Instrument Science Board
Cryogenics and Vacuum for the 3G-GW Einstein Telescope

Fulvio Ricci

ET-WPIV Organisation

Vacuum and Cryogenics

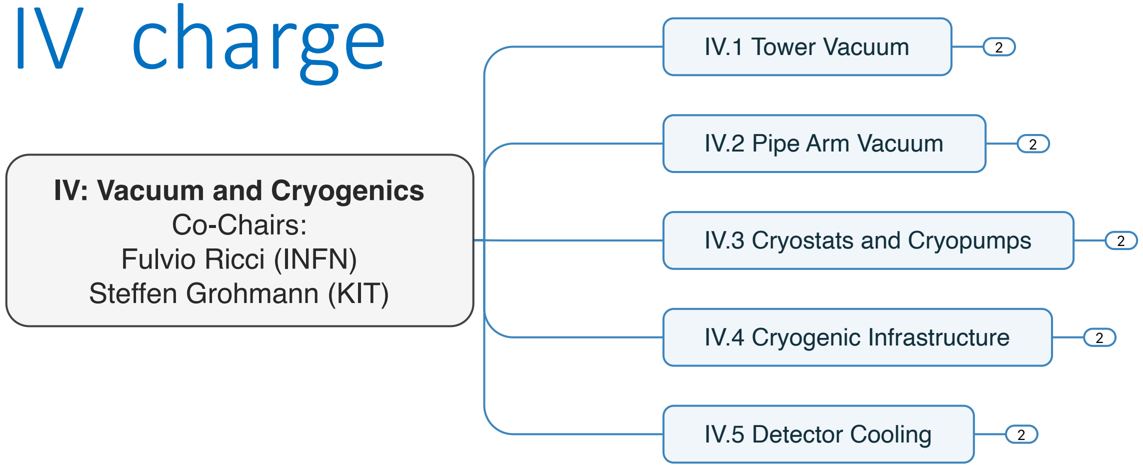
Chairs: Steffen Grohmann (KIT, Germany)
Fulvio Ricci (University of Rome, 'La Sapienza', Italy)

Work Package	Chairs	Institution	Country	Expertise
Tower vacuum	Antonio Pasqualetti	EGO	IT/FR	VIRGO vacuum group leader
	TBD			
Pipe arm vacuum	Paolo Chiggiato	CERN	CH	Head of vacuum, surfaces and coating group
	TBD			
Cryostats and cryopumps	Christian Day	KIT	DE	Project leader vacuum in the EU nuclear fusion programme
	Roberto Cimino	INFN	IT	Senior expert surface lab
Cryogenic infrastructure	Steffen Grohmann*	KIT	DE	Professor of refrigeration and cryogenics
	TBD			
Detector cooling	Piero Rapagnani	University of Rome, 'La Sapienza'	IT	Senior expert cryogenics
	Steffen Grohmann*	KIT	DE	Professor of refrigeration and cryogenics

*Interim until replacement becomes available

WP IV charge

WP IV.1 The work package includes the design and the cost evaluation of the various vacuum chambers hosting the super attenuator, i.e. the upper part of the cryostat for the LF interferometer and the entire tower for the HF interferometer including the vacuum chamber hosting the payload. The design of the auxiliary towers is also part of this WP.



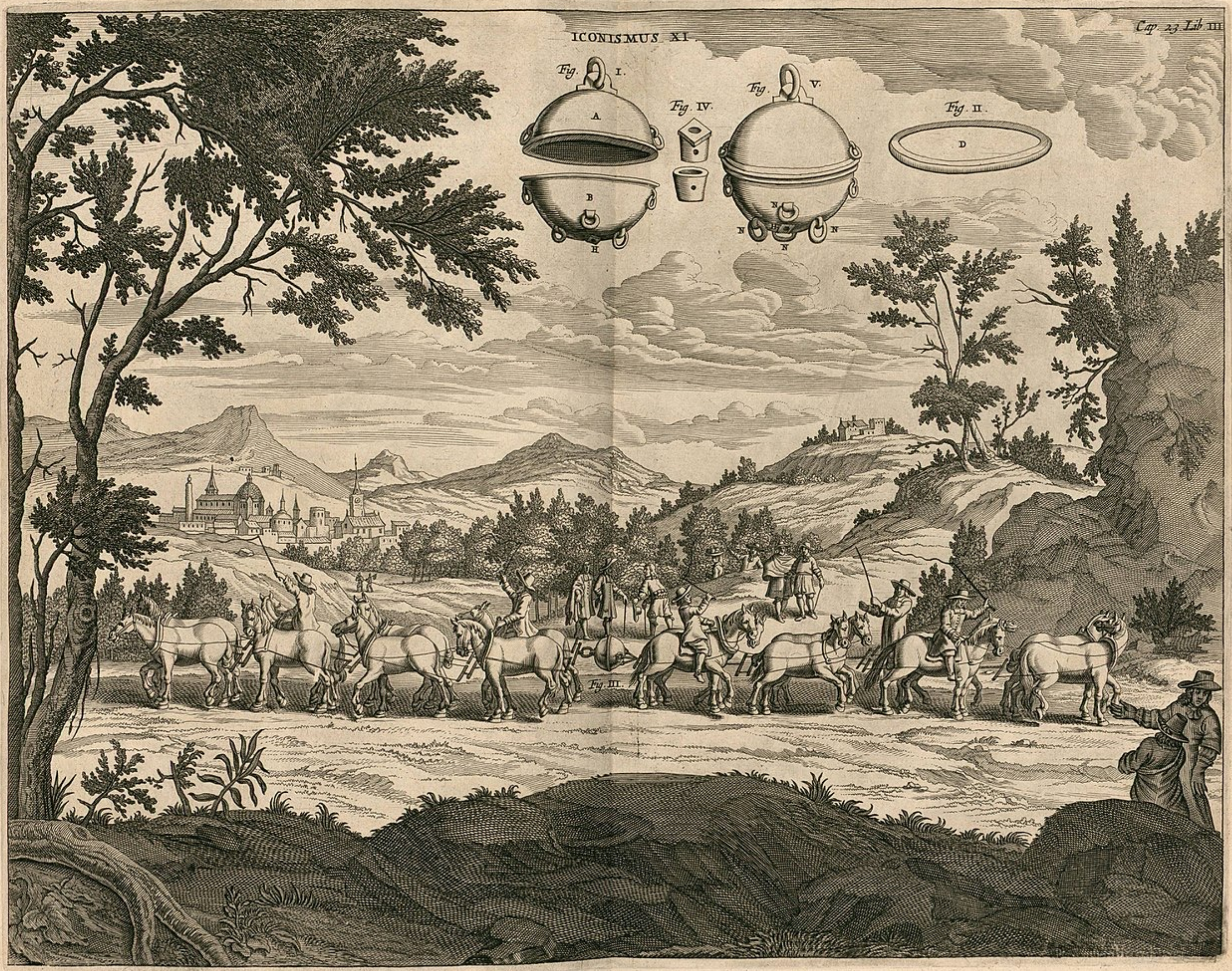
WP IV.2 is devoted to the design of the almost 120 km vacuum pipes. WP activity includes material qualification with handling procedures, the pipe system design and the complexity of the installation of four parallel pipes in the tunnel. Transportation constraints, assembly procedure and related special tools should also be studied. Procedures

WP IV.3 the scope of WP IV.3 comprises the cryostats (thermal shield systems) hosting the payloads of the LF interferometer as well as the cryopumps to limit and maintain the best vacuum achievable around the cryogenically cooled mirrors decoupling it from the incoming flows from the pipe arm vacuum and from the vacuum part containing the suspension system under all modes of operation.

WP IV.4 is devoted to the design of the cryogenic infrastructure. It includes the specifications of cooling and gas handling systems, including transfers lines between surface and underground installations, and the cryogenic safety concept. The design also includes the seismic and acoustic insulation of the cryogenic infrastructure from the interferometers.

WP IV.5 is devoted to the design of the cryogenic payload cooling system of the LF interferometer and the interface between payload and refrigeration line. It includes parallel investigations of both the actual baseline design using pulse-tube cryocoolers and the alternative development of a He-II detector cooling system. WP IV.5 is closely related to WP IV.3 in order to avoid particle condensation on the payload optics.

