ET-LF Mirror Temperature

Workshop Conclusions

Outline

- Summaries from breakout rooms
  - Heat extraction path
  - Thermal noise modelling
  - Vacuum design

Heat extraction path

Heat extraction path design - summary of breakout room discussion

We need to agree with suspension people about a viable scheme for ET-LF payload.
We think that a series of dedicated meeting of all involved working groups should be scheduled.

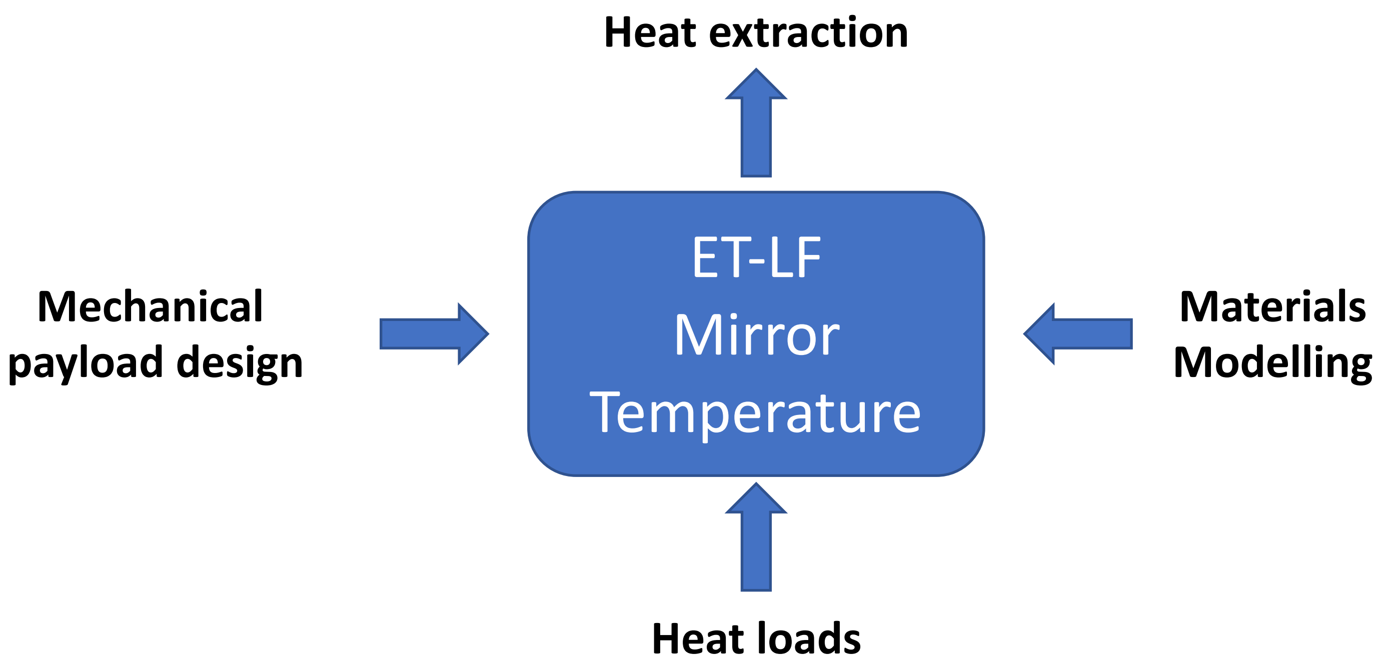
- See final slides

Payload features desirable from the Heat Extraction WP are:

- We need a **heavy mass** as close as possible to the mirror **to sink the vibrations** of thermal path links.
- We need a **thermal shield around the mirror** (suspended to marionette or not).
- We must ***preserve as much as possible the low dissipations of the marionette pendulum*** (for instance, using the suspension cable as a heat link)

ET-LF mirror temperature

- Aspects influencing the ET-LF mirror temperature



Action 1: Heat load

- **Heat load contributions**
  - ❖ Coating absorption
  - ❖ Substrate absorption
  - ❖ Thermal radiation (from pipe arms)
  - ❖ Surface regeneration (removal of adsorption layers)
  - ❖ Actuators
- **Documentation in ET Wiki**
  - Collect values in **heat load table** and update in regular intervals
  - References to code, documents etc.
  - Consideration of steady-state and transients

