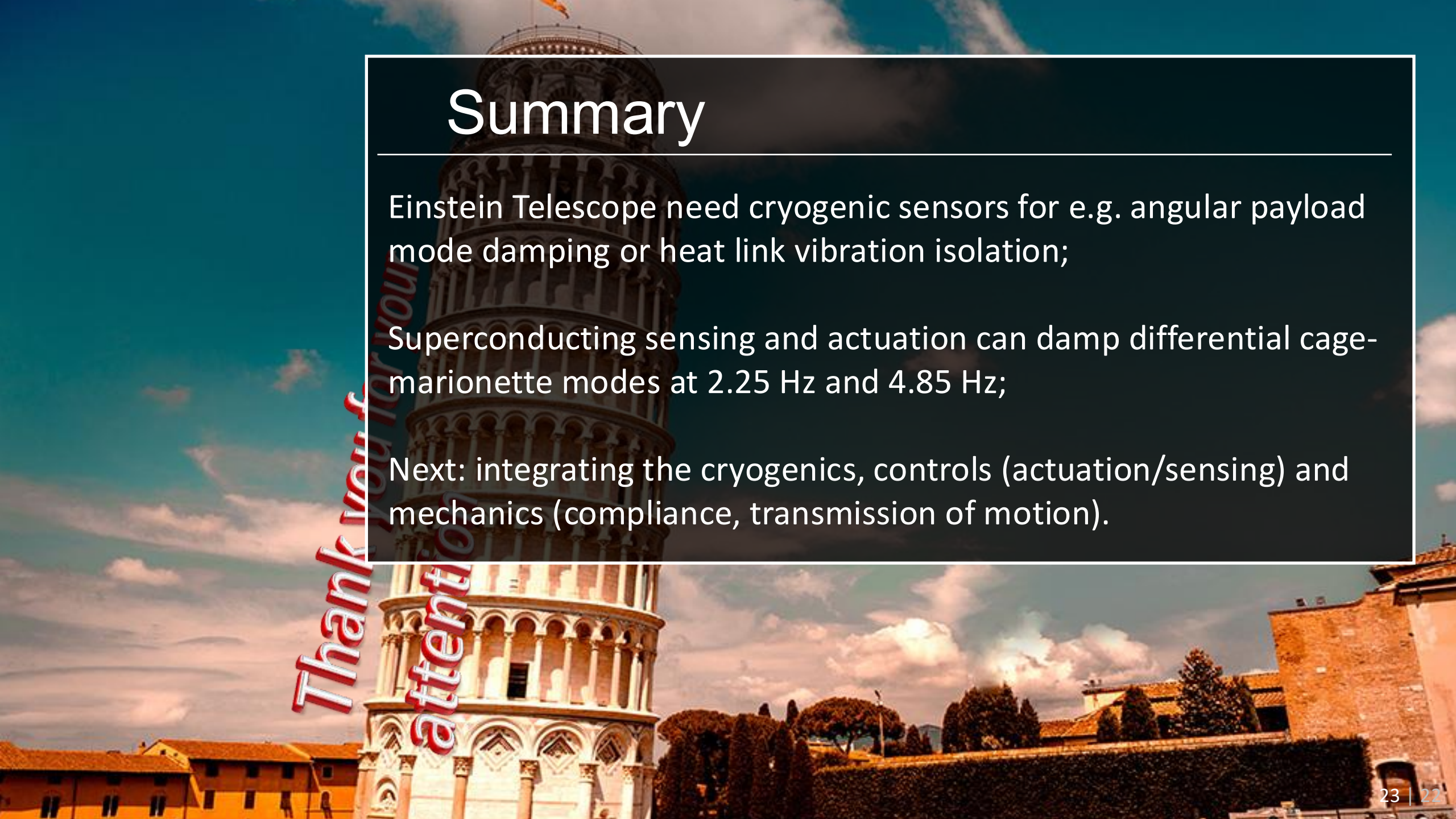


Summary

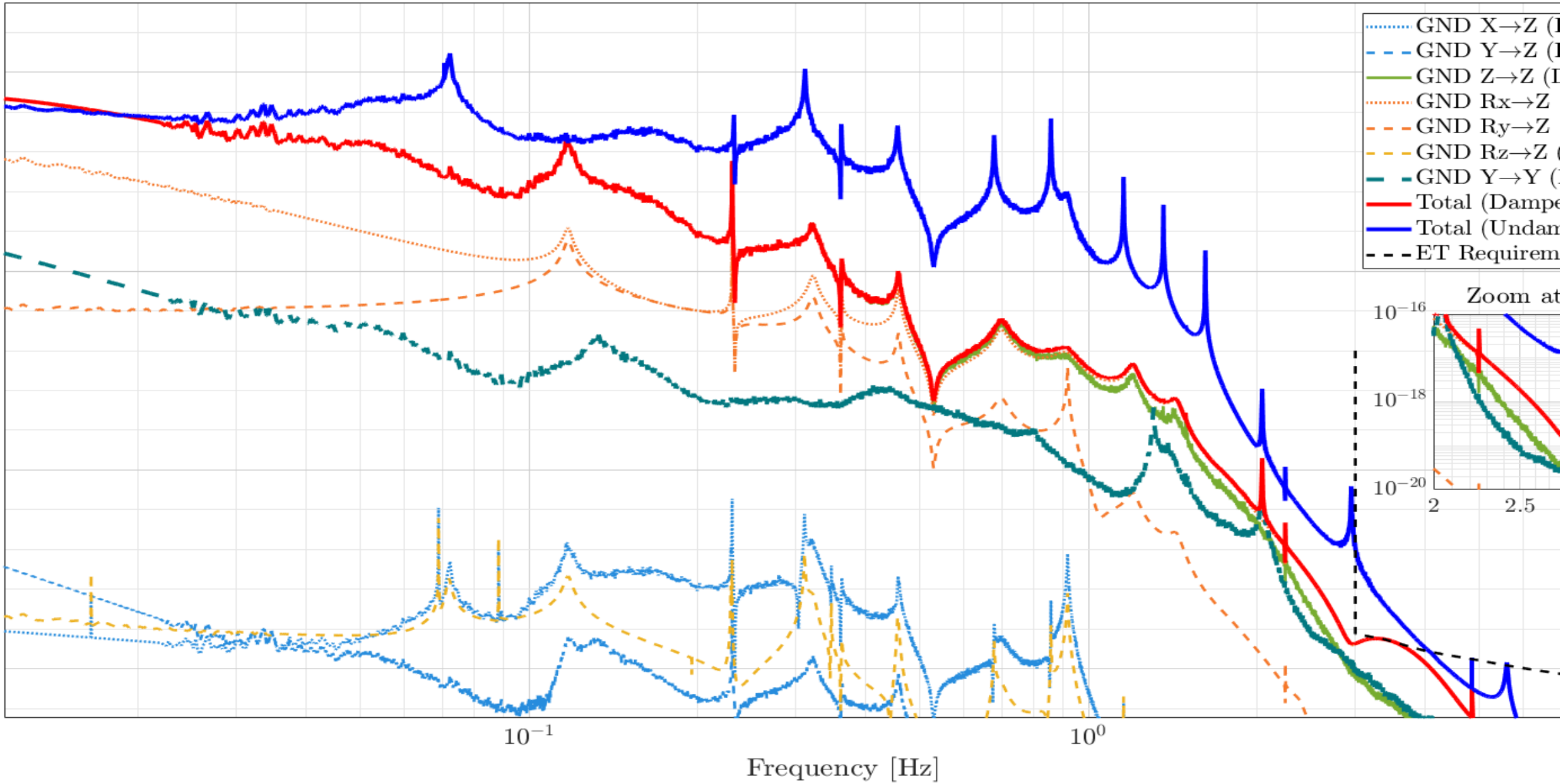
Einstein Telescope need cryogenic sensors for e.g. angular payload mode damping or heat link vibration isolation;

Superconducting sensing and actuation can damp differential cage-marionette modes at 2.25 Hz and 4.85 Hz;

Next: integrating the cryogenics, controls (actuation/sensing) and mechanics (compliance, transmission of motion).