VACUUM



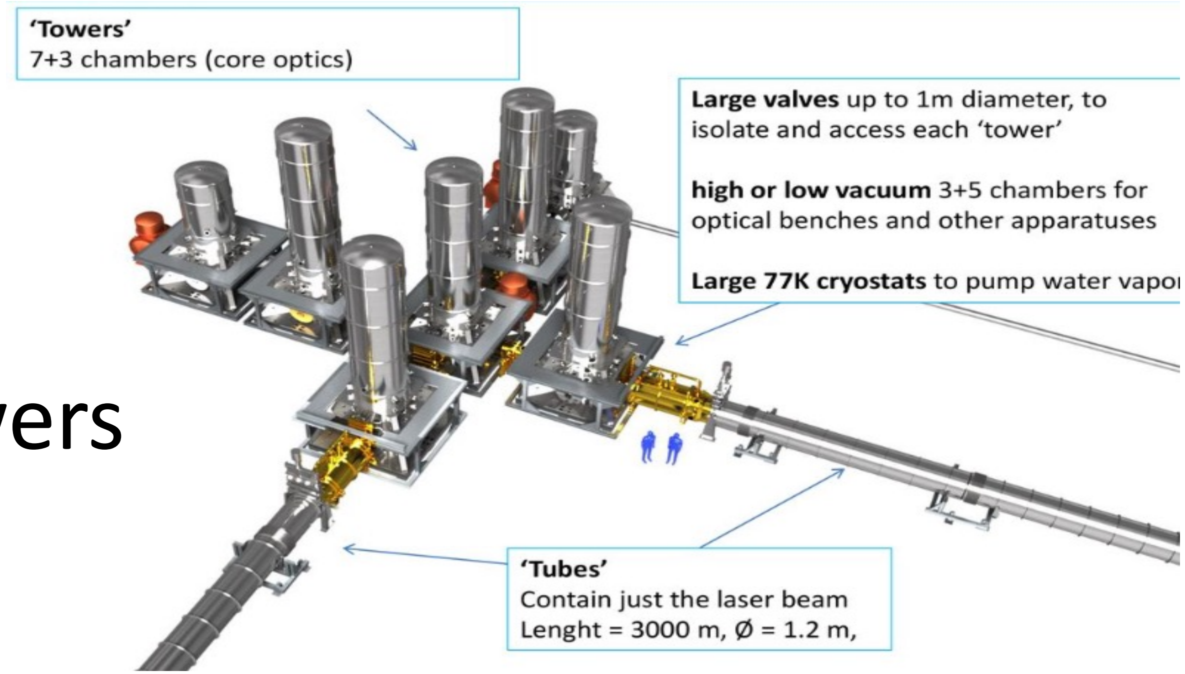
Ultra High Vacuum

Tubes

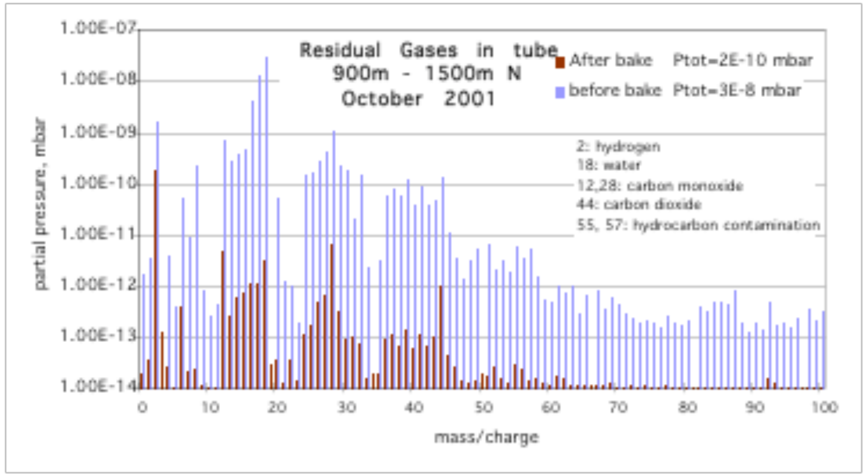
Large Valves

the shear part of the 12 metric tons axial load when one side only of the valve will be in vacuum

Towers



Bake out issue



VIRGO Vacuum System

The Vacuum requirements to beat
- noise generated by pressure fluctuations below $S_{hh} \sim 10^{-24}$ /Hz $^{1/2}$
- mirror quality deterioration

Residual partial pressure; H_2 10^{-9} mbar, 10^{-10} mbar other gases
10^{-14} mbar hydrocarbons

6 km Tube:
V = 6786 m^3 , S=1.2 10^4 m^2 ----->> Permanent pumping ~39 kl/s
11 Pumping Stations for each tube (Ti Subl .+ Ion Pump) ➔ total 22 stations
10 Vacuum Towers Area : Upper part HV (TMP Pump 1.5 kl/s)
Lower part (mirror zone) UHV (Ti Subl .+ Ion Pump)

ET Vacuum System

Provisional numbers

The Vacuum requirements to beat
- noise generated by pressure fluctuations below $S_{hh} \sim 5\ 10^{-25}$ /Hz $^{1/2}$

Residual partial pressure; H_2 1×10^{-10} mbar, 1×10^{-11} mbar other gases
Water 5×10^{-11} mbar, 10^{-14} hydrocarbons

120 km Tube:
V = 130,000 m^3 , S=4.2 x10^5 m^2 ----->> Permanent pumping ~300 kl/s/inter.
20 Pumping Stations for 10 km each tube (Ti Subl .+ Ion Pump) ➔ total 240 stations
Each Vacuum Towers Area : Upper part HV (TMP Pump 1.5 kl/s)
Lower part (mirror zone) UHV (Ti Subl .+ Ion Pump)

Scaling the VIRGO experience

Standard approach

- Stainless steel 304L (4 mm thick), cleaning, welding, baking procedures
- Tube construction and firing far from the site

Negative impact

- Cost too high (just the cost of the raw material ~20 M€)
- Bake out in the underground environment problematic
- Logistic issues ➔ about ~11,000 elements (12 m) to be transported

R&D on material for the tubes

- Materials alternatives to Stanley steel:

- Low carbon steel (produced through Ruhrstahl-Hausen vacuum process) ---lower price factor (*gain at least a factor 3 in price*),
  - Negative aspects
    - Corrosion
    - Degassing rate
    - Inclusions
    - Surface treatments
    - Weldability (with and without coatings)
    - Protection during transport and installation

- Aluminum: thicker tube (*a factor 2 higher*), lower density material (*a factor 3 lower*), higher cost /kg (*a factor 1,25 higher*) …..almost the same cost of Stanley steel
  - Negative aspects
    - Less robust
    - Assembly procedure more complex
    - Metal transitions (if a required) , more expensive and less reliable

R & D on Vacuum

- Tube configuration studies:
  - Corrugated tube (GEO solution)
  - Spiral (LIGO) vs. longitude.+ circul. (VIRGO) welding
  - Nested tubes with a thin inner thin tube for UHV and an outer low vacuum tube (R. W. proposal)
- Alternative pumping system
  - Extensive use of Getter pumps

- Large valves:
  - Improved lifetime, quality check…. how many?

Design Study

- Tube Production and installation
- Tower Production and installation

Interface with the infrastructures constraints

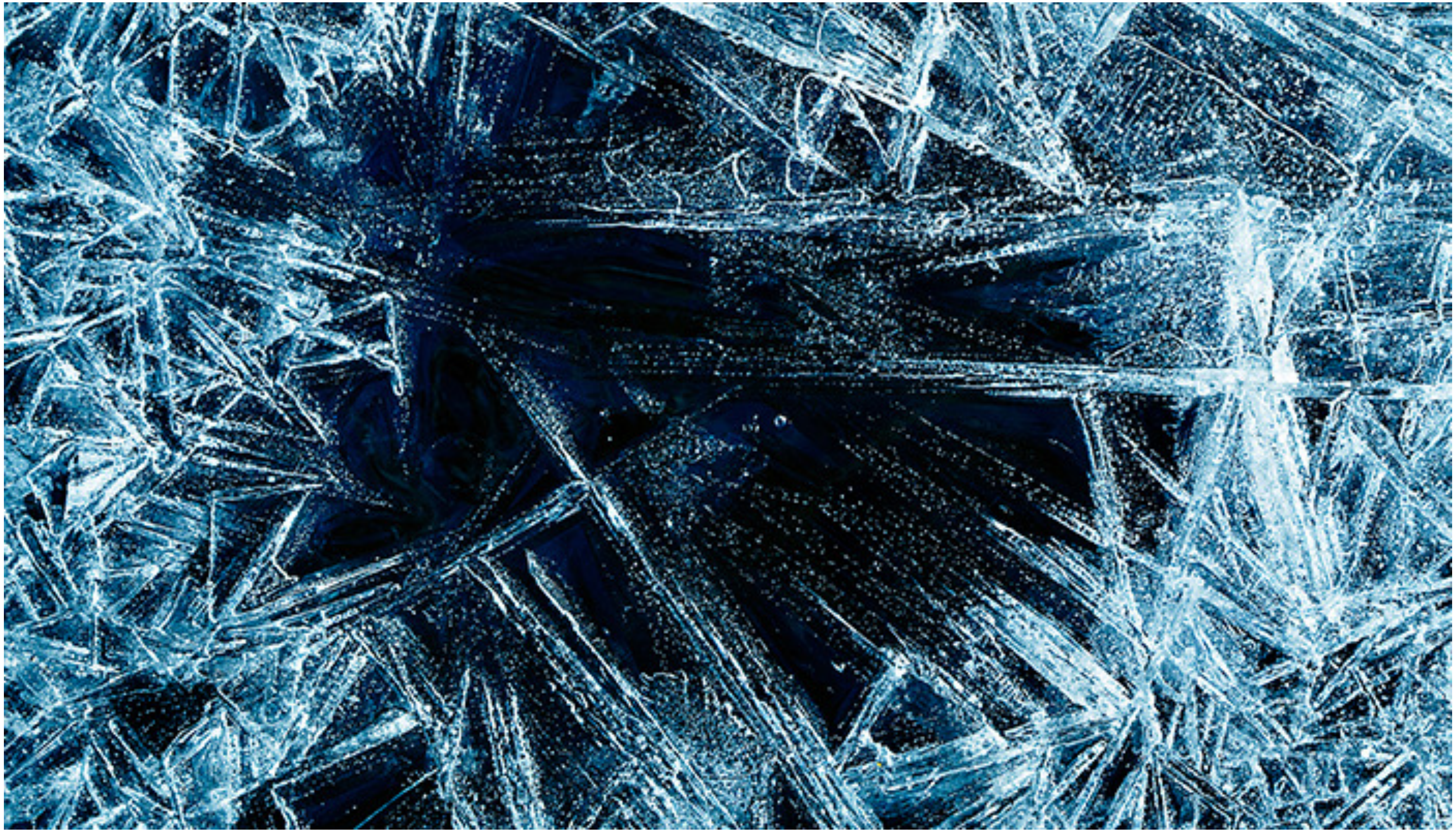
Deliverables

Light Technical Design Report

- Project baseline for design, subsystems & materials, production, assembly tools, installation, service, ...
- Industry involvement

Keep the cost as low as possible !!!

