Large volume cryogenic detectors (lessons from CUORE and beyond)

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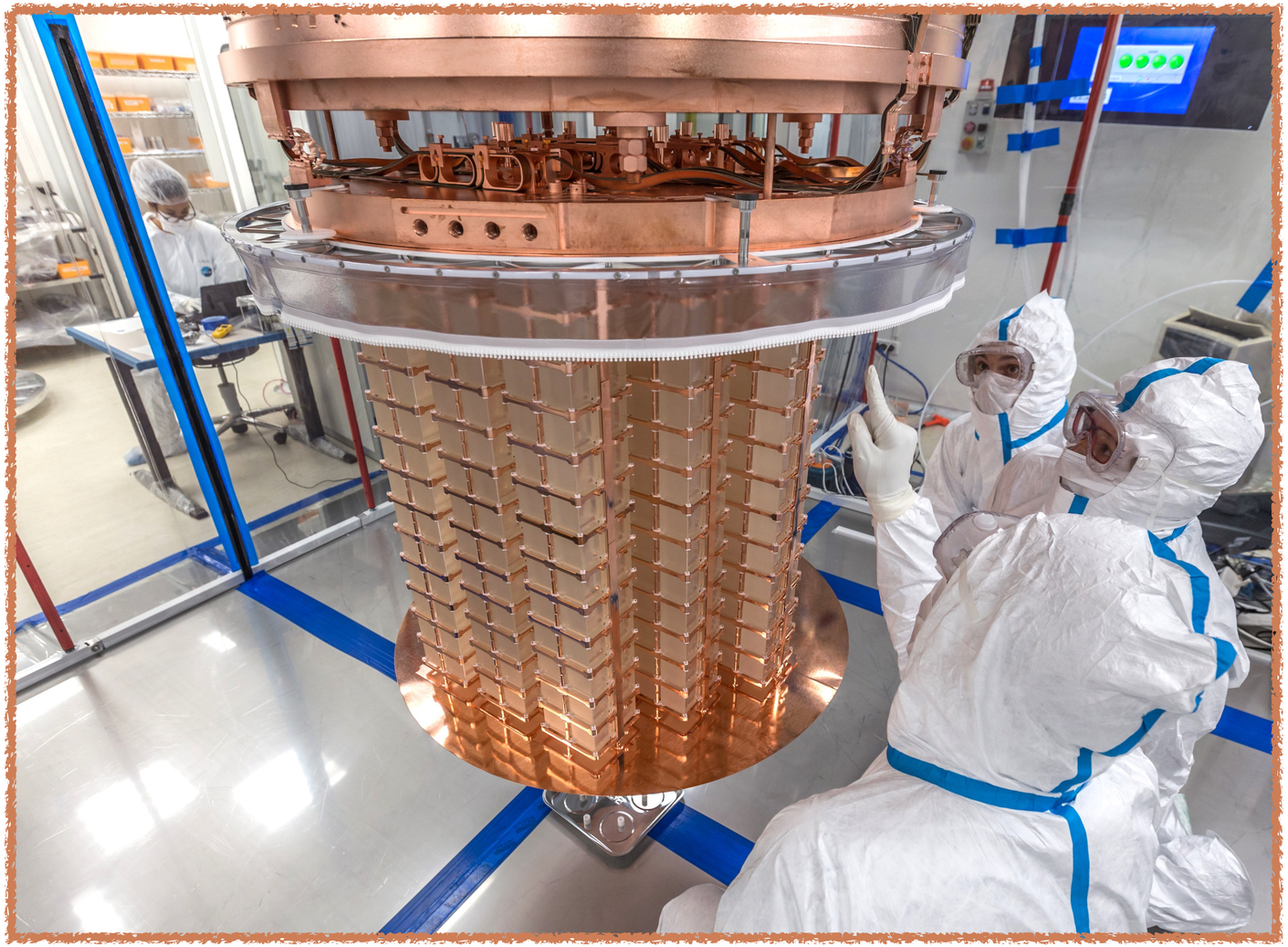


CUORE

INFN
Istituto Nazionale di Fisica Nucleare

Disclaimer

All frontier particle physics projects are difficult, complex and challenging. This is a matter of fact. All of you know how much commitment, how many management skills and how much effort are needed.

CUORE has been a great training camp experience. The challenge of a ton scale cryogenic experiment has been a dream for many, starting from the visionary ideas of Ettore Fiorini back in the ‘90s. Now CUORE is a reality: built and running. Still the features of such a detector need to be fully exploited.

CUORE represents the first step in a new era for cryogenic detectors. Now moving to newer and more challenging project is not anymore a dream but still a great enterprise.

A favourable view point

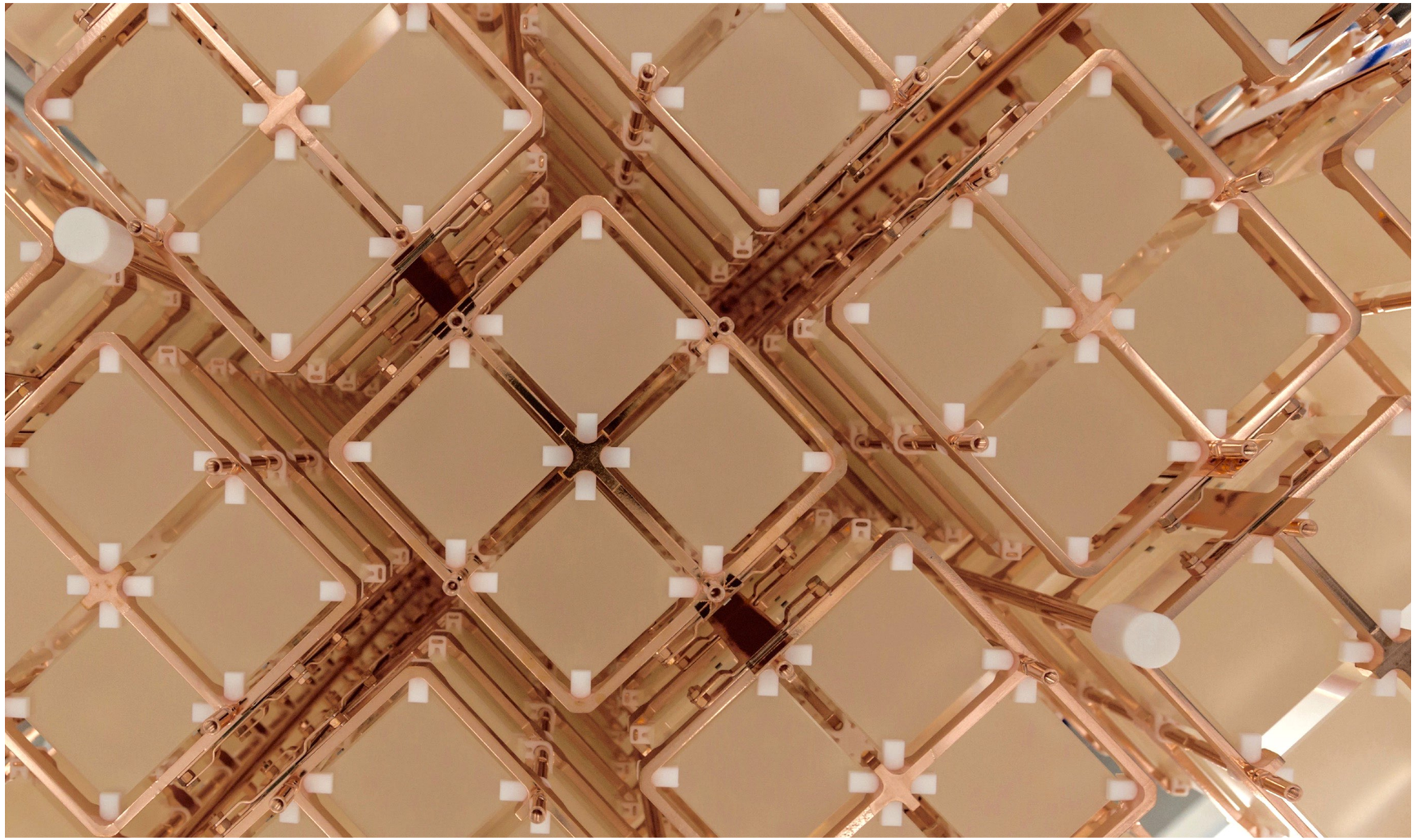
Working at LNGS since the very beginning of CUORE and being involved in many of the construction/ commissioning/start up operations has been a unique opportunity to learn what CUORE can teach to the upcoming generation of projects.

CUORE is a complex experiment

CUORE is a complex experiment, operated in complex environment.

Detector:
→ low background
→ high resolution

Cryostat:
→ Low temperature
→ Low background
→ Low vibration



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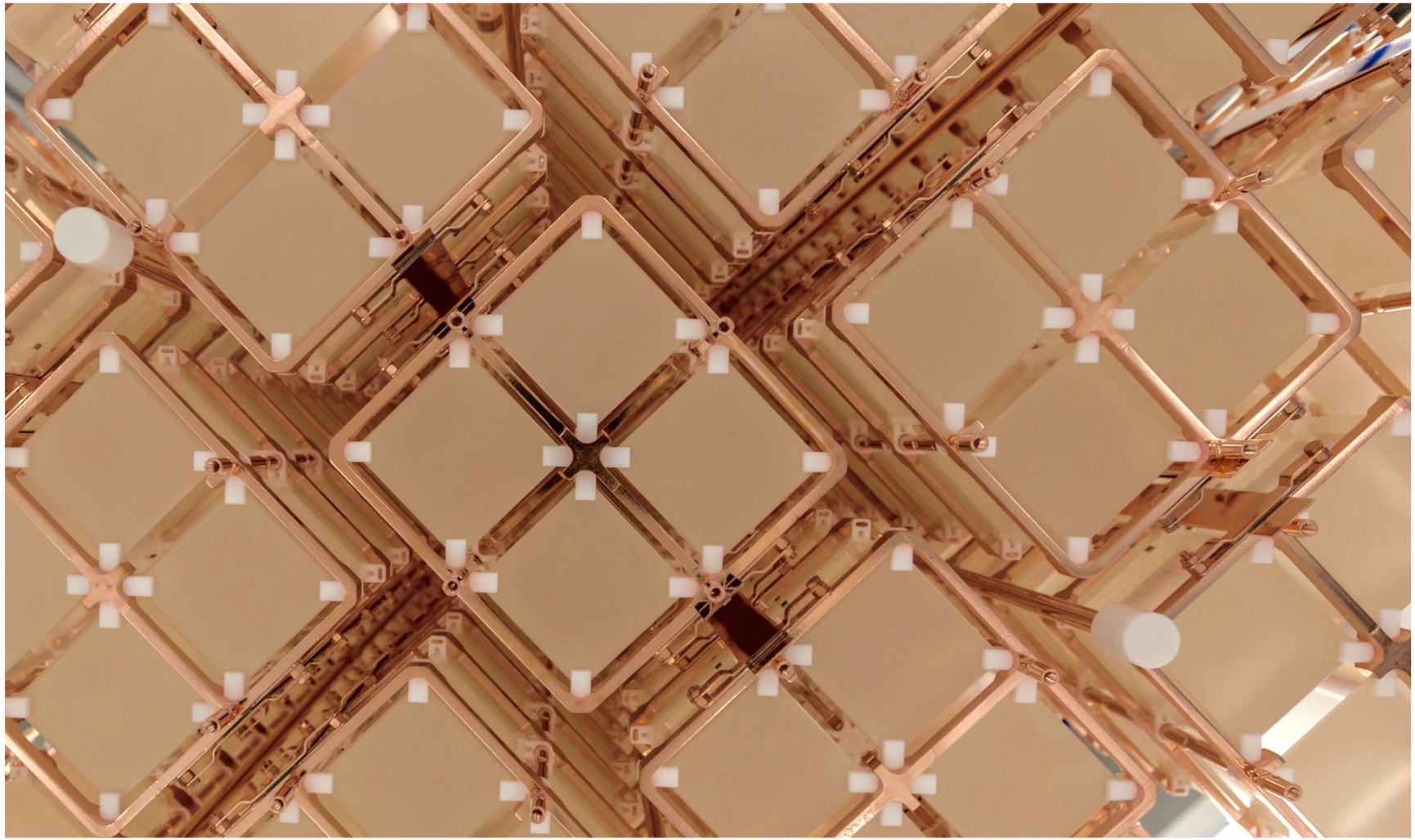


CUORE cryostat (I)

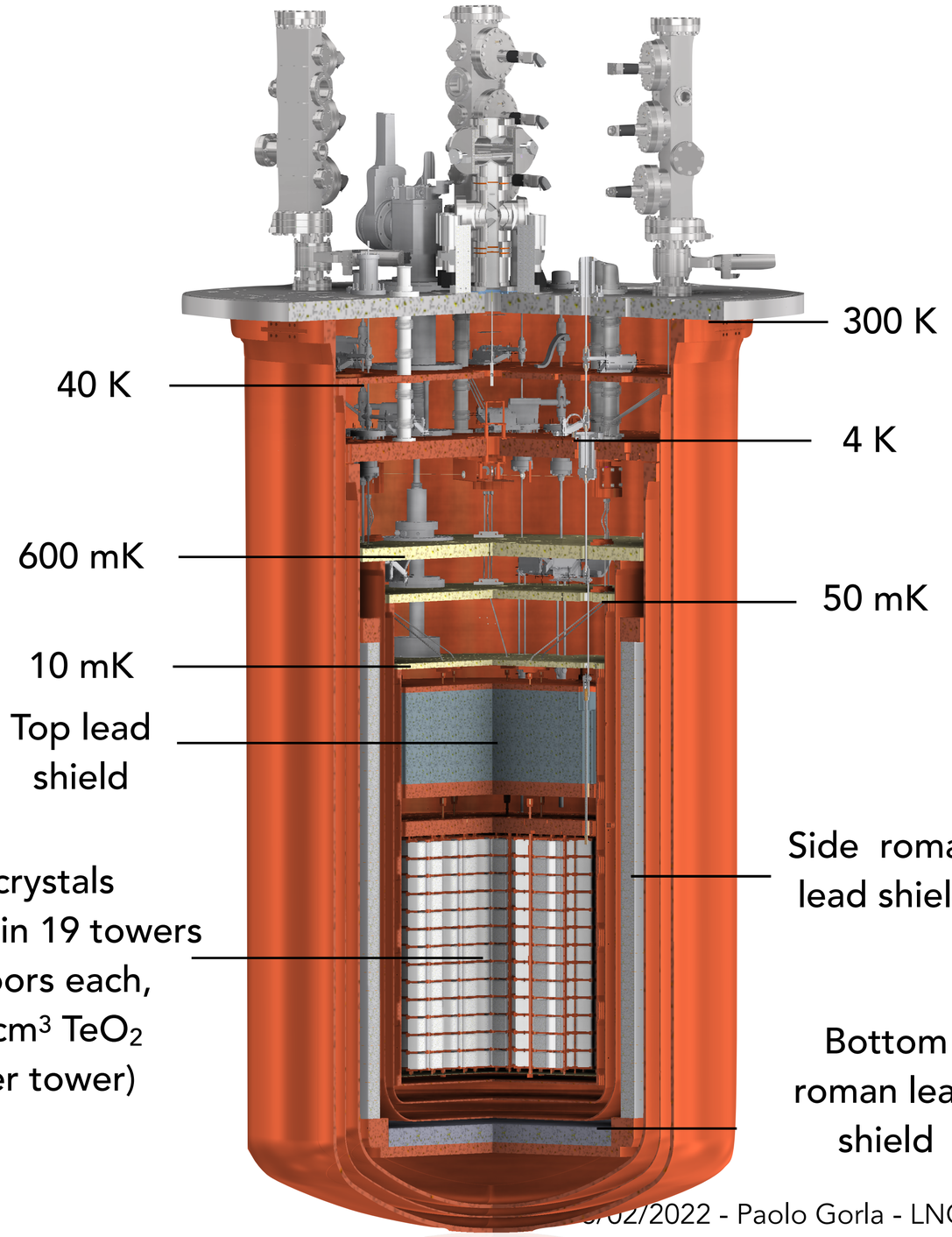
Requirements

The CUORE detector is hosted in a cryogen-free cryostat (mass < 4K: ~15 tons of Pb, Cu and TeO_2):

- Operating temperature 11 -15 mK (base T~7 mK) on an experimental volume of ~1 m^3
- Designed to guarantee extremely low radioactivity and low vibrations environment
  - Energy resolution: goal of 5 keV at $Q_{\beta\beta}$
  - Low background: goal of 10^{-2} cts/(keV·kg·yr) at $Q_{\beta\beta}$
- Low vibrations
- Run for 5 yr

Solutions

- Cryogen free cryostat → Lower downtime
- 5 (4) Pulse Tubes (PT) down to ~4K
- Dilution Unit (DU) down to ~7mK
- PT phase cancellation

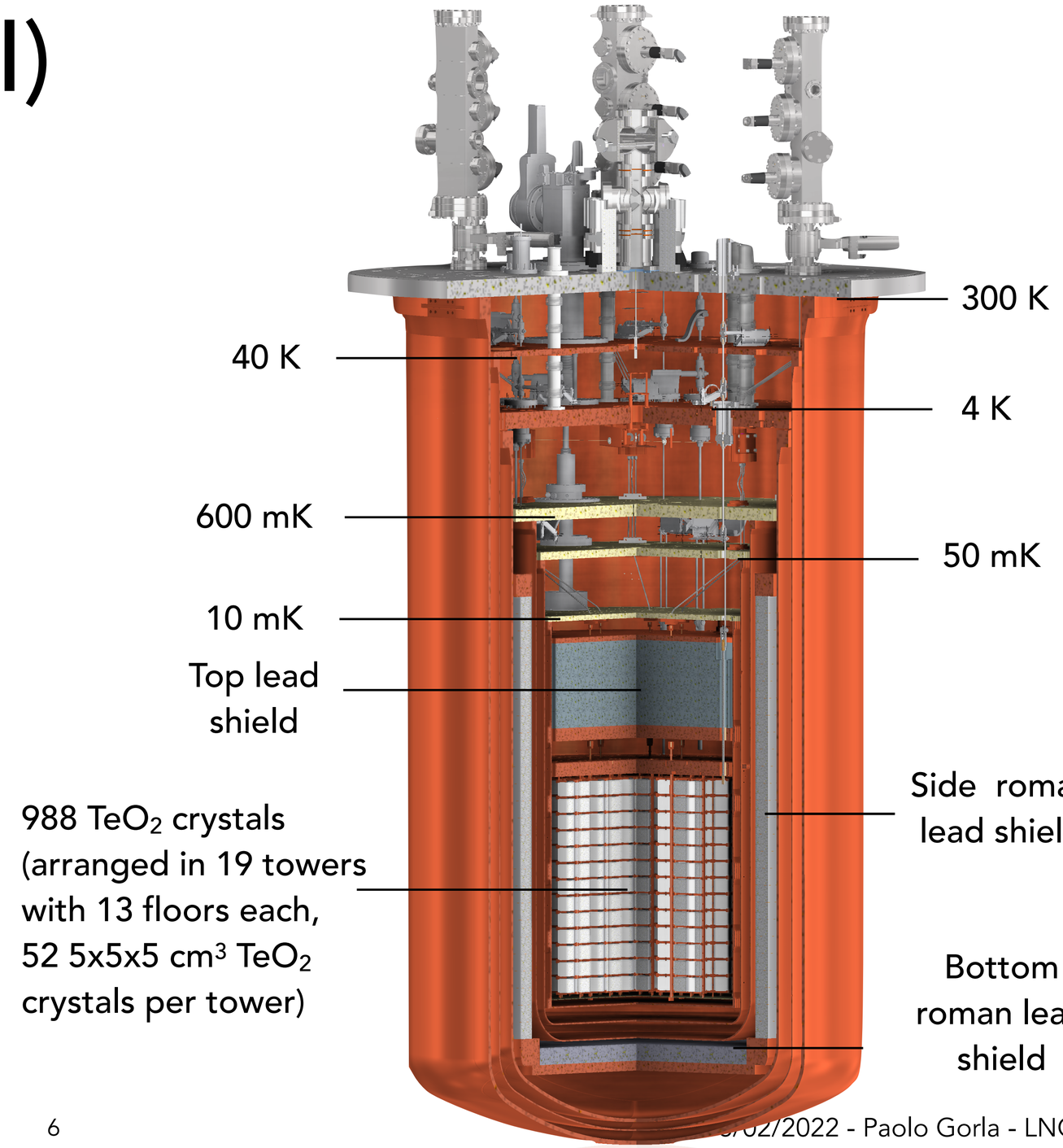


CUORE cryostat (II)

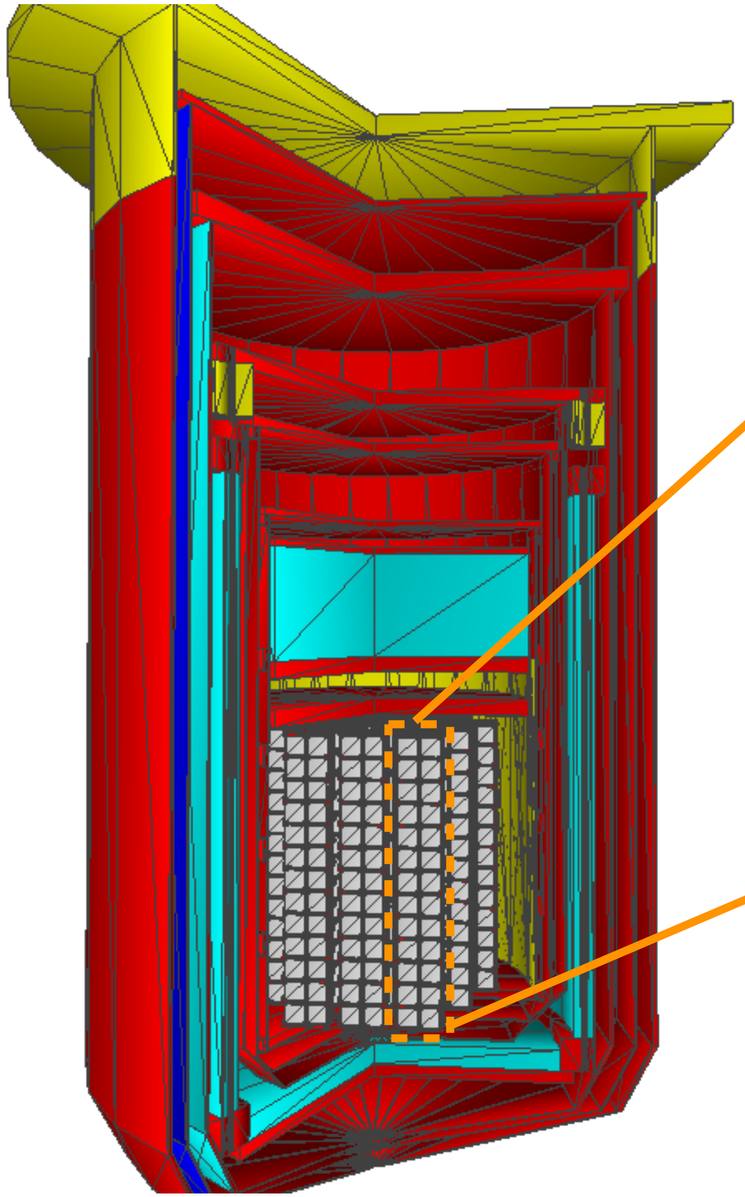
Custom design and commissioning

No company or engineer available to develop/ design the full CUORE cryostat. Most of the work internal to the CUORE collaboration: design took 3 years and commissioning took 4 years but results are impressive.

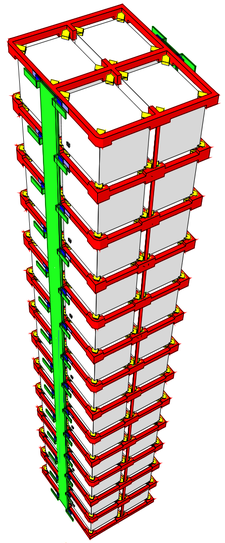
And now we know how to do it better.



Everything but clean



Any single CUORE component or part has been selected and validated for low contamination content. The full bkg expectation projected via MC simulations.



Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

Crucial contribution from LNGS low background facility (STELLA Lab) and low contaminant traces identification facility (ICPMS Lab)

Dilution unit: hunt for 7 mK (aka the coldest cubic meter in the known universe*…)

CUORE CryoReview, April 2013

L.Taffarello (INFN- Padova): “ We need a machine as powerful as the Challenger and as performing as the F12”

* credits to J.Ouellet - MIT

Dilution unit: hunt for 7 mK (aka the coldest cubic meter in the known universe…)

Leiden Cryogenics knows how to do it!

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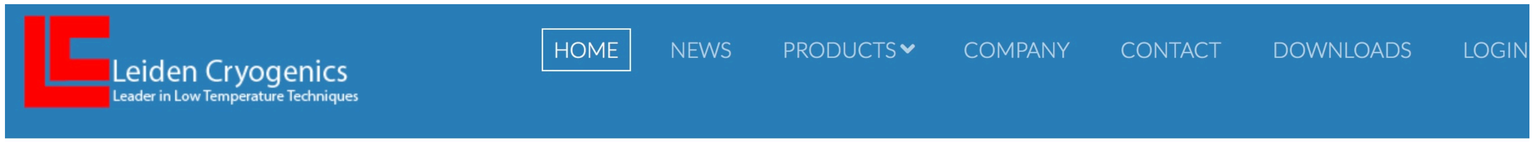


Leiden Cryogenics, new Cryogen Free CF-CS110 model

With pride we announce our newest Cryogen Free CF-CS110 model,

this new system with 490mm diameter mixing chamber plate to provide a large sample space.