Action 2: Cryostat mechanical design parameter space

	Item	Cathegory	Value	Comment
1	**Mirror**			
1.1	Diameter	A	x…y mm	Determined by beam size
1.2	Mass	A	x…y kg	Determined by thermal noise
1.3	Bulk material	B	Silicon or sapphire	Silicon baseline
1.4	Coating(s)	B		
2	**Last stage suspension**			
2.1	No. of fibers	A	4	
2.2	Diameter	A	>= x mm	Mechanical strength
2.3	Length	A		
2.4	Material	B		
3	**Platform 1**			
3.1	…			
…	**Next steps:**			
…	- Structure the design space into functional elements			
…	- Assign space/volumes for the functional elements - …			
…				
N	**Cryostat vessel**			
N.1	Diameter	A	< 4 m	Maximum lorry height 4.0 m, maximum width 2.55 m
N.2	Height	A	x…y m	

The mechanical cryostat design determins the heat extraction path, the noise modelling and the vacuum design!

Action 2: Cryostat mechanical design parameter space

- Example specification item:

No.	Item	Value / Range
1.1	Mirror diameter	≥ x mm ≤ y mm x to y mm
	Additional information - Reference to documents - History - …	

The mechanical cryostat design determins the heat extraction path, the noise modelling and the vacuum design!

- Store and update the **cryostat design parameter table** in the ET Wiki
- First meeting t.b. organised shortly

Messages regarding mirror temperature

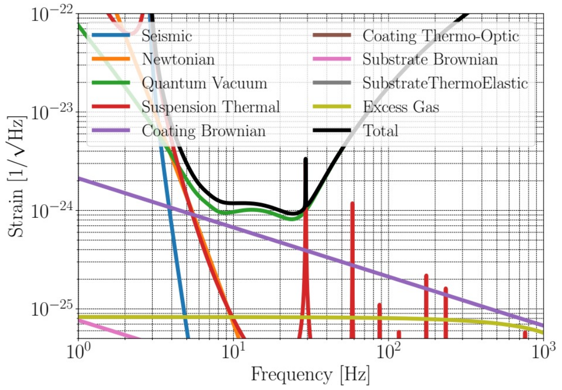
- In the short term, a mirror temperature of ≤ 20 K is feasible

- In the medium – long term, temperatures of 10 K and lower can be achieved

Thermal noise modelling

Goals

- derived a realistic noise budget to make sensible decision on the mirror temperature.
  We need:
  1) suspension thermal noise model
  2) mirror thermal noise model(s)
  3) temperature dependency of the material parameters



1 and 3 are currently missing, actions for the best way to move forward.

2 is present, will include multi-material coating, presence of ice

Subgroup notes in a shared document:

https://etherpad.in2p3.fr/p/ET_Cryo_noise_budget

Suspension thermal noise model (summary)

- Actions:
  - ➔ adaptation of the GWINC suspension model for AdV (in Matlab) as a start
  - ➔ thermal model to dimension the fibers
  - ➔ connection with ET-pathfinder and CE