Residual Seismic at Mirror: Closed-Loop, Longitudinal



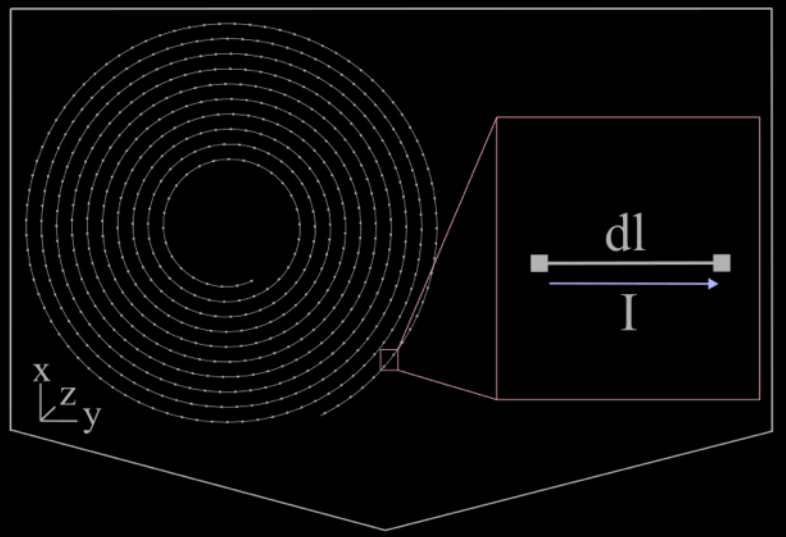
$$\phi_{12} = L_{\mathrm{c}}(I_{\mathrm{c1}} - I_{\mathrm{c2}}) + (M_{\mathrm{c1s}} + M_{\mathrm{c2s}})\frac{-M_{\mathrm{c1s}}I_{\mathrm{c1}} + M_{\mathrm{c2s}}I_{\mathrm{c2}}}{L_{\mathrm{s}}}$$

$$I_{\mathrm{c3}} = \phi_{12}\left(\frac{-2M_{\mathrm{cs}}^2 x}{d_0 L_{\mathrm{s}}(2L_{\mathrm{eff}}L_3 + L_{\mathrm{eff}}^2)}\right)$$

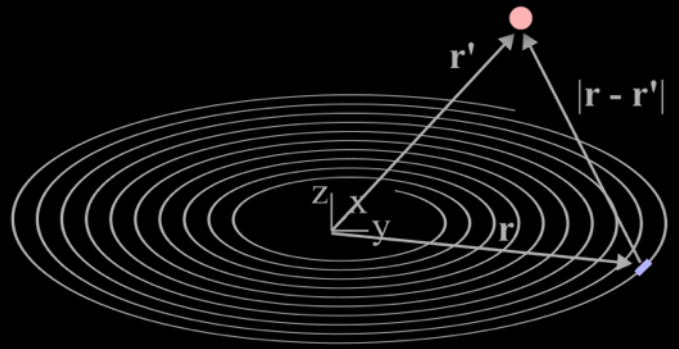
M = mutual inducance
L = coil inductance
I = currents through coils
d_0 = distance coil – SC flag

Analytical model in Matlab (1/2)

- Infinitely thin wires
- Based on Biot-Savart law
  - Divide coil in small segments
  - Calculate magnetic field contribution of all segments

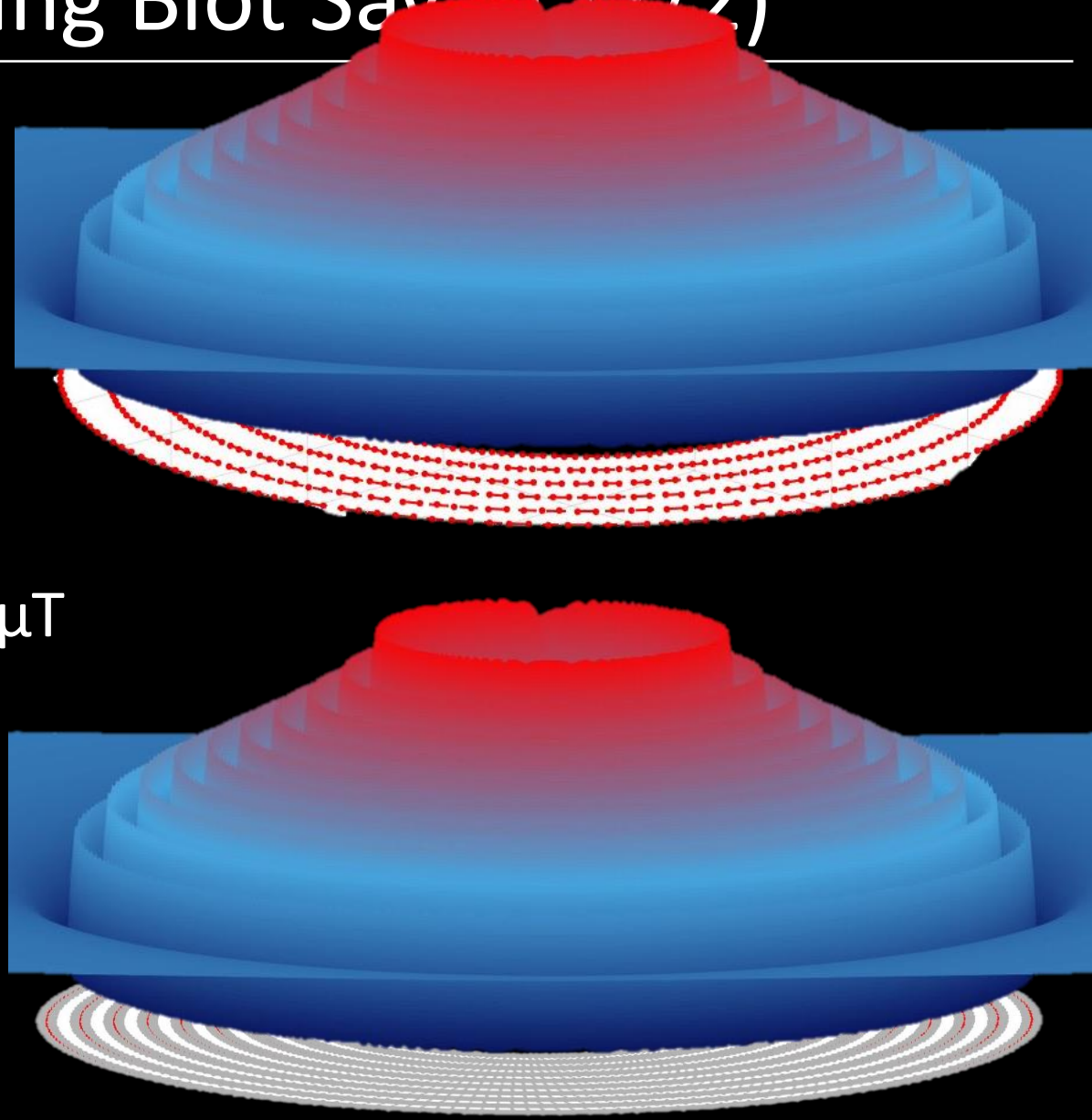


- Wire width by using several parallel wires
- Difficult / impossible to simulate superconductor

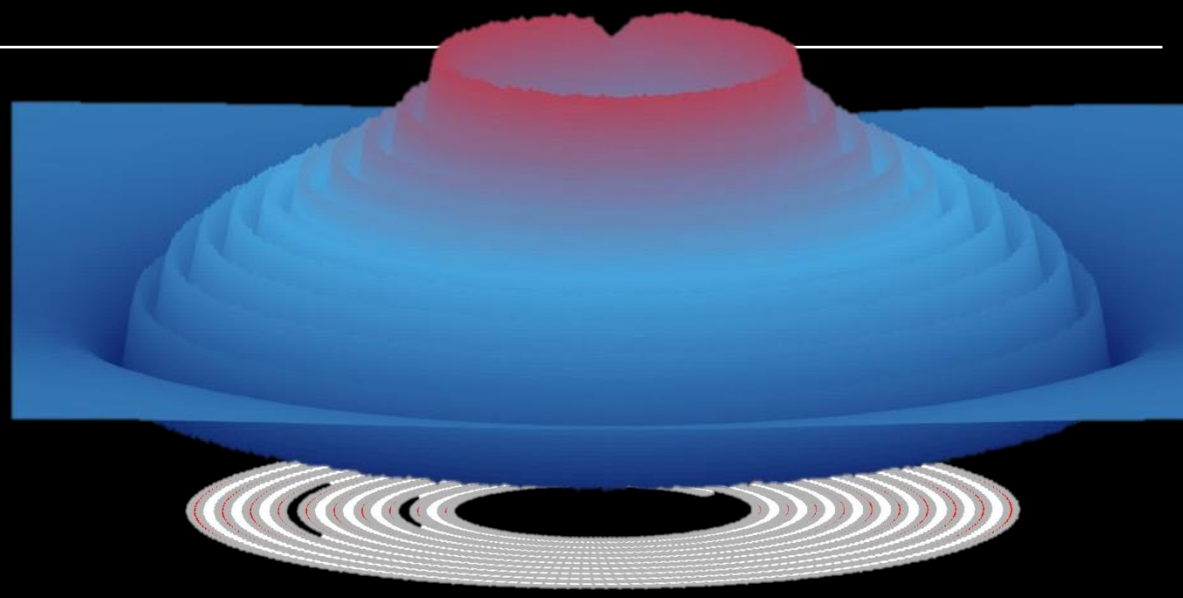


Analytical model in Matlab using Biot Savart (2/2)

