GOOD VIBRATIONS NEAR ABSOLUTE ZERO

Experiments in cryostats at very low temperatures, for example as performed at Leiden University, have to be protected against vibrations arising from the cooling equipment. A multi-disciplinary team comprising Dutch research institutes, engineering agencies and external experts designed and realised a double-frame vibration isolation solution. A primary frame supporting the experiment is mechanically isolated from the outer, secondary, frame which supports the vibration-generating pulse tube refrigerator. As a result, the dominant vibrations are suppressed.

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The Leiden Institute of Physics has a long tradition of researching all kinds of phenomena at very low temperatures. It was in Leiden that Heike Kamerlingh Onnes, with his co-workers, became the first physicist in the world capable of liquefying helium. He quickly realised that for a scientist it is not enough to work with one's own ideas and inventiveness. It is wiser to surround oneself with people that have the technical expertise and knowledge of materials and production. Therefore, he founded the Leiden Instrument Makers School (LiS), which to this day has been engaged in educating world-class instrument makers.

Now, more than one hundred years later, much has changed in cryogenics. Reaching a temperature of 4 K, when helium liquefies, has become much easier. Today, 4 K is the starting point to reach even lower temperatures, just 0.01 degree above absolute zero. After going to 4 K with a first cooling stage, the second cooling step is performed by a machine called a dilution refrigerator (see Figure 1) [1].

Pulse tube refrigerator

For a long time, the only option to perform the first cooling stage was a 'wet' cryostat, which relies on liquid helium for its cooling power. The helium is boiling and thus remains at a constant temperature as long as the helium bath is periodically refilled. In fact, it can consume approximately 100 litres of liquid helium every week. Since this is rather expensive, 'dry' cryostats, or cryogen-free refrigerators, have been developed in the past ten years. Combined with a dilution refrigerator, they can also reach

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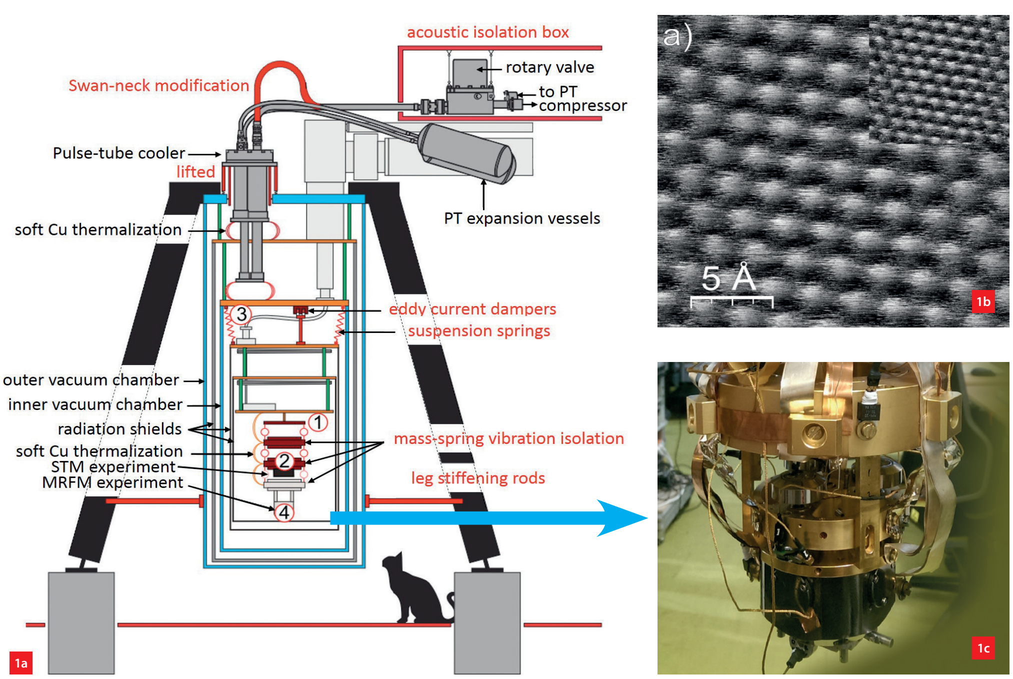


1 *The commercial pulse-tube-cooled, cryogen-free dilution refrigerator.*
(a) Schematic representation with vibration-reducing modifications in red. The various vibration measurements are indicated by the numbers: 1: SQUID at the mixing chamber plate. 2: SQUID at the second mass. 3: Geophones at the 3 K plate. 4: MRFM (magnetic resonance force micoscopy) vibration measurement inside MRFM set-up (aluminium box in the order of 10 x 10 x 10 cm³).
(b) First scanning tunnelling microscope (STM) image with atomic resolution of graphite.
(c) Close-up of MRFM set-up

0.01° above absolute zero, but the first cooling step is not derived from the boiling of pre-cooled liquid helium. Instead, a pulse tube refrigerator (PTR) is used [2].