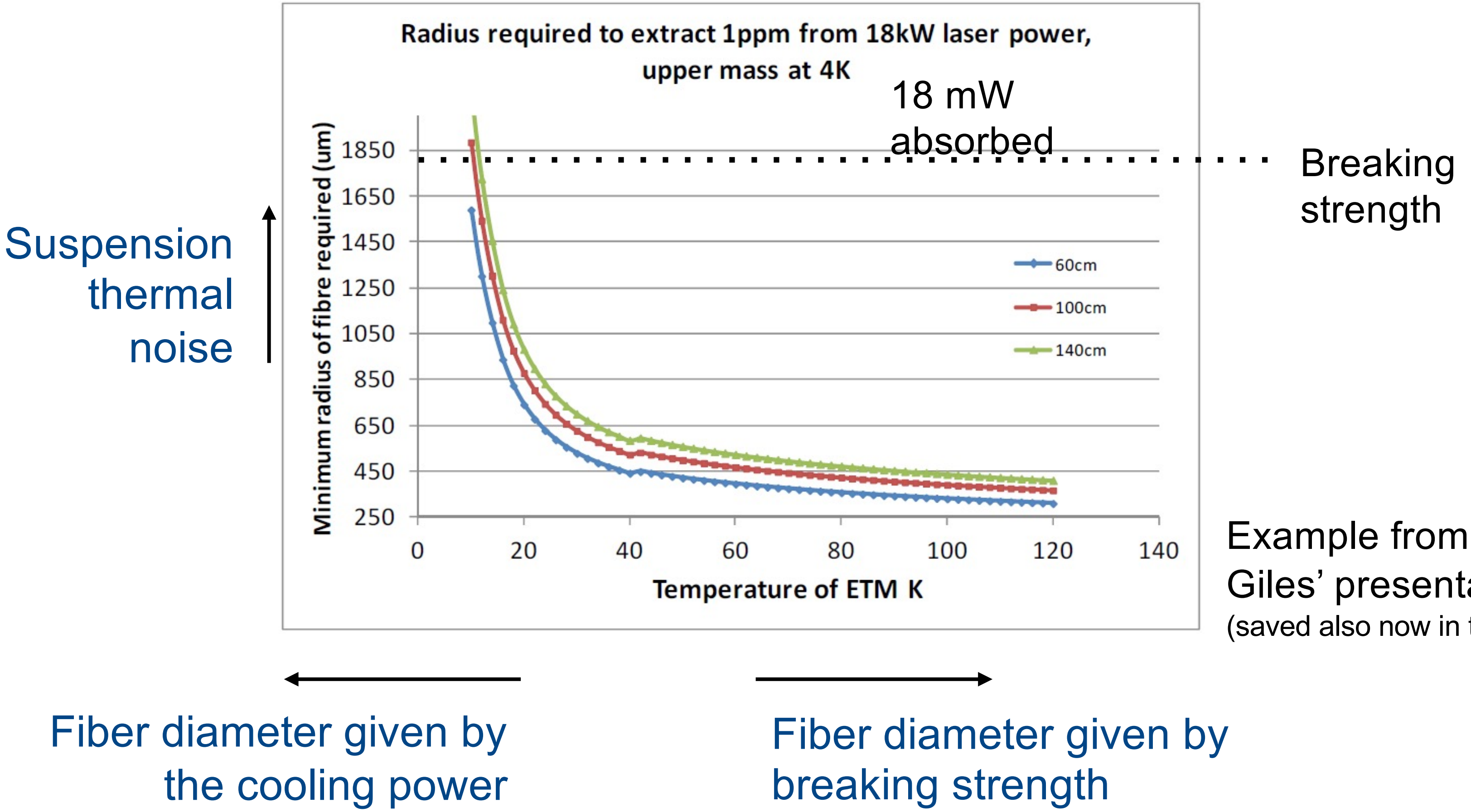
Dedicated WP (III.1), critical work now, please join to contribute!

For the long term: FEM and analytical models of the suspension with realistic estimates of the mechanical losses and thermal conduction at joints.

Experimental data will be crucial

Suspension simple thermal model

- to have quick results based on a simple model
  - → assume 0.05-0.2 W of heat absorbed, monolithic suspension
  - → calculate the fiber diameters to reach a target temperature



Example from a previous Giles' presentation
(saved also now in the WPIII.1 wiki)

Temperature dependency of materials

Parameter	T	Fused silica Value	Fused silica Ref.	Sapphire Value	Sapphire Ref.	Silicon Value	Silicon Ref.
heat capacity (J/kg K)	10 K	6.3	[374]	0.085	[508]	0.276	[509]
	20 K	25.2	[374]	0.72	[508]	3.41	[509]
	30 K	54.6	[374]	2.6	[508]	18.55	[509]
	300 K	738	[374]	781	[508]	713	[509]
thermal conductivity (W/m K)	10 K	0.098	[361]	2900	[361]	2110	[360]
	20 K	0.13	[361]	15700	[361]	4940	[360]
	30 K	0.18	[361]	20700	[361]	4810	[360]
	300 K	1.5	[361]	46	[361]	148	[360]
thermal expansion	10 K	2.2×10^{-7}	[376]	1.0×10^{-9}	[508]	8.8×10^{-10}	[509]