And the double pulsed tube cooling with an expected Tmin ~ 5 mK,

and Cooling power ~ 2500 microW @ 120 mK

LEARN MORE CONTACT

And today you can just buy it!

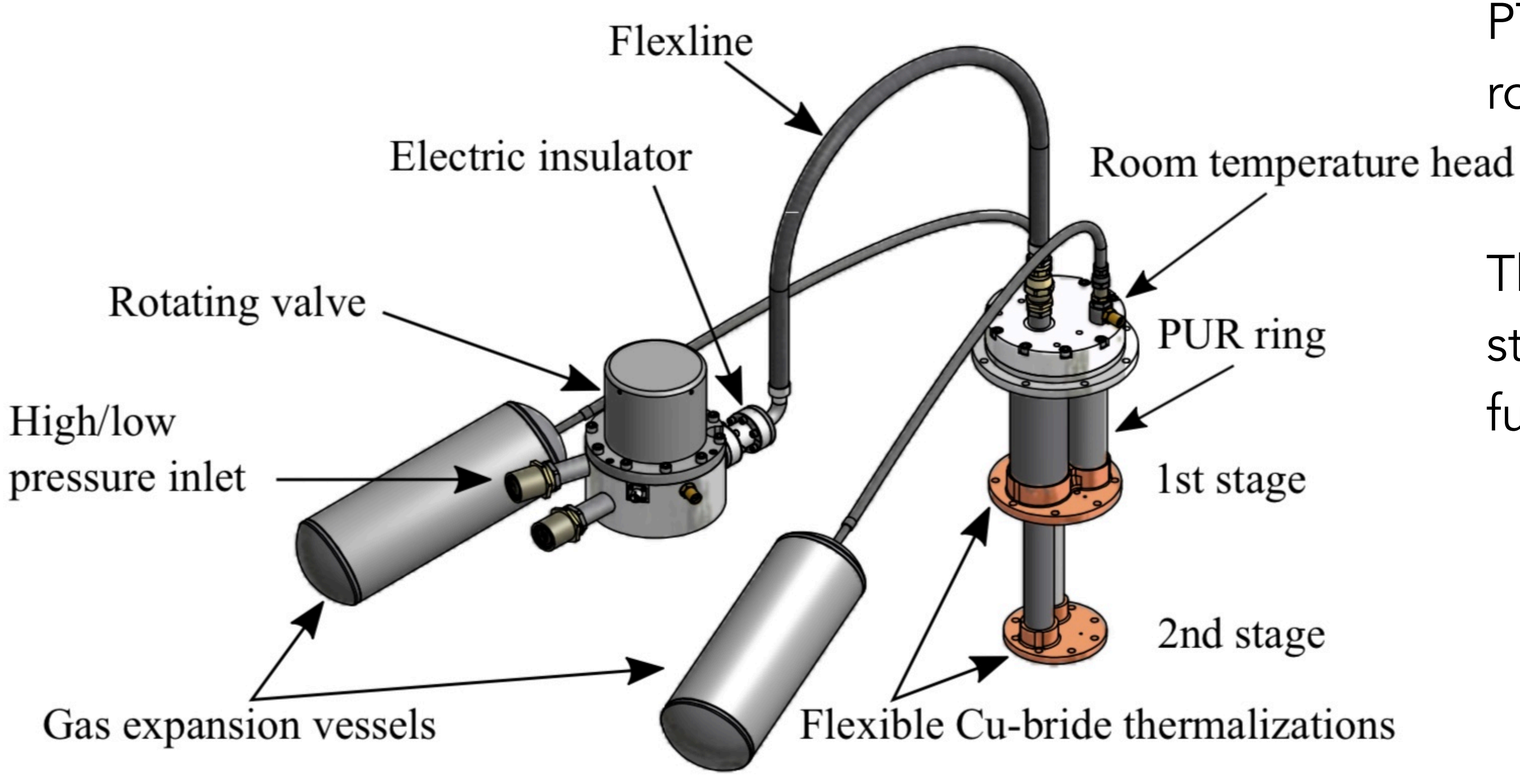
Dilution unit: hunt for 7 mK (aka the coldest cubic meter in the known universe…)

And then you just need to insert it in a large enough cryostat providing all the proper temperature stages.

To cool down the full cuore mass you need to **remove ~1*10⁹ J of enthalpy.**

Where can you get such an impressive cooling power?

Cryomech pulse tubes



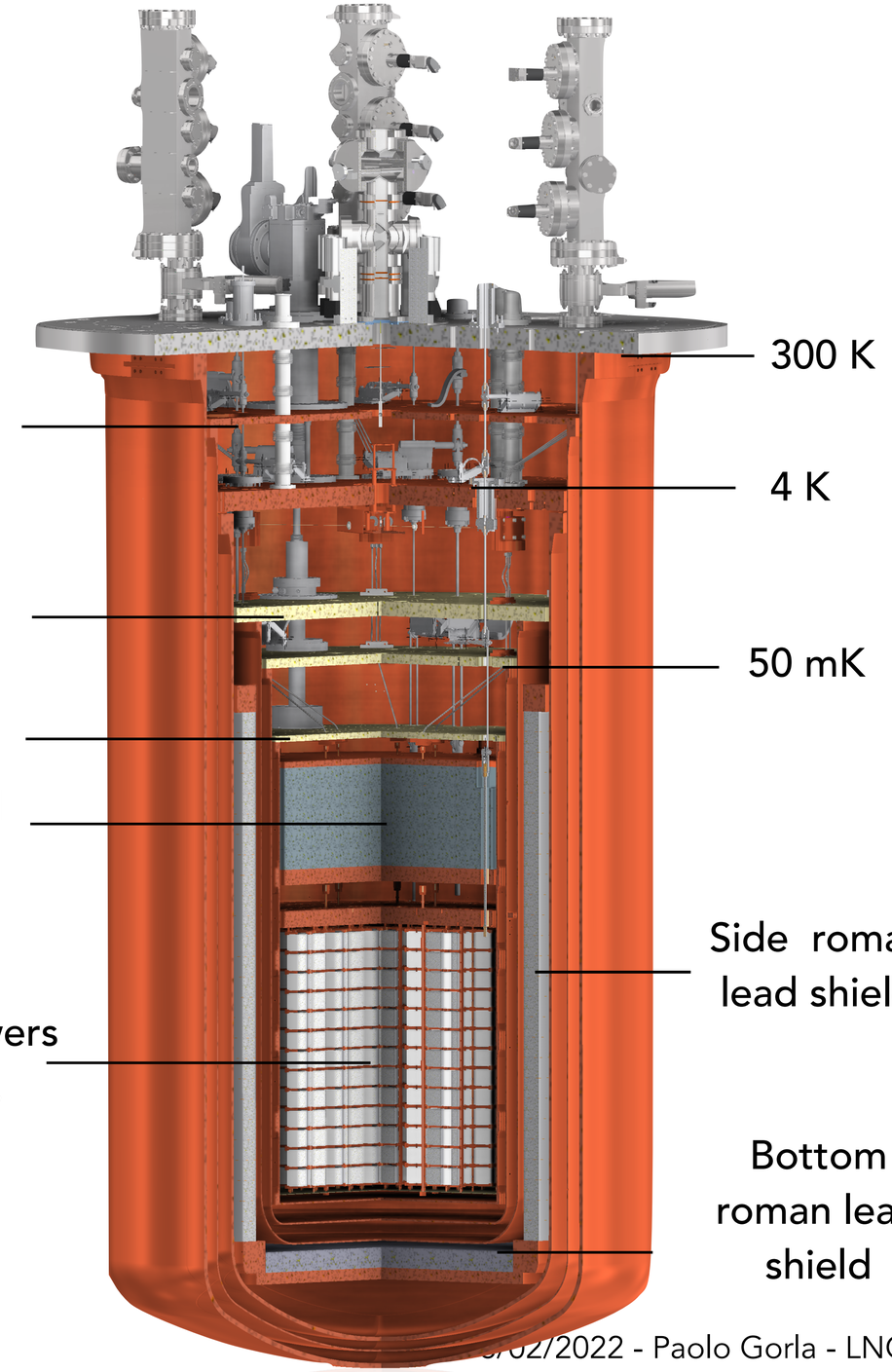
CUORE cryostat is equipped with 5 (4 operating at the time) Cryomech PT415 Pulse Tubes with remonetized rotating valve.

These PTs provide ~3.5 K at the 2nd stage and ~35 K at the 1st stage for the full CUORE cryostat.

CUORE cryostat (III)

Building a cryostat

The production, cleaning and assembling of the CUORE cryostat has been a challenge for engineers and companies, given the selection of materials (e.g. copper is not engineers favorite material to design 6 m^3 wide vessels-vacuum tight).



CUORE cryostat (IV)

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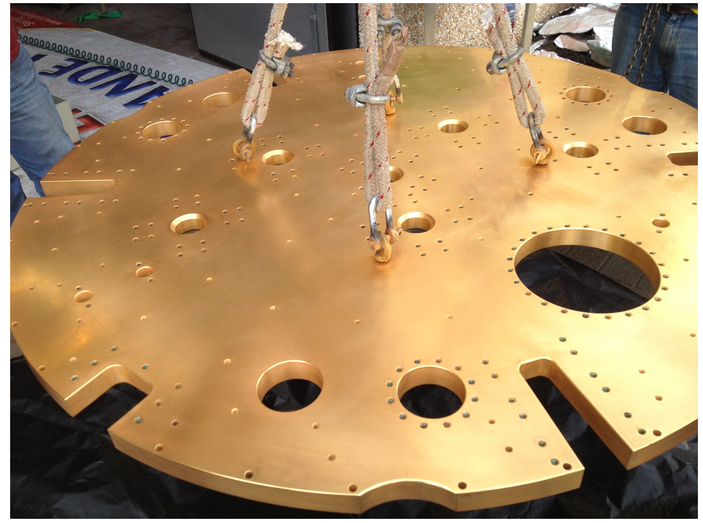
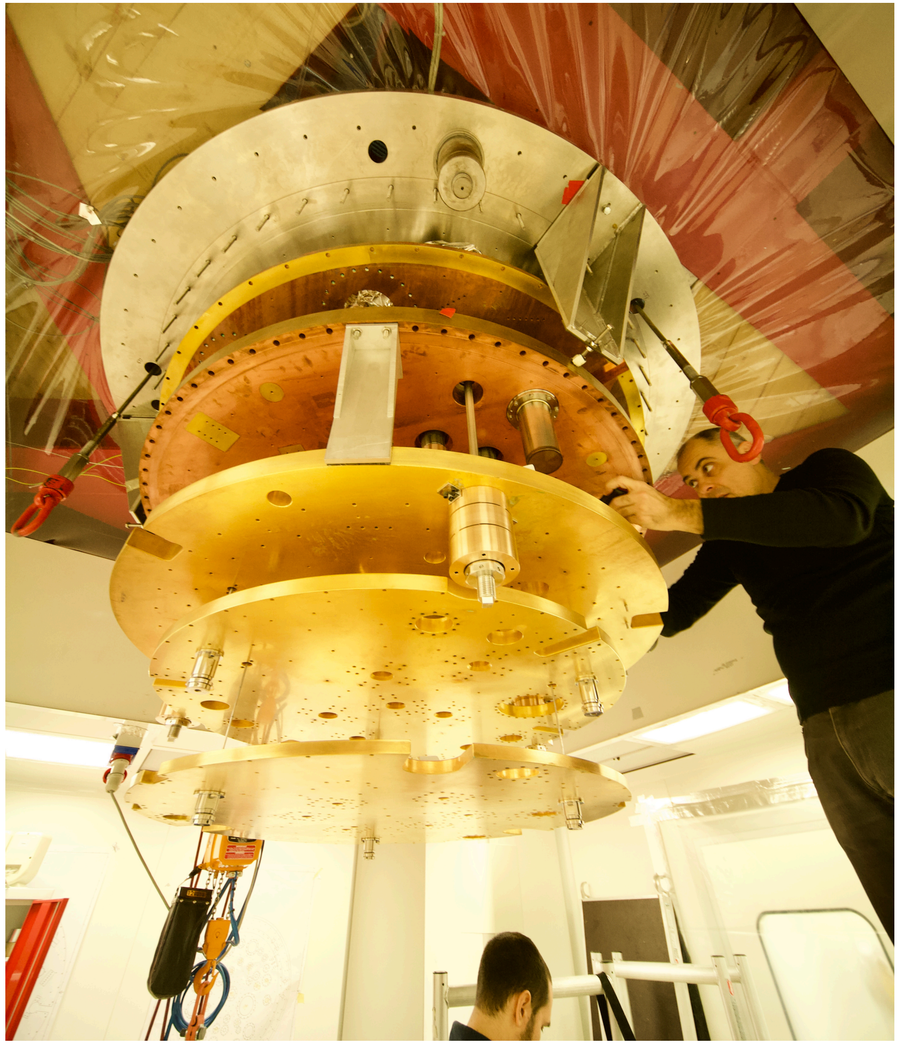
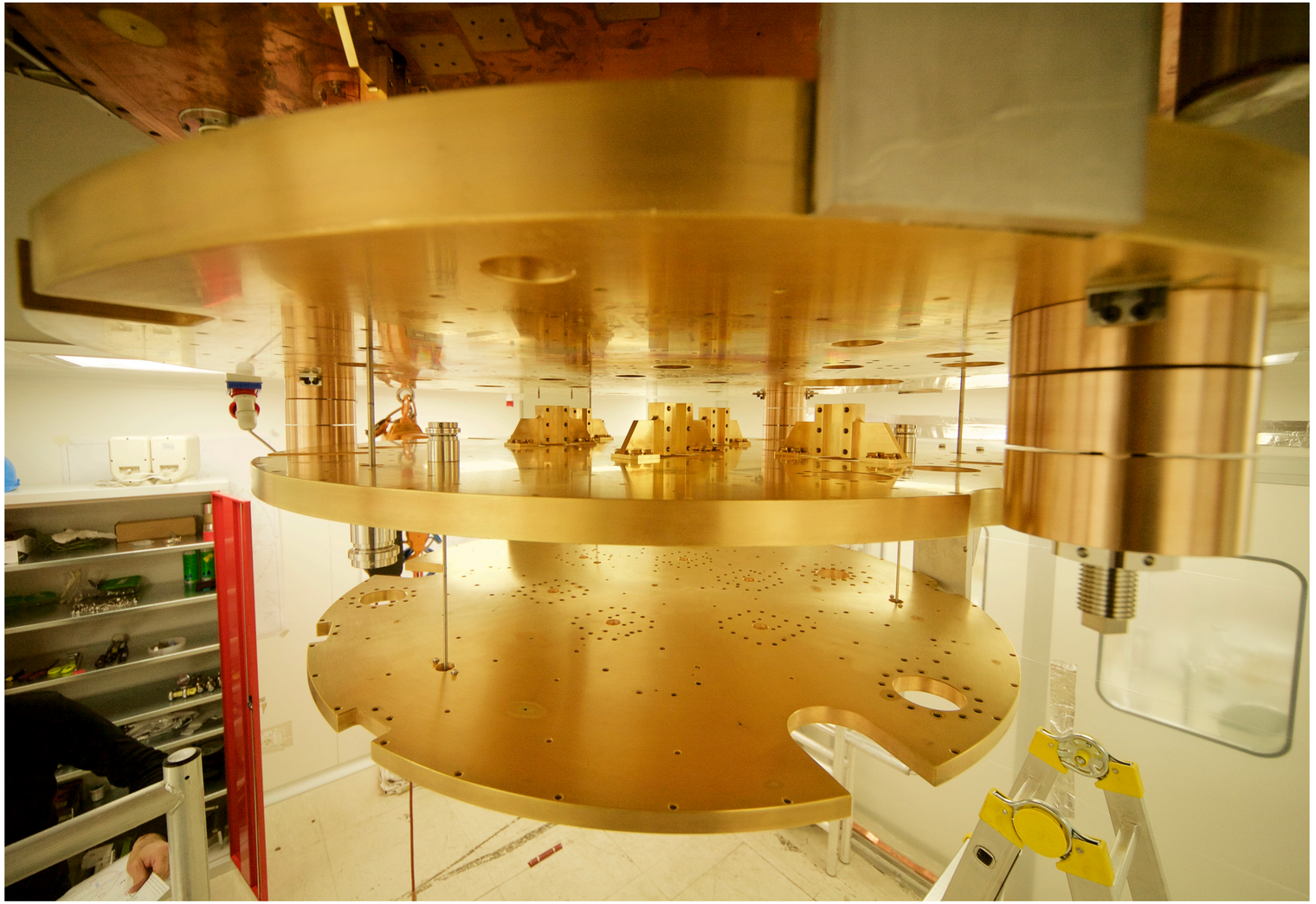
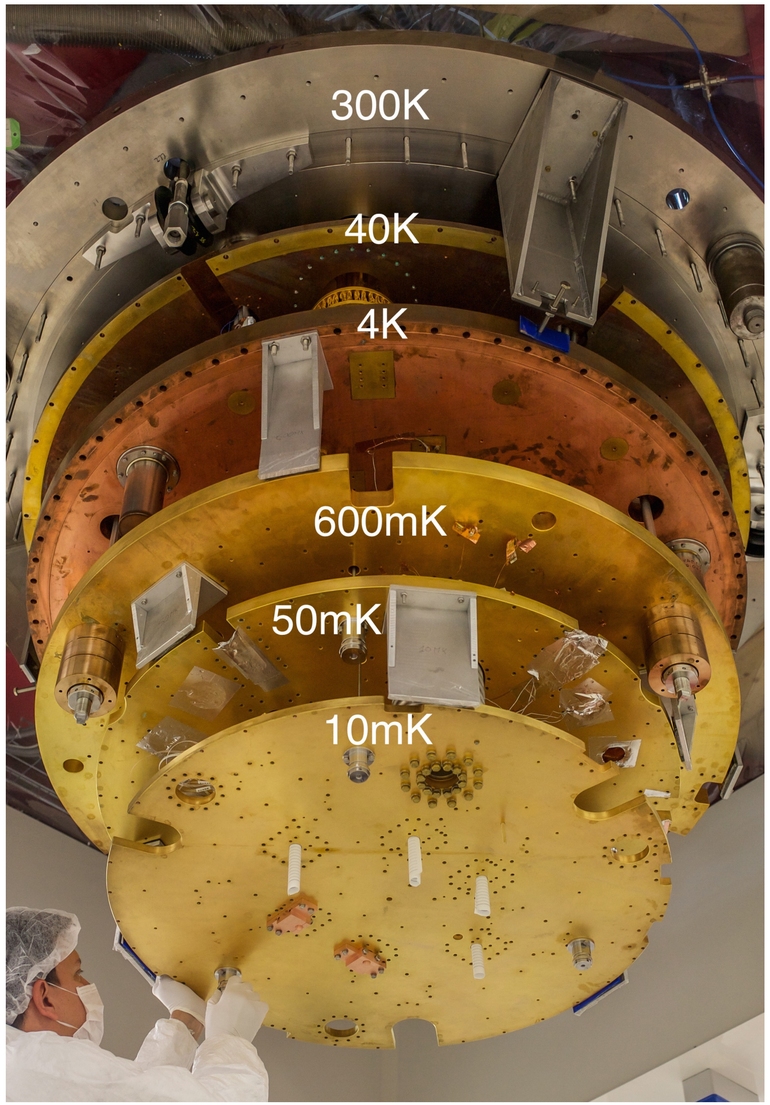


CUORE cryostat (V)





Cryostat assembled



300 K

35 K

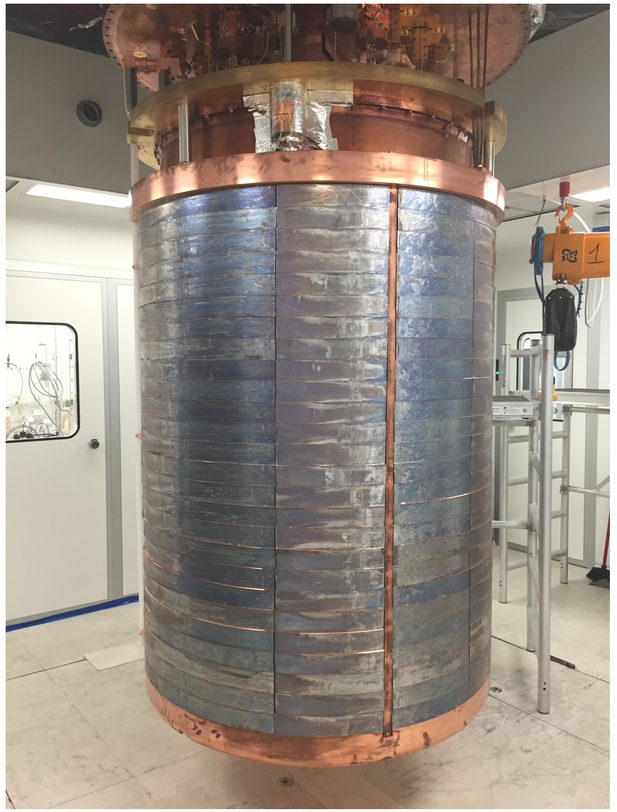
3.5 K

800 mK

50 mK

7 mK

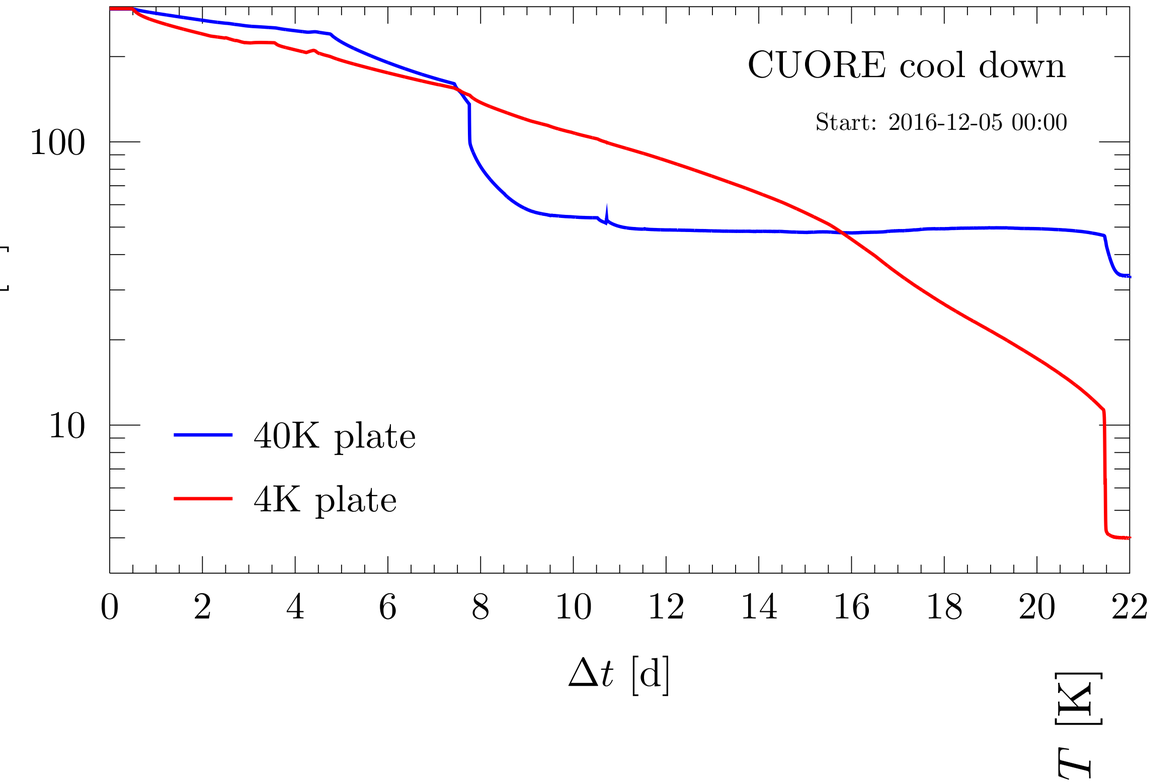
All the cryostat components well thermalized at the different stages (including top Pb @ 50 mK and lateral roman Pb @ 3.5 K). No evident temperature gradient or heat leak.