The PTR uses a closed circuit of helium gas that is periodically compressed in the warm part of the system and subsequently expanded in the cold parts of the PTR, which are located inside the cryostat. This makes the cryostat cold enough for operating the actual dilution process in the second cooling step. In contrast to the wet cryostats, no helium is consumed because of the closed circuits, resulting in low(er) operating costs and theoretically unlimited time for experiments at temperatures close to absolute zero.

A 7 kW helium compressor, in combination with a PTR, can provide a PTR cooling power of 1.5 W at 4 K. Compared to this, the dilution refrigerator's cooling power is minute, only a few milliwatts. And with decreasing temperature, this small power decreases even more, resulting in a cooling power of only a few microwatts at the cryostat's base temperature of 0.01 K. These extremely low temperatures are so useful when performing scientific research that many tens of these cryostats are built every year. The Netherlands can be proud that many of these are built in Leiden, by the Dutch company Leiden Cryogenics and the Finnish company Bluefors, that both were founded, unsurprisingly, by Dutchmen who were educated at Leiden University and LiS.

Not only do the PTR-pre-cooled cryostats have lower operating costs and unlimited operating time, another advantage is that their volume for the experiments is much larger (by a factor of 10 to 100) than in cryostats that are cooled through the consumption of liquid helium. This allows for the design of experiments at low temperatures that are much more complicated as there simply is much more space to build complex apparatus.

Vibration isolation

So, for research on the quantum materials of the future through the use of scanning probe microscopes (SPMs) such as the AFM (atomic force microscope) [3] or the STM (scanning tunnelling microscope) [4], it is now possible to use more complex cryogenic motors needed for the microscope's (nano)positioning, which is quite difficult at these very low temperatures.

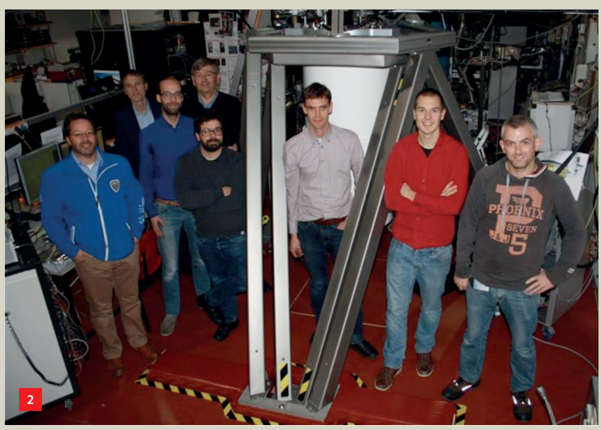
In order to perform the envisioned experiments on the nanoscale it is of course of utmost importance that the vibrations which originate from the compressor and the PTR will not disturb the experiments. Until recently it was not possible to create images with an STM inside a pulse-tube-cooled cryostat at atomic resolution as shown in Figure 1. In addition, as was recently demonstrated in Leiden, science continues to demand that technology further stretches its limits with ever lower temperatures, better nanopositioning and even lower vibration levels.

The time that an individual researcher could move the boundaries of technology, only aided by technicians employed by the university, seems to have passed. In order to proceed with more accurate SPM research at low temperatures, the Leiden researchers needed to improve the design of their cryostat. They looked for new solutions to block the vibrations generated by the compressor in order to prevent them from reaching the vibration-sensitive microscope, located inside the cryostat. It turned out to be very important for the scientists to cooperate with various experts from different companies. But how do you find the people with the required expertise willing to collaborate? Using a research subsidy from NWO, the Dutch Organisation for Scientific Research, a project team was constituted (see the box).

Project team

Multidisciplinary collaboration between research institutes, engineering agencies and external experts in the Holland Instrumentation network was created to achieve something that none of the individual partners would have been able to do on their own. The project team (see Figure 2) consisted of:

- Project leader: Philson Consulting, Philip Sonneveldt
- System engineering/dynamics/thermal: Hittech Multin, Pieter Kappelhof and Evert Hooijkamp
- Construction: ACE ingenieurs & adviesbureau, Gijs Akkermans, Joep Braam, Joao Ribeiro and Ben van Essen
- Mechatronics and seismic vibration measurement and isolation: Innoseis, Mark Beker and Alessandro Bertolini
- Realisation: Fine Mechanical Department Leiden University, Fred Schenkel
- Low-vibration cryogenic systems: Leiden Spin Imaging, Dian van der Zalm
- Scientific input: Leiden University, Martin de Wit and Gesa Welker
- Fabrication: Kasteel Metaal
- Customer: Leiden University, Tjerk Oosterkamp