From first ET-TDR

- Actions:
  - → materials database hosted in the Vac-Cryo wiki
  - → joint effort with CE to not duplicate work
  - → for optical parameters, wavelength dependency
  - → highlight missing parameters → R&D plan

Beyond the workshop

- Keep the effort going :
  - → contact the WP III.1 leaders

WP III.1 Observatory Design and Noise Budget	Stefan Danilishin	Teng Zhang

  - → joint the dedicated meetings within the noise budget WP
  - → mailing list link here

- Will contact the names in our shared document to contribute to the material database

Vacuum design

(Vacuum Consequences of) mirror Temperature:

- **Mirror Temperature** will define **tower operating pressure** since at cryogenically temperature gas will cryosorb on the mirror surface inducing:
  - detrimental effects on the optical properties (few 100s of nm ice)*.
  - K. Hasegawa, et al, Phys. Rev. D 99, 022003 (2019),
  - Add heat load to the mirror (~100mW every few nm!!)*

  S. Tanioka, K. Hasegawa, and Y. Aso, Phys. Rev. D 102, 022009 (2020),
  - Add thermal noise (tens of laser wavelenght → >~ 300 nm)*

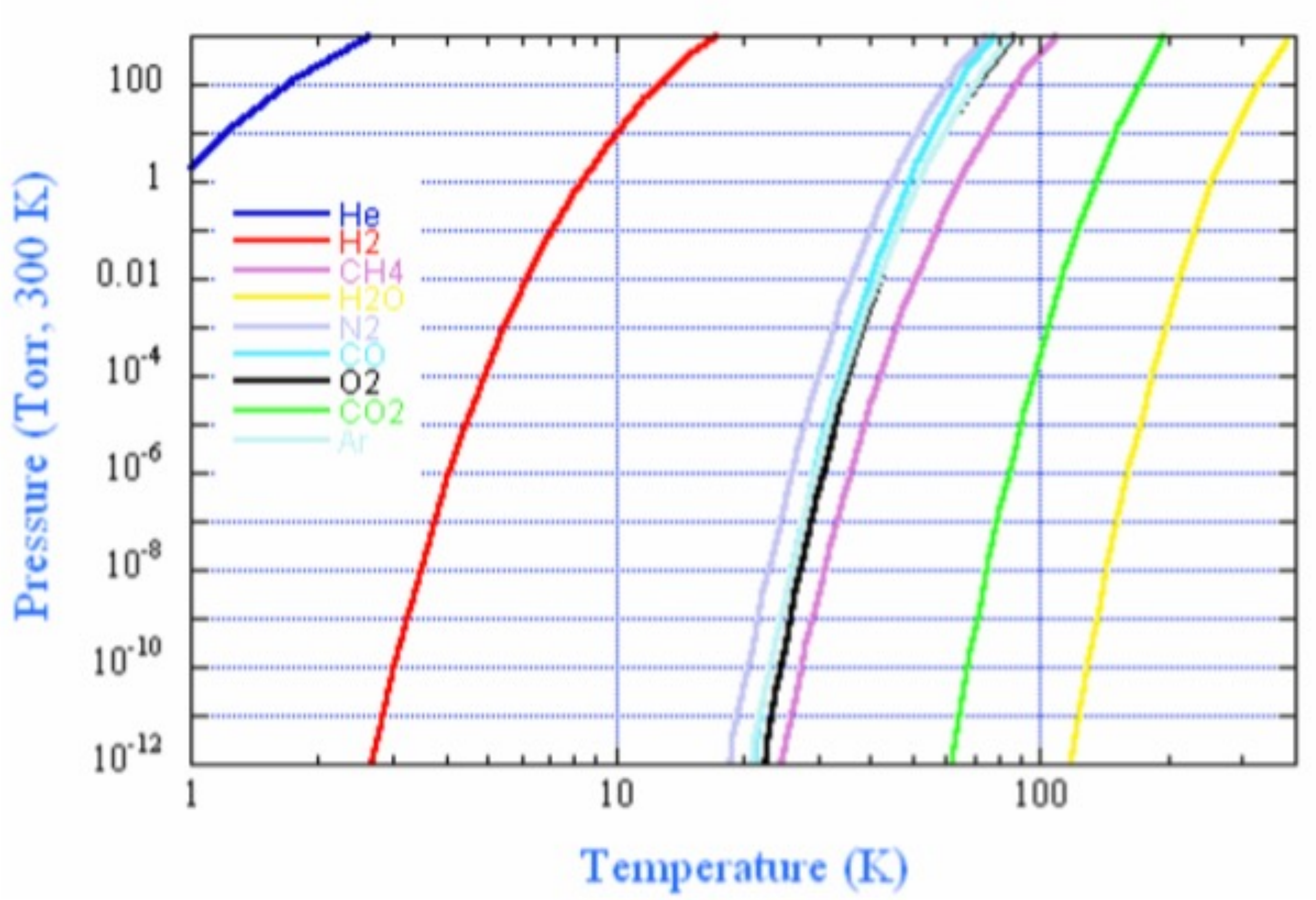
  Jessica Steinlechner and Iain W. Martin PRR 1, 013008 (2019)
  - Add low angle scattering laser light (unclear in size and effect)
  - ....