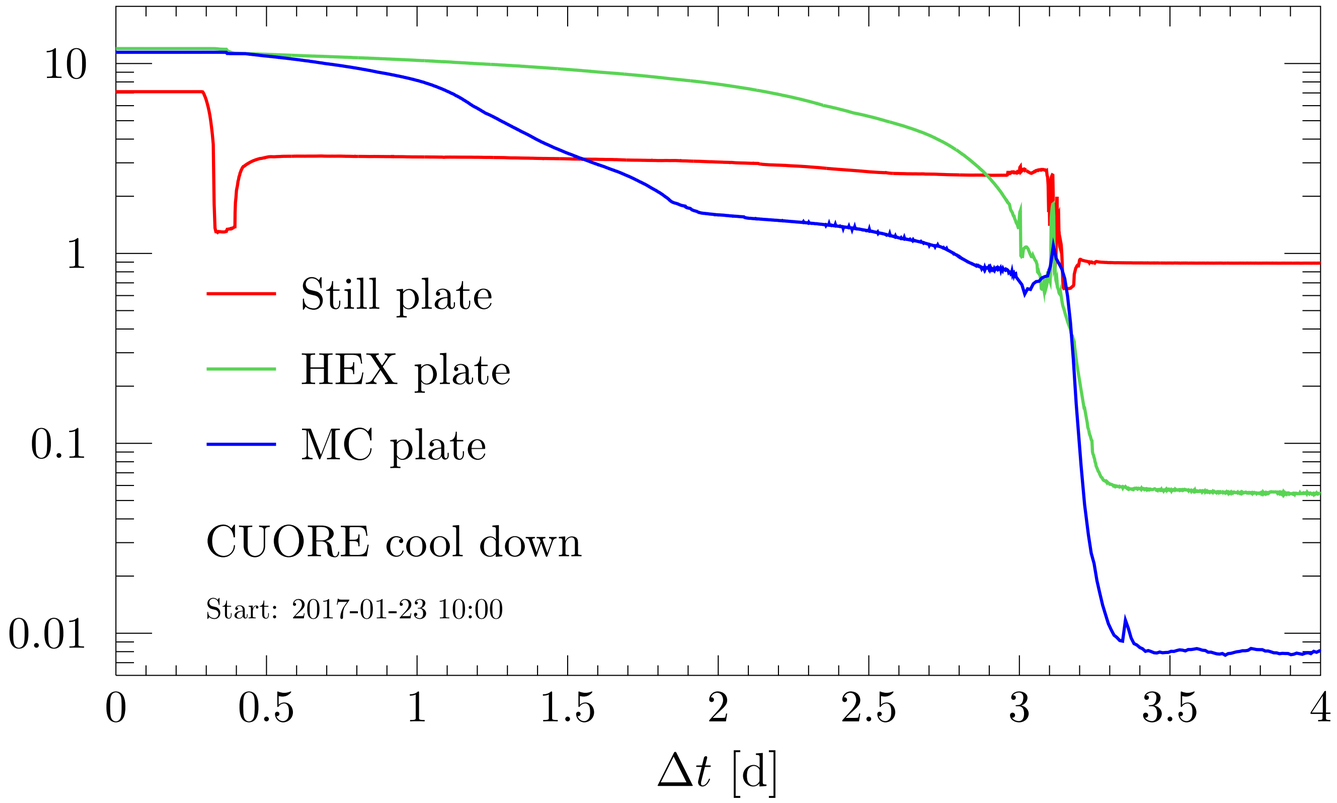


Never-ending cleaning

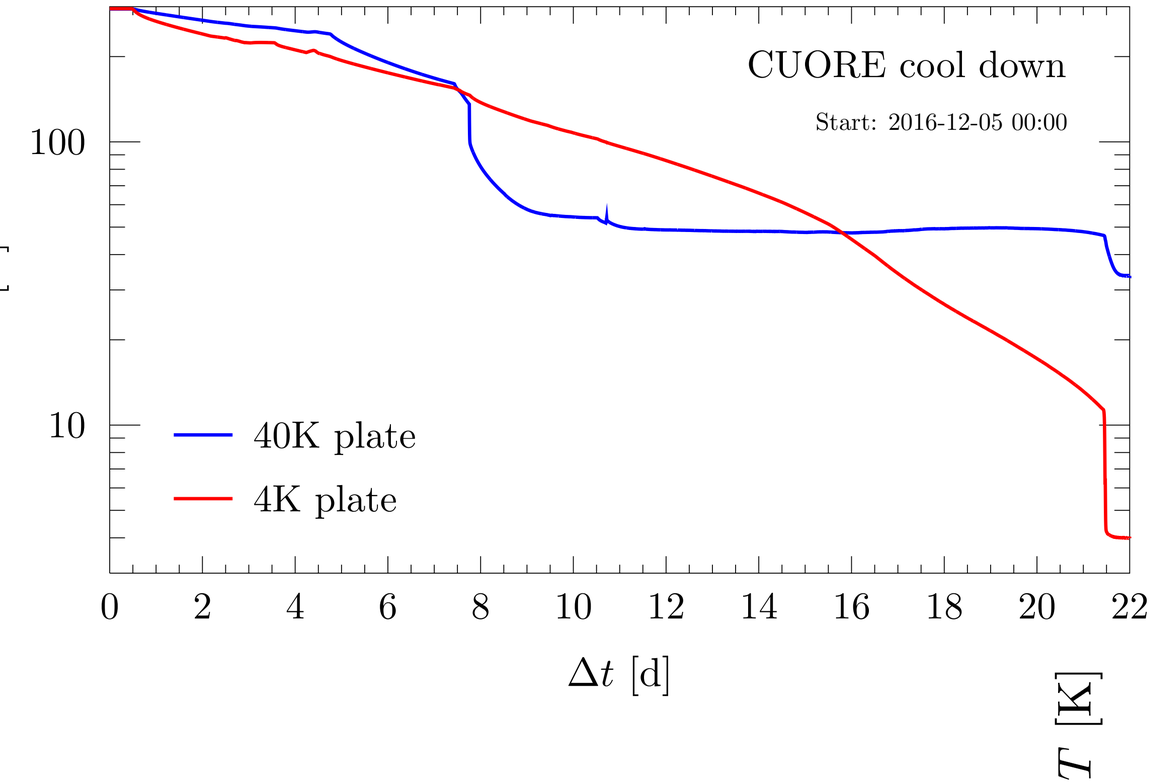
Custom procedure modifying a commercial water/ vacuum cleaner with a citric acid solution system.

Cool down

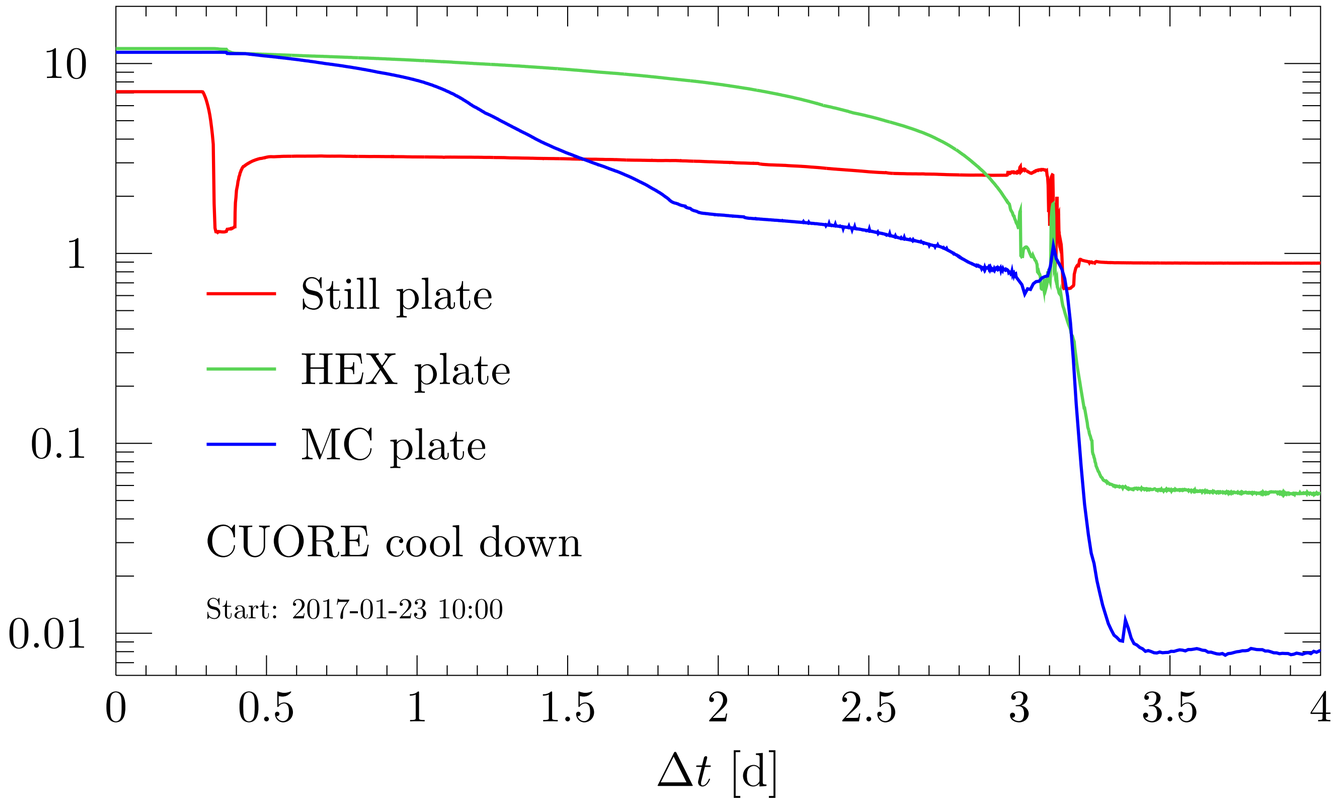

CUORE cool down
Start: 2016-12-05 00:00
100
10
40K plate
4K plate
0
2
4
6
8
10
12
14
16
18
20
22
Δt [d]
T [K]


10
1
0.1
0.01
Still plate
HEX plate
MC plate
CUORE cool down
Start: 2017-01-23 10:00
0
0.5
1
1.5
2
2.5
3
3.5
4
Δt [d]

Cool down

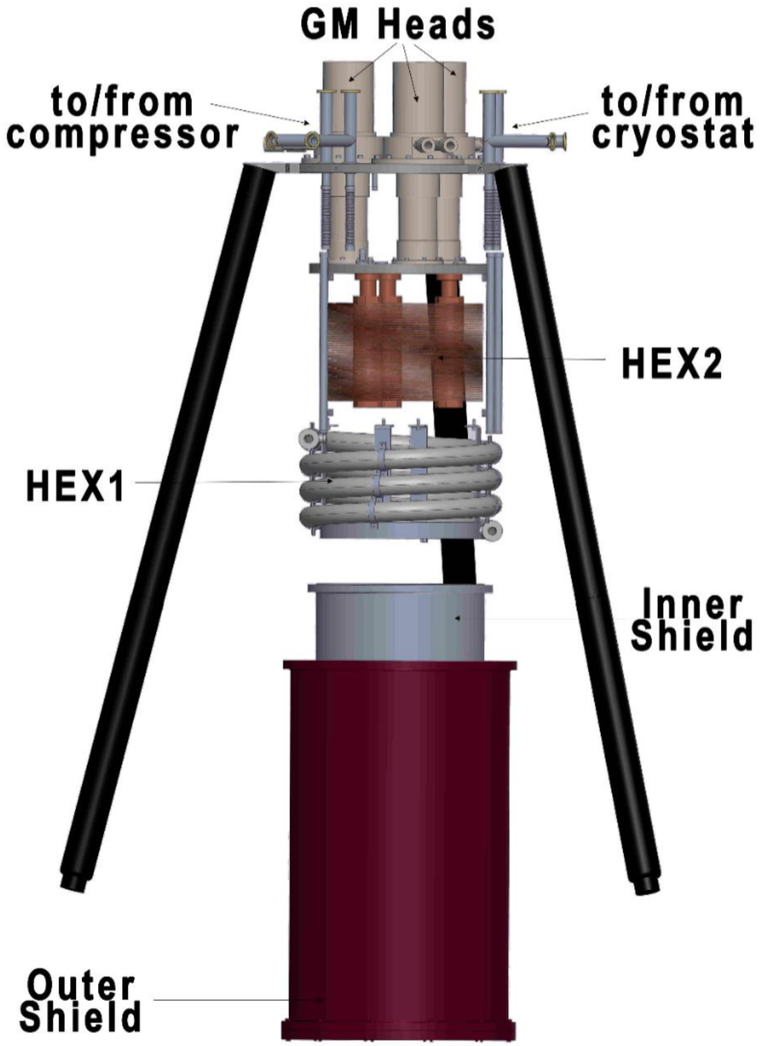


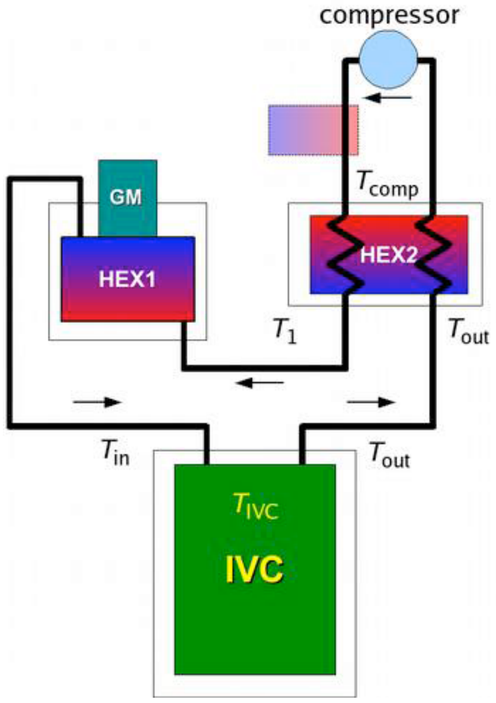
Cooling down the CUORE cryostat takes 40-60 days (including the 2 weeks pumping to remove heat exchange He gas). R&D cool down in the CUORE cryostat: not more than 2/year (3?)

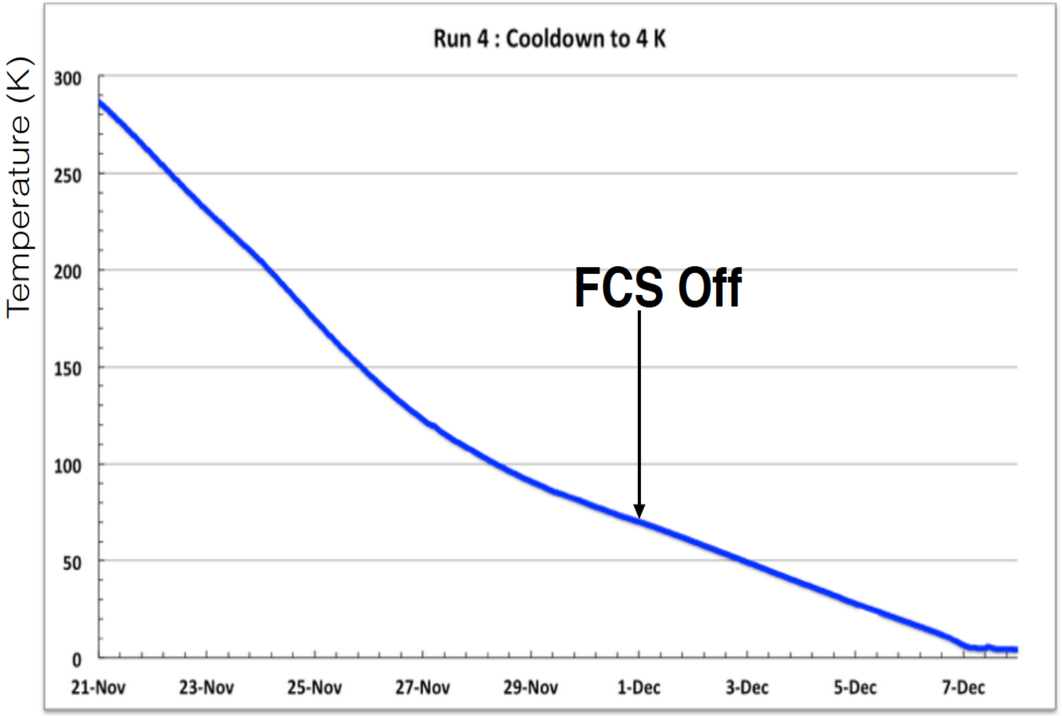


Fast cooling (?)

Pre cooling system based on 3 GM AL600 cold heads (600W @ 80K, 100W @ 30K) to inject cold helium in the cryostat. Cool down to 4 K of about 15 tonnes was performed in 17 days: fast cooling was used up to ~ 75 K.







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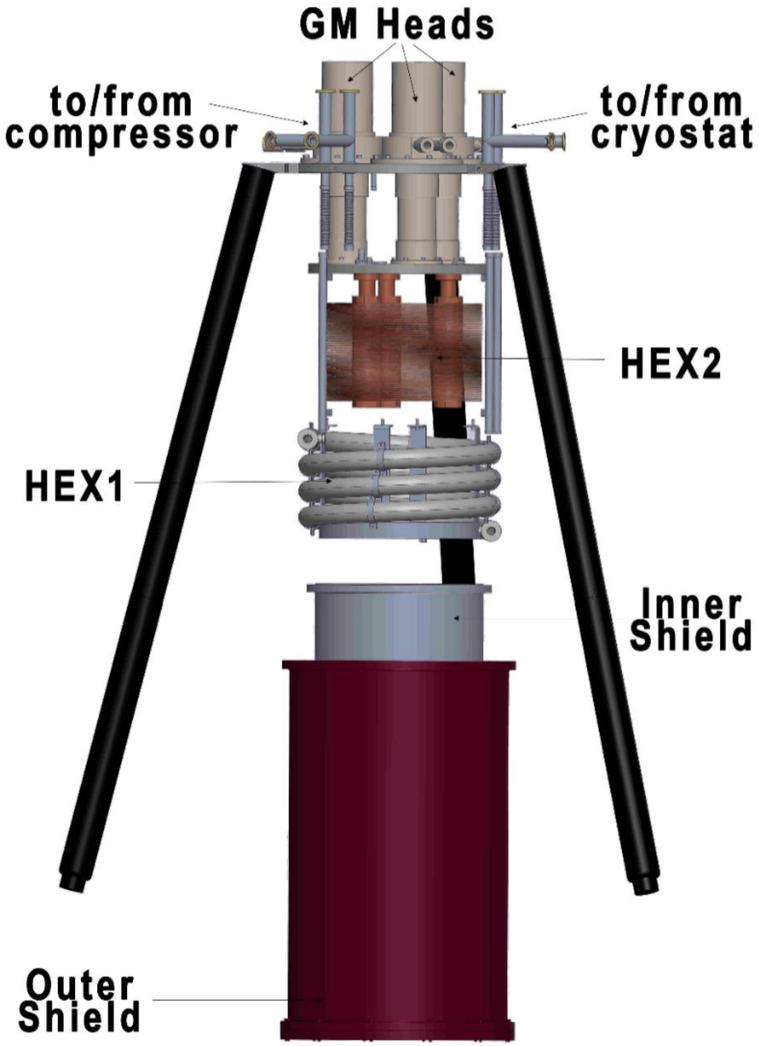
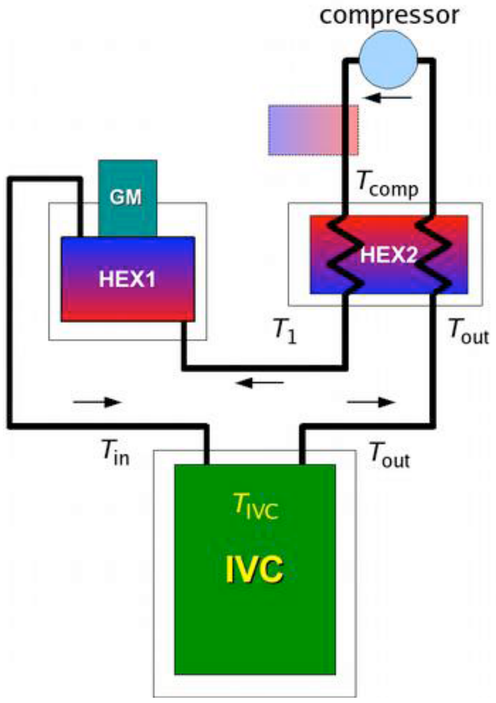
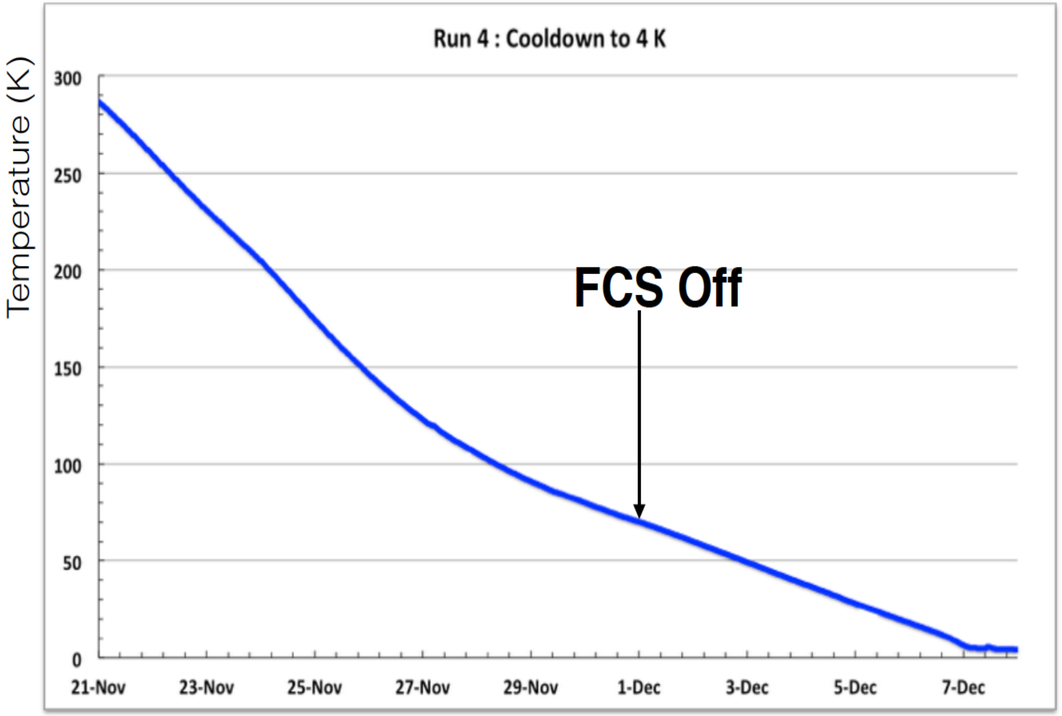
4 PT system gave indications to be strong enough to cool down the cryostat without fast cooling (stress/ageing for PTs in non standard configuration?)