2 *Team members with the new double frame of the cryostat.*

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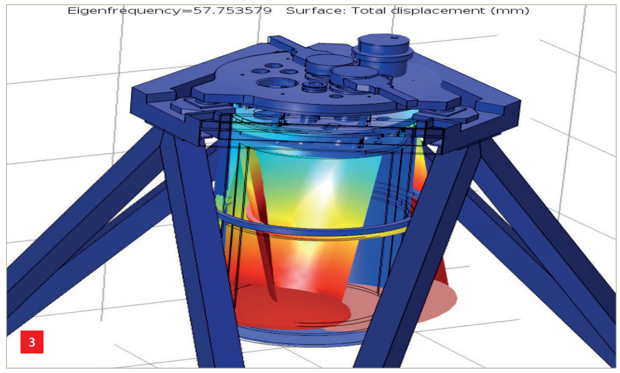
Design

The first idea of Leiden University was to make an improved design of the heat-links (copper braiding) between the pulse tube and the cryostat. The rotation of the valve switching the pulse tube back and forth between the high-pressure output of the compressor to the low-pressure input of the compressor, as well as the expansion of the gas in the pulse tube results in undesirable vibrations of several micrometers of absolute motion in the cryostat, thereby compromising the accuracy of the experiments (STM and MRFM, i.e. magnetic resonance force micoscopy).
In order to overcome this issue, the following goal was formulated: design a vibration isolation solution to mitigate the influence of the pulse tube on the measurement probes, by means of an improved heat-link. This can be done passively or actively.

Further studies proved that due to the multi-stage plate design of the cryostat, vibrations coming from the pulse tube should be considered as the main contribution. Isolating the pulse tube from the rest of the cryostat was considered to be of primary concern rather than redesigning the heat-links. This would be achieved by creating a high-stiffness secondary support structure or frame on which the pulse tube could be mounted.

To close the cryostat's vacuum chamber, there was still a need for a flexible, though vacuum-tight, connection between cryostat and pulse tube, an edge-welded bellow in this case. Due to the forces arising from the pulse tube and the desired reduction of vibration levels, the team determined that the frame and vacuum connection would need to meet the following requirements: the pulse tube frame's stiffness in all translational directions needs to be as high as $1 \cdot 10^8$ N/m and the stiffness of the bellow in all translational directions would have to be lower than $1 \cdot 10^3$ N/m.

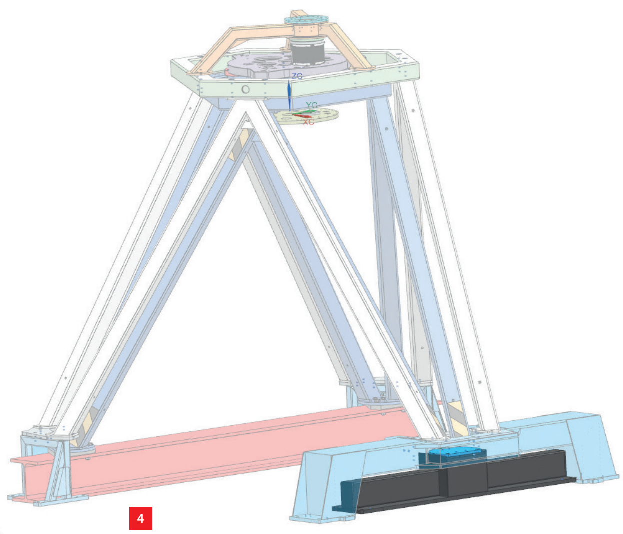
The dynamic behaviour can be described by the modes of the structure and is a key factor in the reduction of the vibrations. Here, the modes were obtained by numerical modal analysis performed on a finite-element model in COMSOL Multiphysics (see Figure 3) [5]. The mode shape of the inner structure showed a movement similar to that of two, out-of-phase, pendula. The combination of the first modes, including the mode shape shown in the figure, was used to compute the frequency response functions belonging to the loading of the pulse tube. By modifying the design parameters (e.g. contact stiffness values) and studying the resulting dynamics obtained via the modes, the effect of different design concepts could efficiently be quantified.



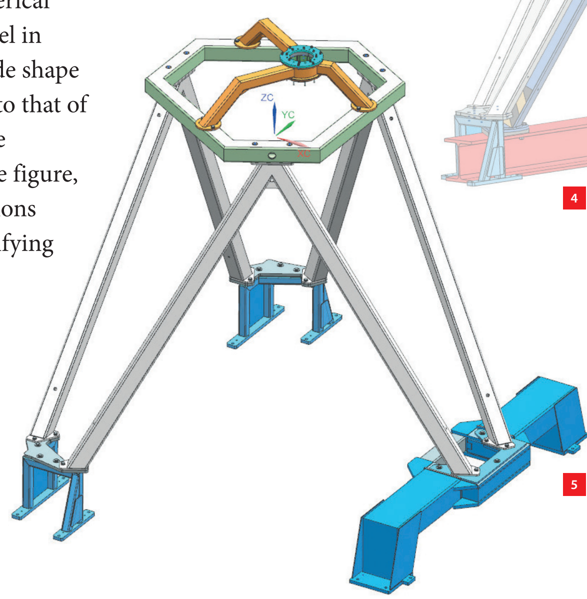
3 The mode shape of the inner structure similar to two out-of-phase pendula.