* To be crosschecked by ISB

Cryogenic vacuum

- At low Temperature and at the expected pressures of p< 1x 10^{-10} mbar a number of gasses (N_2 H_2O, etc. will condense on cold mirror
- Assumed Sticking coefficient S_c= 1.

Defining:
1 L (Langumir) = 1x 10^{-6} mbar x 1s
For S_c= 1 ; 1 L ~ 1Monolayer criosorbed~ (H_2O ~ 0.3 nm)
→ In 1x 10^{-10} mbar it takes 10.000 s (~3h) to build up a ML.



Saturated vapour pressure from Honig and Hook (1960)

For H_2O any T < 125 K will have the same challenges

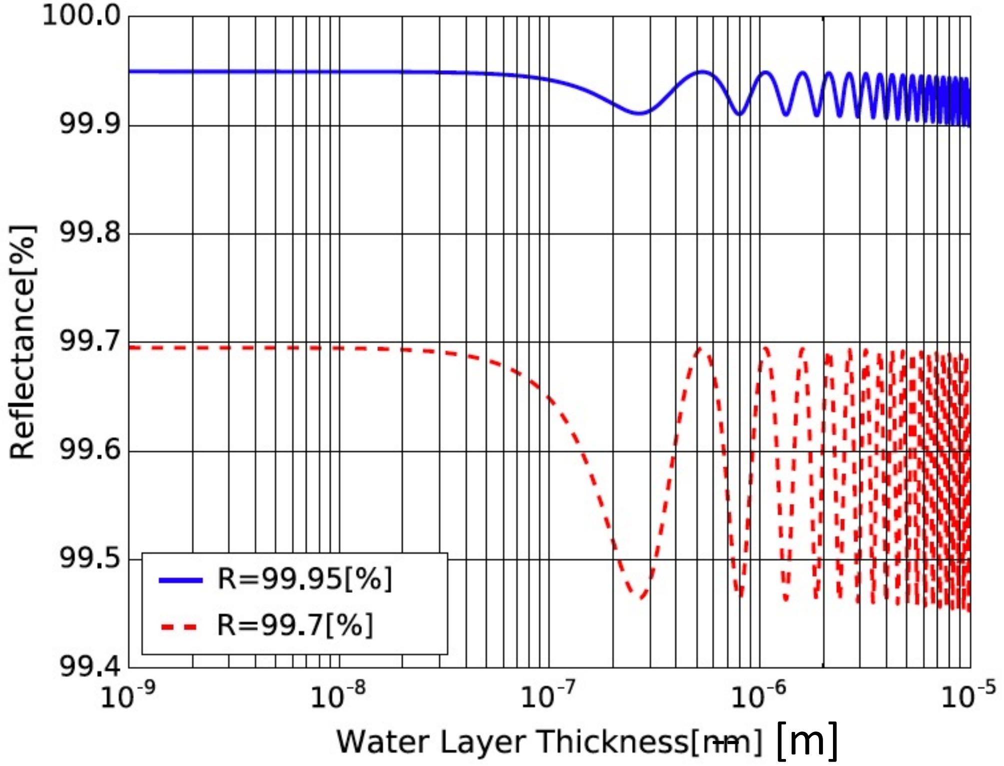
Frost on Mirror Optical properties:

PHYSICAL REVIEW D **99**, 022003 (2019)

Molecular adsorbed layer formation on cooled mirrors and its impacts on cryogenic gravitational wave telescopes

Kunihiko Hasegawa,[1,*] Tomotada Akutsu,[2] Nobuhiro Kimura,[3,4] Yoshio Saito,[1] Toshikazu Suzuki,[1,3] Takayuki Tomaru,[3,4] Ayako Ueda,[3] and Shinji Miyoki[1,†]

Reflectance changes induced by molecular adlayer growth



- From the literature: studies at KAGRA show that already after 100 nm of H_2O ice Reflectivity gets affected .

100 nm H_2O → ~ 30 L → In P_{H2O} ~ 1x 10^{-10} mbar it takes 10.000x 30 s (~90 h) to start observing detrimental effects!!!

If P_{H2O} ~ 1x 10^{-12} mbar --> ~ 1 year

Great design challenge!

Frost on Mirror Adsorption properties:

Optical loss study of molecular layer for a cryogenic gravitational-wave detector

Satoshi Tanioka, Kunihiko Hasegawa, and Yoichi Aso
Phys. Rev. D **102**, 022009 – Published 27 July 2020

R. A. Matthew *et al.*, Einstein gravitational wave Telescope (ET) conceptual design study, ET-0106C-10, https://tds.ego-gw.it/ql/?c=7954 (2010).

ET Available thermal budget ~ 100 mW

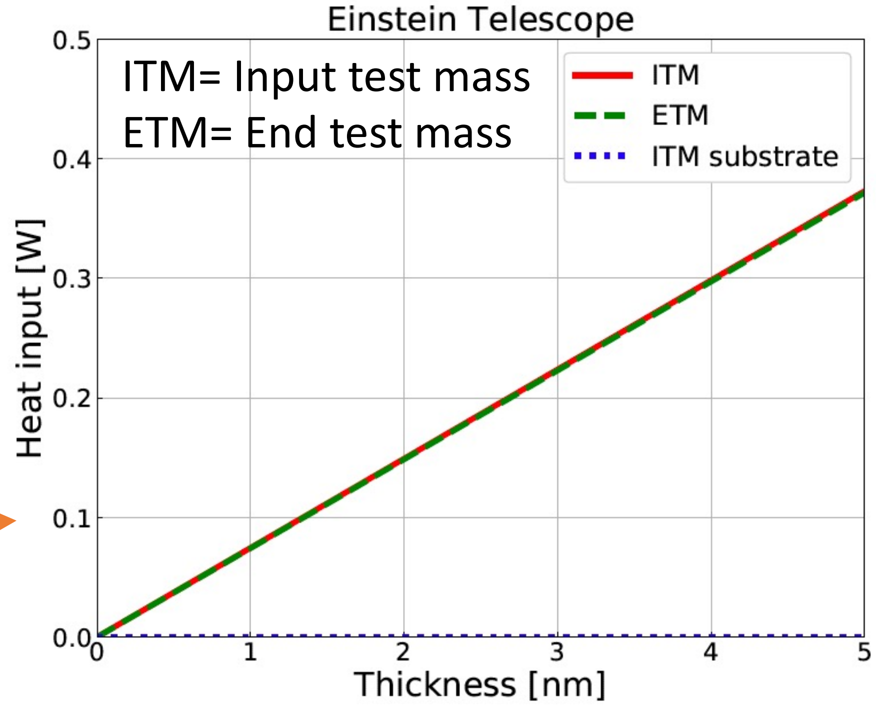


FIG. 6. Heat input to each test mass mirror in ET induced by the optical absorption of CML. As a result of strong absorption of amorphous ice, the heat load to test mass exceeds 100 mW even when the CML thickness is only a few nm. It should be noted that the radiation from the beam ducts is not taken into account for the case of ET.