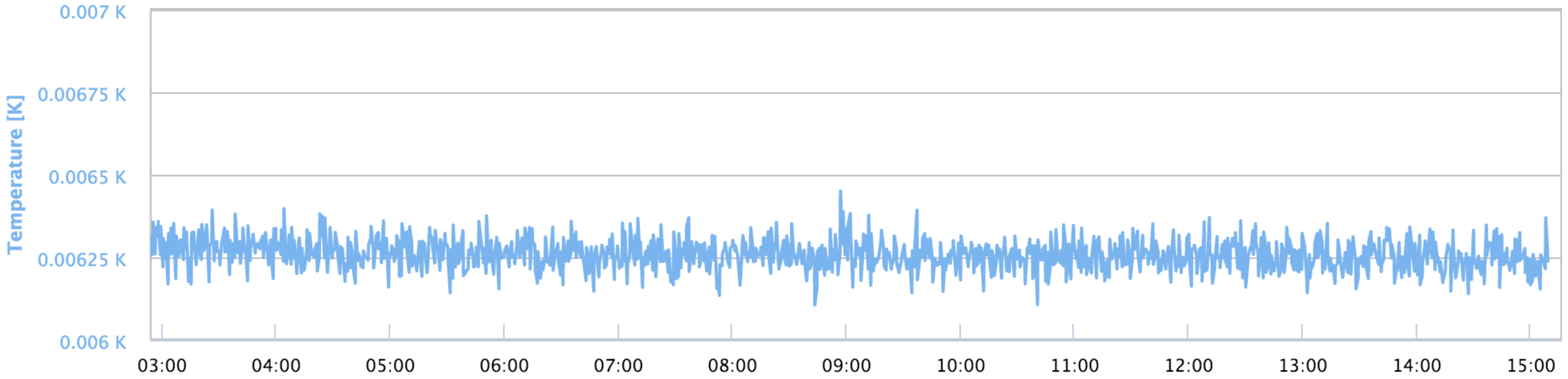






Base temperature*

- Reached a minimum of **(6.3 ± 0.2) mK**



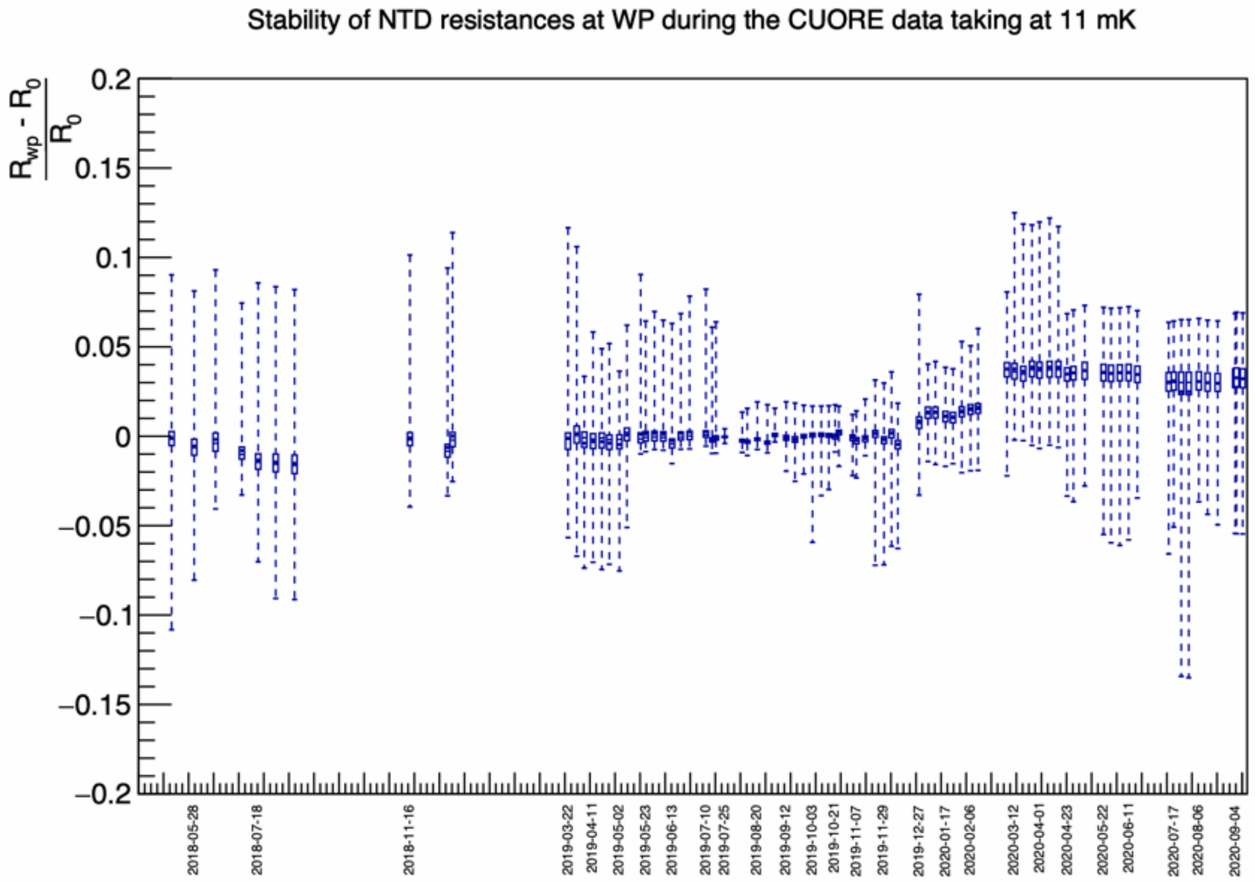
Stable over more than 70 days

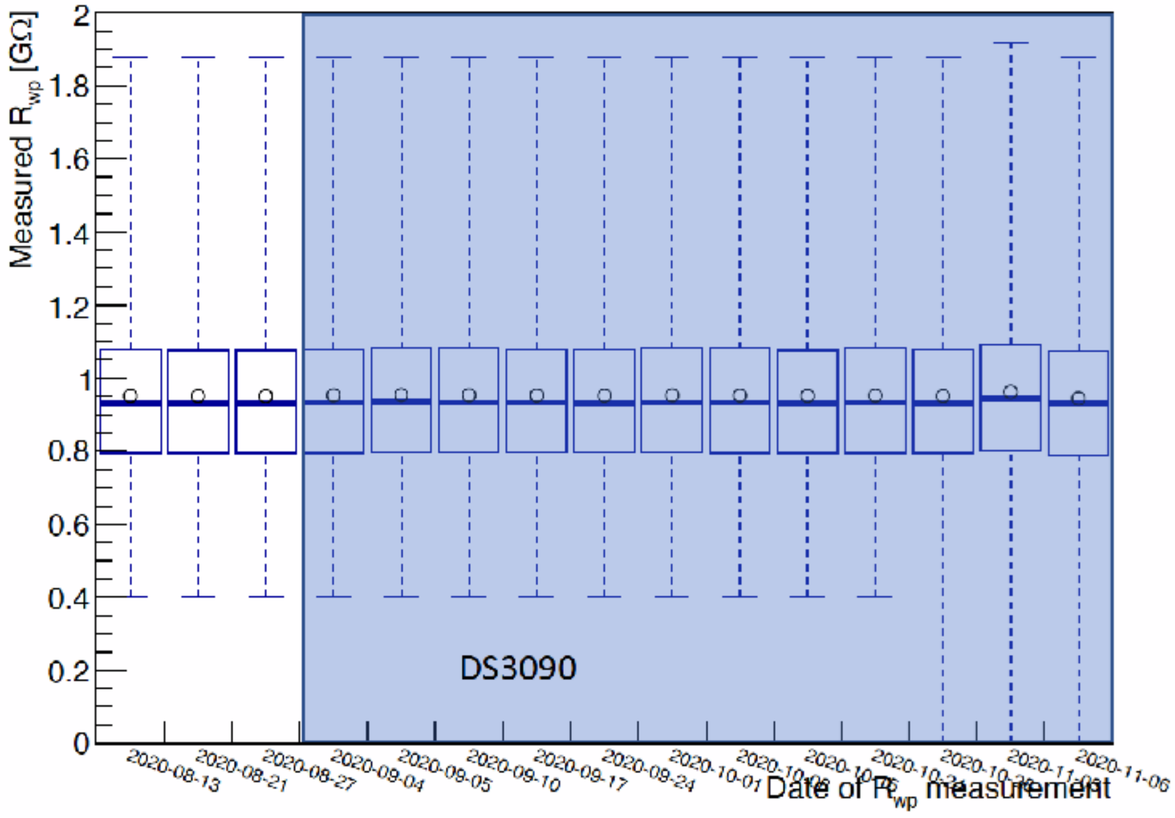
- Cooling power **3 μW @ 10 mK**

*Data from commissioning run without detectors

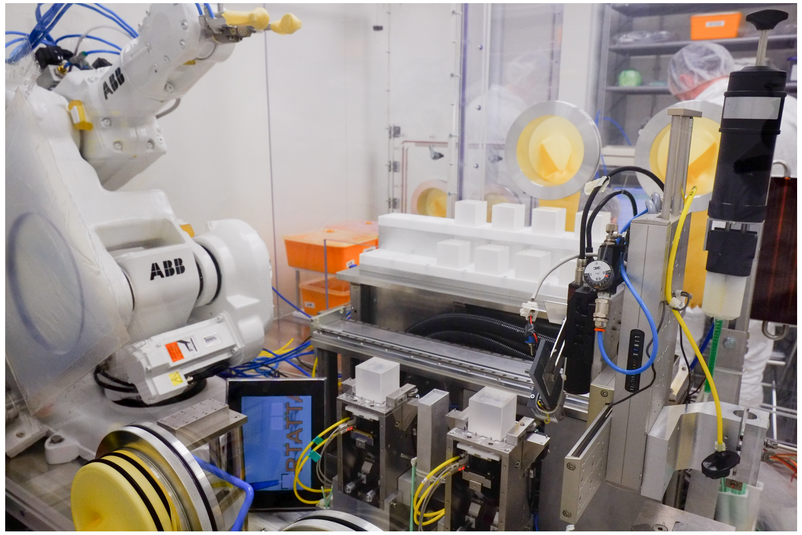
Temperature stability

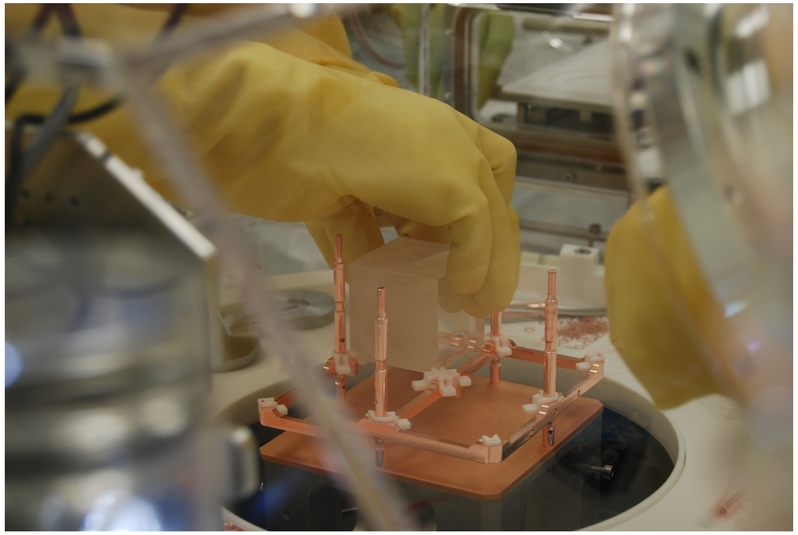
Cryostat stability + PID temperature control guaranteed stability of NTD resistance better than 1%

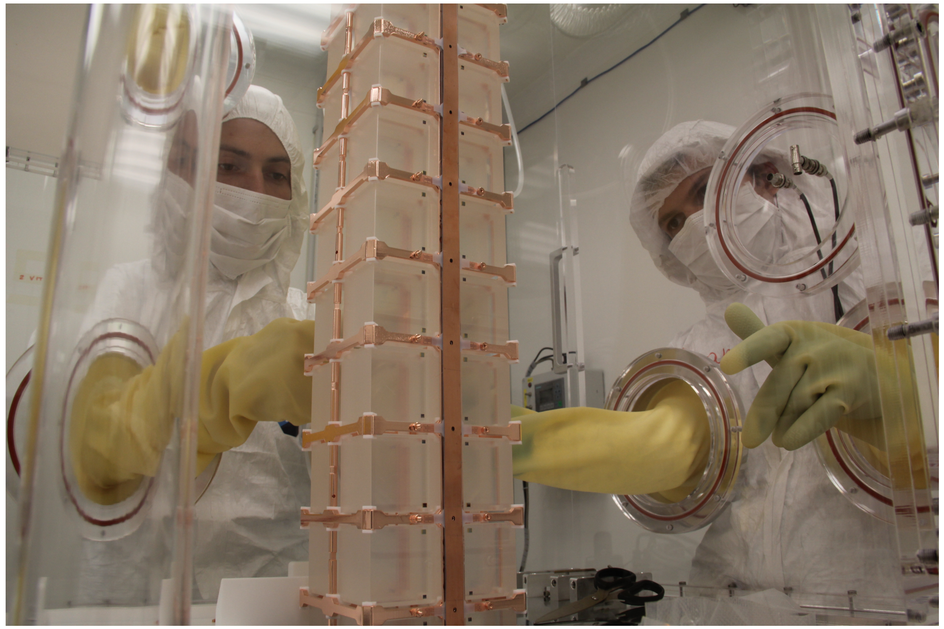


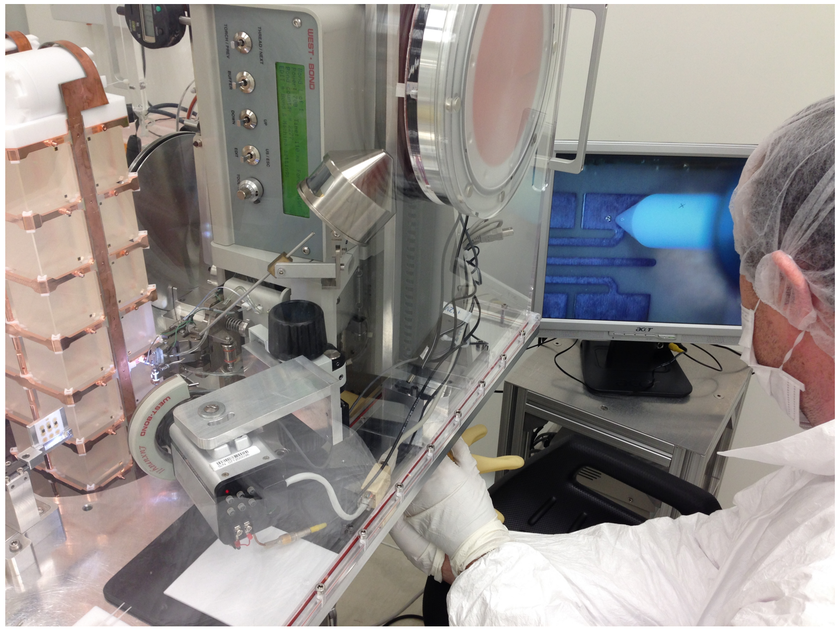


Building a detector





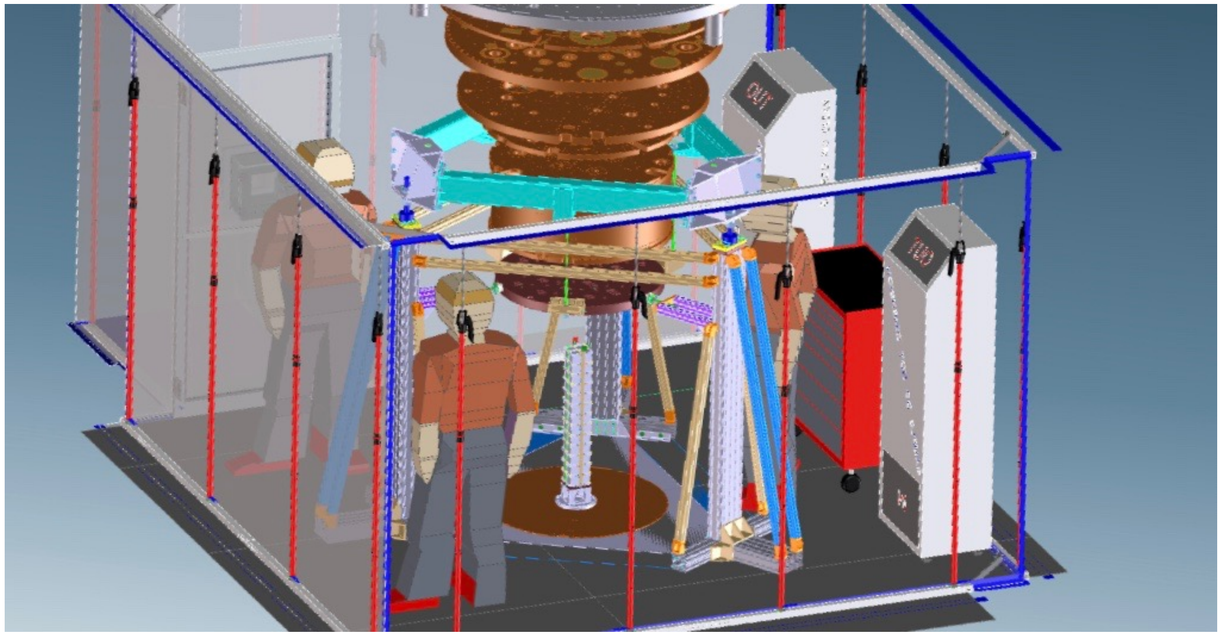


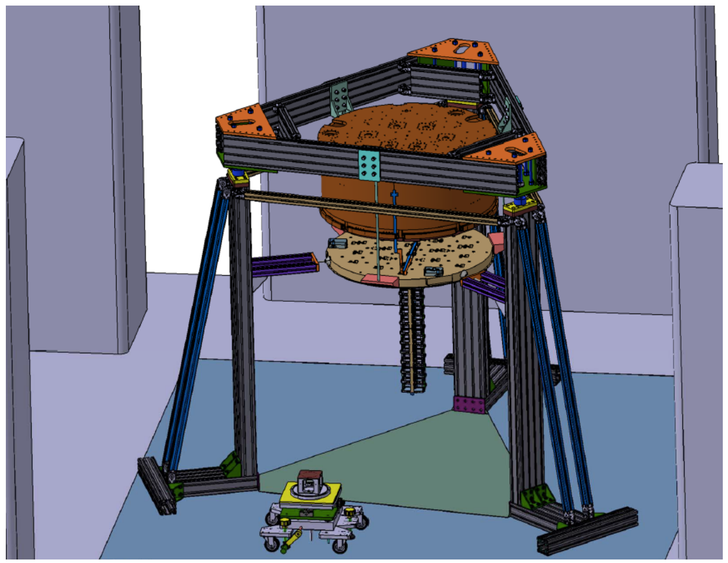


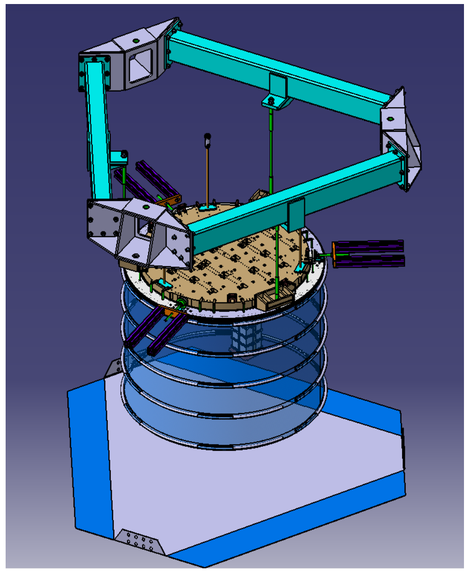
Detector installation (II)

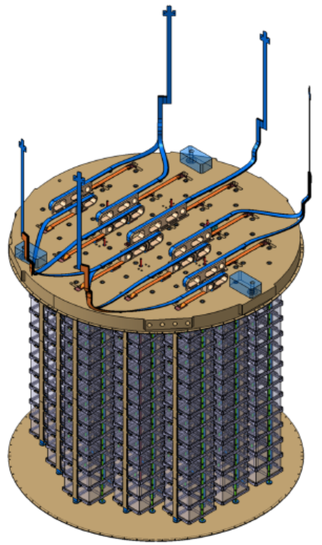
…the final installation had to be performed on the cryostat:

- First time towers exit N_2 atmosfere. Rn free air mini-clean room (CR6) **<50 mBq/m³**
- Special procedure to access CR6
- Complex set of tools to install towers under Tower Support Plate (TSP)

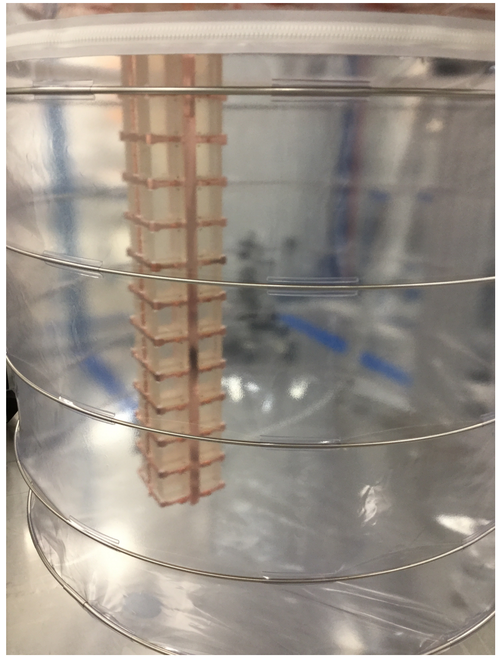
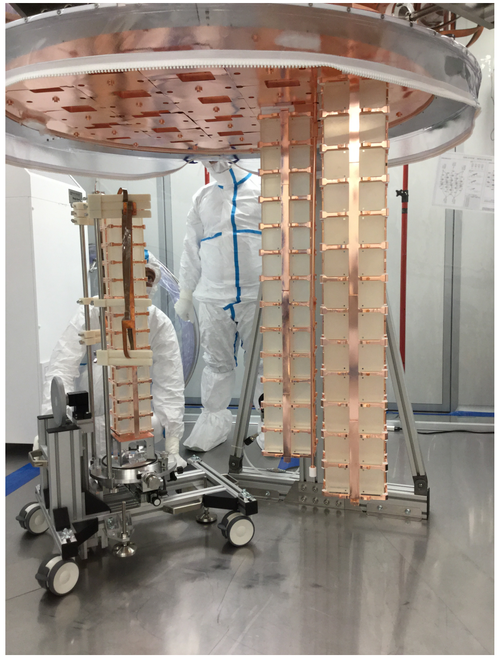
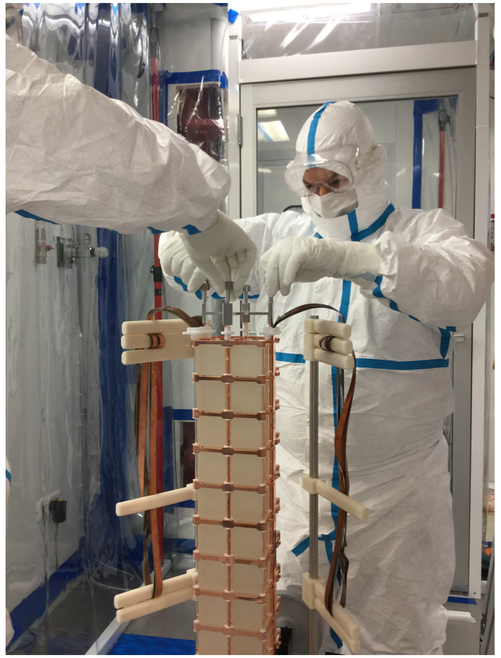
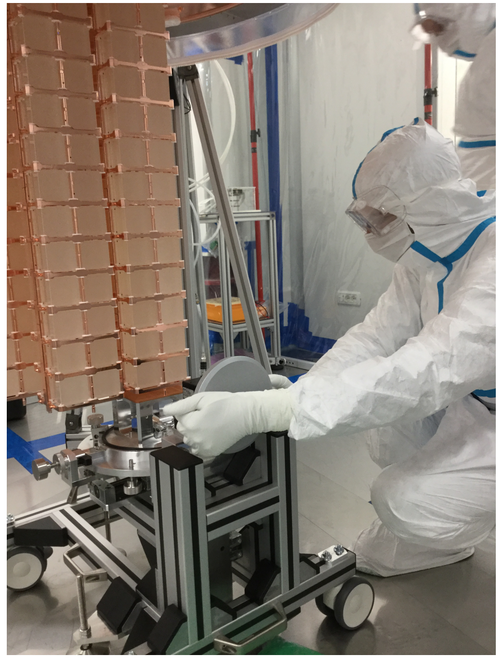
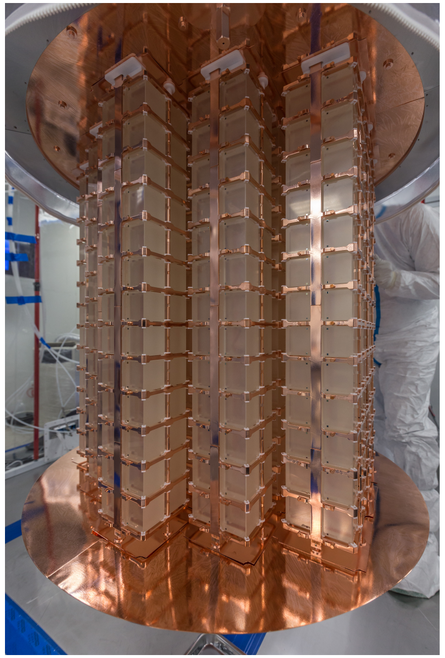
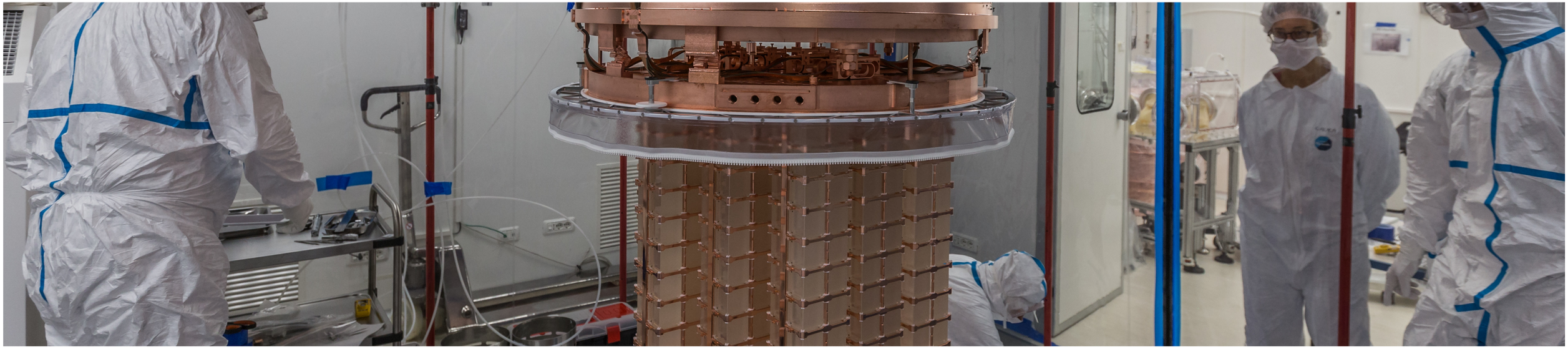