The end result was an outer secondary frame, with structural design similar and parallel to the one already holding the cryostat, but mechanically isolated from the primary frame. The primary frame was the result of an earlier phase of the project that together with several other improvements resulted in achieving atomic resolution inside a dry cryostat at 15 mK [6].

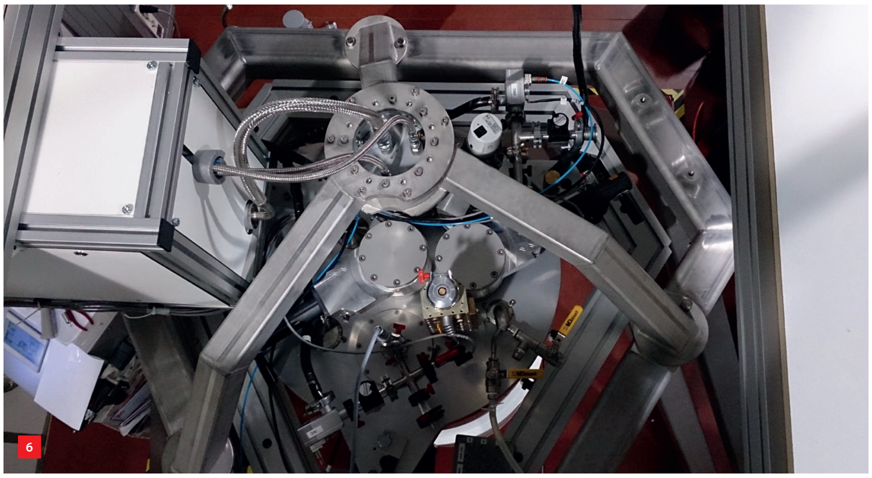
Because of volume constraints, due to the floor and the instrument foundation layout at Leiden University, a welded bridge-like construction was designed to support the primary and secondary frames without any mutual mechanical connection (see Figure 4). The new frame which reaches over and around the cryostat has the sole purpose of holding the pulse tube (see Figure 5). This frame was designed to be sufficiently stiff to eliminate the motion of the pulse tube despite the high forces exerted on it by the high-pressure line coming from the compressor.



4 Bridge-like construction of the primary and secondary frame.



5 CAD layout of the cryostat's external structure.



This result, along with Leiden Spin Imaging's profound knowledge and know-how [7], was used for the new secondary frame that has an alternative hexagonal ring welded ring on top (see Figure 6), in which the pulse tube is mounted. Its stiffness is as high as required. The edge-welded bellow, however, is still ten times stiffer than desired.

As a result, the vibrations generated by the pulse tube are constrained by the secondary frame, as the pulse tube is being held by this frame and is only weakly connected to the primary frame. Consequently, the vibrations generated by the pulse tube no longer enter directly into the primary frame, which is supporting the cryostat.

Results

Kasteel Metaal has produced and delivered the secondary frame to Leiden University. First results show a significant improvement. Physical proof of the isolation of the vibration is obvious when you put your ear to the frames. In the secondary frame you can hear the pulse tube 'sing'; on the primary frame, right next to the other frame, you hear nothing.

The improvement through vibration isolation is demonstrated in Figure 7 by comparing the accelerations of a geophone before and after the new frame was installed. In the figures a cumulative number (integrated value) is presented as a function of the frequency; the accelerations are presented as a root-mean-square figure by integrating up to the frequency on the x-axis. Most important is that the steps that were previously present at 1.4 Hz and 2.8 Hz (the frequency of the pulse tube) are no longer observed. The vibration level now appears to be limited by the vibrations present in the laboratory.

To conclude

The researchers are looking forward to repeating their measurements in the new Leiden University measurement laboratory, which is expected to open in July 2017. Then they will know whether the vibrations have improved by a factor of ten in amplitude or whether they may have reduced even more.

The results from this multi-disciplinary collaboration have helped Leiden University to acquire additional funding for investments in equipment for future research projects. Part of these investments will fund the development and implementation of improved vibration isolation solutions.

6 *Top view showing two hexagonal rings, one holding the pulse tube tripod and another holding the cryostat itself.*

7 *Improvement of vibration isolation performance.*
(a) Acceleration.
(b) Motion.

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