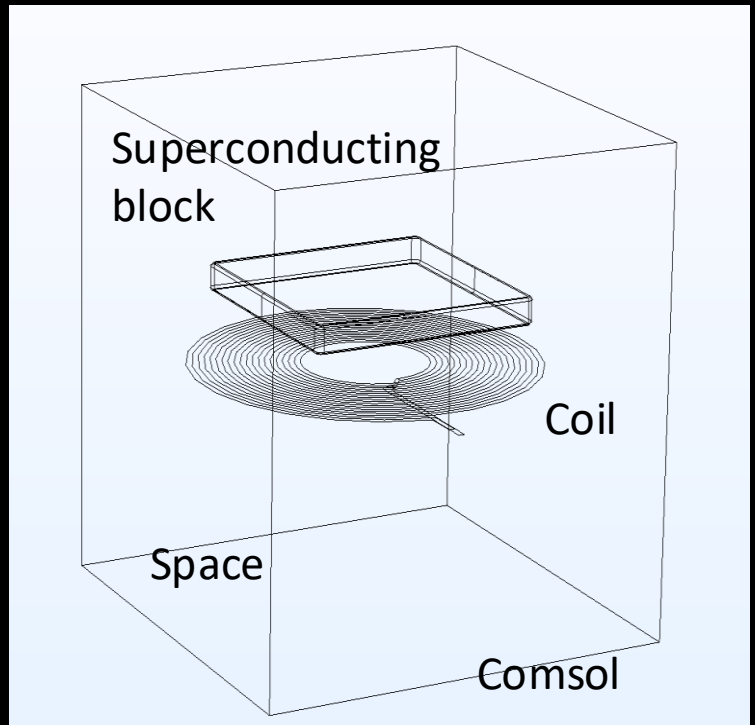
- Coil configuration:
  - 0.1 A
  - 10 windings
  - .25 cm and 0.75 cm respectively
- Maximum magnetic field fraction of µT
- Resulting magnetic pressure is size µN (or ~10 µN/A)



Numerical model in Comsol



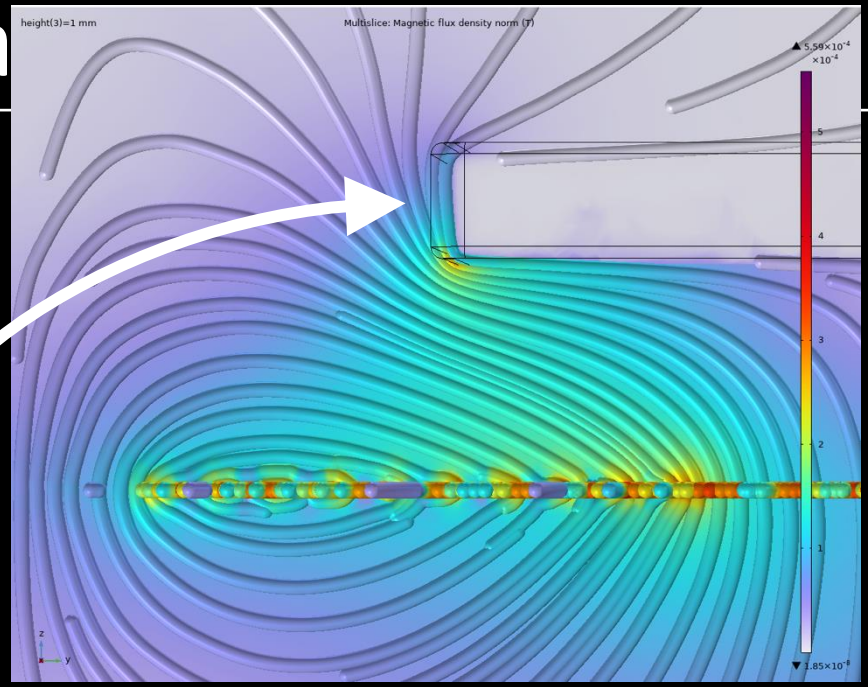
- 3D model of planar coil
  - Possible to incorporate coil width and height
  - Same coil geometry as in analytical model
  - Without sc maximum magnetic field: 0.21 mT (Comparable to analytical model)



29

Numerical model if 1-coil push actua

- Superconducting block (SB) and 1 single coil:
  - 10 windings
  - 0.25 cm and 1.5 cm inner and outer radius
  - 0.1 A
  - Varying distance between SB and coil
- Possible to include superconductor
  - Magnetic field lines are expelled!
- Magnetic pressure on superconductor



Sc – coil distance (mm)	Force (µN)
2	0.11
1.5	0.24
1	0.53
0.5	1.2

Vacrysim – vacuum and cryogenic simulations toolkit.
Tower integration: compact shields around cryogenic payload

Vacrysim

- Full cryogenic and vacuum simulation package.

- Calculates heat flows, temperatures during cool-down and molecular flow, pressures, migration of molecules (diffusion/permeation/adsorption) in all surfaces/volumes in the model.

- Cryogenic:
  - Define the full model. We built up the tower, arms, cryogenic shields, suspension system, and payload from basic building blocks: rectangular blocks (planes), cylinders, cones and spheres (dome).
  - Each of these blocks can contain holes; rectangular holes by fitting several rectangular blocks together or cylindrical/conical hole shapes in any building block
  - Cylinders,domes (partial spheres),cones fit together.
  - For all building blocks, define the orientation and the emissivity of each part of the surface, and whether it is connected to another block.
    - In total in the simulation I used about 500 building blocks, with about 70 holes for piping, wires, connecting arms/pumps.
    - In total the properties of about 2000 surfaces are defined.
  - Generated a few billion start tracks → scatter radiation from surface to surface until it is adsorbed (ran(x)<emissivity surface). If scattered, we can model diffuse scattering or specular scattering
  - Build up radiative view angle matrix: radiative transfer from one surface (depends on geometry, emissivity of all surfaces in the tracks in between) can be calculated as dQ(t)/dt = alpha (T1(t)^4 – T2(t)^4)
  - Build up compound objects: e.g. the mirror, the monolithic suspension, the reaction cage+baffles and screens, the marionette, the cold filter, the inner shield, the middle shield, the outer shield, passive shields, Iplegs+filters, tower, cryotrap, cold baffles etc.
  - For each of these compound objects, calculate the radiative transfer coefficients towards all other objects in the simulation
    - (by summing all transfers from all building blocks that are common to each pair)
  - For each of these compound objects, define also conductive links
    - Here, I assume bulk conductance for Copper (3R), Aluminum (6082), Stainless steel, Silicon, and the Kagra 6R Aluminum wires. The average length and cross-sectional area of such links between the center of 2 compound objects is specified.
    - Also transfer to cryogenic fluids can be specified; this is tracked in the code
  - In this manner, the diferential equations for the time evolution can be integrated by having fewer elements (in this simulation 46)

Vacrysim, cryogenic modeling

- For the compound objects (e.g. the cold filter or the reaction cage) we can thus calculate from the building blocks
  - 1) the latent heat at a given temperature. I start at 300K ajnd calculate the total heat.
  - 2) the radiative transfer from this object to all other objects in the simulation
  - 3) the conductive heat transfer using the defined links between the objects
  - 4) transfer to cryogenic gases is also modeled.