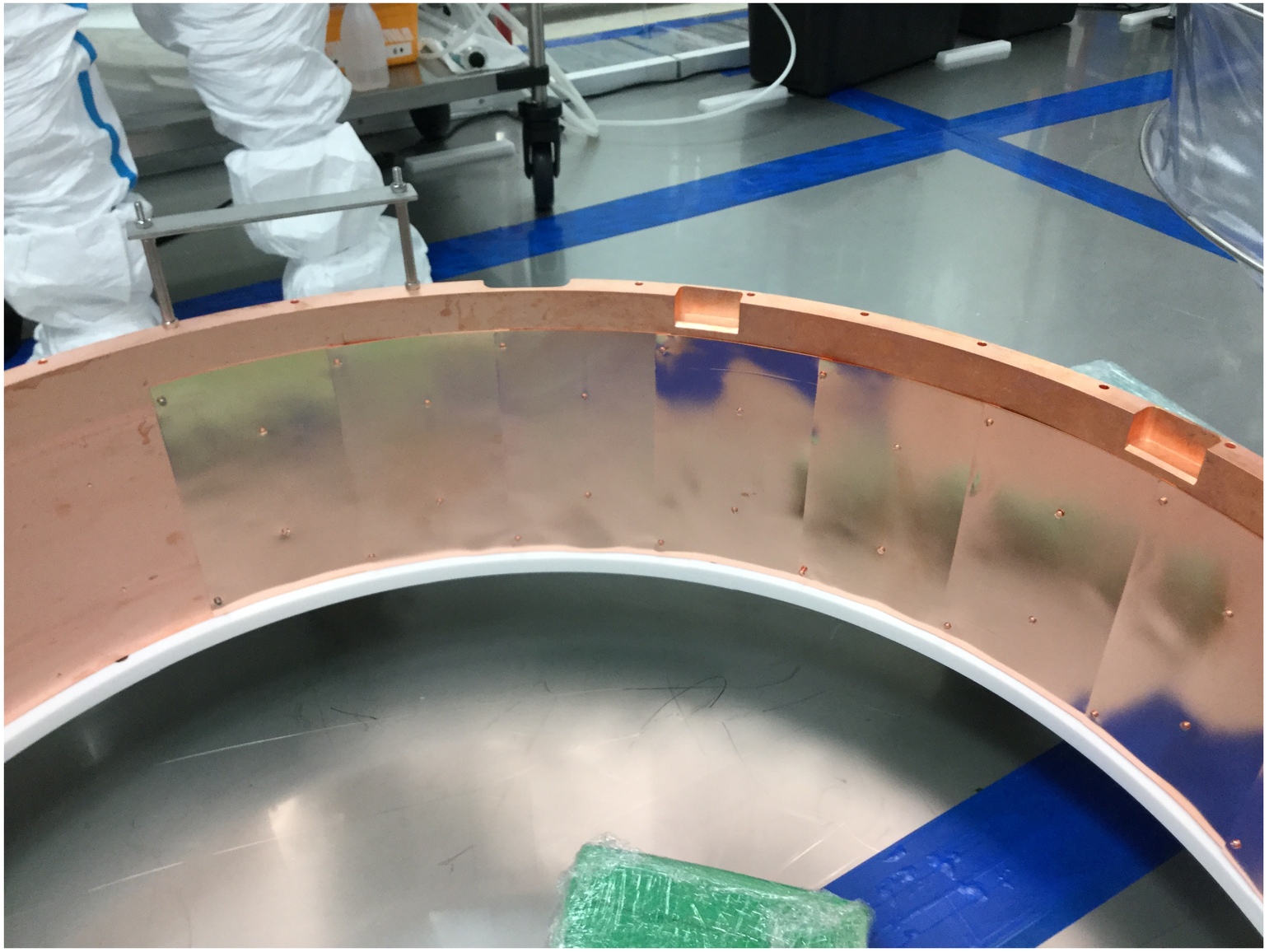




Assembling an experiment

10 mK shield



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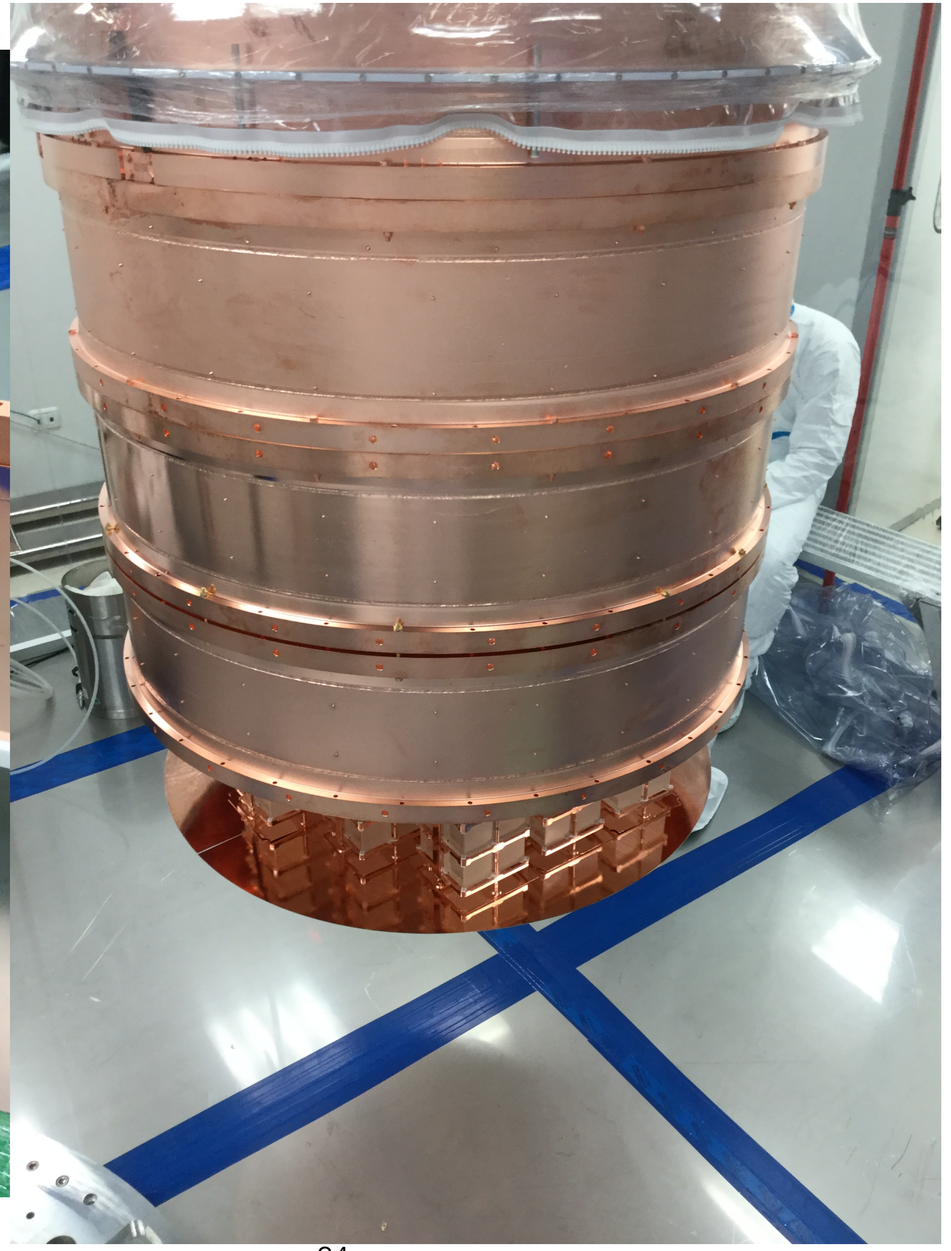
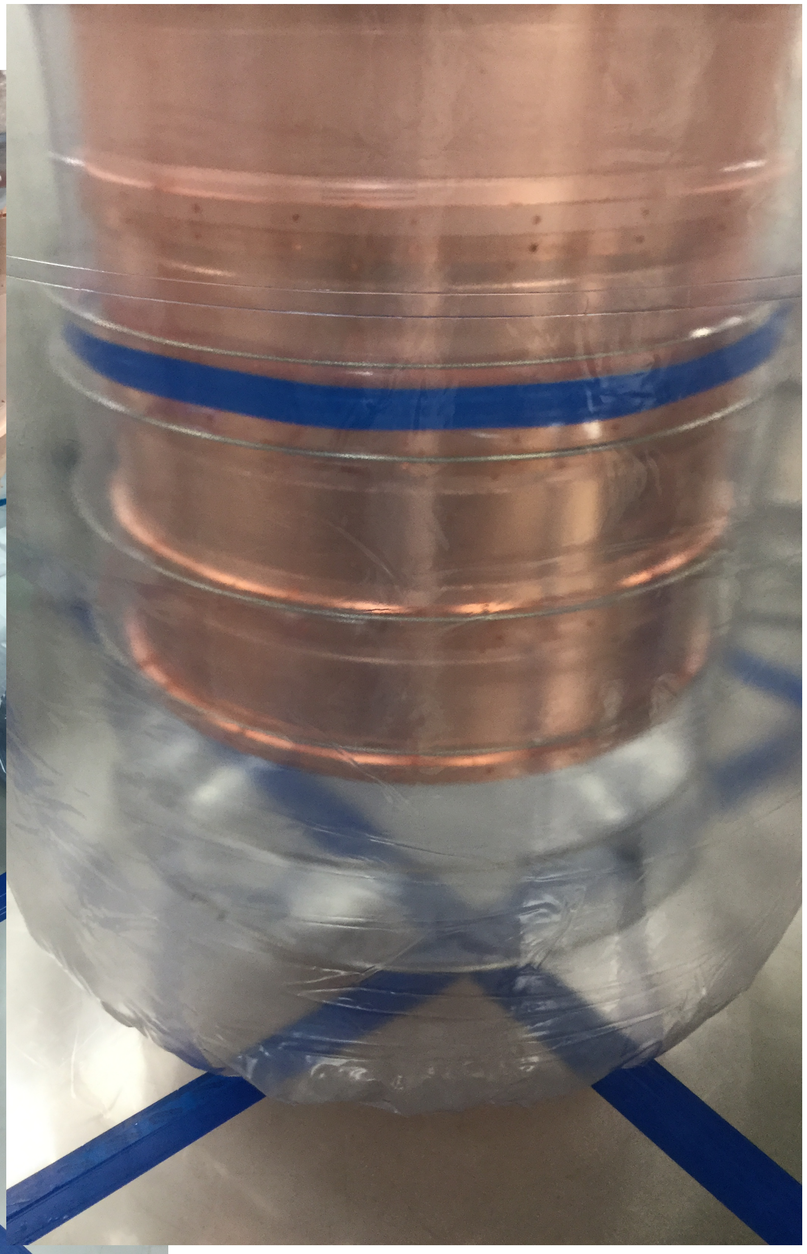


10 mK shield



Closing cryostat (I)

Opening/closing the CUORE cryostat is not an easy business: vessels weight between 290 kg (HEX shield) and 1600 kg (OVC). Roman lead shields weights 5400 kg. A dedicated 3 hoist lifting system with support rings was developed to allow closing/opening.

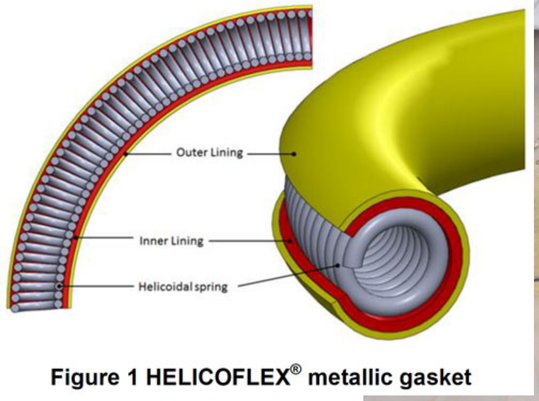
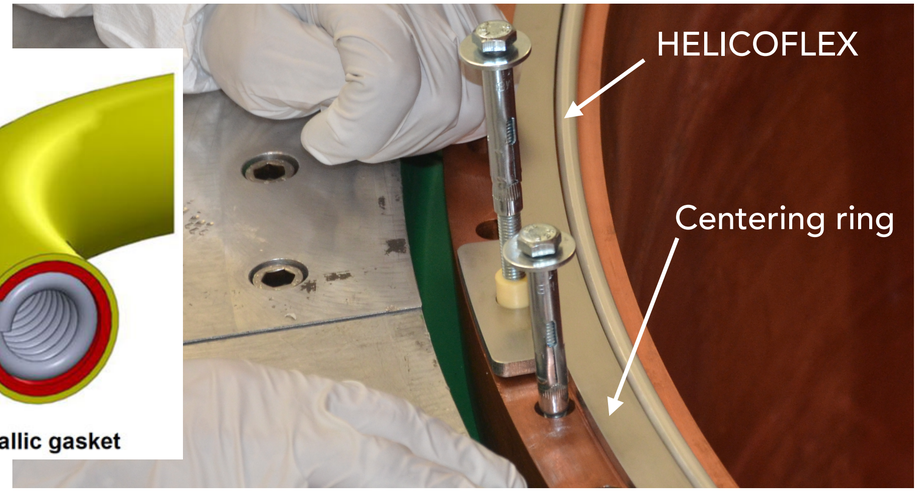
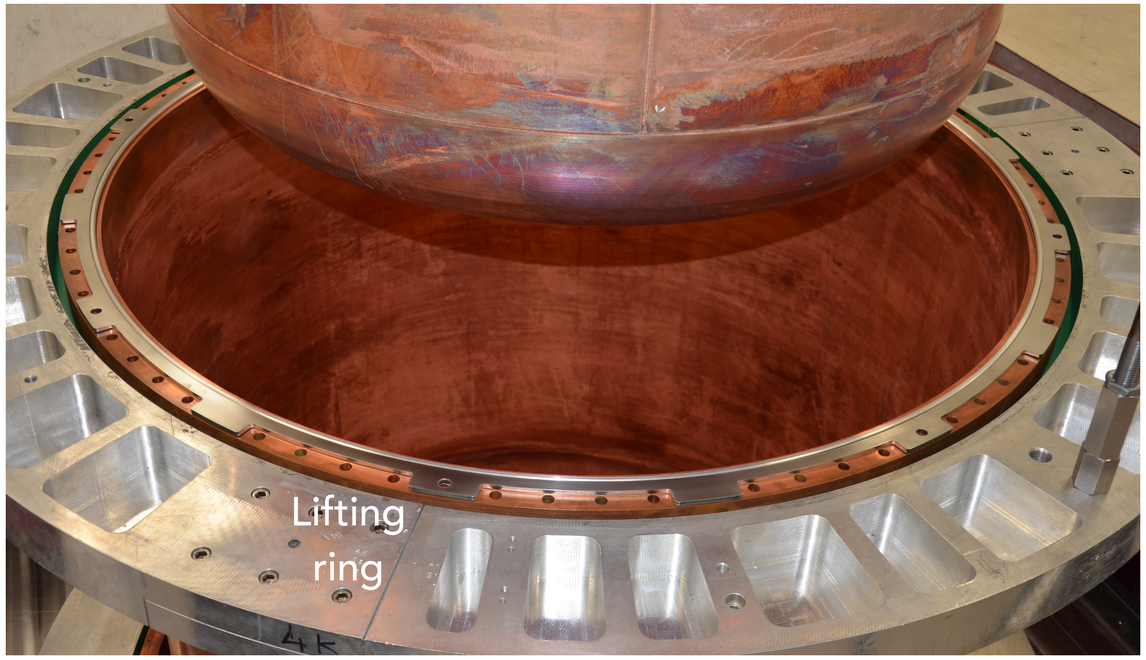
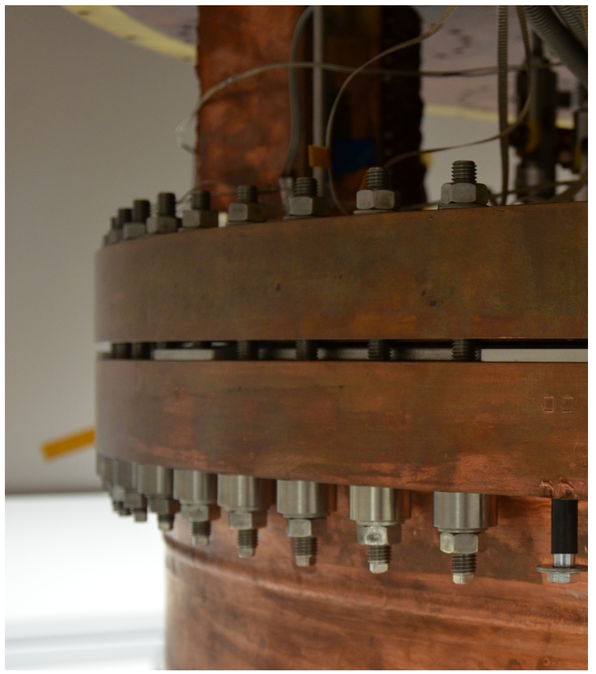


Figure 1 HELICOFLEX® metallic gasket

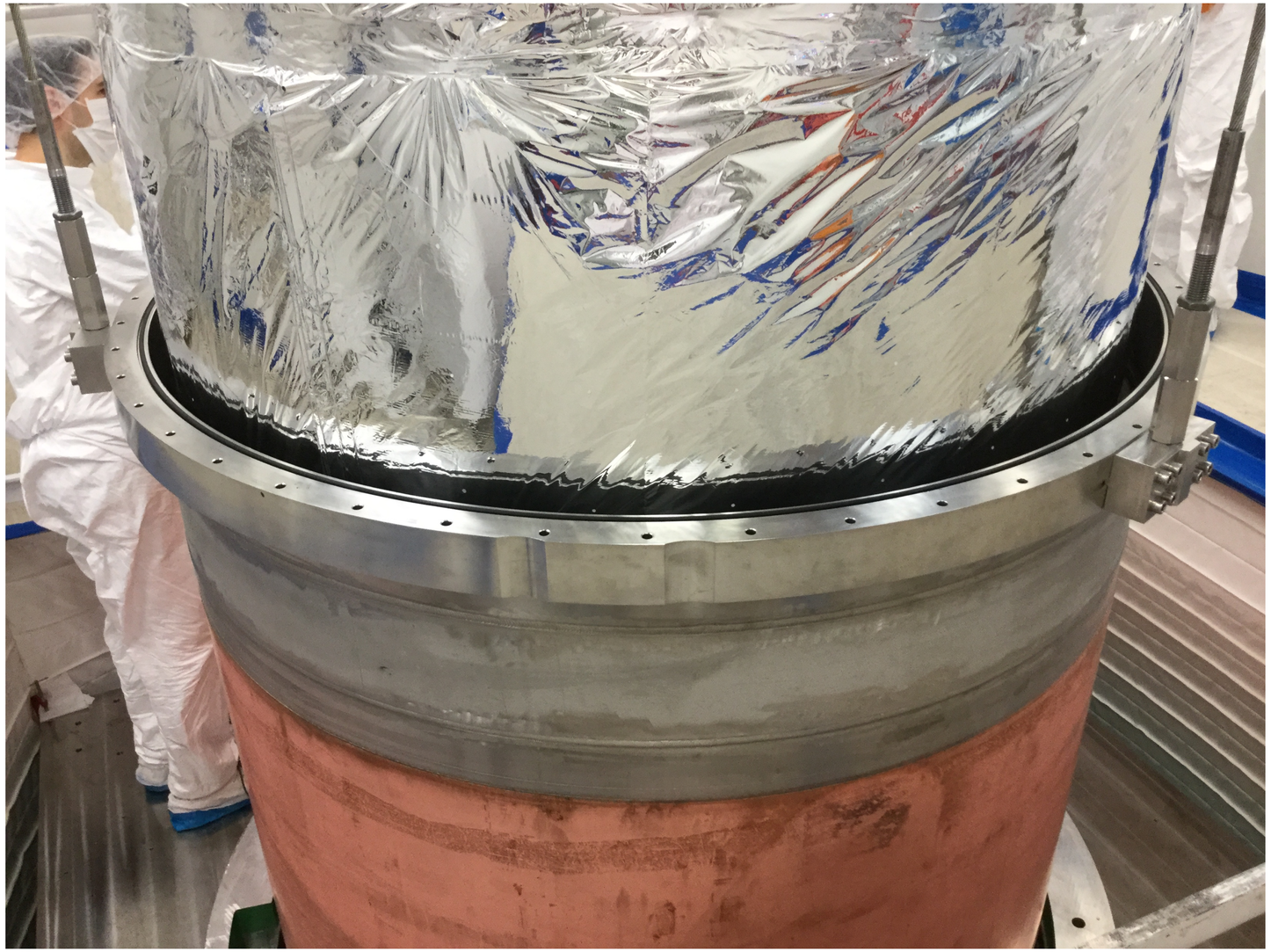




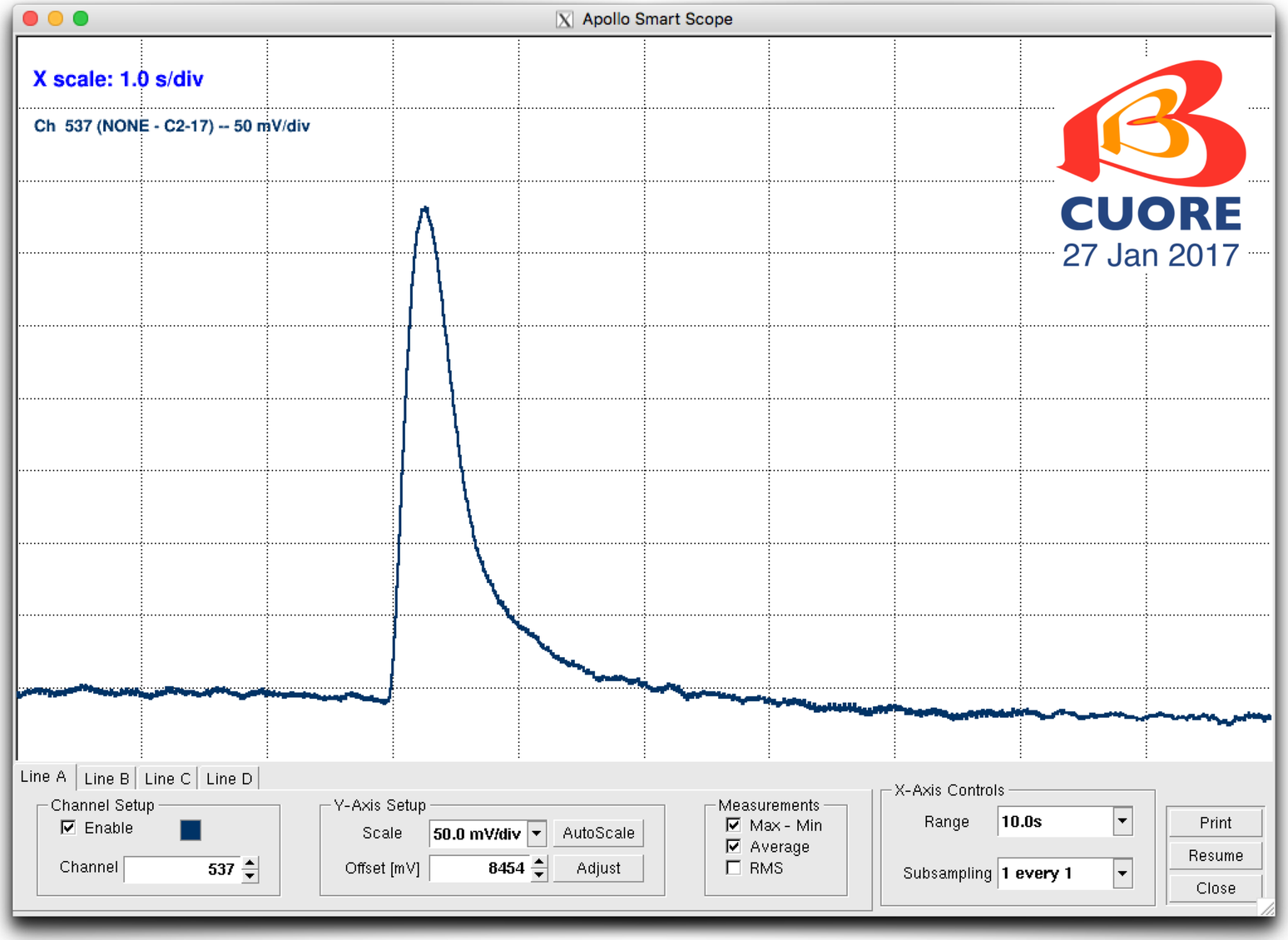
The sealing of the IVC was implemented with HELICOFLEX o-ring technology (expensive and delicate). Full closing of the cryostat takes 1 week.