Cryogenics



Cooling strategy

- Baseline solution (KAGRA): No cryofluids, cryo plan based on PT cryocoolers

In favor

higher duty cycle

less manpower

Against

higher level of vibration

higher electric power

Infrastructure requirements

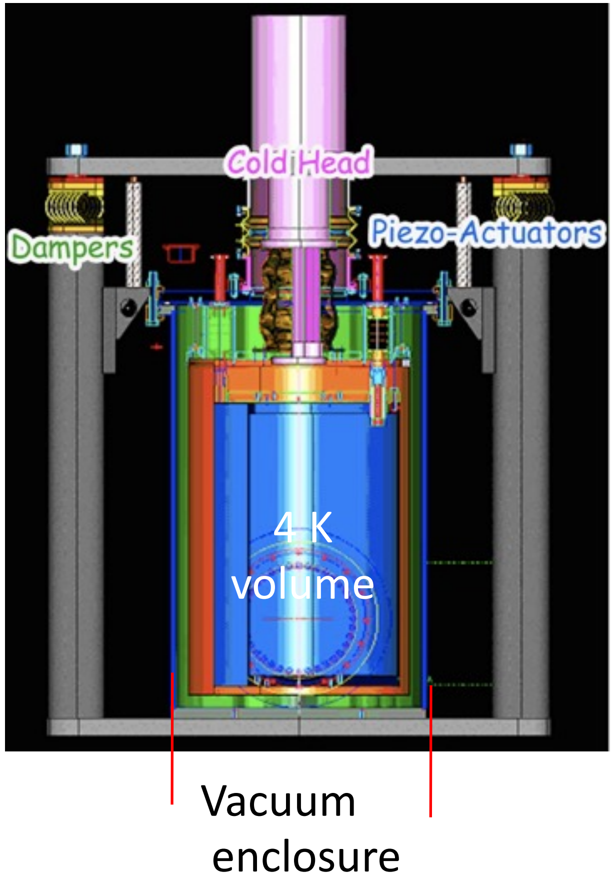
pressure lines distributed along the main caverns

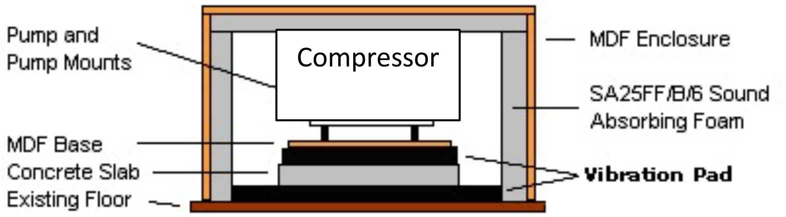
compressors allocated in auxiliary caverns

efficient water refrigeration system

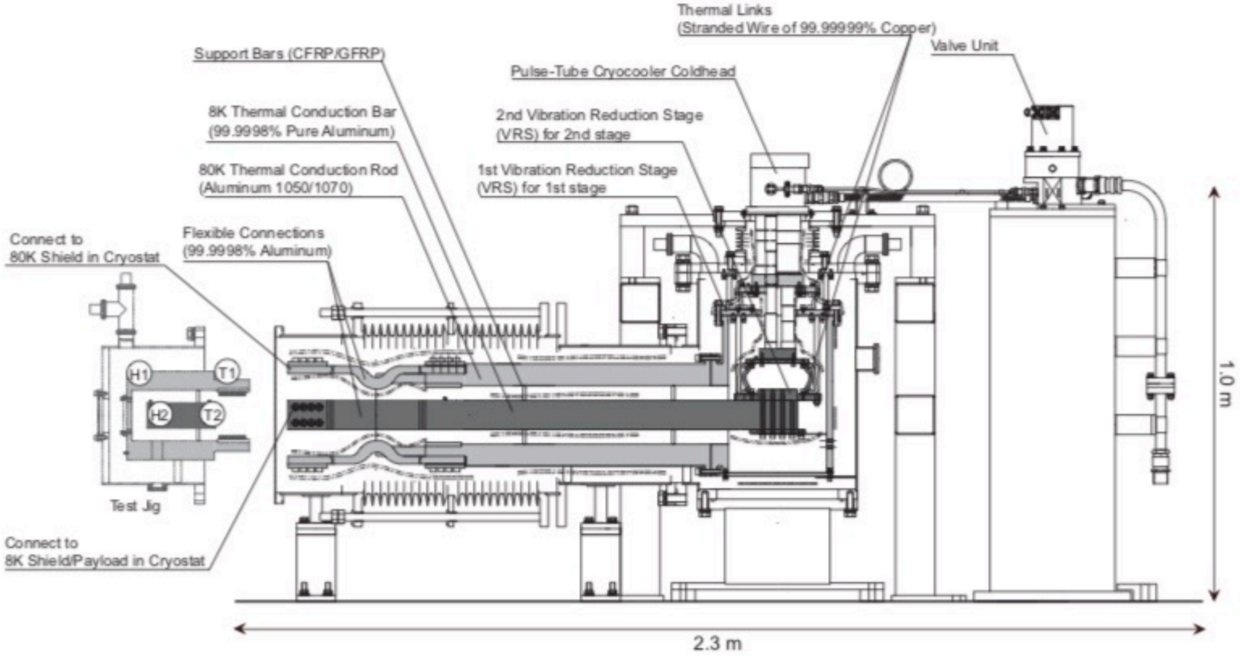
R&D

improvement of the vibration compensation system





KAGRA Cooling unit



The sectional view of the very-low-vibration cryocooler unit. 8 K thermal conduction bar is coloured in dark grey and the 80 K thermal conduction rod is coloured in light grey.

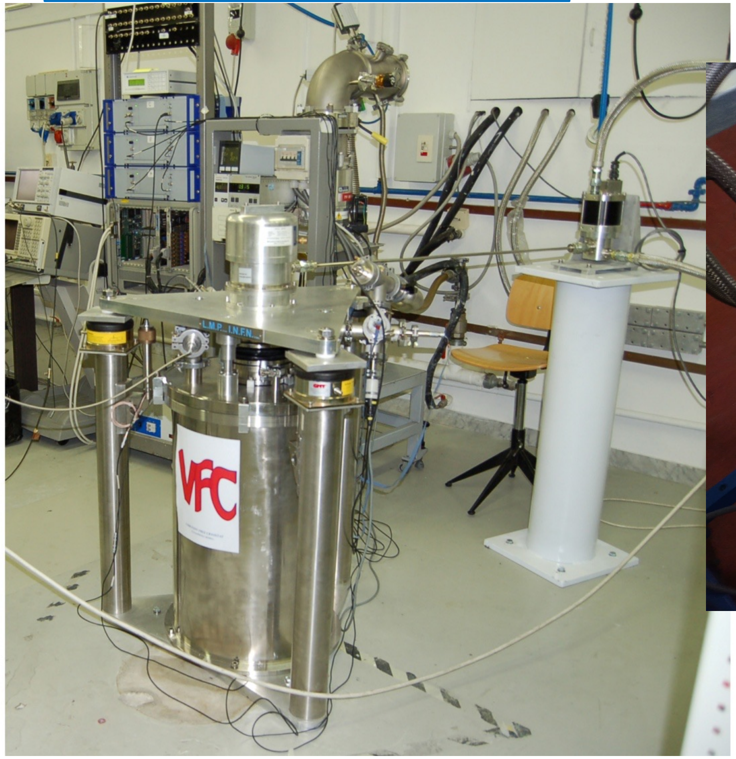
PT refrigerator
SHI RP- 082BS, 0.90 W at 4 K, 35 W at 45 K

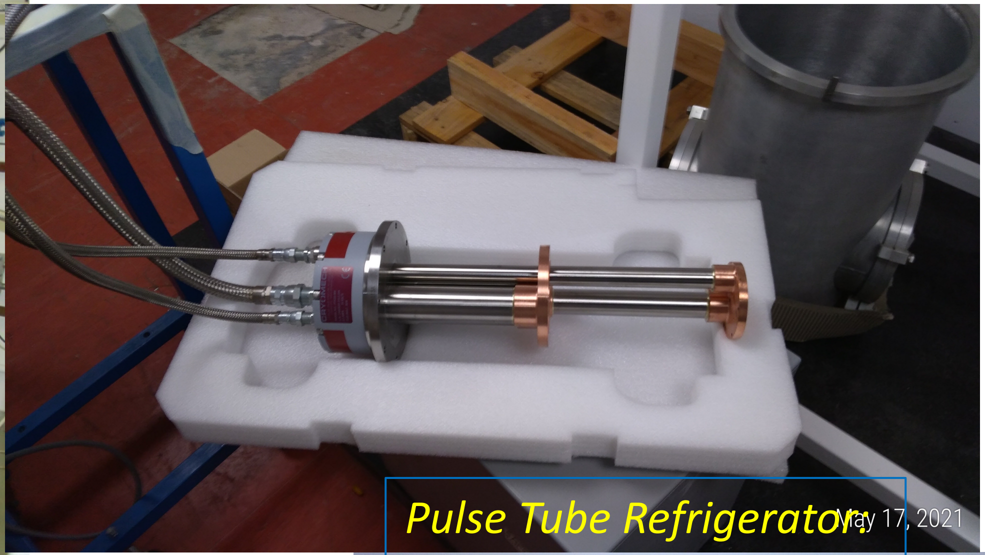
Protype development in Rome: the Cooling Unit