- Numerically solve the coupled equations as a function of time, to obtain the cool-down curves, the required cooling power, and the static heat loads.

Cryogenic modeling

- Aim for compact shields around the payload:
  - Allows for IP legs resting on the ground
  - Requires in total less cooling power since the total surface area is smaller
  - Based on ETpathfinder design: the modeled shields contain enough space for the required cryogenic piping.

- Double-walled shields: allow for pumping via staggered holes. Allows for piping/thermal heaters and sensors to pass through without direct line of view.

- Shield design was based on sorption coolers: innermost heat exchanger around 8K, inner shield 15K, middle shield 40K, LN2 shield 80-100K, passive floating outer shields

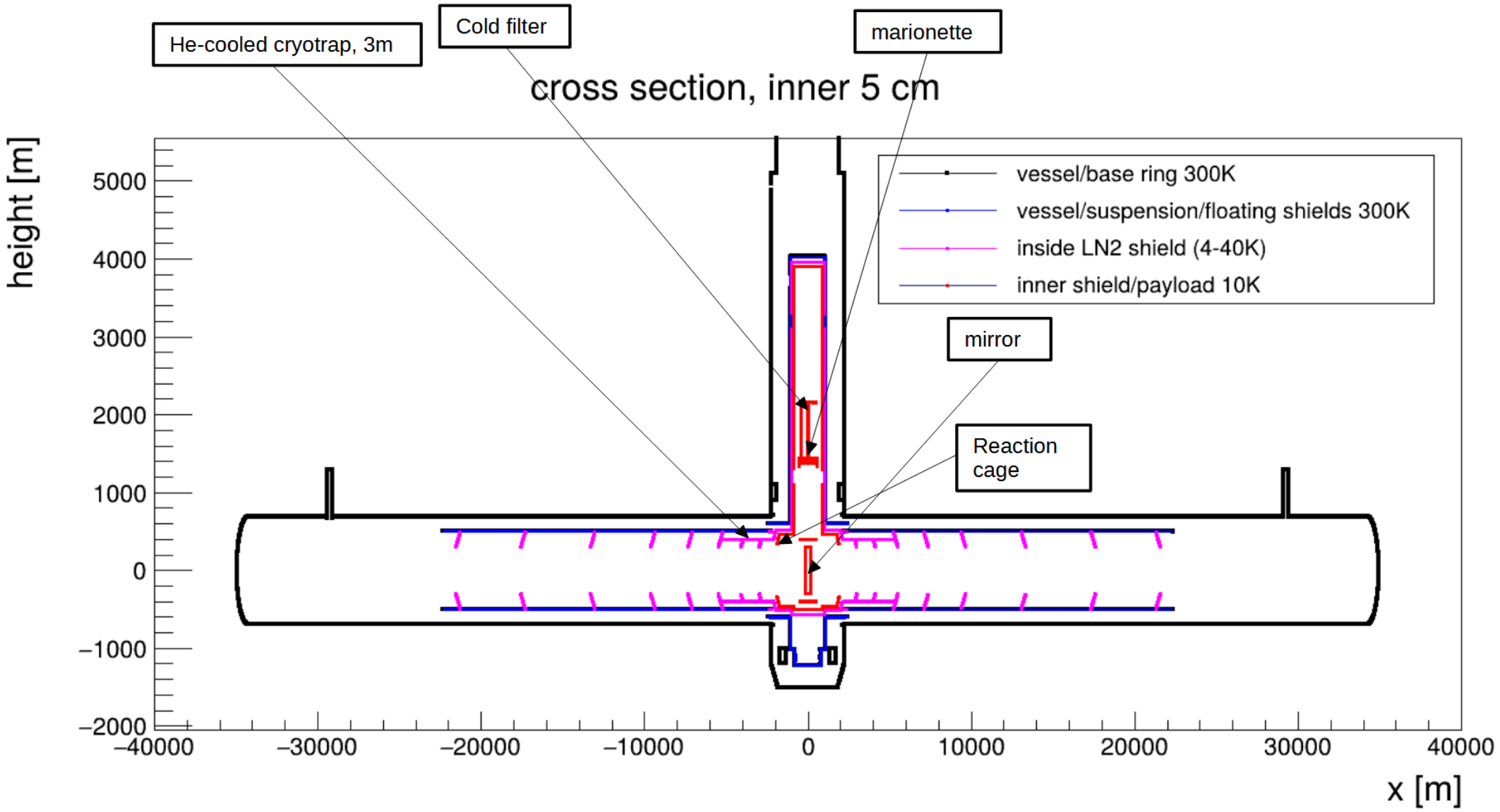
- Payload target temperature around 10K

- Assumed is that jellyfish wires via filters are coupled between the heat exchanger inside the inner shield and the reaction cage, as well as between the reaction cage and the cold filter 7. The cold filter provides some vertical damping via the blade springs and has a horizontally stiff coupling (thick rod) to the center of the marionette, which is assumed a monolithic silicon coupling (but sapphire should give same results)

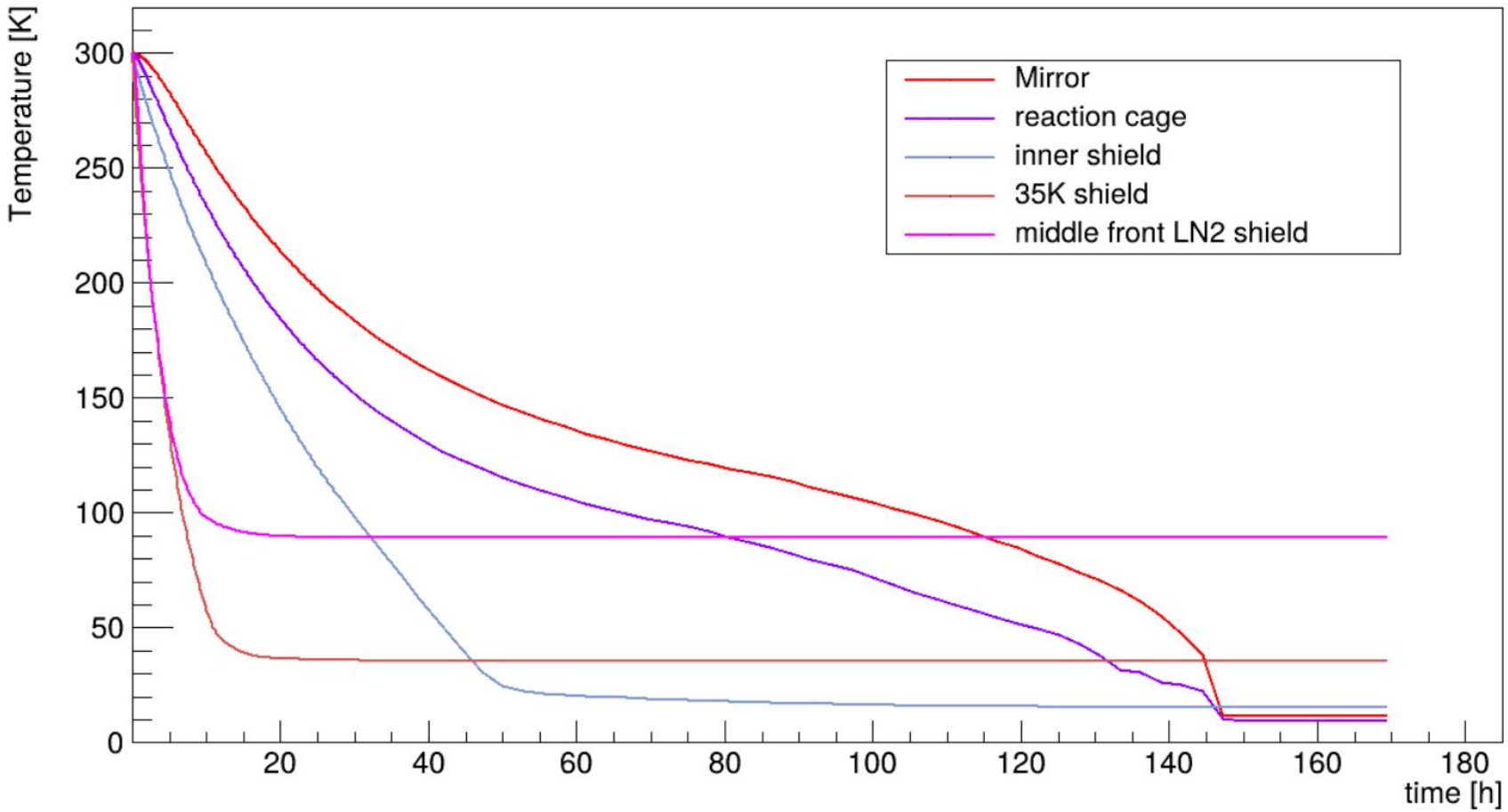
- Assumed is that for the monolithic coupling from mirror to marionette, thick beams of silicon with flexures under pressure can be built – relatively high conductive transfer between mirror, marionette and center of the cold filter; the limit is in the jellyfish wires.