Closing cryostat (II)

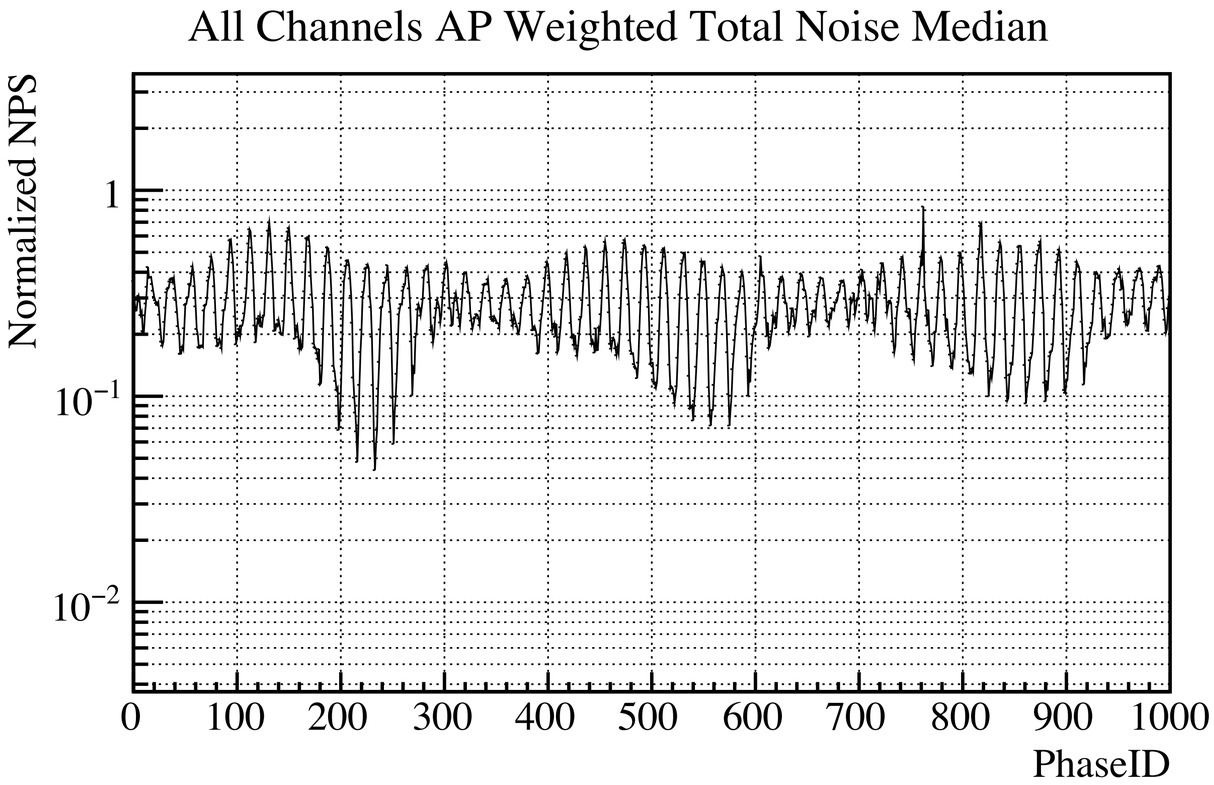


First CUORE pulse

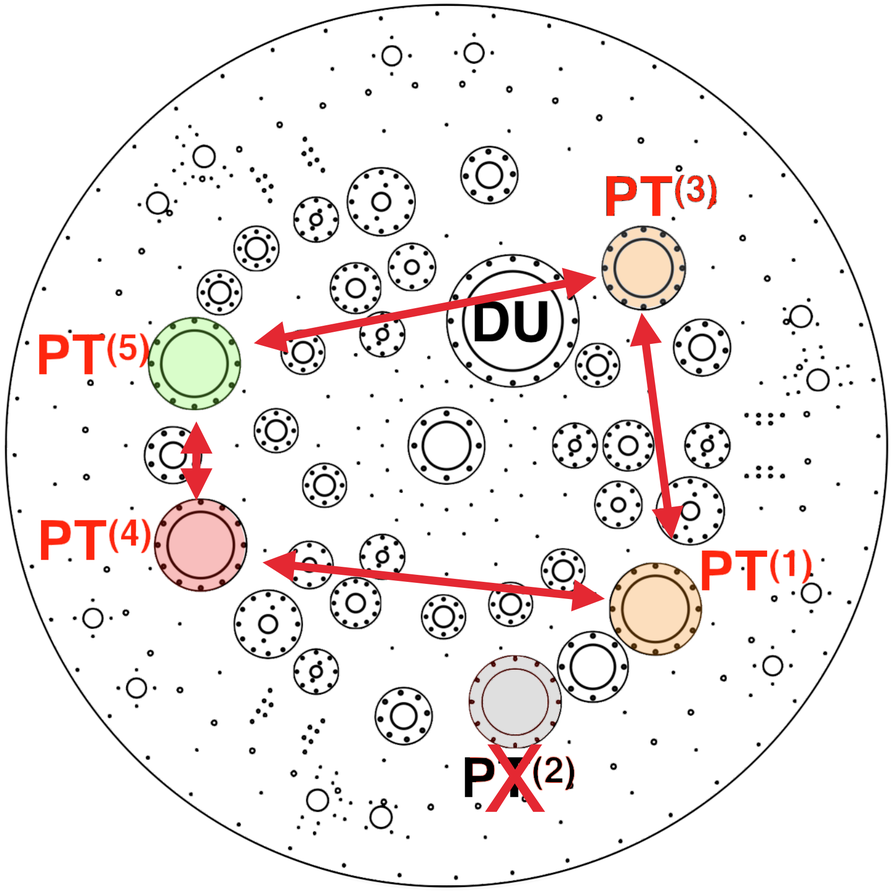


But the challenges just started…

PTs induced vibrations

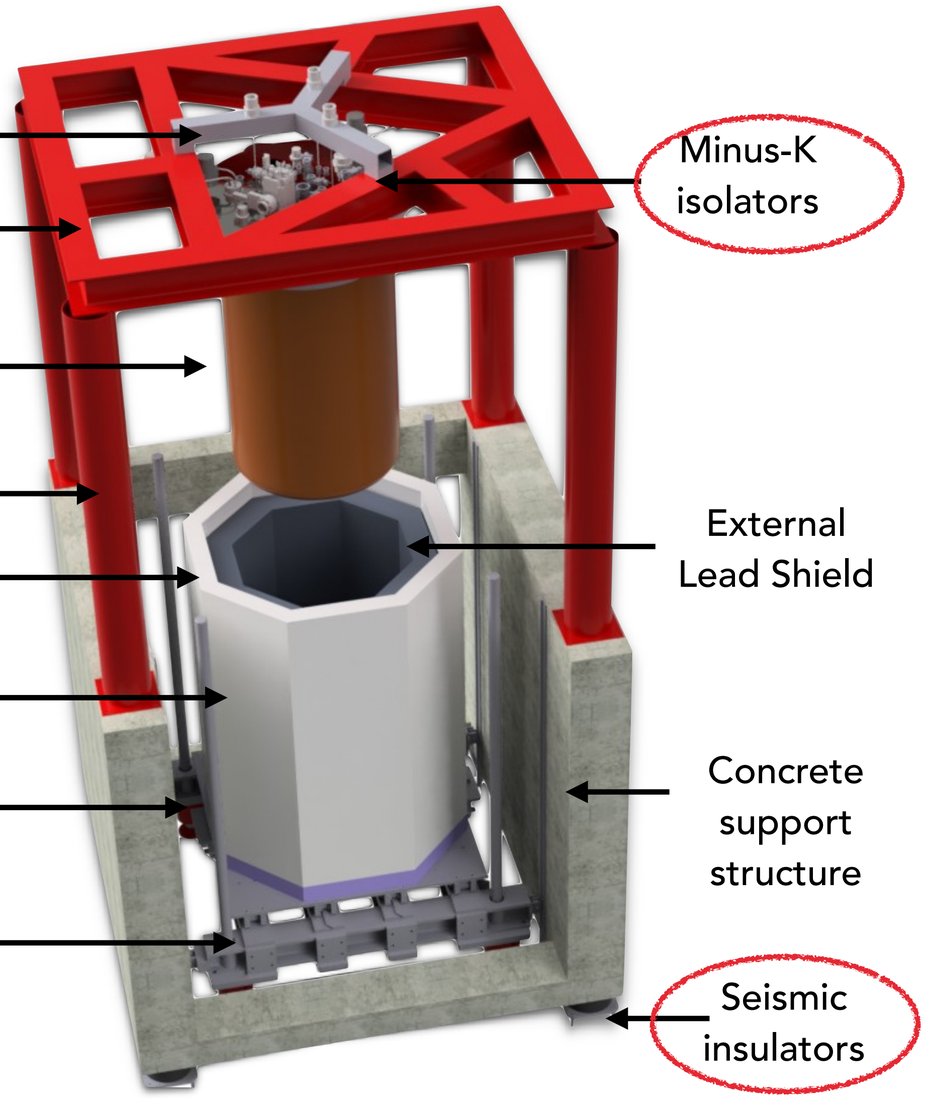


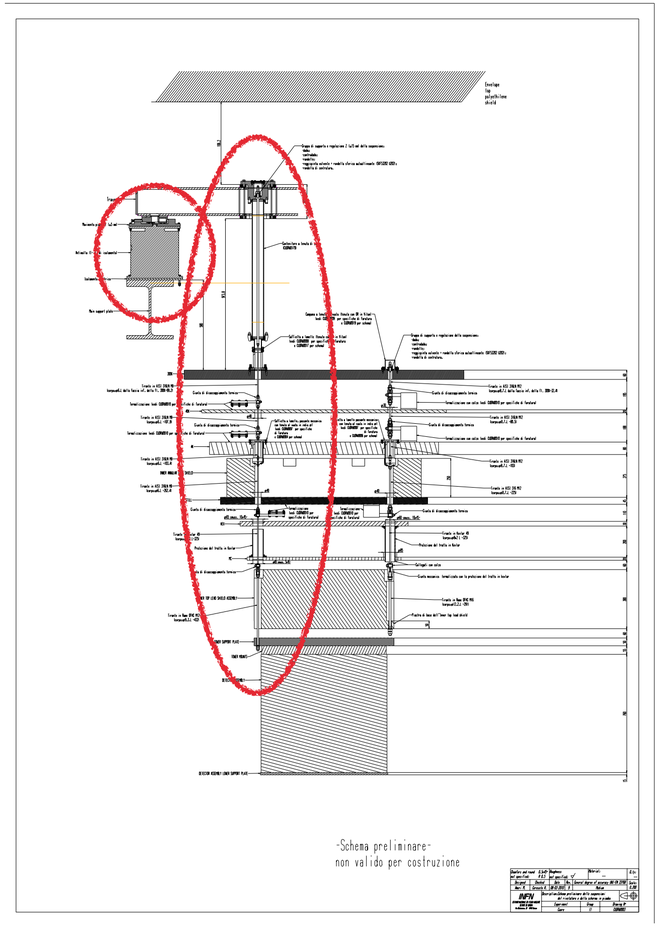
Top of the Cryostat



PT phases change noise of orders of magnitude.

The forced pendulum

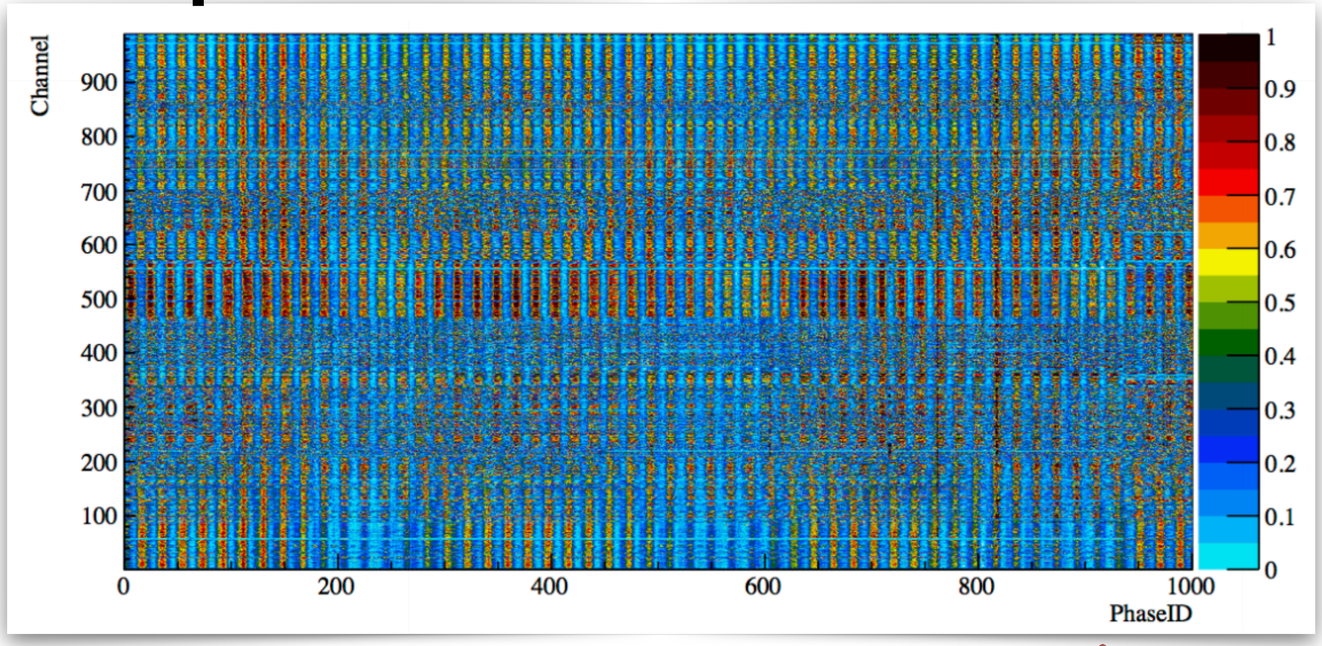




All the CUORE vibration suppression systems designed to cut external vibration sources

But if the main source is on the cryostat (PTs) this ends up in a forced pendulum system

PT phase cancellation



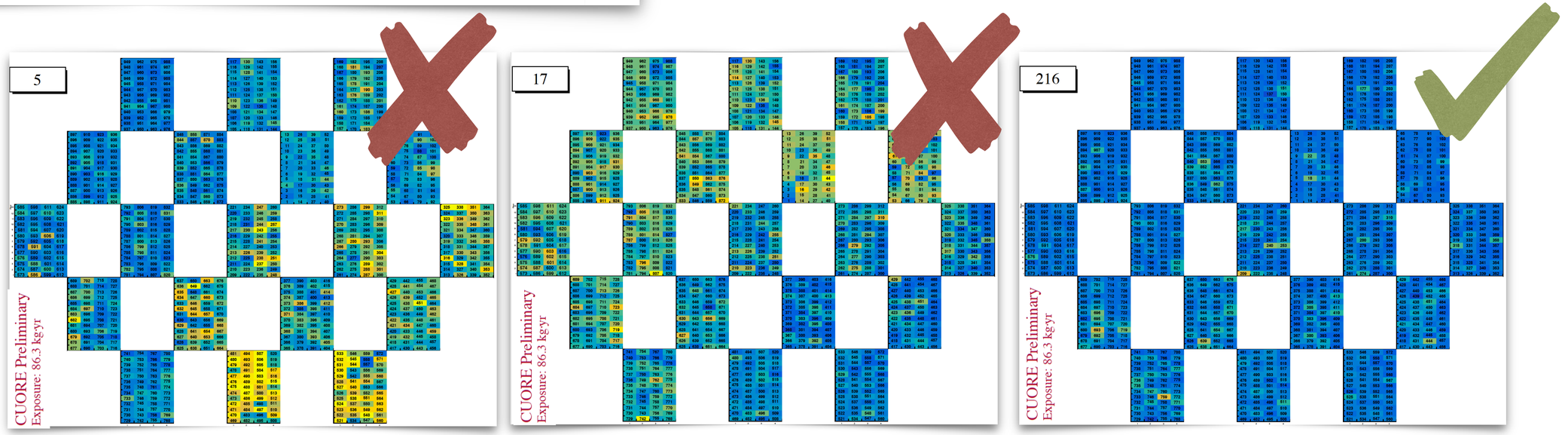
Attenuation of Pulse tube induced vibrations:

(1) Switch to Linear Drives to control PT motor heads -> reduce temperature variations on the Mixing Chamber

(2) PT phase scan to find the phase configuration that actively minimize the PT induced vibrations

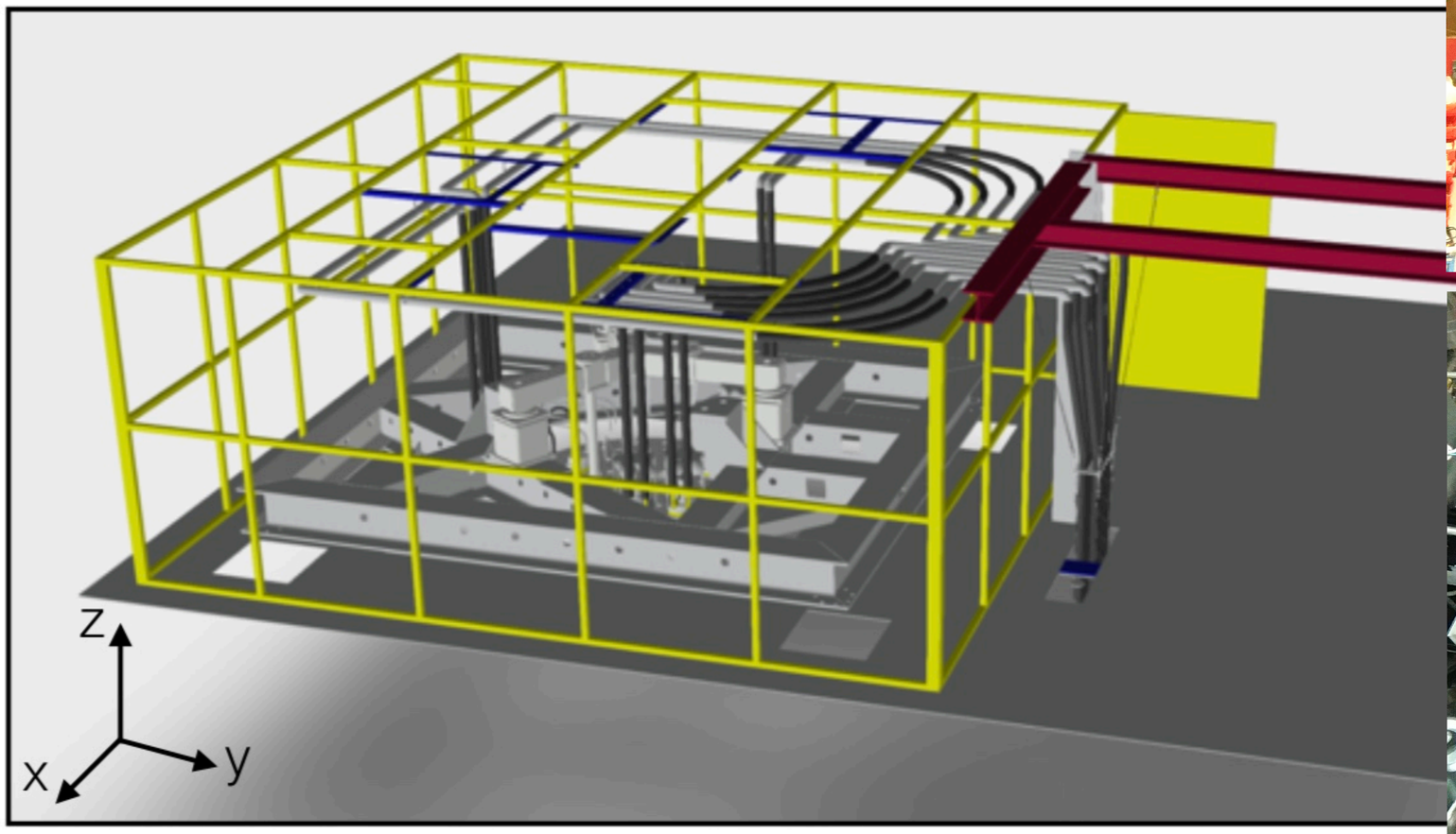
Cryogenics 93 (2018) 56–65
arXiv:1712.02753

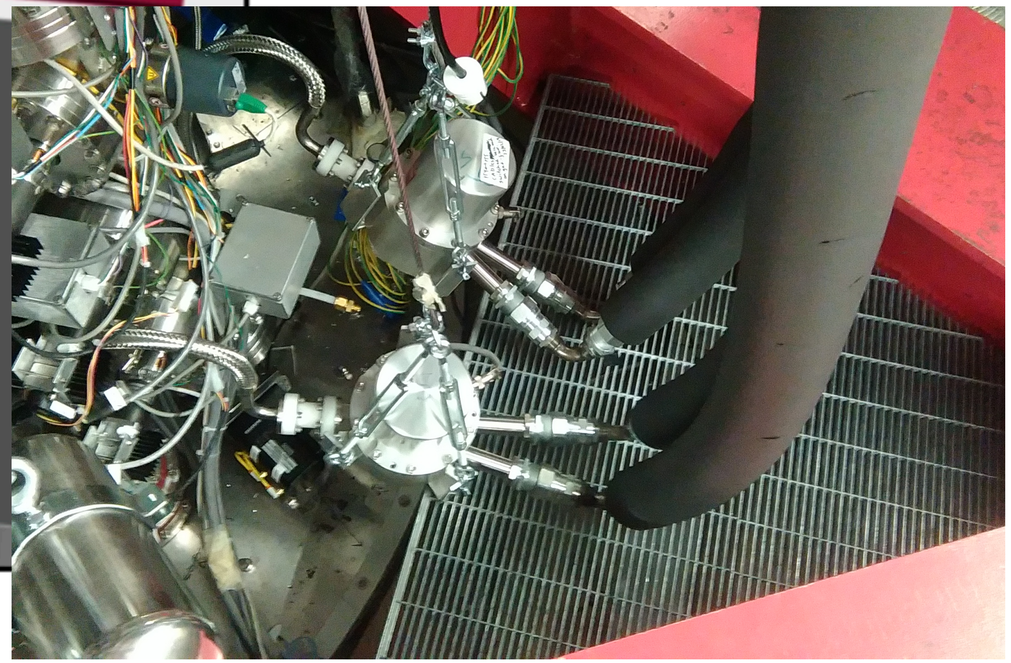
Example of the PT induced noise for three different PT phase configurations



Vibration dissipation

As vibrations from pulse waves are unavoidable, dissipating vibrations far away from the cryostat is crucial

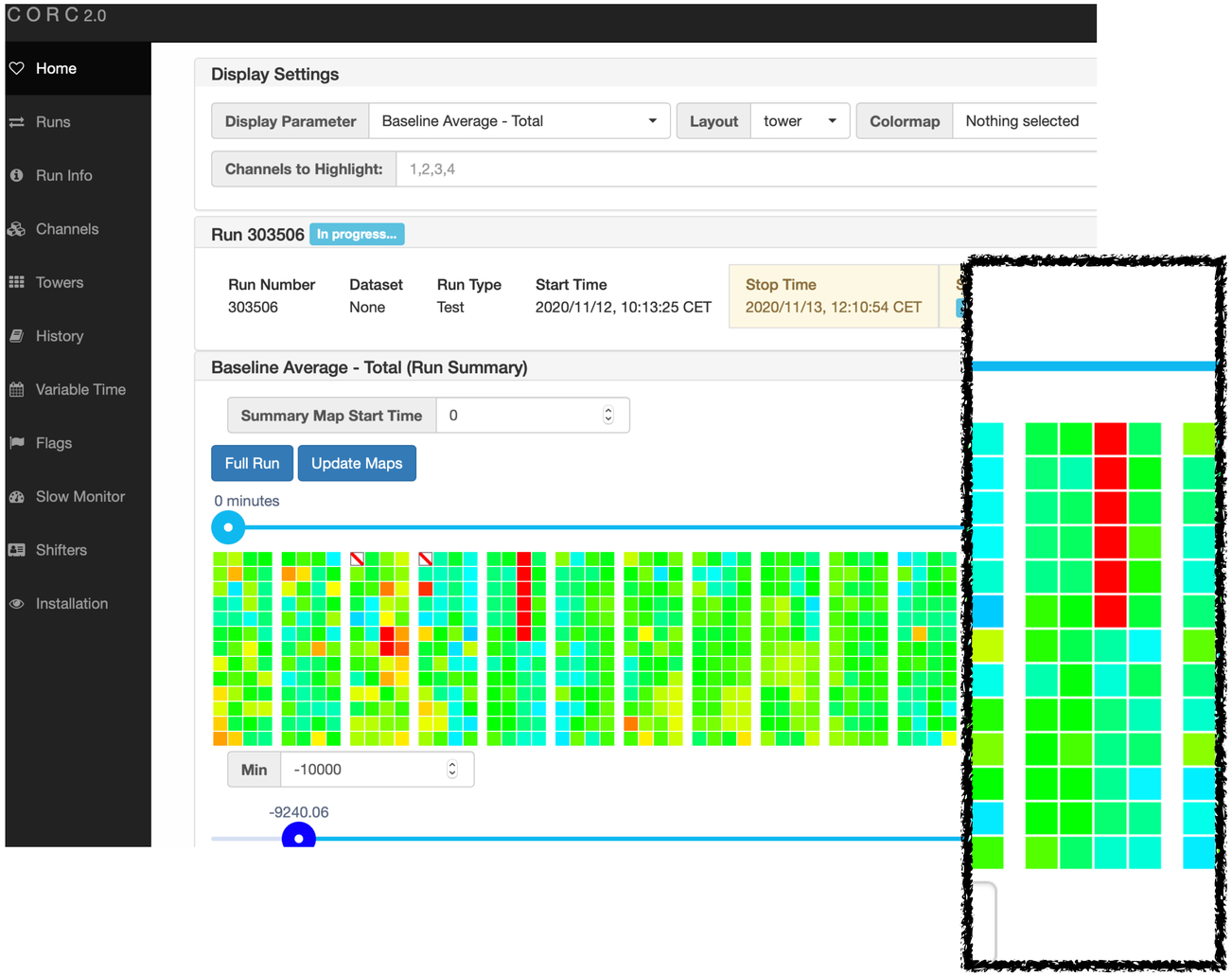




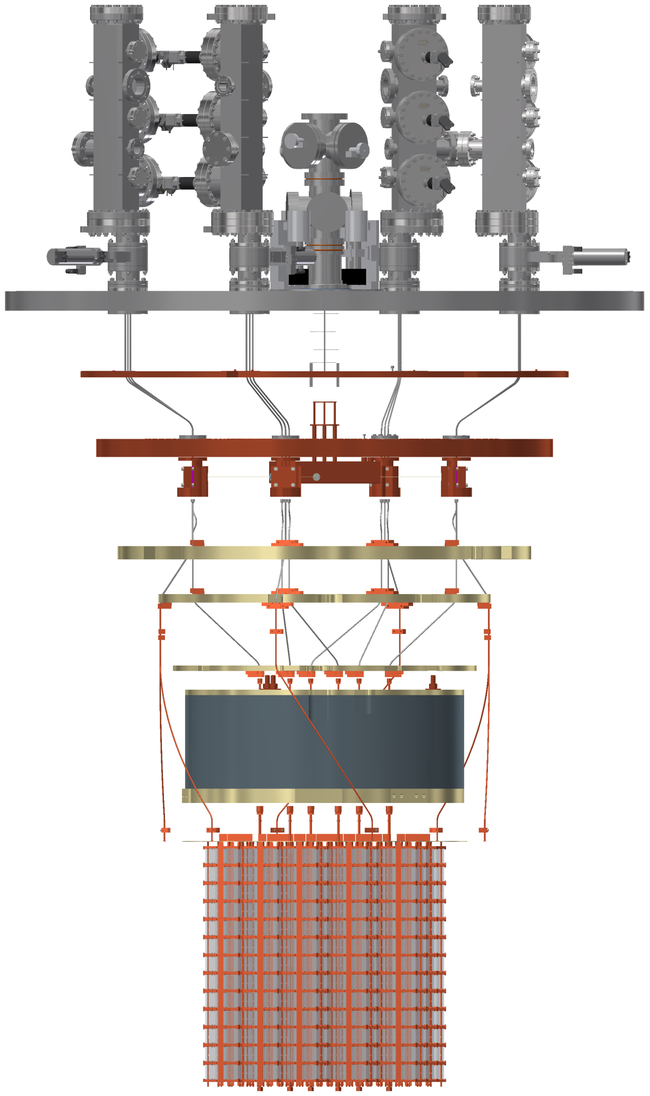
Vibrations in the cryostat

Another important ingredient to the fight to reduce vibrational noise (improve energy reposition) comes from the evidence that noise seem to be signal strip related. The Cu-Kapton bands carrying the bolometer signals have a by column organization and this is well respected by specific vibrational noises.