AMALDI RESEARCH CENTER

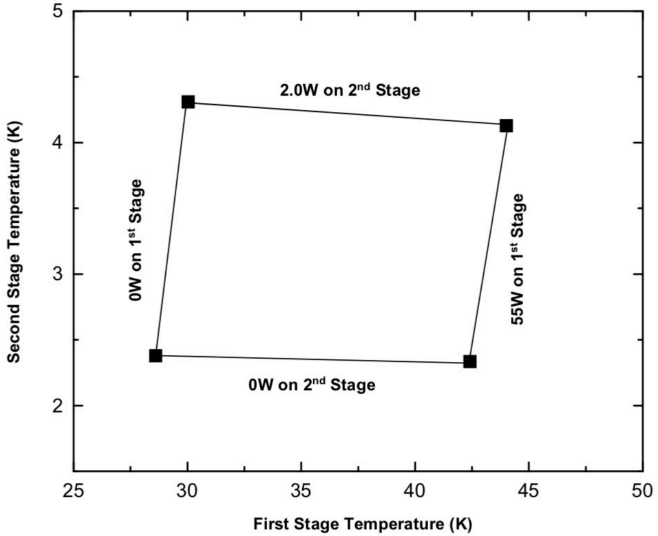
Collaboration:
Sapienza univ. , INFN Rome & LNGS / CERN

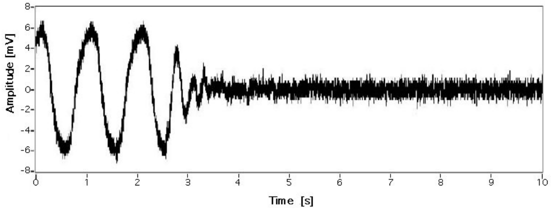
Active cancellation noise

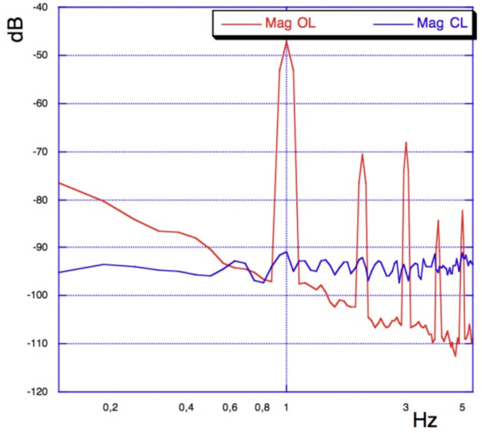




Pulse Tube Refrigerator:
Model CRYOMEC PT420





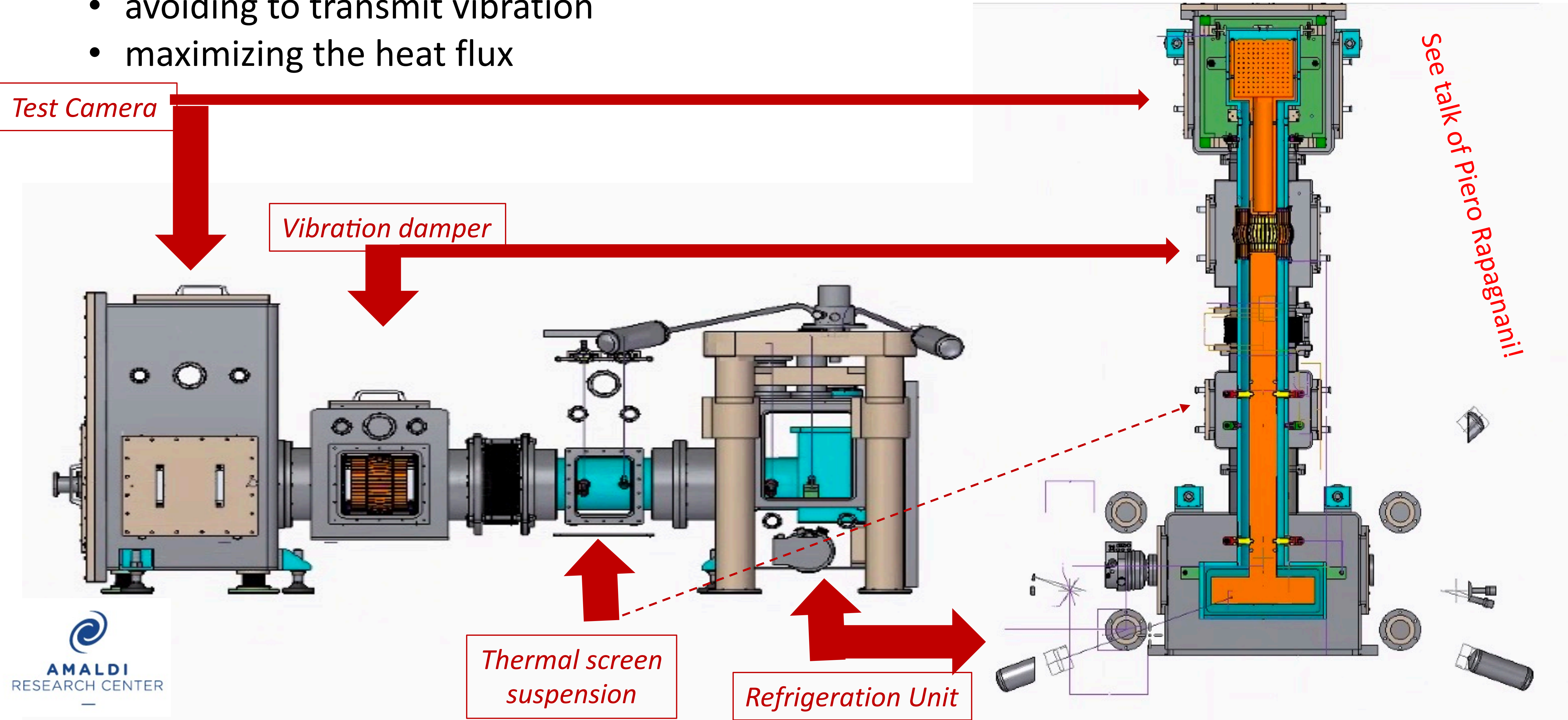


Protype Construction on the way

The issue is how to bring the refrigeration power

- avoiding to transmit vibration
- maximizing the heat flux

In orange the refrigeration path
In bleu the thermal screen
In grey the vacuum chamber



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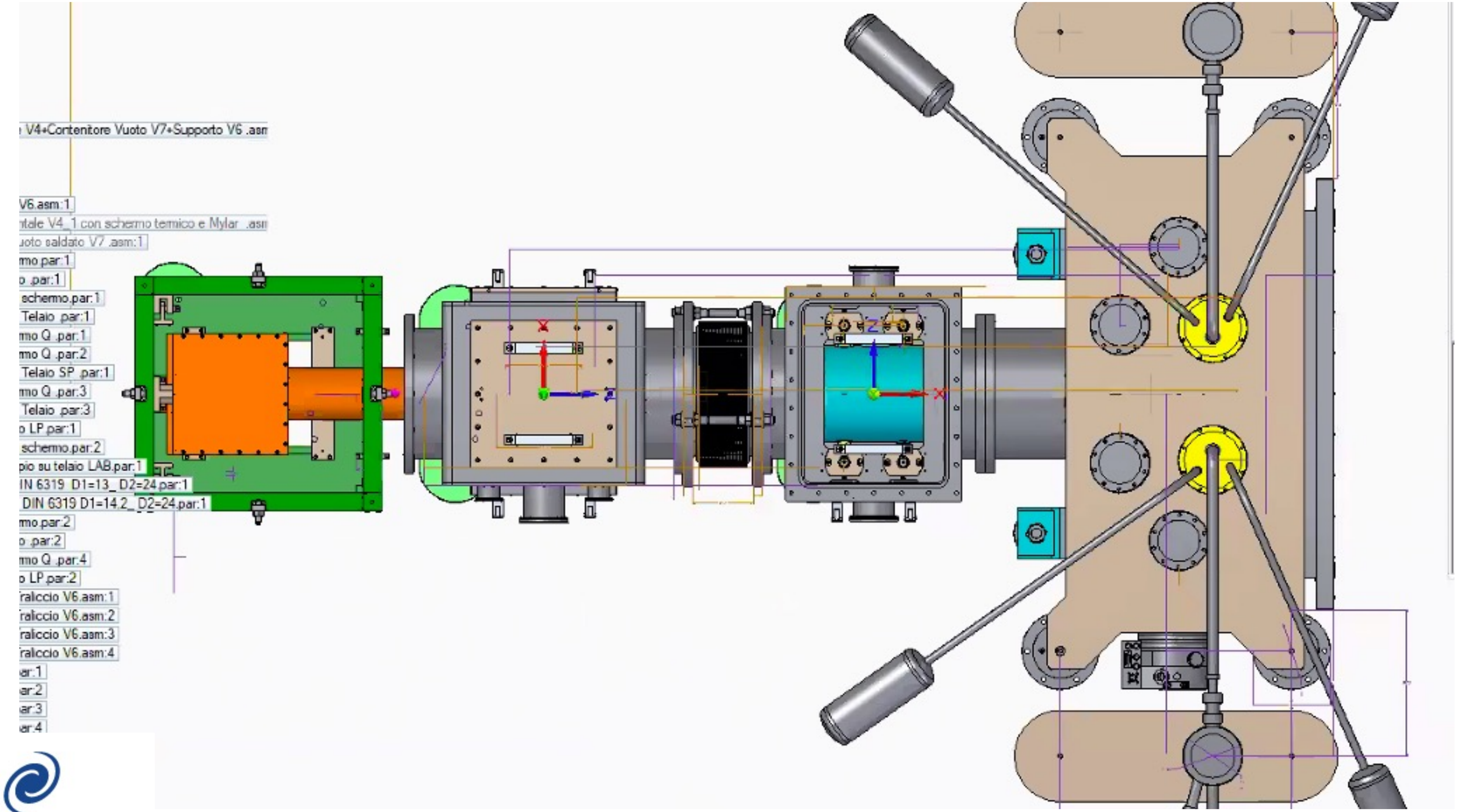