- Assumed are cold traps , Helium-cooled up to 5m downstream/upstream and LN2 cooled up to 22.5 m downstream/upstream
  - I placed cold baffles inside the LN2 shield c.f. Hanke – ET-0417A-23
  - I think that for a full design, these baffles need more shielding.

Cryogenic modeling



Cool-down curves



Cool-down curves. assumed is a very good contact between cryogenic fluids and shields. In practice the initial cryogenic flows will be smaller hence the initial cool-down proceeds a bit slower. After 150 hours the system is in thermal equilibrium.

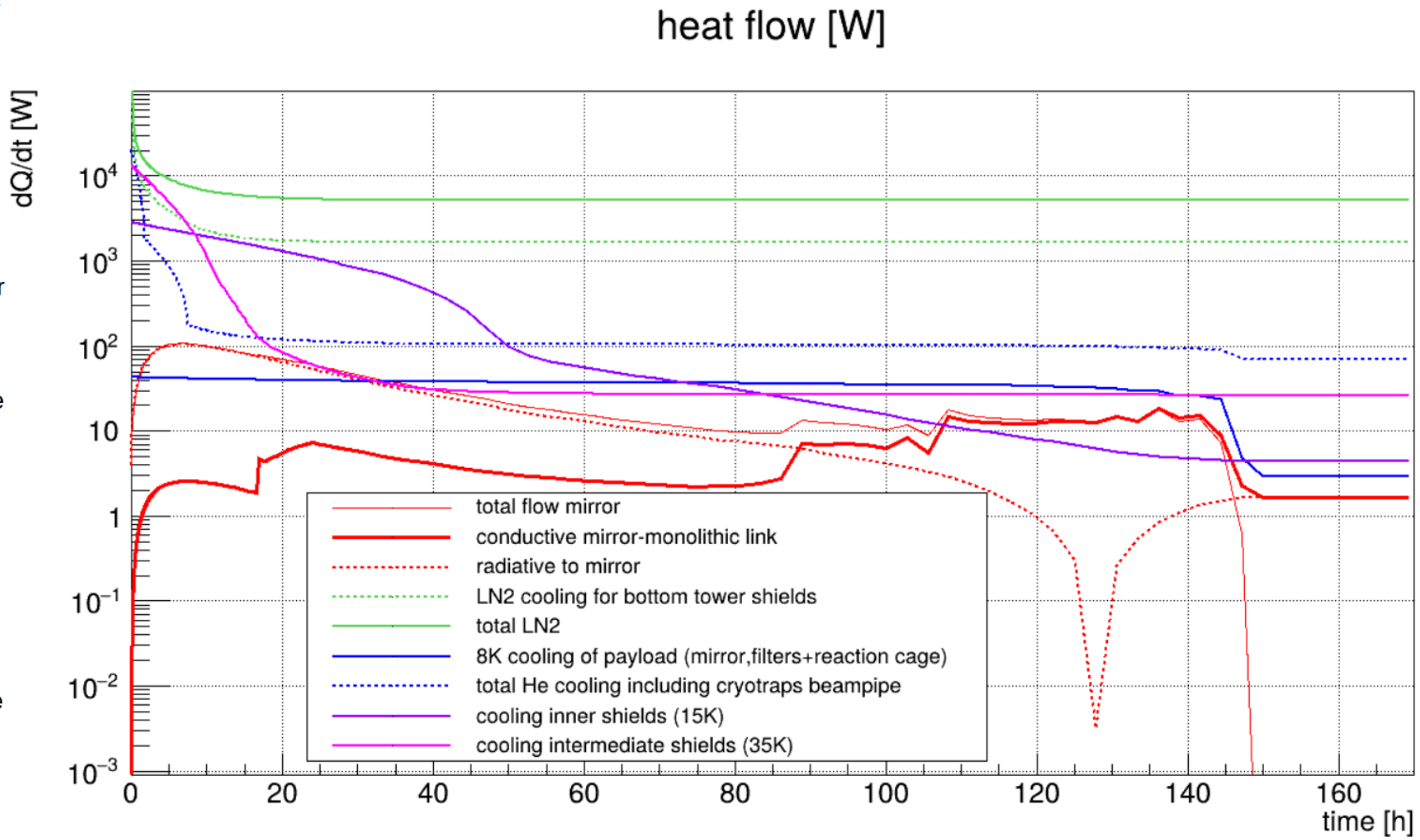
Cool-down powers

Heat flow into different bodies (for the same calculation as the temperature curves on previous page).

LN2 cooling is provided to the cryotraps, to different shields and baffles, and at different points of the shields around the payload. After a day, about 5 kW cooling power is needed around the tower (about 100l/h of sub-cooled LN2).

The first 4 days, radiative cooling of the mirror dominates. When the temperature of the reaction cage comes below 40K, the jellyfish wires start to become efficient. Here, 5000 wires with diameter 0.15mm between cold filter and 8K platform are assumed (1m length, catenary loop).

Mirror needs 1.5W cooling power in the end, inner shield about 7W, intermediate shields 30W, and the LN2 shields about 5 kW.
Can be optimized by choosing more passive shielding/different cryoducts.



Vacuum calculations

- Tracking of molecules during pump-down is done by generating outgassing at all surfaces. The model allows for adsorption and desorption of water on steel, aluminum, Copper; CO and CO2, diffusion of hydrogen in stainless steel SS-304/SS-316 or ferritic steel, evaporation and sublimation of molecules as function of temperature, migration of gas through polymers.

- We included 0.6 m^2 surface of Kapton cable (mantle thickness 0.2 mm) around the payload (for heaters, sensors, and actuators filter7) and 5 m^2 of Kapton cable mantle in the tower (which may be an underestimate). Temperature-dependent outgassing (leading to initial 1/sqrt(t) behavior) is included.

- All metal surfaces start with a full monolayer of water and multilayers according to sublimation curves. We assume a Temkin-like isotherm for outgassing that reproduces 1/t behavior as common in literature, and we assume 2e19 molecules/m2 for stainless steel in the monolayer.

- We generated about a million start tracks starting from the surfaces and followed the molecules until they hit a pump (geometrically modeled as a hole in the tower or beam pipe). We included 4 holes in the tower (8 m above mirror) and 2 holes in the beampipe (29m from the tower) for a total pumpspeed of air at room temperature of about 22.7m3/s.

- The total vacuum system modeled has a volume of about 390 m3 and a surface of 1665 m2. Our model gives for Nitrogen an average pumpdown speed of about 18m3/s, indicating that the conductance of the vacuum vessel itself is sufficient for efficiently pumping down. On average, particles travel about

- For all surfaces, the number of hits from surface to surface and the total traveled distance is stored (typically ~7 km and around 20,000 hits).

- In the time evolution for the coupled differential equations, the incident rates at each surface is calculated, the new density profiles for hydrogen in steel and rest gases in polymers are calculated, surface adsorption/desorption and recombination is calculated (as function of the temperature of the surface) and the flow of gases between all surfaces is updated. This coupled system has a few thousand parameters and the equations are stiff (i.e. if a surface is cold, the incident gas may freeze and the pressure decreases in microseconds). A 6th-order Runge Kutta stepper with adaptive stepsize is used and the total number of molecules in the system is tracked, to re-assure that no numerical errors creep up. Still, time steps of microseconds are needed in some cases for hydrogen (changing concentrations in the oxide hide) and water (rapid filling of monolayers, rapid pressure drop due to sublimation on cold surfaces).