For the future (CUPID) a new design of the strips with better mechanical decoupling will be mandatory



Calibration



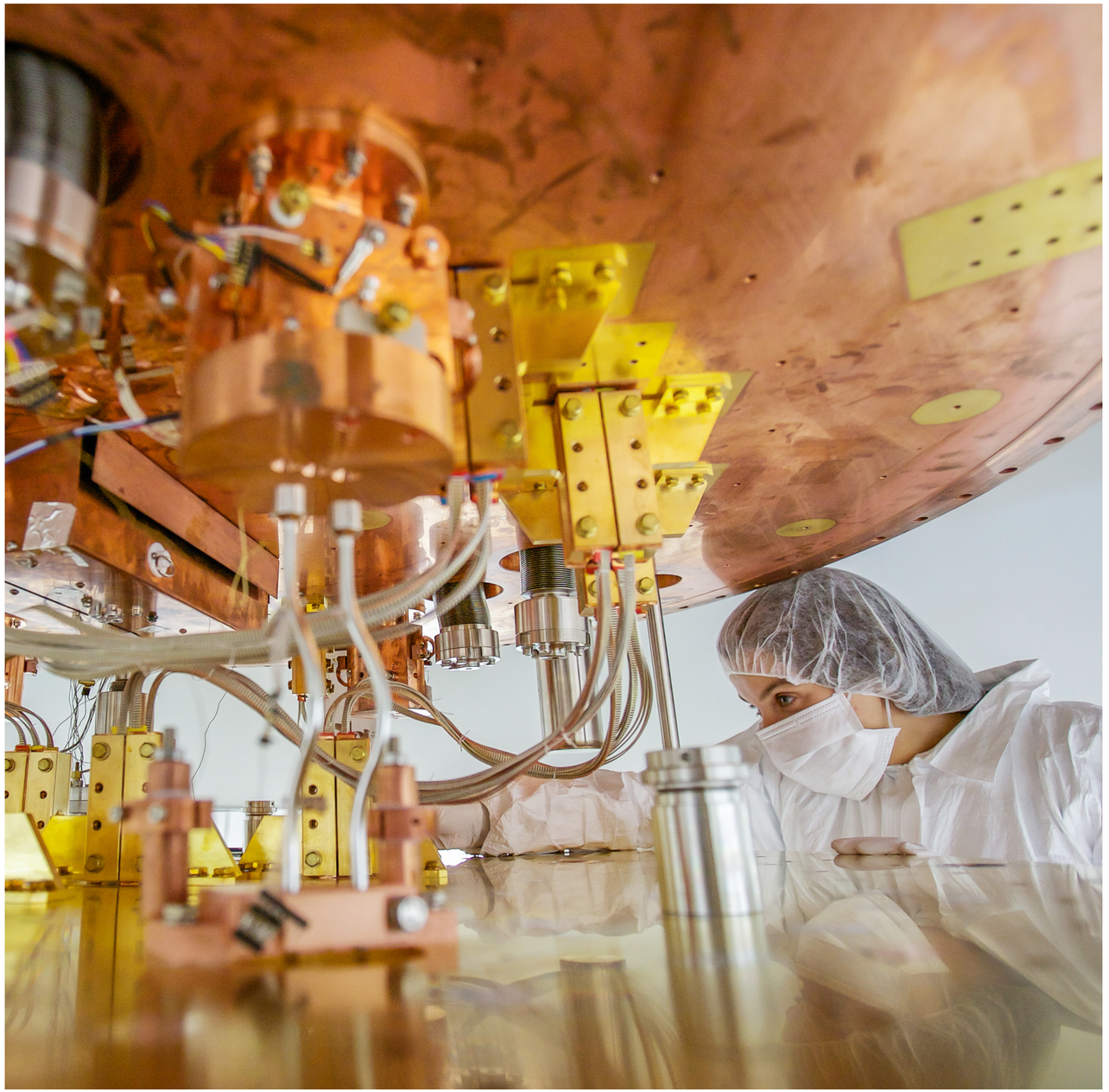
CUORE is calibrated with a ^{232}Th gamma source (strings)

CUORE calibration has been designed to get inside the experimental volume to maximise exposure and avoid self-shielding. Unfortunately the system showed some criticality due to its complexity.

Currently a backup system that illuminates the detector from outside the cryostat is being used with good results (longer exposure, less uniform but extremely more stable).

Take home messages

CUORE cryostat is an extremely successful environment to operate bolometric detectors. So far it has been operating for 4 years in steady conditions without a complete warm up.



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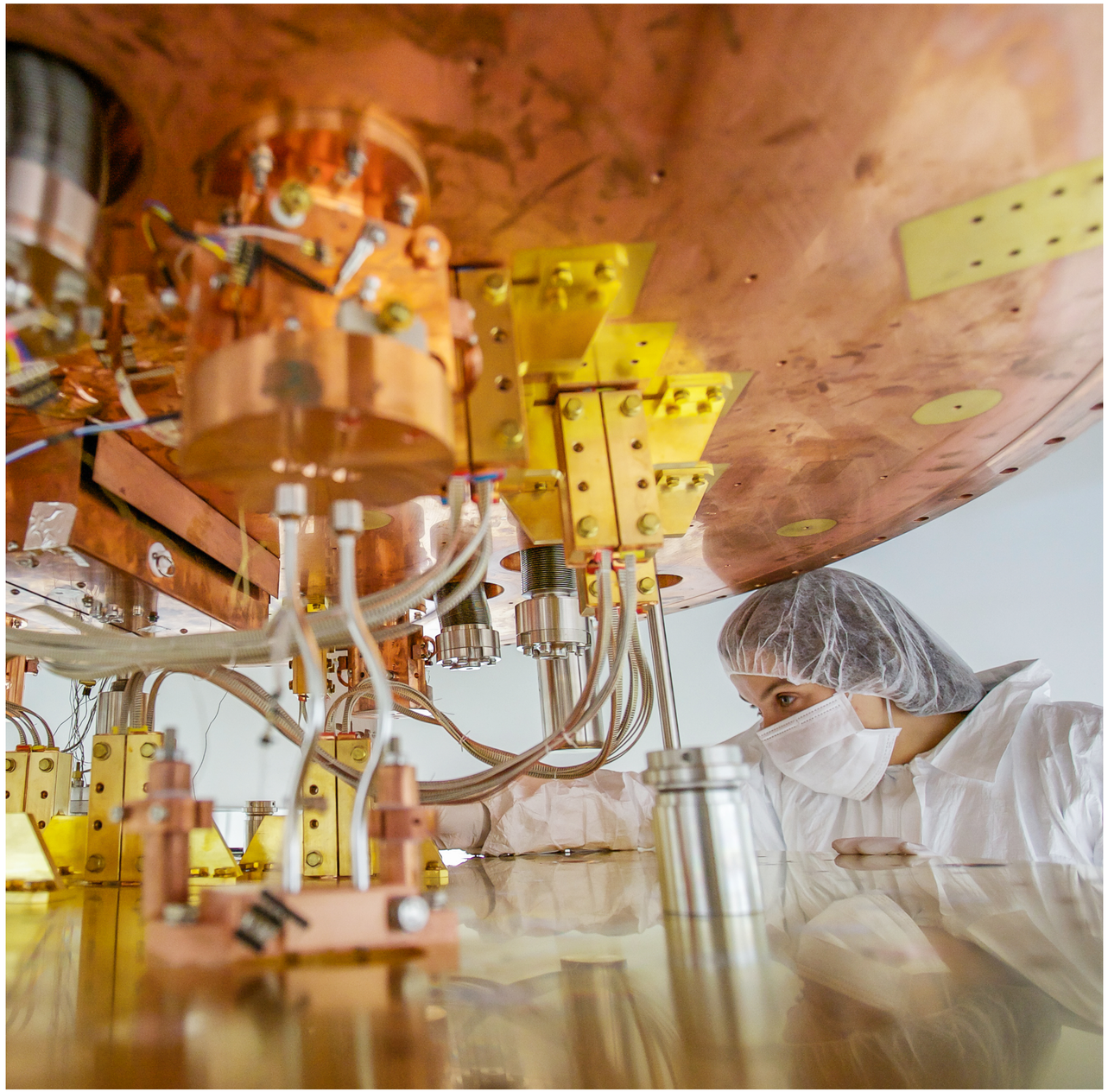
CUORE data quality and exposure are the best confirmation of the efficiency of the system (1 tonne*y soon on Nature, 1.5 tonne*y already collected).



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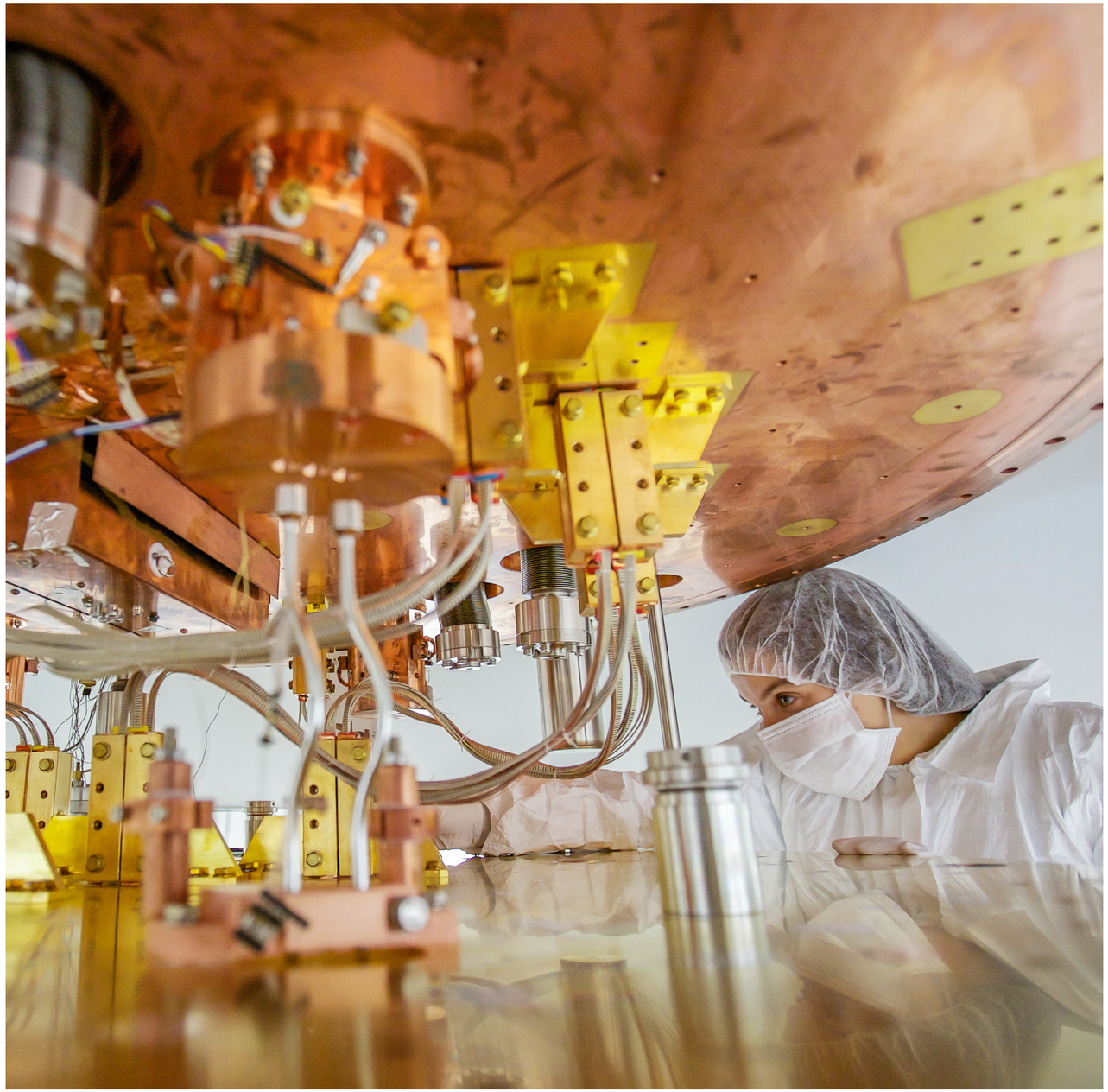

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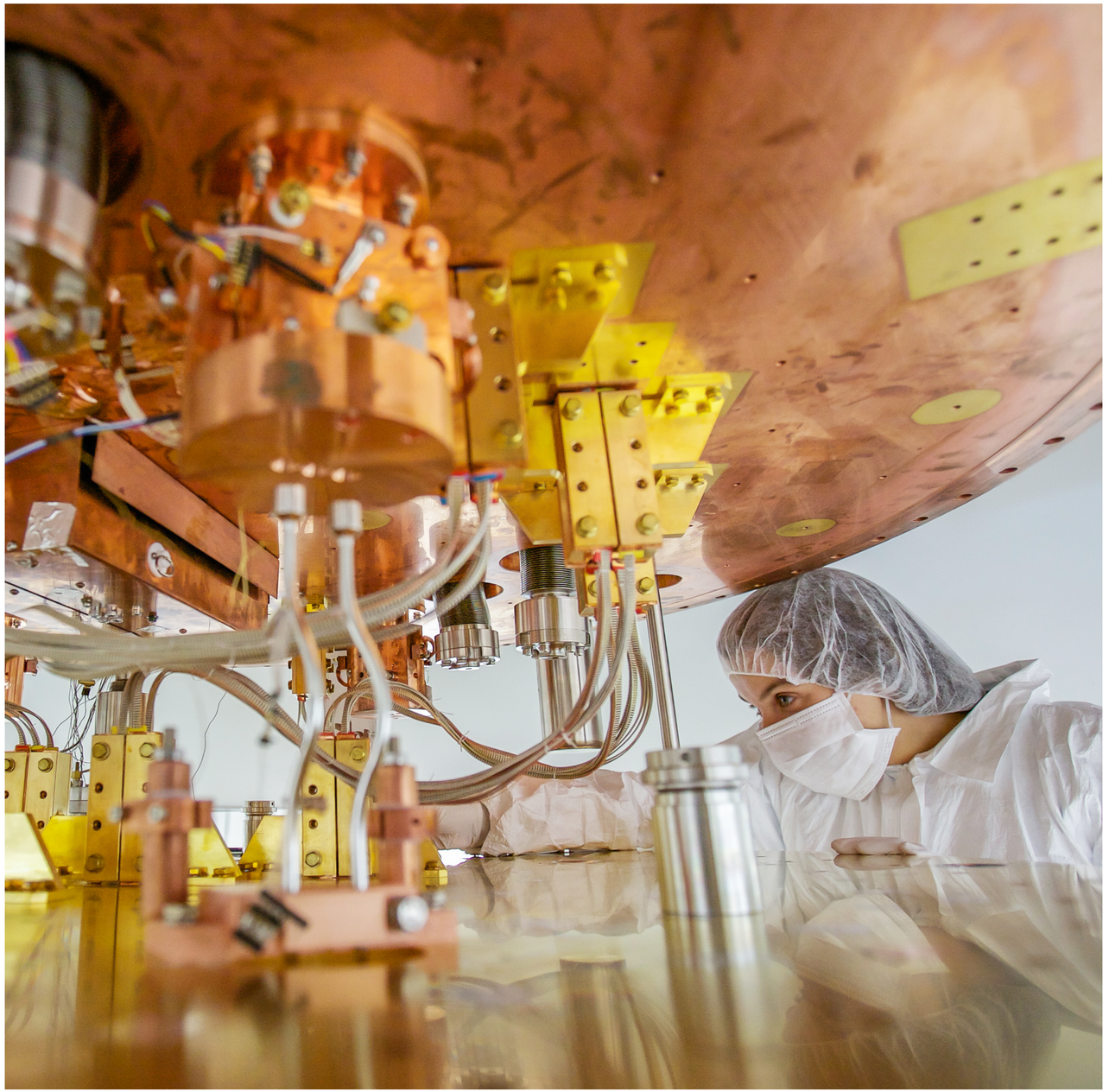

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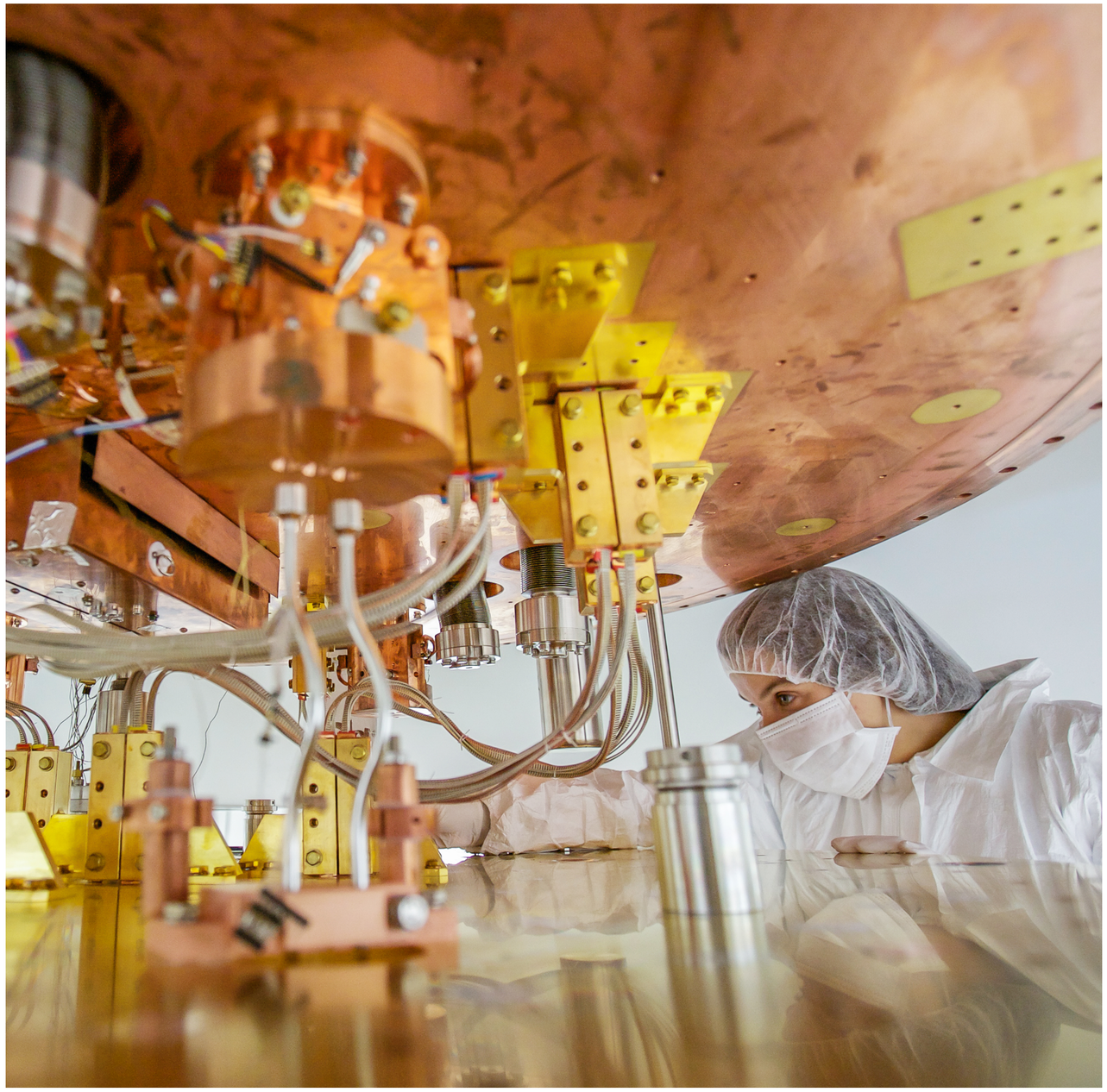
The technology and knowhow are mature for an upgrade of the CUORE cryostat.



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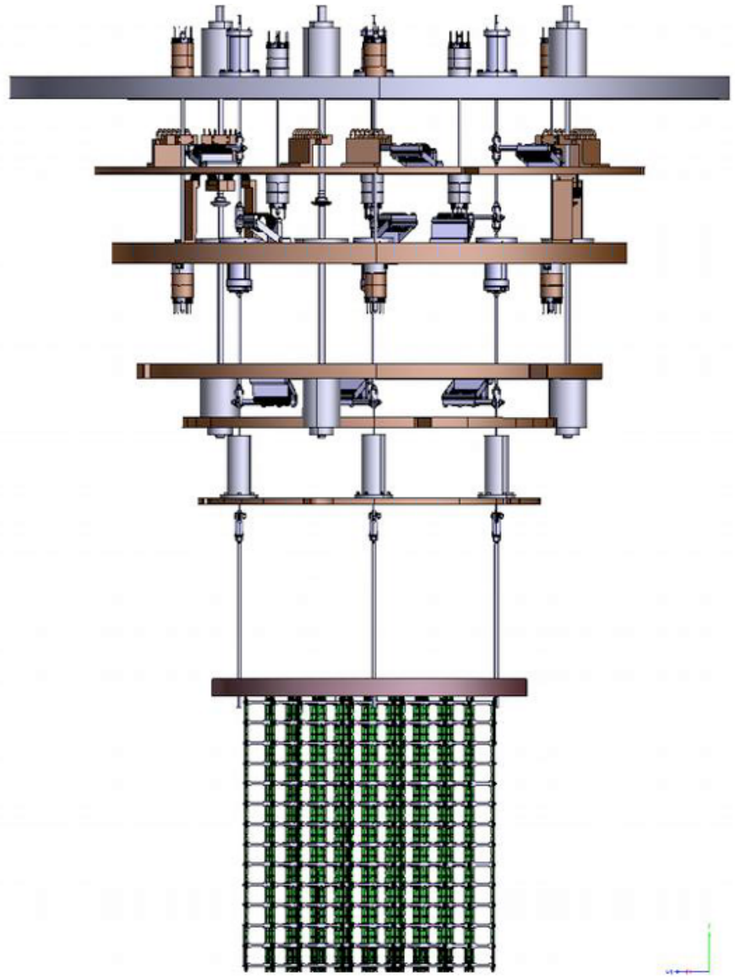
Maintenance (II): Possible reparation of the leak between IVC and OVC. In operation this does not generate problems (both volumes are in vacuum) but during cool down we are forced to keep OVC pumped to avoid heat exchange.

Improved rigidity

Rigidity: Improving the stops that keep the joints at the different plates rigid (avoiding pendulum effects). Improvements may be needed at 40K, 4K, HEX and MC levels. Also lateral Pb shield thermalization may be improved.