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RESEARCH CENTER

More on Active Noise Cancellation

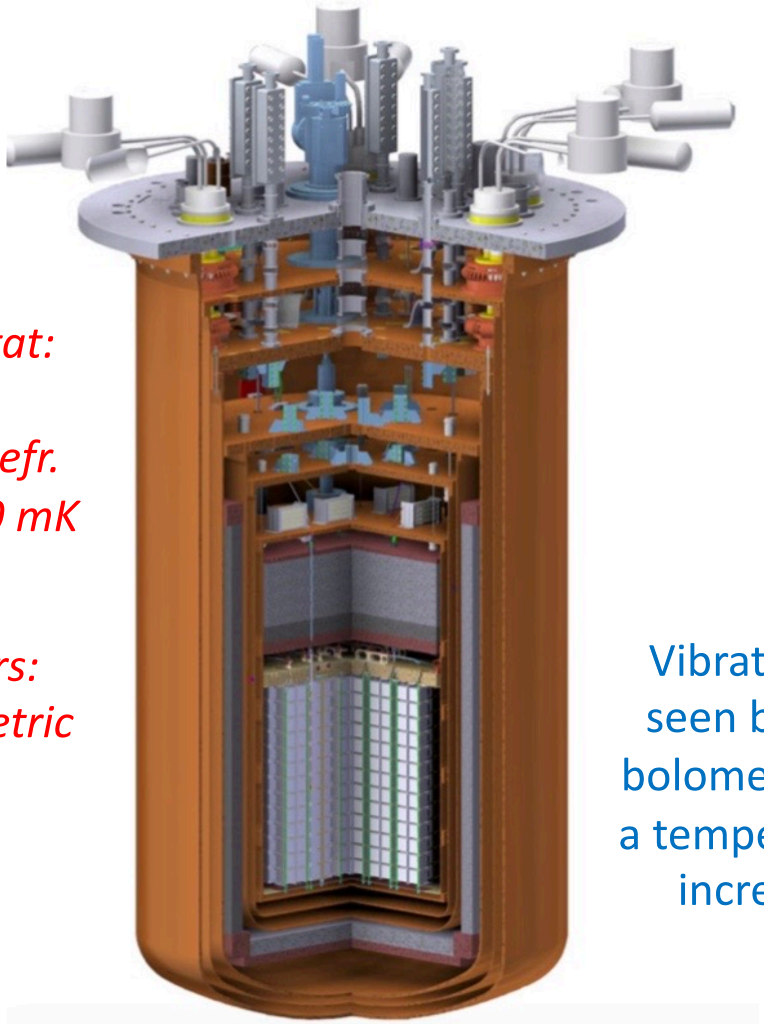
V. Dompè, C. Bucci, L. Canonica, A. D'Addabbo, S. Di Domizio,
G. Fantini, P. Gorla, L. Marini, A. Nucciotti, I. Nutini ,C. Rusconi, B. Schmidt, B. Welliver
Journal of Low Temperature Physics (2020) 200:286–294 https://doi.org/10.1007/s10909-020-02435-0

Cancellation method developed for the Double Beta Decay experiment CUORE in the INFN Gran Sasso laboratory

<u>The technique consists in driving and stabilizing the PT relative phases at the minimum noise configuration</u>

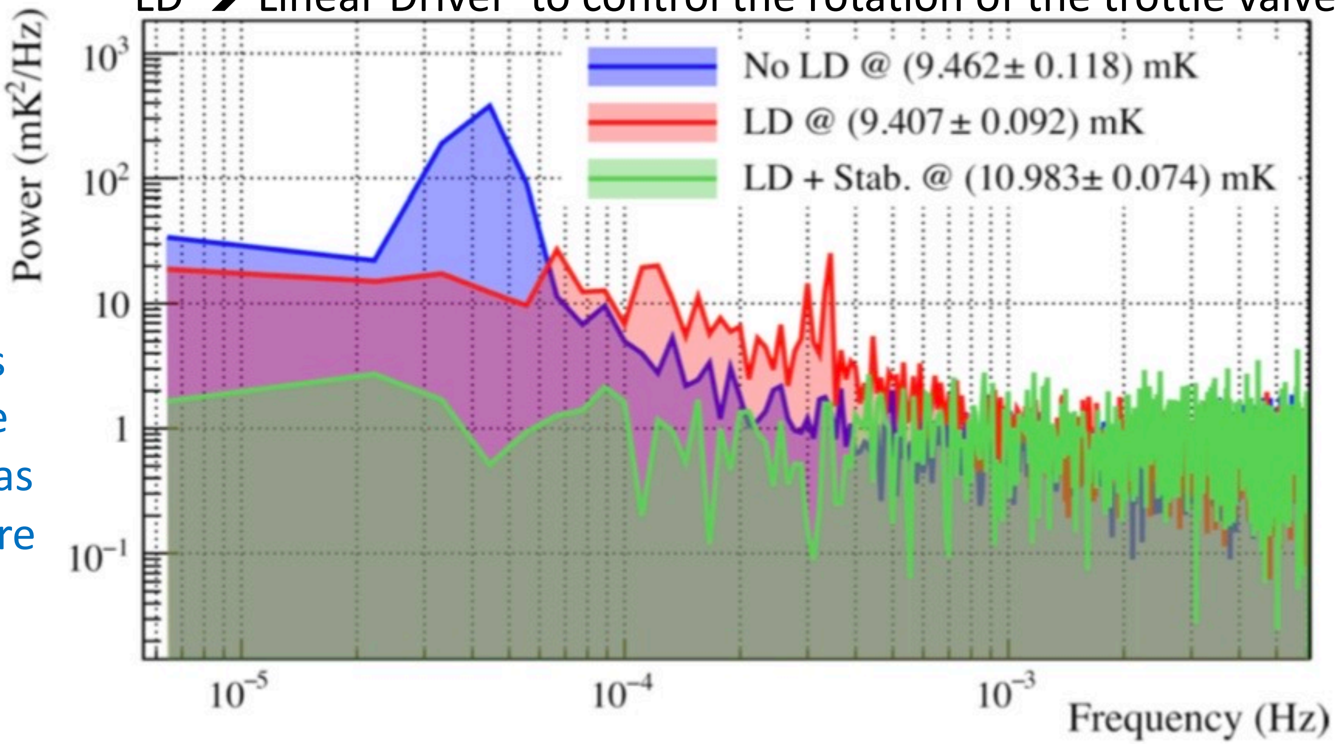
CUORE cryostat:
cryogen-free
PT + $^3He^4He$ refr.
1.5 tons at 10 mK