1 nm H_2O → ~ 3 L → In P_{H2O} ~ 1x 10^{-10} mbar it takes 10.000x z s **(~9 h)** to start observing detrimental effects!!! → A drift of mirror T due to augmented heat adsorption! And???

If P_{H2O} ~ 1x 10^{-12}mbar → ~ 1 month

All that must be cross checked but:

FROST is an issue!

Need of mitigation strategies:

- Passive methods
- Active methods

Passive mitigation methods:

Very low base pressure in:

- Very big volumes
- Very complex structures
- Optimization of transients (cooling down etc)
- → VERY HIGH COSTS AND R&D REQUIRED

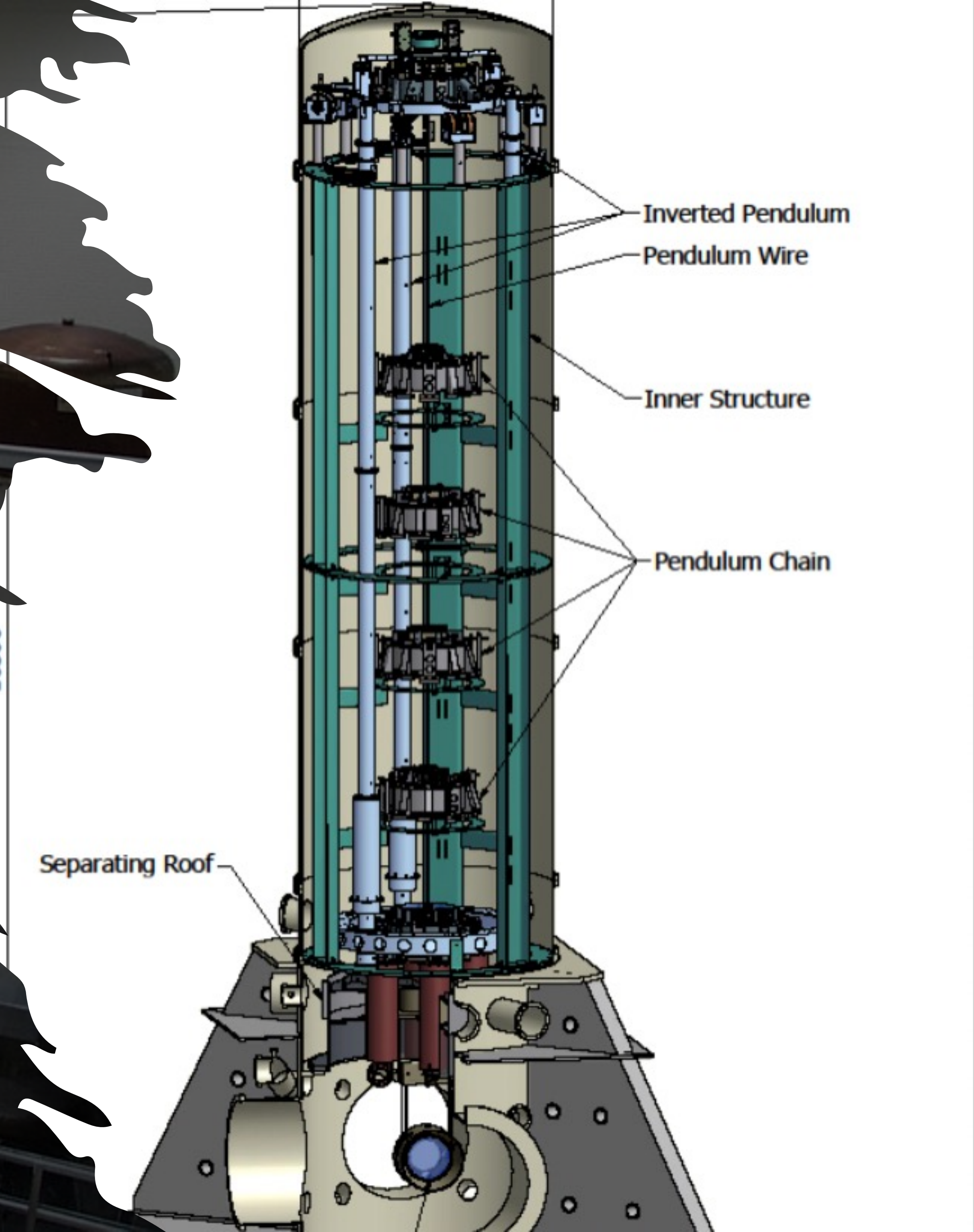
to reach:

P_{H2O} ; P_{CO} ; P_{CH4} < $1x\ 10^{-12}$ mbar

Severe limitations in design and material choice in the tower!!!

P_{H2} < $1x\ 10^{-10}$ mbar

Importance of P transient (integral gas load !)



Passive methods will certainly be implemented

For the sake of the project, active methods needs to be there

➢ Active methods:

- **Thermal methods:**

Bringing the mirror or its surface above **125 K.**

- **→ non thermal methods**
- Exiting the overlayer molecules to induce their (non-thermal) desorption!

Mitigation methods

thermal

Warm up above 125K.

How long and how often???.

Possibly implying unacceptable GWD downtime!

Great impact on design: Temperature cycles AND improve $P_{H2O} < 1 \times 1x\ 10^{-13}$ mbar

CO_2 Laser

CO_2 Laser beam penetrated some microns within the mirror surface:

Can induce damage to optics?

Can give H_2O ice sufficient thermal energy to be removed (>125 K) without heating the mirror?

Inductive?

Non thermal

UV Photons

UV light induce electronic transitions in H_20 and its desorption

H_2O yield ~1×10^{-3} molecules/photon

UV photons induce defect formation deteriorating optical properties

Electrons

Low (20-200 eV) Electrons induce transitions in H_20 and its desorption

H_2O yield ~1×10^{-1} molecules/electron

Low en. electrons penetrate only nm below the mirror surface

Charge issues- can be cured by electron irradiation too

.....

Some (random) questions from the break-out section:

- From Stuart Reid:
- What are of the optics (face/entire surface?) do we need to keep ice off? Do we need to keep ice off whole face?
- **Do we keep a steady-state buffer layer of ice on the surface? This may prevent damage to the mirror/coatings from the ice-removal method *e.g.* CO_2 laser, electron/ion bombardment, other e/m radiation? At what thickness is optical absorption a problem?**
- How stable does the mirror temperature have to be? Does ice on the mirror surface cause unpredictable thermal loading? Can this cause temperature drift or temperature gradients are a problem?
- Can we estimate the possible thermal gradients due to known absorption of e.g. the mirror coatings, and ice.
- How do we measure the mirror temperature? Can this be done from internal modes? Other optical properties that can be tracked?
- Does ice cause scatter? Does this couple to low freq noise?
- Scatter – is this low-angle too? Do we need to worry about this? How do we assess to potential of low angle scatter from ice build-up?
- Do we need to worry about carbon build up on mirror surfaces too?
- Generally – how does ice change reflectivity, absorption, scatter, TN…?
- **Generally – we need to hear more from KAGRA on their experiences.**

Conclusion

- Mirror 10< T < 125K shows same issues
- ISB WP's should consider frost formation as unavoidable at LT. (it is only a question of time!)
- Estimates of tolerated thickness must be provided to conceive the tower vacuum system to be compliant with one (?) year long runs few months (?) down-time.
- Effective Mitigation methods needs to be studied or "fast" temperature cycling must be foreseen to avoid unacceptable long down times.
- Need to find the best compromise among many requirements