New cabling

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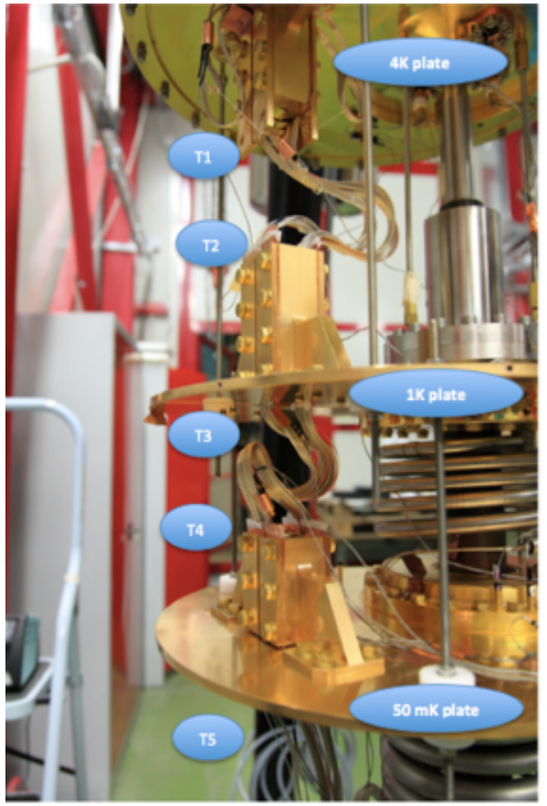

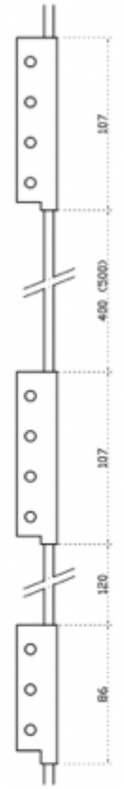

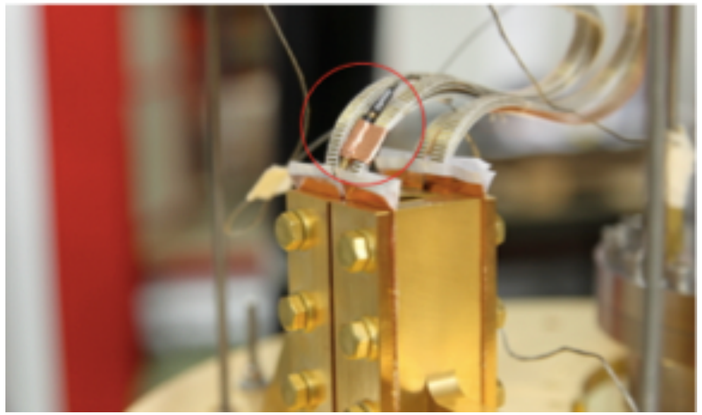

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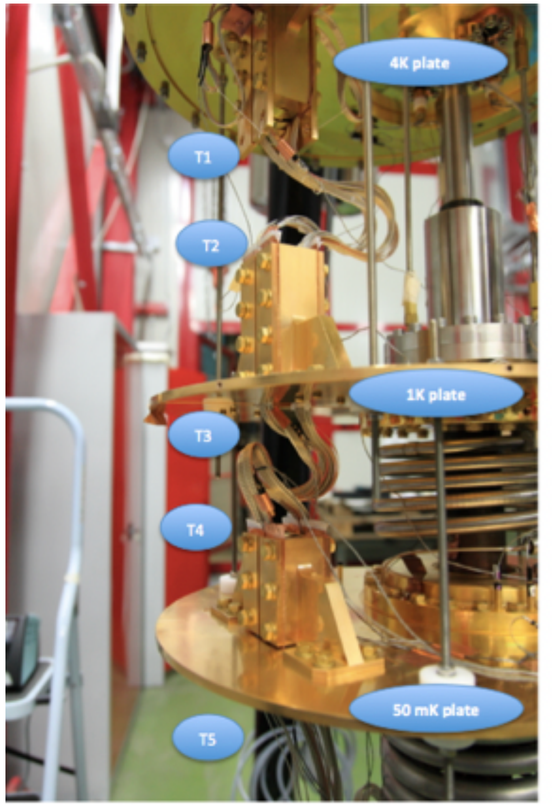

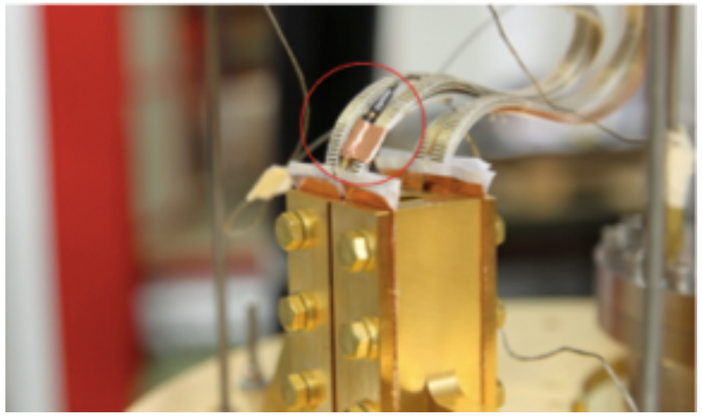

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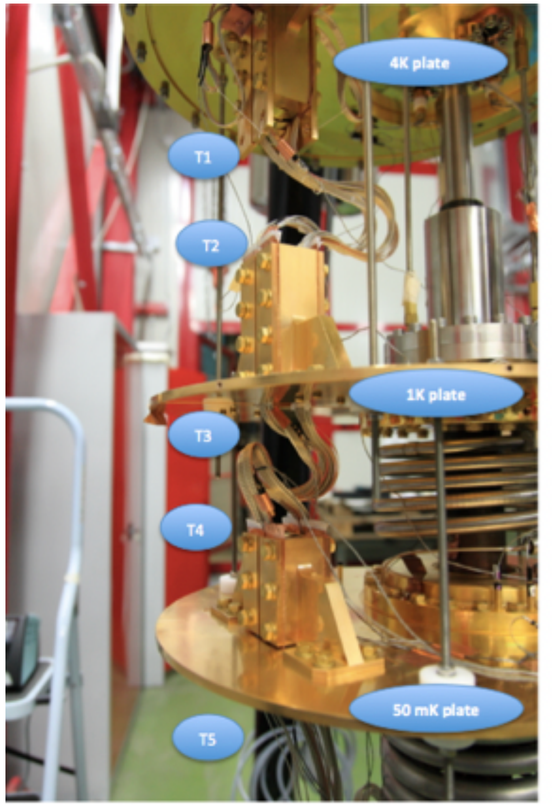

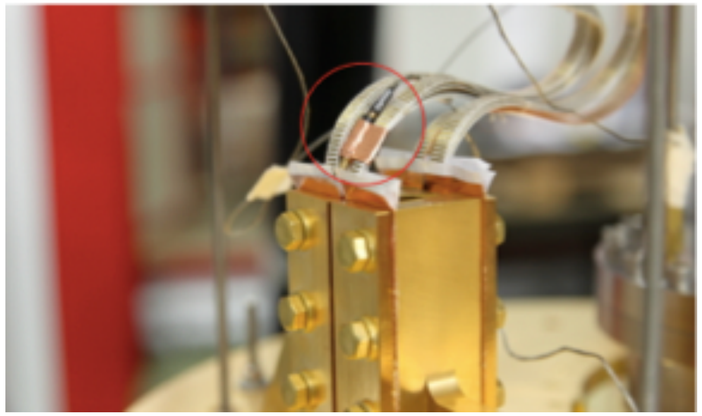

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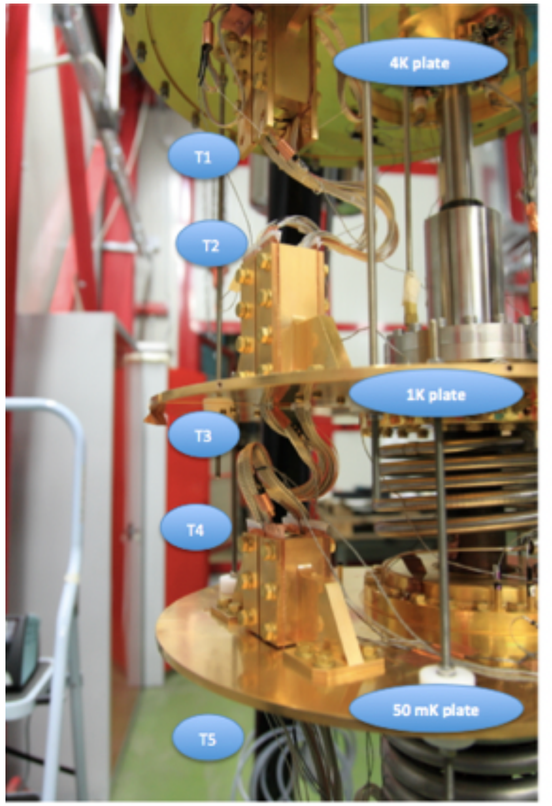
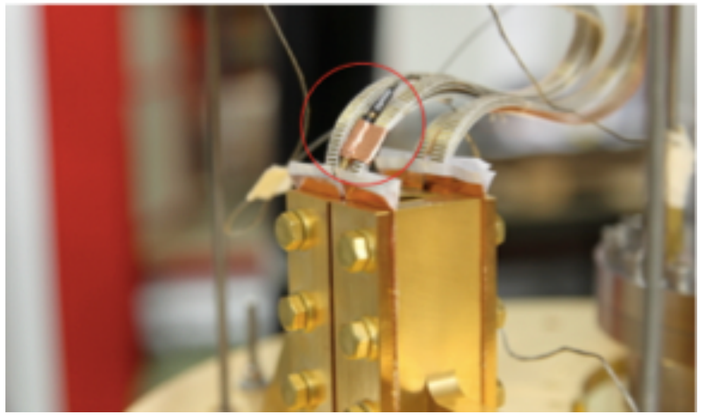
New junction boxes at MC stage with more compact design may be needed.





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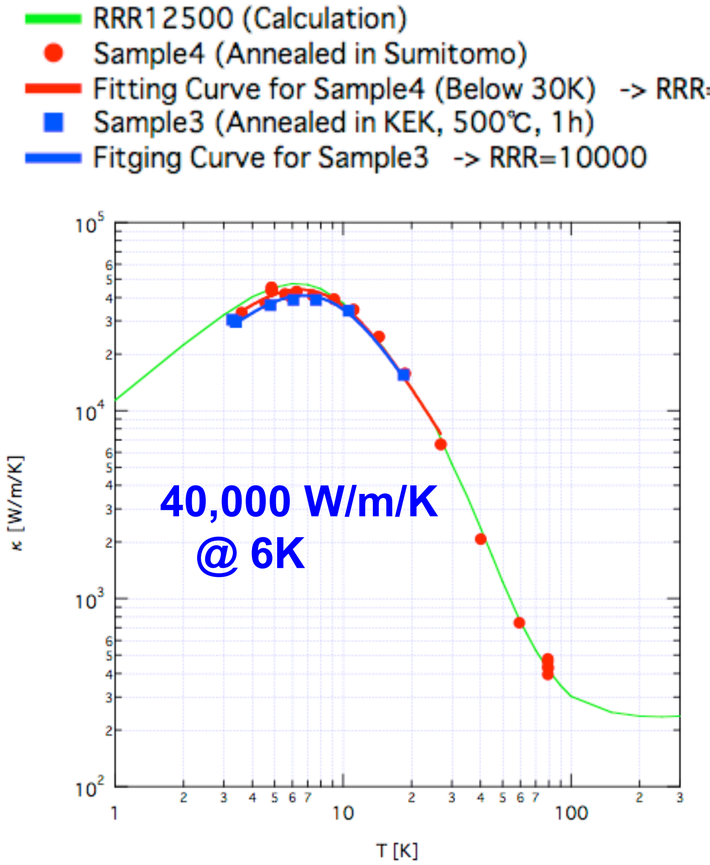
Many ideas to improve this configuration: soft Al strips (developed for gravitational interferometers application KAGRA/ET), softer copper wires, He gas…

Radical improvement of the noise cancellation will require redesign the cryostat-PT coupling (possible for new cryostats) but optimization of the current system are under investigation

6N Purity Al Heat Link

Extremely soft and good conducting high purity Al braids

KAGRA



Teion Kogaku 46, (2011) 415-420

Thermal / Electrical conductivity at cryogenic temperature proportional to material purity.

This is important to realize weekly connected heat links to cryogenic payload

Stranded cable (made of many thin wires) has advantage to have small spring constant.

$$k = n \times k^{(1)} = \frac{3nE\pi d^4}{64l^3}$$

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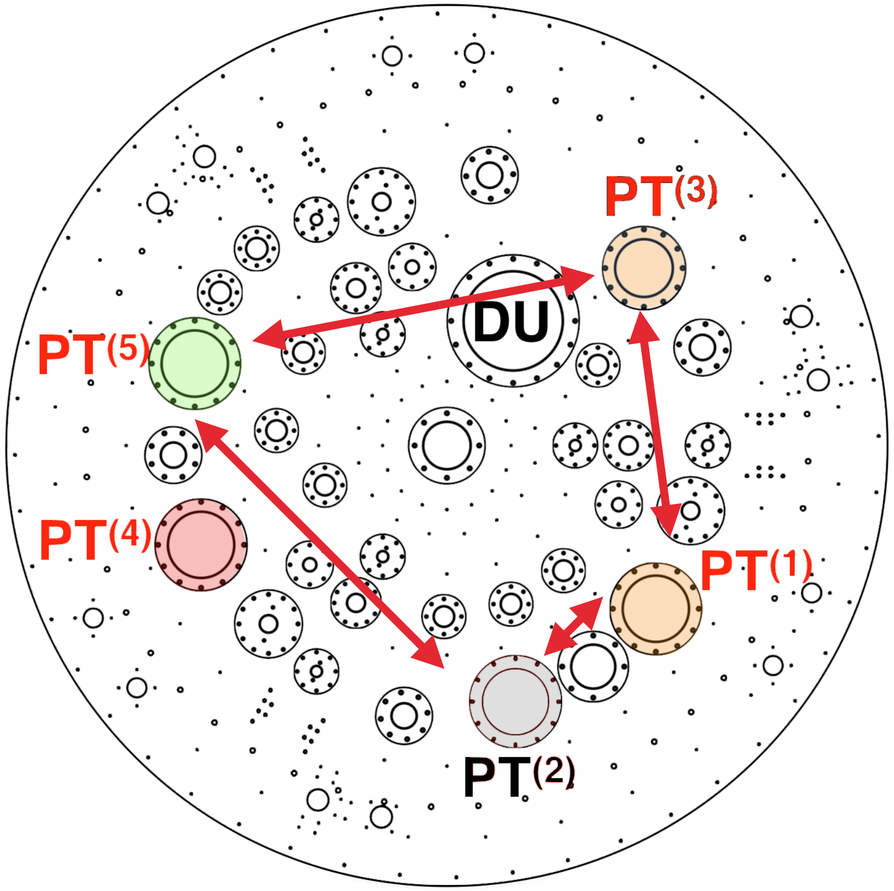
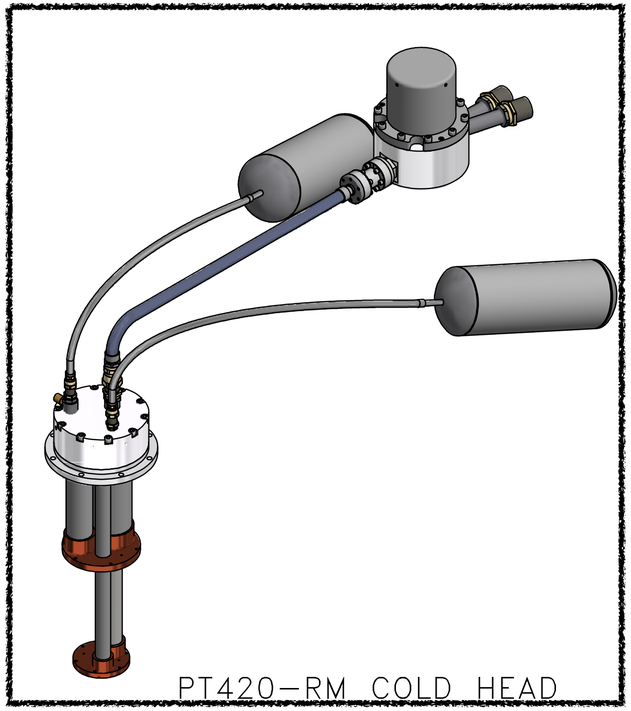
Improving PTs?

Moving to PT 425 (2.2W @ 4.2K W/ 45W @45K) can be a interesting improvement as it may allow to reduce the number of PTs.

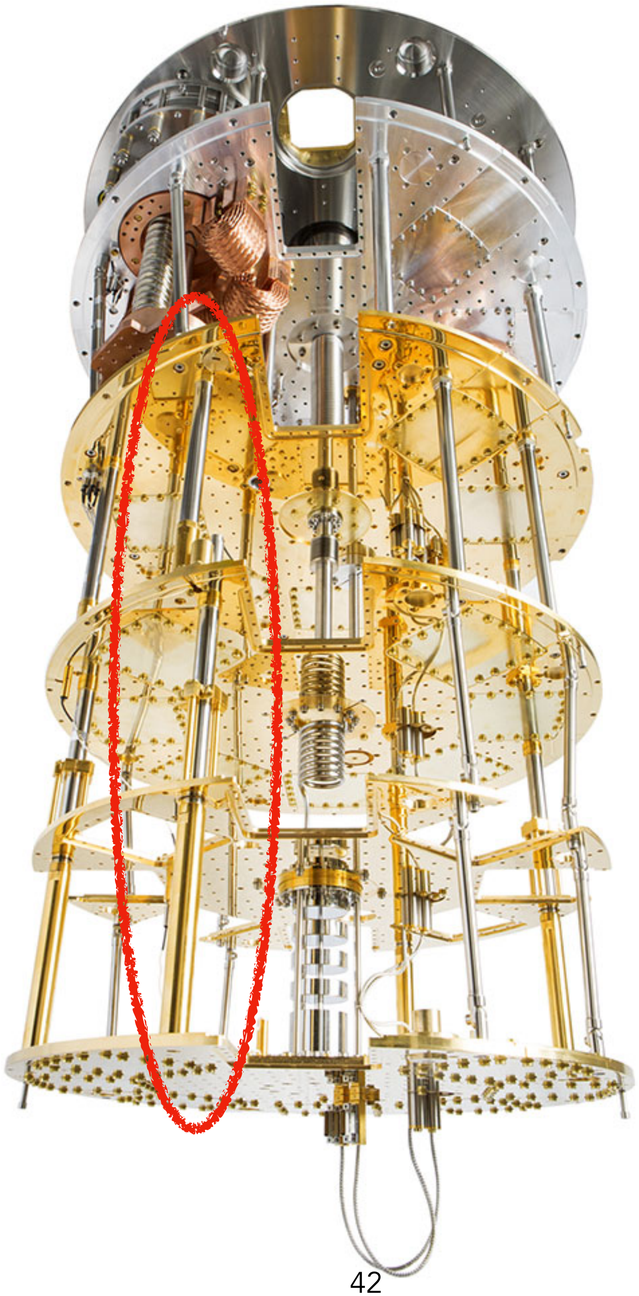


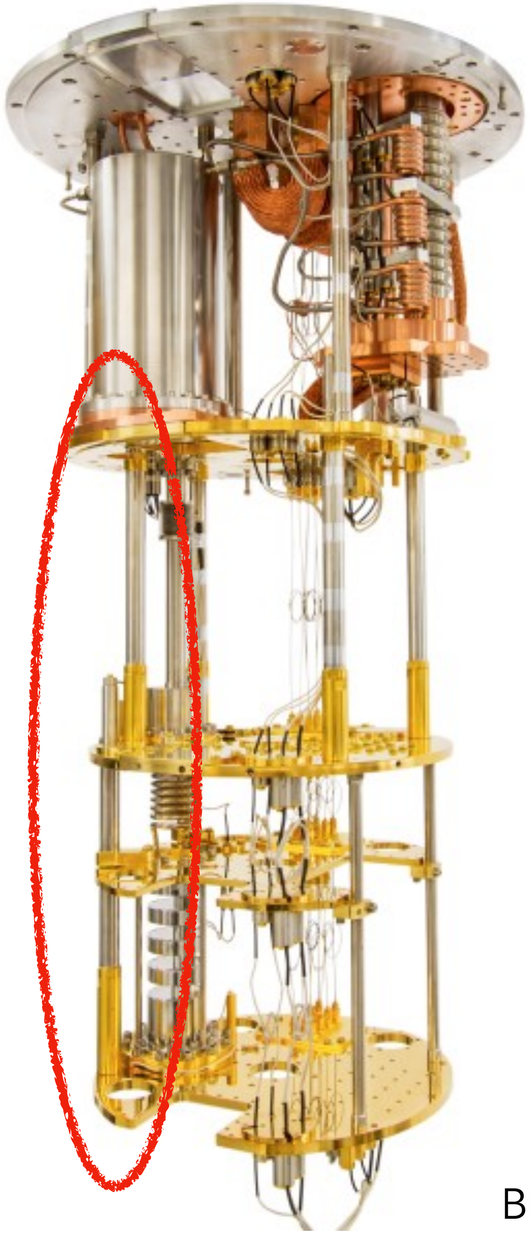
Moving from 4+1 to 3+1 PTs may improve phase cancellation and control system but a dedicated study is needed before taking this decision.



IVC vacuum

CUORE IVC is vacuum tight to allow insertion of heat exchange gas (He) during cool down. Can this be avoided? BLUEFORS and other companies are already offering single vacuum dilution unit with thermal lines to cool down the experimental mass/ volume up to few hundreds of kg.





BLUEFORS ©

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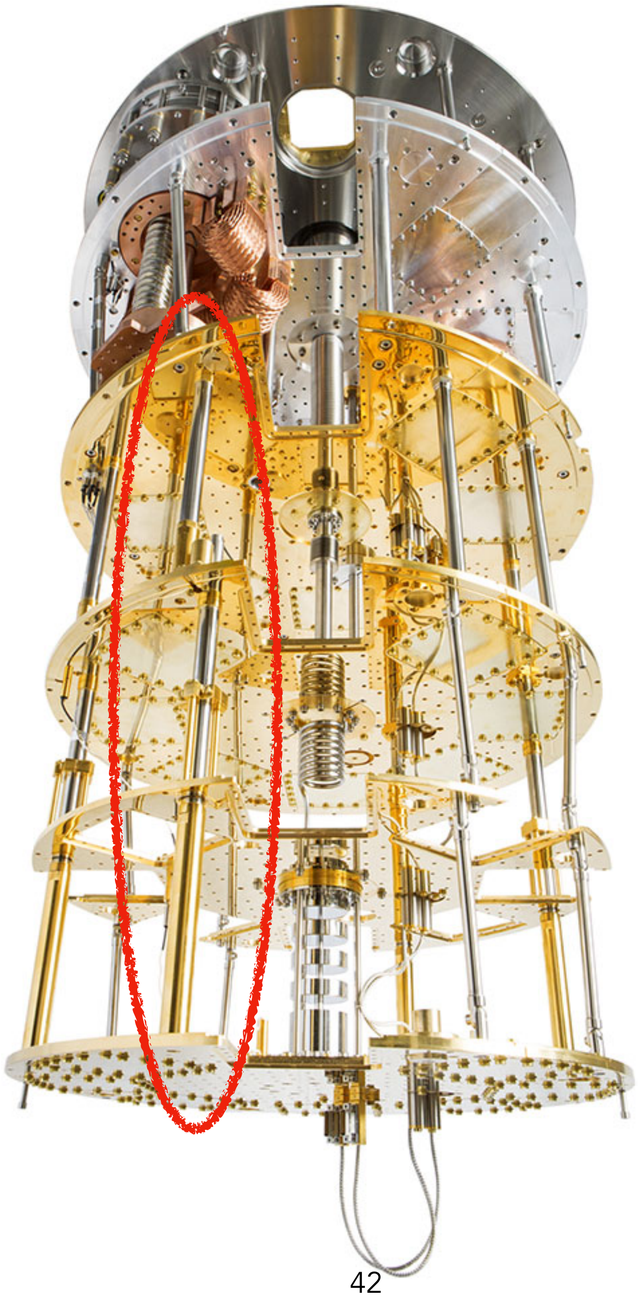
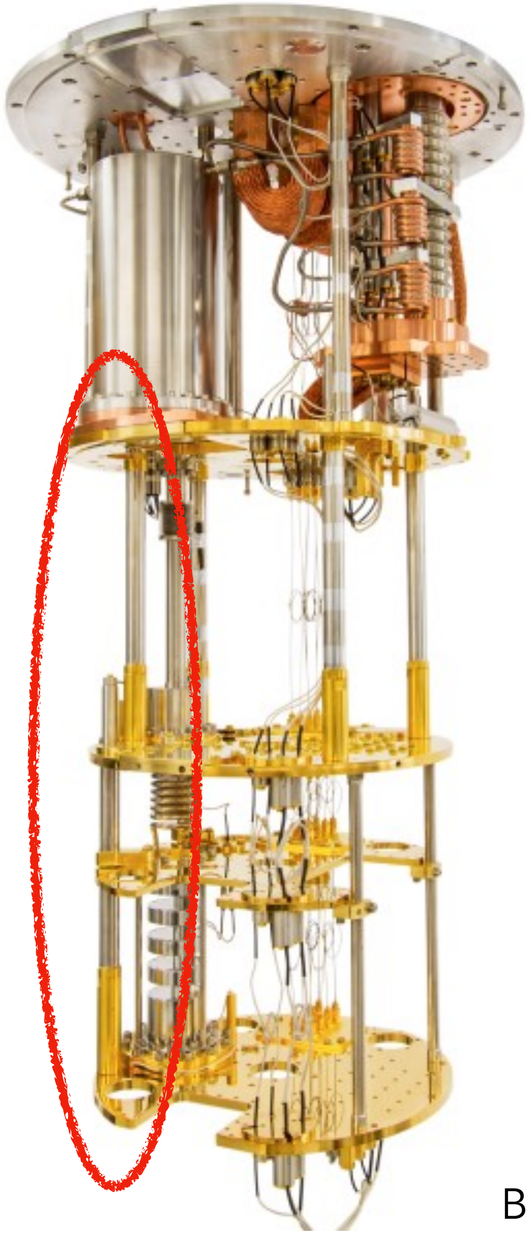
This is not an option for CUPID but next generation cryostats may explore this option.





BLUEFORS ©

Take home messages (II)

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Next generation of cryostat will profit from all the know how accumulated and design better performing cryostat using smarter solutions for vibration suppression.

The End