998 sensors:
TeO_2 bolometric crystals



Vibration is seen by the bolometers as a temperature increase

LD ➔ Linear Driver to control the rotation of the trottle valve

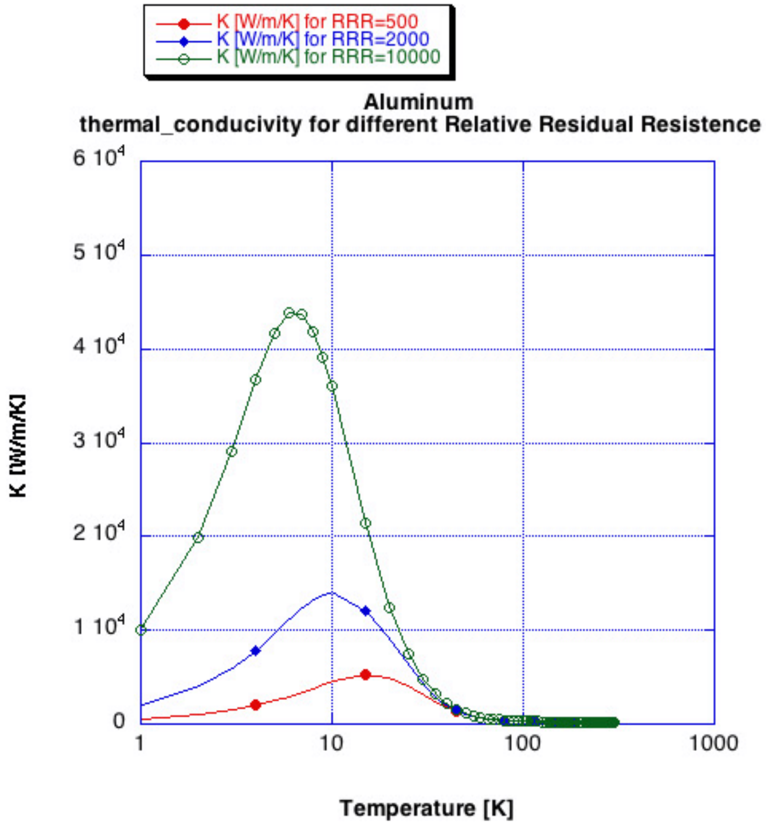


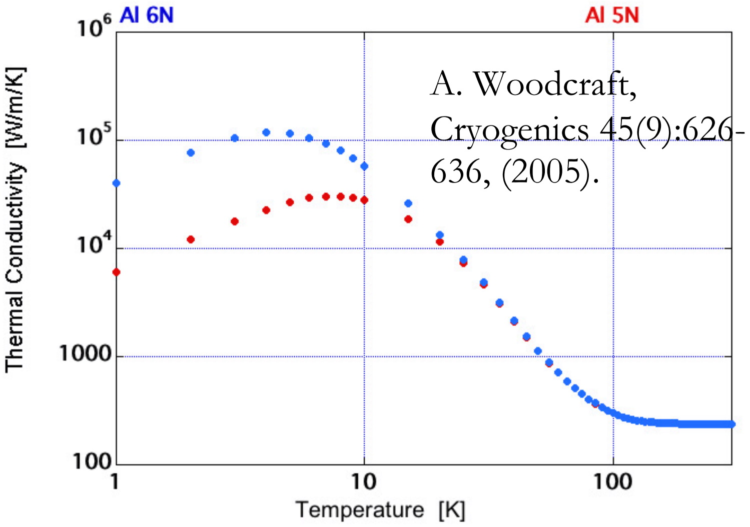
Materials for Thermal Links

Pure Materials as aluminum and copper

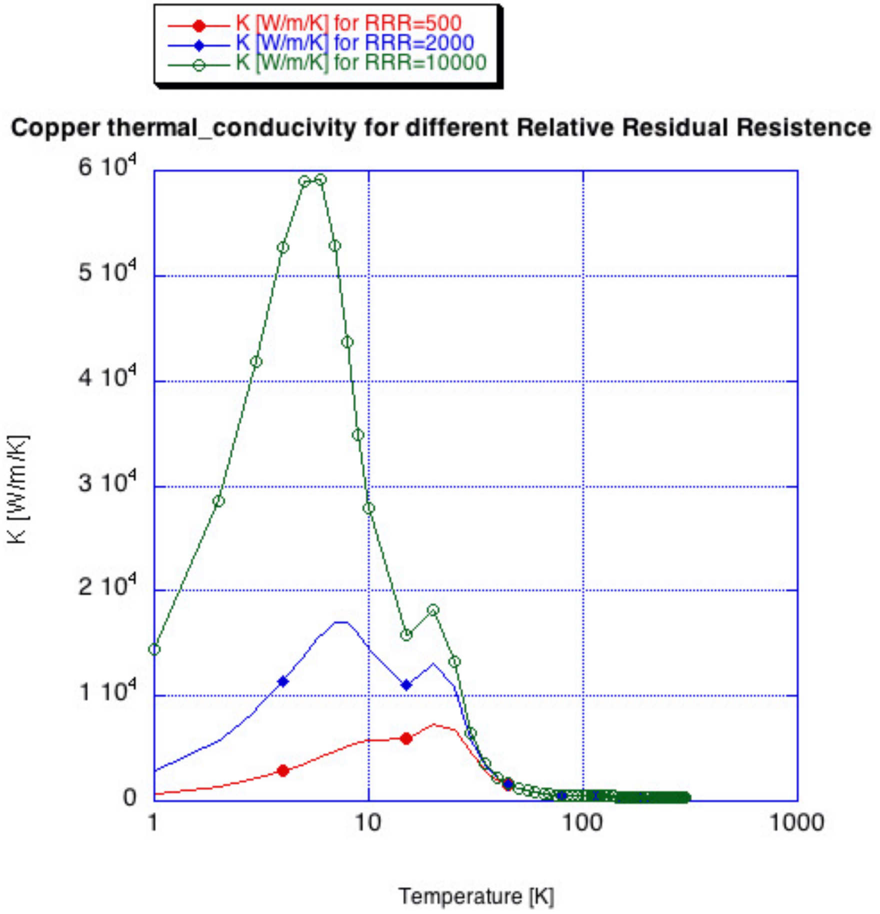
RRR = $\rho_{\text{room temperature}}$ / ρ_o

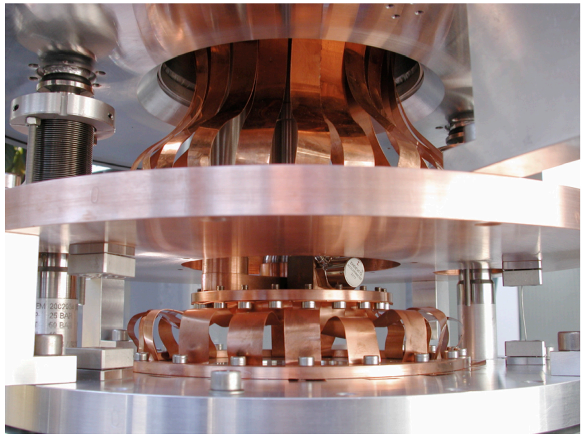
where ρ_o resid. resist. at T~0 K



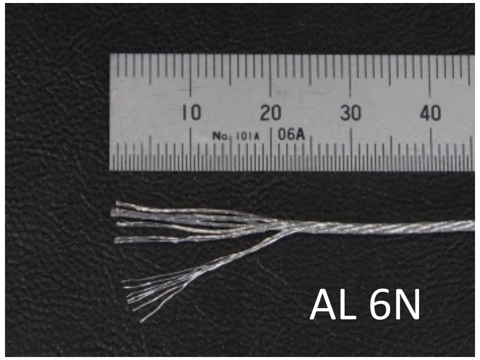


A. Woodcraft, Cryogenics 45(9):626-636, (2005).





T. Yamada et al. Cryogenics Volume 116, June 2021, 103280



Cooling strategy based on Cryofluids

Use of cryofluids

In favor

- quiet system
- thermally stable

Against

- lower duty cycle
- more manpower
- more stringent safety issue

Infrastructure requirements

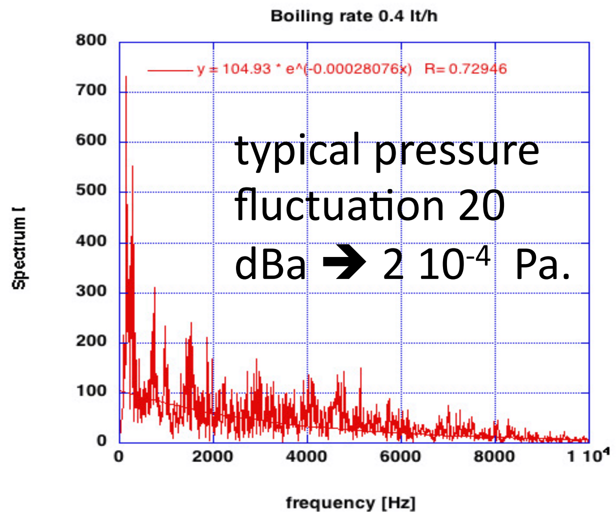
- transfer lines from the surface to underground
- liquefier plans in the external laboratory

R&D

- study related to the boiling noise
- [feasibility study of a cooling system based on He II (no boiling!!!)]

See dedicated talk of Lennard Busch and Steffen Grohmann

Boiling noise



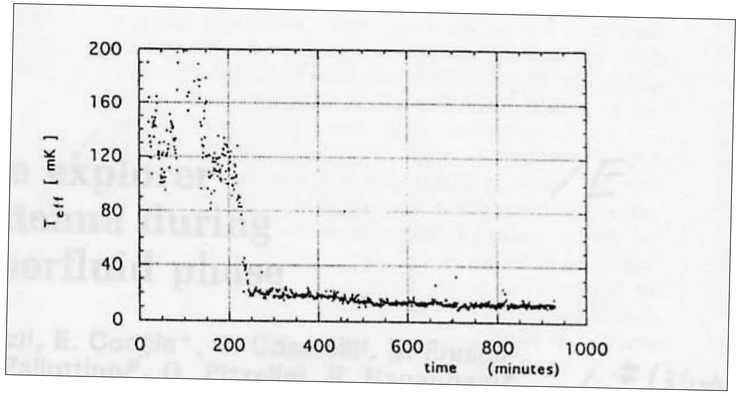
For example in the case of the GW resonant antenna Explorer x_{rms} ~ 10^{-10} m @ 4K with an evaporation rate of a liquid Helium ~2 lt/h

Cryofluid approach

Easier to deal with low vibration (**good**)
More complex implementation (**bad**)

To keep low vibration ➔ Use of no-boiling cryogenic liquids at atmosphere pressure

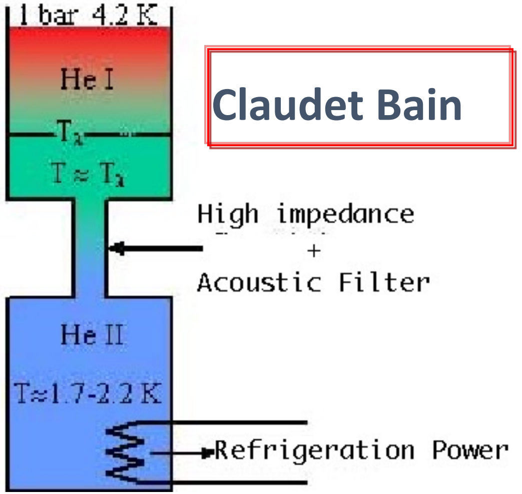
Technique ➔ keep the liquid at atmospheric pressure at a temperature below the the boiling point



N_2	77 K
He II	4.2 K

Optimum solution➔ to apply this technique with superfluid helium

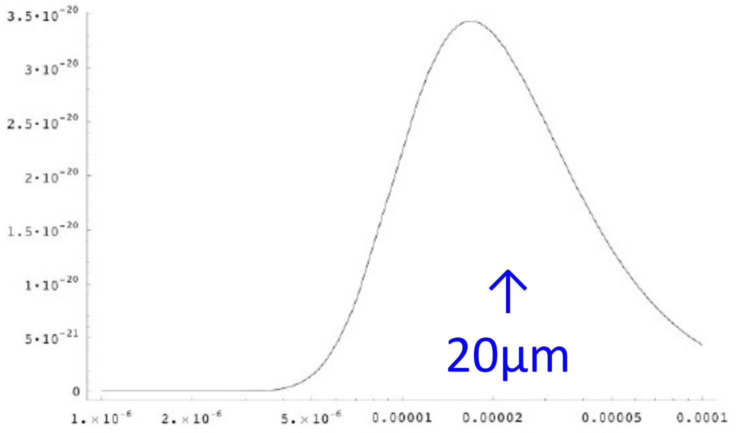
- Super fluid helium at atmosphere pressure !
- No boiling !
- Enhanced heat removal capability of unsaturated superfluid helium
- Massive use of Super fluid helium is possible: super fluid helium is widely used for cooling the LHC superconducting magnets



