Low-vibration high-cooling power 2-stage cryocoolers for ground-based astronomical instrumentation

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ABSTRACT

This paper describes the outcome of a survey reviewing commercially available state-of-the-art high-cooling power 2-stage cryocooler systems for a potential use in powerful scientific instruments for ground-based astronomy. We present the development of a dedicated test-bed as well as vibration and performance measurements on different 2-stage refrigerator systems. As a result of this investigation program, one system was selected as ESO's new standard 20 K closed cycle cooler offering substantial advantages in flexibility and orientation insensitivity along with best compromise for a low vibration device with high cooling power. The new cryocooler type was integrated with VLT instrumentation. A concept for a comprehensive vibration test program at VLT is presented in order to define admissible vibration spectra for future instrumentation.

Keywords: Cryogenics, closed cycle cooler, vibration, VLT-I, ground-based astronomy

1. INTRODUCTION

Extreme resolution capabilities and increased sensitivities of modern telescopes and instrumentation implicate significant susceptibilities to mechanical disturbances. Especially for the very sensitive VLT-I experiments (the world's largest interferometer) even low level excited vibrations are very critical or unacceptable. Mechanical closed cycle coolers were introduced at ESO almost 20 years ago. They are mainly used to provide the cryogenic temperature levels as required for infrared detectors and instruments. Over the last two decades the performance and reliability of these cryocoolers has constantly improved and their relatively low maintenance and operation effort compared to complex cryo-fluid systems was increasingly appreciated. Nowadays many companies are offering 'plug and play' high-cooling power refrigerator systems based on proven technology available off-the-shelf. Despite quite a number of benefits, all these coolers also induce potential problem areas first of all non-negligible mechanical vibrations. With the last stage of completion of the VLT-Interferometer a new dimension in sensitivity was achieved also clearly revealing perturbations caused by the cryocoolers of adjacent VLT instruments. As a consequence ESO started an extensive vibration reduction campaign. One of the tasks involved was a comprehensive survey and test program of alternative cryocooler systems. Particular emphasis was put on vibrations caused by these cryogenic refrigerators together with demanding requirements on cooling power and operation temperature range. Potential candidates have to meet the following specifications:

- 1^{st} stage cooling power: 100 W @80 K
- 2^{nd} stage cooling power: 5 W @20 K
- Lowest reachable 1^{st} stage temperature: 45 K
- Lowest reachable 2^{nd} stage temperature: 10 K
- Orientation free operation
- 'Low' vibrations
- Reliable availability and service
- Well-engineered technology

At first the available technology was assessed. There are five common types of cryocoolers but only some of them reached real industrial standard. Facing the requirements coolers based on pulse-tube (PT) and Gifford-McMahon (GM)

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principles seem to be well suited offering high cooling capacities and fairly good efficiencies. Pulse-tubes are known to have low vibration levels as they do not have moving parts in the cold end, but their performance is highly orientation sensitive. Whereas GM machines with their cold displacer mechanism will always produce vibrations but are robust against any orientation. Their widely use in cryopumps in semiconductor fabrication led to many improvements and high reliability.