Vacuum calculations

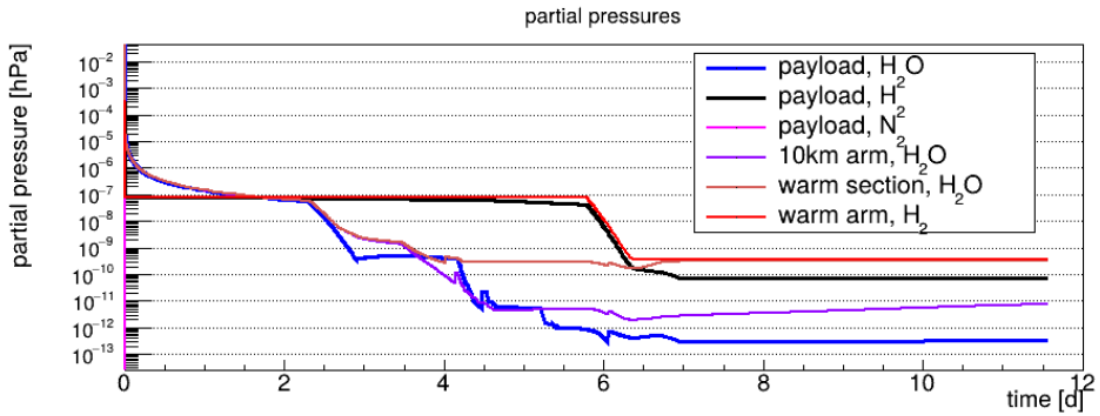
Latest calculation. Nitrogen pressure drops below 1e-12 hPa in 700 seconds. The monolayer of water causes 1/t dependence for the first 2,5 days, leading to a pressure of 1e-7 hPa after 2,5 days of pumping, while heating the total system to 343K (and the arms even warmer at 365/400 K). This is needed to get rid of some of the initial water.
We keep the payload and tower/arms warm while cooling down the shields/cryotraps, so that the ice buildup starts at the shields.

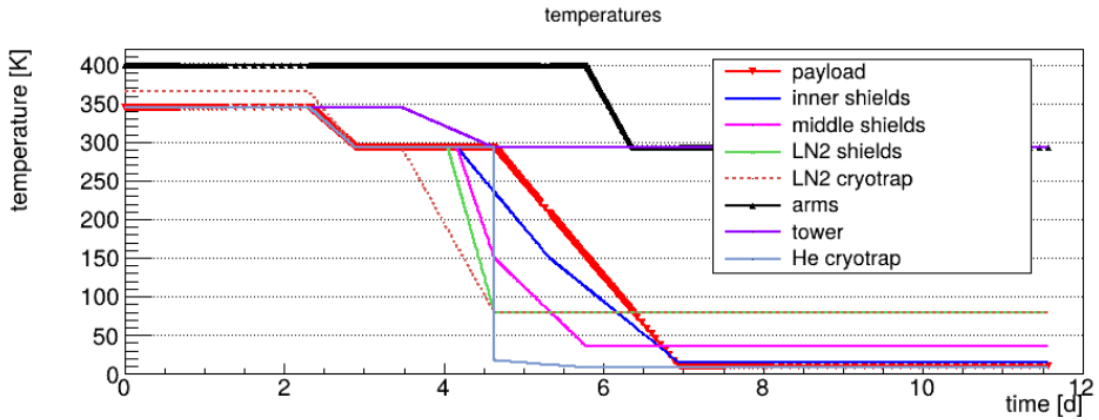
In this calculation I assumed an ultimate steady-state outgassing load from the 10km beampipe of 1e-6 (mbar l/s) hydrogen and 1e-7 mbarl/s H2O; the hydrogen flow from the warm section equals 1e-5 mbarl/s of hydrogen and 1e-4 mbarl/s of water (the part flowing from arm towards cryotraps)

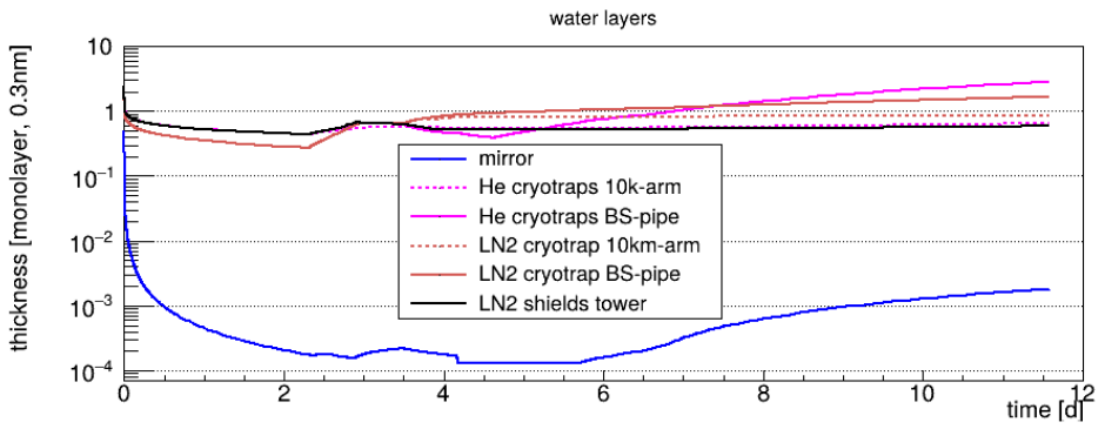
I assume ferritic stainless steel for the 10km arm and austenetic steel for the tower/the warm section. In order to get low H2 outgassing, the austenetic steel has been pre-baked for about 60 hours at 620 K, to reduce the concentration of hydrogen near the surface. (This calculation for all the different SS parts took several days, about 100 billion time steps in evolving the differential equations to get the profiles right).

In the top plot you see the average rate around the payload and in some other sections of the vacuum system as a function of time. After 10 days the rate is slowly going up, to be dominated by ballistic flow from the gas load of the warm BS pipe.

Middle plot shows the different temperatures of different sections. Bottom plot shows the layer thickness of water; if below 1 then this is the partial coverage of the surfaces.