Cryotraps to stop thermal input

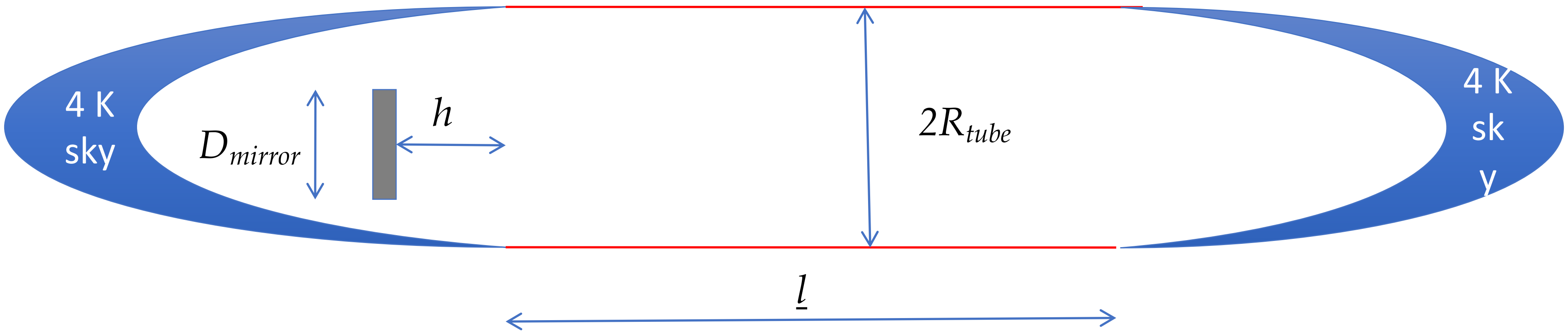
Radiative exchange Stefan-Boltzmann law

300K Black body radiation



Design of cryotrap is part of the technical design !

Crude estimation of the thermal input, assuming constant the temperature of the cylindrical tube (ε_{tube}~1) and assuming that the heat intensity impinging on the mirror is constant along the mirror surface and equal to that at its center.



To keep the thermal input constant , if we increase D_{mirror} we have to increase also the trap lengh h of the same percentage

The Old Cryo-Payload – 2010 –
Silicon Fake mirror ➔ ϕ 350 mm, 22 kg

See the talk of Ettore !!!

2021 Activity

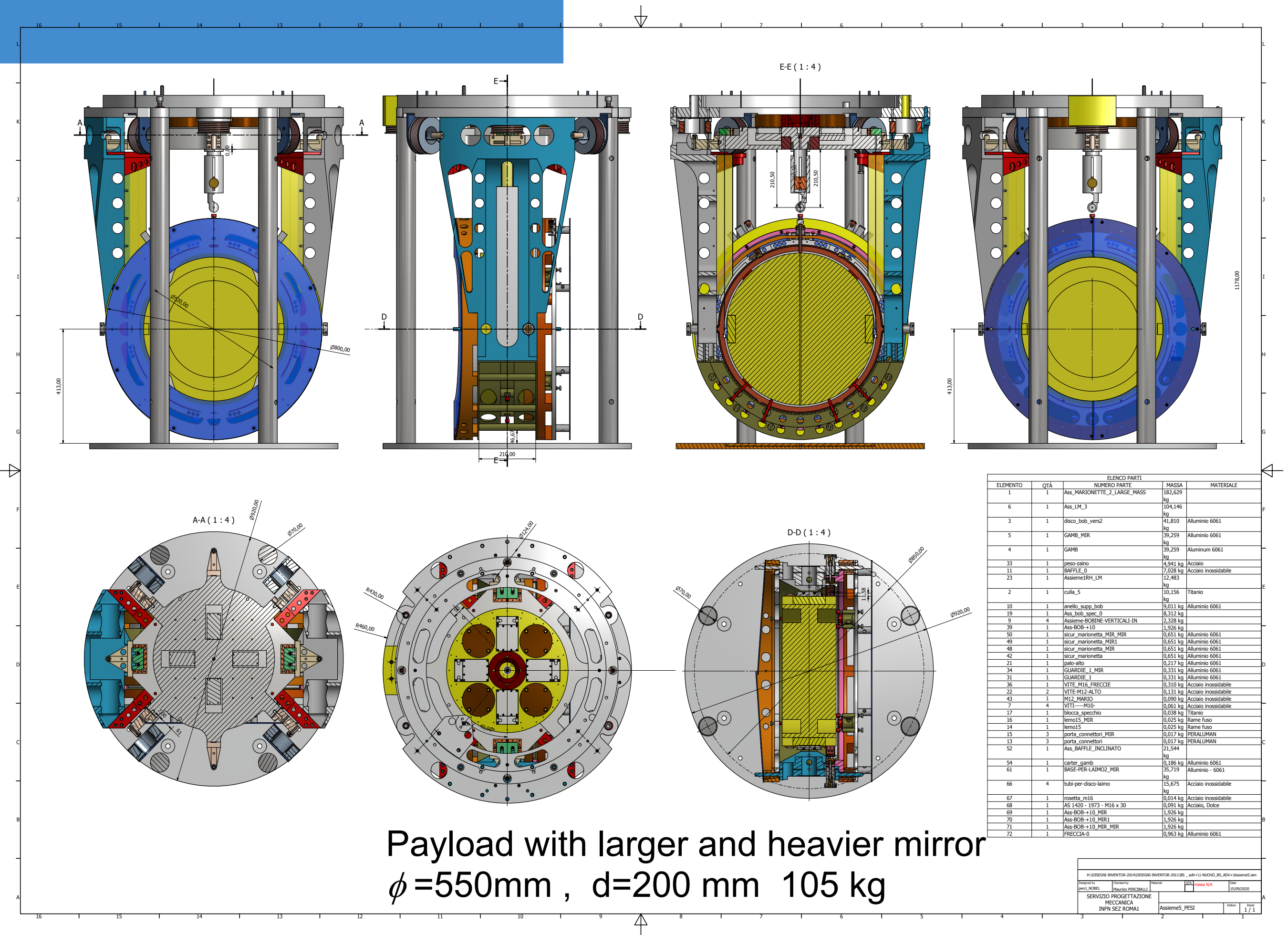
-] Completion of the laboratory infrastructure in Rome

-] Construction of the prototype of the ET Refrigeration line

-] Design of a cryo payload prototype

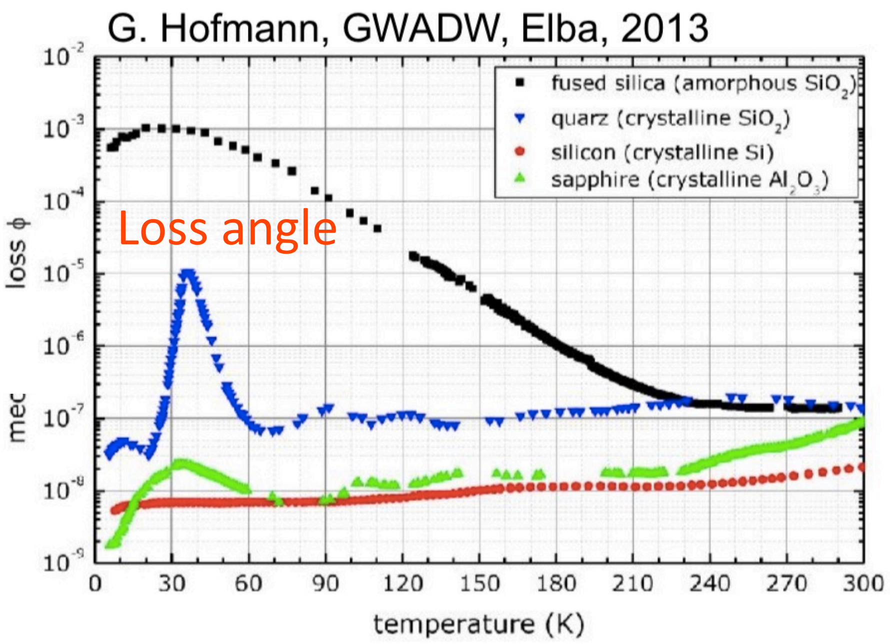
-] Design of a Cryostat for the large mass Payload