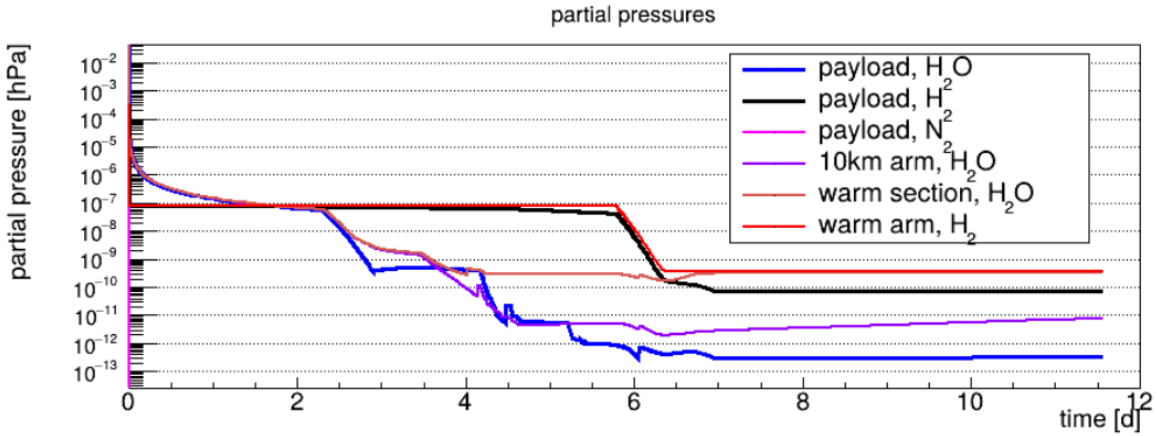
Vacuum calculations

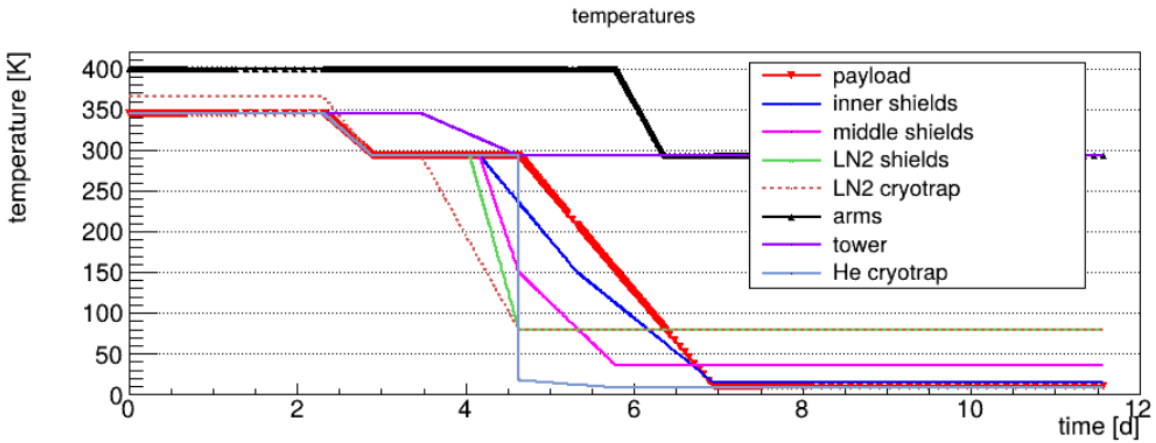
Same plot, with the bottom panel a zoom of the ice buildup at the mirror. After 7 days the newly entered water comes from the load of the beam pipes; the water in the tower has been distributed on the shields. Note that we have about 800 m2 of cold surfaces with the cryotraps and the shields; that is why the ice buildup is slow: 1mbarl at room temperature corresponds to about 2.4x10^19 molecules; they are basically frozen on the shields. Most freeze on the cold baffles of the cryotrap or the 20-m long LN2 shield. Since we have about 800m2 of cold surface we freeze about 10 monolayers per year on average on the shields; highest rate is on the He-cryotrap+baffles where we get about 0.5 layers/day.

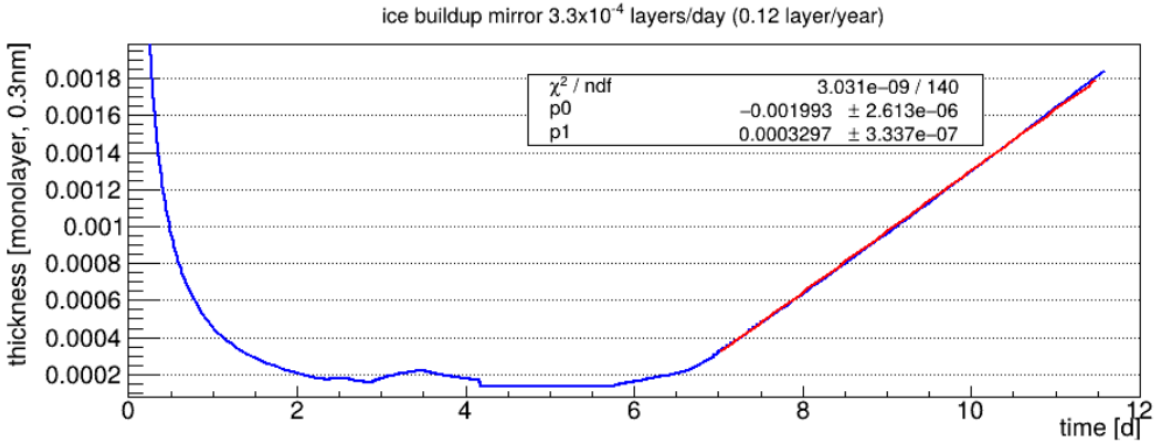
On the mirror the ice buildup is much slower, it is fitted in the zoom to be 3.3e-4 layers/day or 0.12 layers/year, about 1500 times slower than on the cryobaffles (see fig prev. page)

Actually this rate is dominated by ballistic flow from the BS-pipe section so the mirror side facing the 10km arm will have even less ice growth.

The double-walled shields contain staggered holes (total about 1m2) for vacuum conductance and straight holes at the top (and along the beampipes) to face the tower at the top; 4 holes for wires to the cold filter have a diameter of 4 mm. The conductance through those holes is included in the calculation, as well as the outgassing of >5m2 of kapton cable mantle in the warm section. Direct flow does not freeze on the mirror due to the presence of the cold filter below these holes.





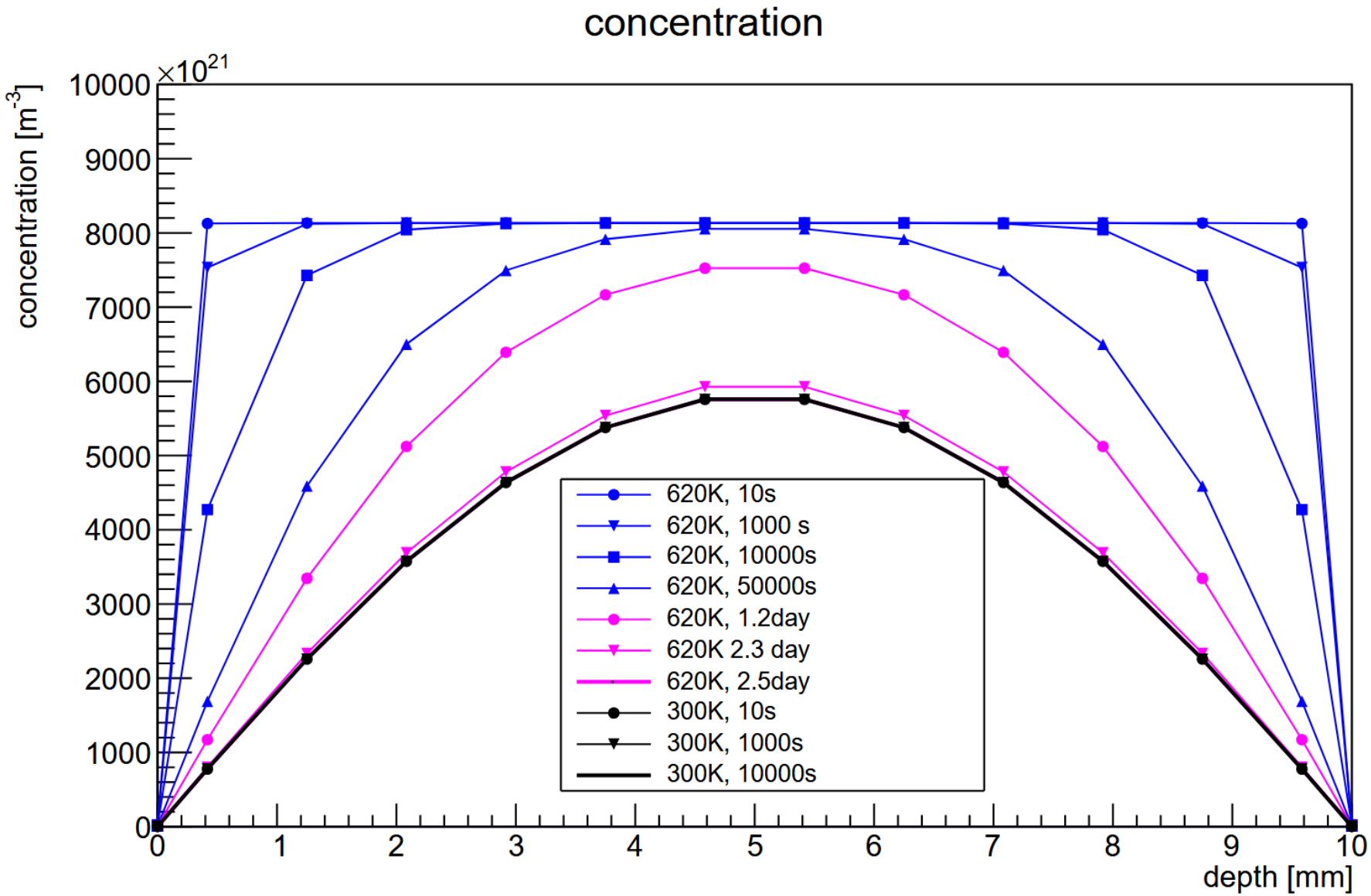


Vacuum calculations

- Total surface: 1864 m2
  - Total Si (mirror, suspension, monolithic part marionette and cold filter) 2.6 m2
  - Total Cu payload 12.18 m2
  - Total inner shield 152 m2
  - Wires inside inner shield 0.58m2, inside tower 6.6m2 of kapton mantle surface
  - Total 40K shield 188 m2
  - Total cold cryotrap+baffels 53 m2
  - Total LN2 shield (including cryotraps) 440 m2

Hydrogen concentrations

- Concentration profiles in 10-mm thick austenetic stainless steel as function of time during pre-bake.



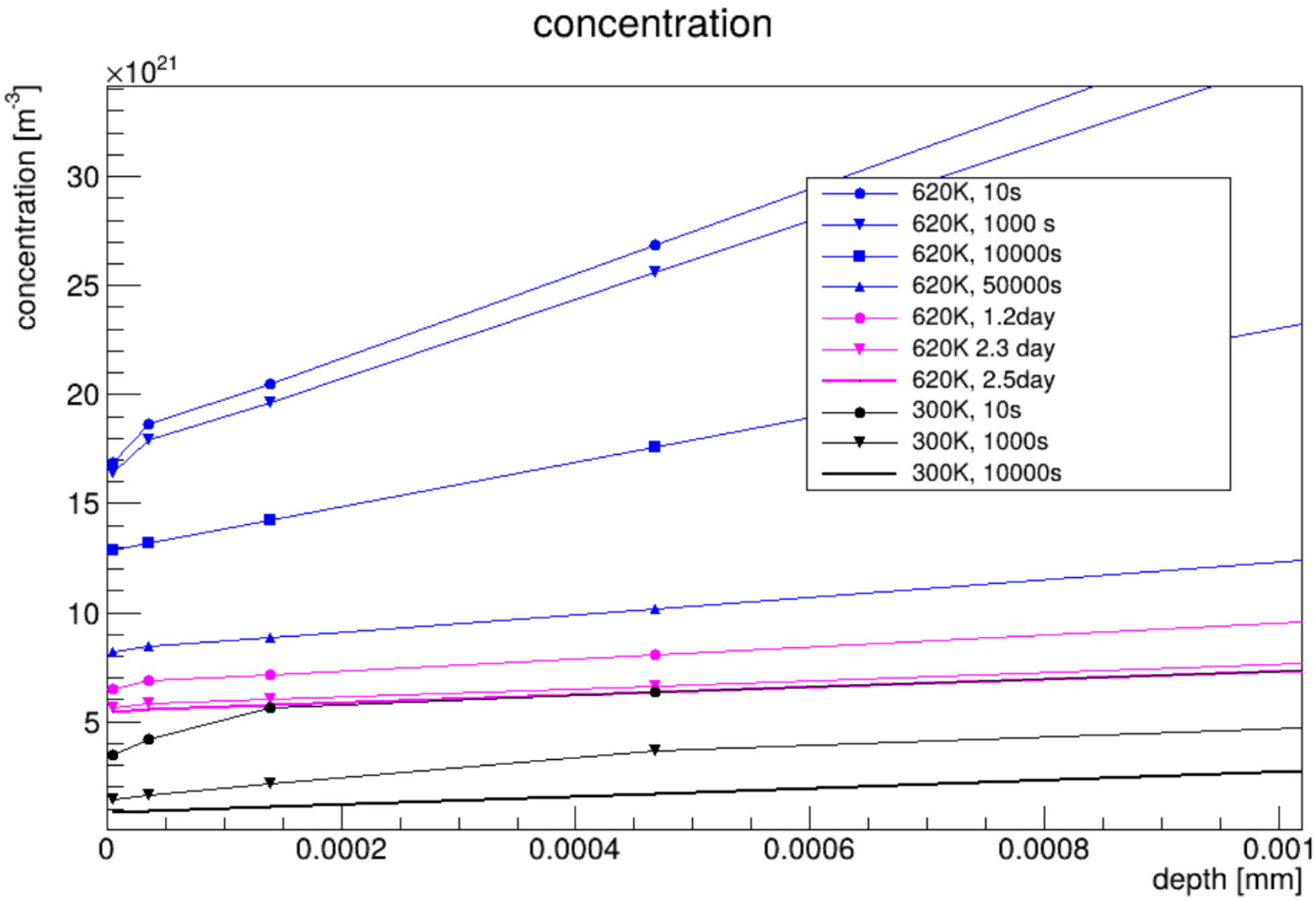
Hydrogen concentrations

- Concentration profiles in 10-mm thick austenetic stainless steel as function of time during pre-bake, zoom at the surface.

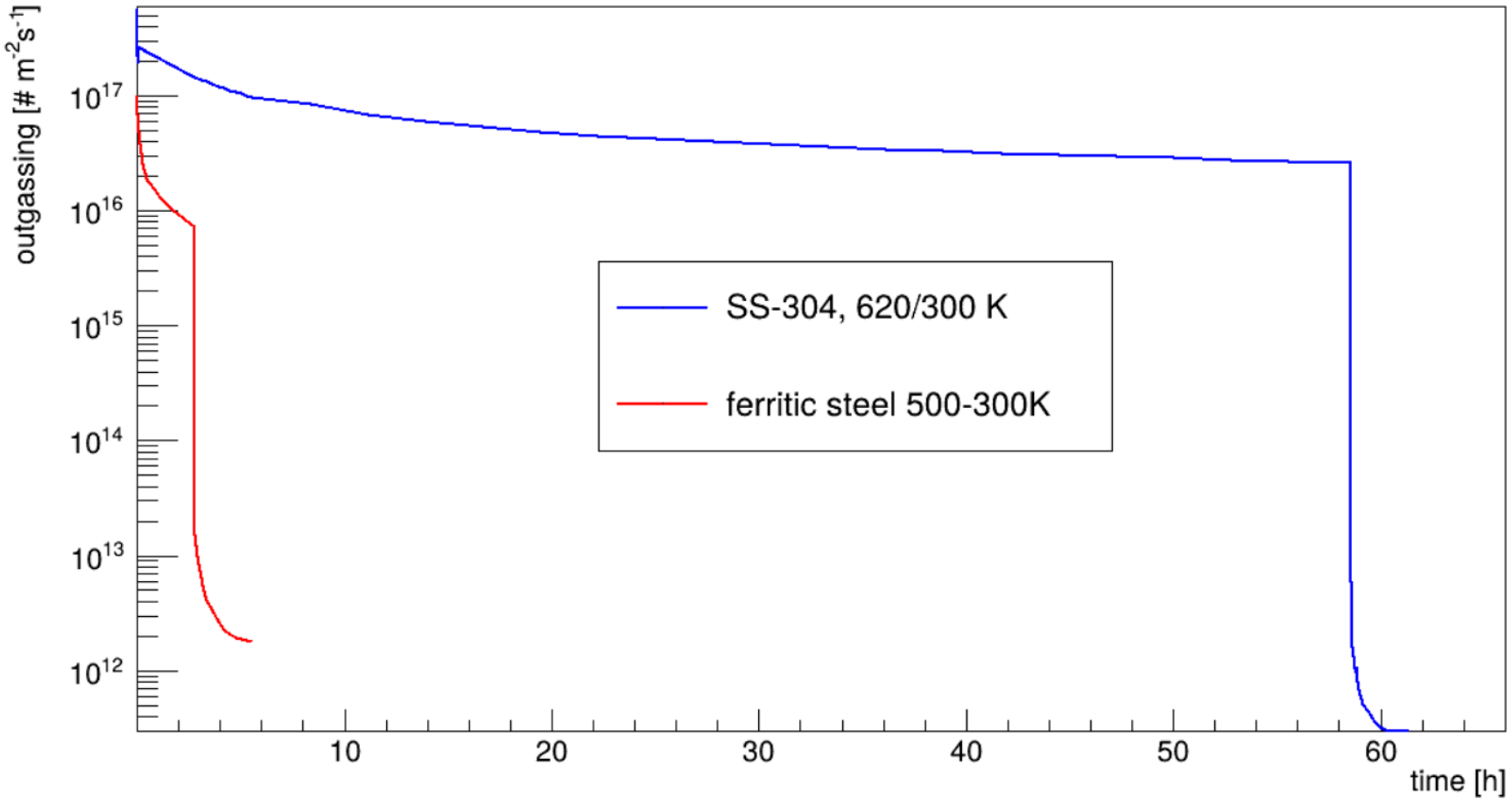
- The recombination step at the surface leads to outgassing of

$$\frac{dQ}{dt} = K_{rec}(T)\rho^2$$

- With rho the density squared in the surface layer and Krec the recombination cross section (exponential dependence on T)



Hydrogen outgassing during pre-bake

Outgassing as a function of time for baking steel at 620K (SS-304 or SS-316) and 500K (ferritic)

After baking, 10000 seconds at room temperature are also included leading to a rapid further depletion in the oxygen hide.