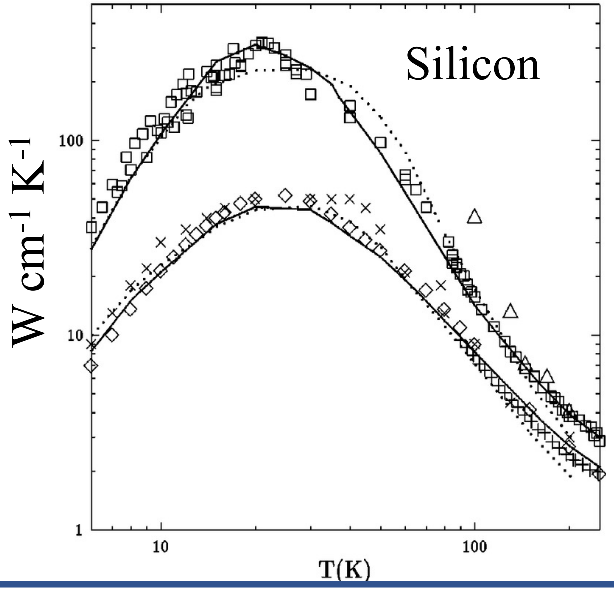
The payload cooling



Payload with larger and heavier mirror
ϕ =550mm , d=200 mm 105 kg

Materials for mirror suspension wires

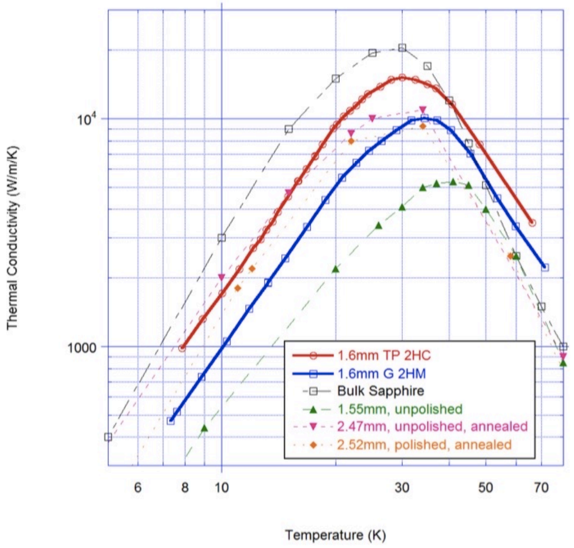


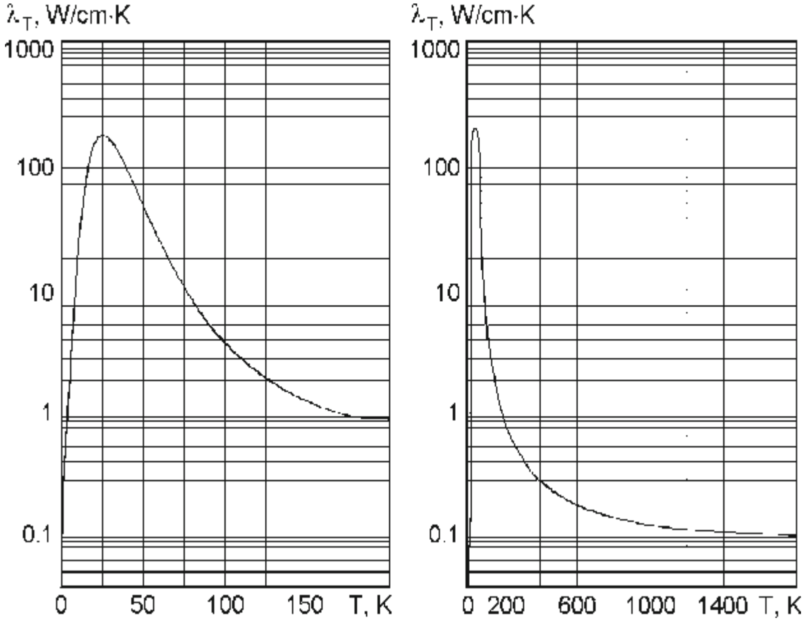


Sparavigna, Amelia Carolina
Role of nonpairwise interactions on phonon thermal transport
0.1103/PhysRevB.67.144305

Report of Allen Scheie NSF-IREU student hosted at the university of Rome Sapienza

Thermal cond. Sapphire (samples with difrerent ϕ and surface status)





Sapphire

Dobrovinskaya, Elena and Lytvynov, Leonid and Pishchik, Valerian: Properties of shappire (1970), https://dx.doi.org/10.1007/978-0-387-85695-7%7B%5C_%7D2

Heavier mirrors and suspension wires for a cryogenic payload

- Heavy Masses:
  - ☑ reduces the recoils (good for suspension thermal noise)
  - ☑ increases the violin modes (good for control)
  - ✘ reduces the vertical modes (bad for control)
  - ✘ Increase of the payload overall weight!!
- Wires Length Increment
  - ☑ reduces the pendulum frequencies (good for suspension thermal noise)
  - ✘ reduces the violin modes (bad for control)
  - ✘ reduces the vertical modes (bad for control)
- Wires Diameter Increment:
  - ☑ increment of the wire sections (good for cooling)
  - ✘ reduces the violin mode frequencies (bad for control)
  - ✘ reduces the dilution factor (bad for suspension thermal noise)

See dedicated talk of Ettore Majorana !

- **Thermal gradient along the wires and different temperatures of the pendulum stages to be included in the computation of the suspension thermal noise**

Main issues related to cryogenics

- Heat extraction from a heavy mirror and suspension wires for a cryogenic payload

(see the Tuesday presentation of Marielle van Veggel)

- Cooling Time

- Safety **: a** crucial issue when we operate in the underground

environment)

- Mirror pollution due to the temperature gradients

- VIBRATIONS and EXTRA ACOUSTIC NOISE!!!

Cryogenics: R&D

In addition to the ET design effort, we will discuss and promote R&D for improved detectors, for example for future ET upgrades. The scope of this division includes work on:

- Simulation of particle sources and shields in the cryostat
- Development of ultra-low noise LF payload cooling systems
- Experimental investigations on LF payload operation, incl. local control

Open point

Numerical study of the cryotrap configuration

-Numerical evaluation of the geometrical factor for the radiative heat transfer

-Molecular conduction evaluation via montecarlo

-

Payload cooling time

- We need to reduce it (up to 1 week per mirror)

- use of the He gas exchange,

a complex solution in a real GW interferometer

- Use a telescopic system to transmit the refr. power via solid

Vacuum & Cryogenics: Preliminary questions

Before the complete design document, we must address urgent issues following from the current design, for example:

- Diameter and bakeout conditions of the pipe arm tubes
- Desired cool-down and warm-up times
- Heat load on the LF mirrors
- ...

Toward a light technical design

For developing the light technical design, the following issues are a priority:

- Preliminary tower vacuum design, pumping plan and interdepencies
- Preliminary design of pipe arms, baffles, pumps etc.
- Preliminary cryostat and shielding design
- Preliminary cryogenic infrastructure design
- Preliminary LF payload cooling design

Conclusion

- WP IV Cryogenics & Vacuum activity for 3G-GW interferometers is started in 2010.

- The previous studies study and the KAGRA experience traced the way that we will pursue to prepare the technical design study.

The ET Instrumental Science community devoted to the project is open to all contributors. Your contribution is welcome

Please subscribe to the mailing list of the at

http://mail.ego-gw.it/mailman/listinfo/et-isb-vac-cryo

Extra Slides

WP.IV 1 Tower Vacuum

- The work package includes the definition of the specifications, the R&D program for material qualifications and handling procedures, the design and the cost evaluation of the various vacuum chambers hosting the super attenuator, i.e. the upper part of the cryostat for the LF interferometer and the entire tower for the HF interferometer including the vacuum chamber hosting the payload. The design of the auxiliary towers is also part of this WP.
  - Viewports, vacuum pumps for the towers, valves, gauges, mass spectrometer and vacuum leak detectors should be included in the design and the cost evaluation.
  - WP IV.1 has interfaces with
  - IV.2 Pipe Arm Vacuum
  - IV.3 Cryostat and Cryopumps
  - In addition, the proposed solutions must be in agreement with those of the other WPs concerning
  - Infrastructure
  - Optical layout of the interferometer
  - Suspension system
  - TCS system
  - Light scattering reduction
  - Interferometer local control
  - Safety plan for the caverns

WP IV.2 Pipe Arm Vacuum

- WP IV.2 is devoted to the design of the almost 120 km vacuum pipes. On the base of vacuum specifications and the lifetime of the entire vacuum system in the underground environment, the WP activity includes the material qualification with handling procedures, the pipe system design and the complexity of the installation of four parallel pipes in the tunnel. Transportation constraints, assembly procedure and related special tools should also be studied. Procedures for the vacuum leak test and for the backing of the 120 km tubes are issues of this WP, as well as vacuum pumps and instrumentation.
- WP IV.2 has interfaces with
- IV.1 Tower Vacuum
- IV.3 Cryostat and Cryopumps
- In addition, the proposed solutions must be in agreement with those of the other WPs concerning
- Optical layout of the interferometer
- Light scattering reduction
- Infrastructure
- Safety plan of tunnels

WP IV.3 Cryostat and Cryopumps

- WP IV.3 is devoted to the design of the cryostats hosting the payloads of the LF interferometer, as well as the cryopumps that limit the particle flow from the tower vacua into the pipe arm vacua in both the LF and HF interferometers. This includes the development of design tools, the qualification of materials and handling procedures, the simulation of the vacuum conditions and the design of the cryostat with thermal shields and cryopumps. Transportation constraints, assembly procedure and special tools should also be studied. In addition, the WP includes the selection of the superinsulation material and the temperature control. The requirements to operate the cryostats and cryopumps must be defined for WP IV.4.
- WP IV.3 has interfaces with
- IV.1 Tower Vacuum
- IV.2 Pipe Arm Vacuum
- IV.4 Cryogenic Infrastructure
- IV.5 Detector Cooling
- In addition, the proposed solutions must be in agreement with those of the other WPs concerning
- LF payload
- Suspensions
- Optical layout of the interferometer
- Light scattering reduction

WP IV.4 Cryogenic Infrastructure

- WP IV.4 is devoted to the design of the cryogenic infrastructure. It includes the specifications of cooling and gas handling systems, including transfers lines between surface and underground installations, and the cryogenic safety concept. The design also includes the seismic and acoustic insulation of the cryogenic infrastructure from the interferometers.
- WP IV.4 has interfaces with
- IV.3 Cryostat and Cryopumps
- IV.5 Detector Cooling
- In addition, the proposed solutions must be in agreement with those of the other WPs concerning
- Infrastructure
- Safety plan of caverns and tunnels
- Safety plan of the surface infrastructure

WP IV.5 Detector Cooling

- WP IV.5 is devoted to the design of the cryogenic payload cooling system of the LF interferometer and the interface between payload and refrigeration line. This includes parallel investigations of both the actual baseline design using pulse-tube cryocoolers in combination with passive and active attenuators of vibration noise, and the alternative development of a He-II detector cooling system. WP IV.5 is closely related to WP IV.3 in order to avoid particle condensation on the payload optics.
- WP IV.5 has interfaces with
- IV.3 Cryostat and Cryopumps
- IV.4 Cryogenic Infrastructure
- In addition, the proposed solutions must be in agreement with those of the other WPs concerning
- LF Payload
- Suspensions
- Optical layout of the interferometer
- Light scattering reduction
- Infrastructure