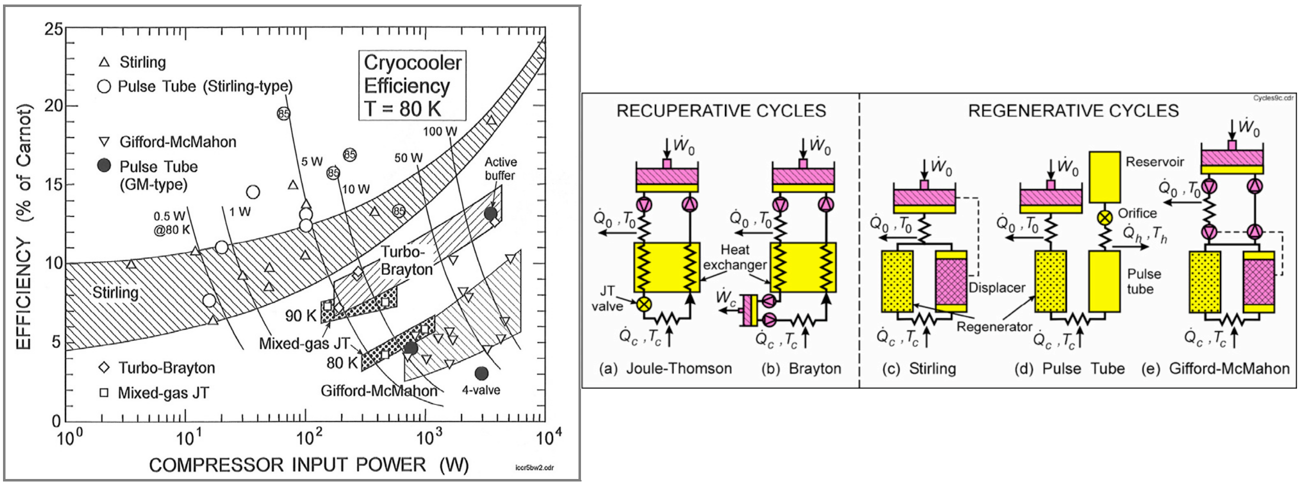

Figure 1: NIST's collection of cryocooler capacities and efficiencies (left), schematics of common cryocooler types (right), [1,2,3]

As a first result the survey and test program mainly focused on Gifford-McMahon coolers. ESO's recent standard high-cooling power 20 K cryocooler the Oerlikon Leybold RGD 5/100 (later also known as COOLPOWER 5/100) with its pneumatically driven displacer was detected to be a major source of disturbances. Newer developments implement motor driven displacers and comparable refrigeration power. Their different driving mechanism is supposed to excite lower vibration levels. The following systems were made available for further investigations and for comparison with present standards:

- Oerlikon Leybold COOLPOWER 10MD
- Sumitomo (SHI) SRDK-408D2 and -408D
- Brooks (CTI) Cryodyne M-1050
- Oxford Instruments, Austin Scientific 1050 CS
- Oerlikon Leybold COOLPOWER 4.2K

2. TEST-BED

A vacuum vessel was designed to universal-fit several different cold head types. The vessel is equipped with two temperature sensors, one for each temperature stage of the cold head, with power heater for both stages, electrical feed-throughs, a pressure gauge and valves to be able to connect to a pumping unit. An optional radiation shield can be mounted on the 1st stage. Helium leakage tests of the assemblies were performed to exclude incorrect measurements of cooling power.

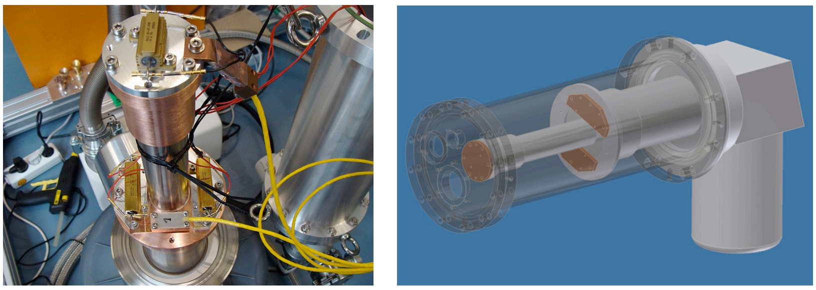

Figure 2: 2-stage cold head with power heaters and temperature sensors (left) cold head mounted in vacuum vessel (right)

Vacuum vessel and integrated cold head are suspended by a single steel cable hanging within a rigid aluminum beam framework. Vibration dampers are mounted between frame and ground floor. The configuration is similar to a simplified pendulum where its frequency is defined by the length of the cable (at least for small amplitudes). Dimensions are to be chosen to gain a pendulum frequency clearly below the expected lowest cooler frequencies of about 1 Hz:

$$\mathbf{f = 1 / 2\pi * \sqrt{g/L}} \quad \textbf{(1)}$$

with $g = 9.81\ m/s^2$ and $L \approx 2.5\ m$

$f \approx 0.3$ Hz

This arrangement allows free horizontal oscillation of cold head and vessel which is necessary for comparative vibration measurements. Accelerometers are attached at the outer wall of the vessel. In order to measure vibrations in three different cold head coordinates their suspension and orientation can be adapted accordingly. An FFT software is used for data acquisition and analysis.

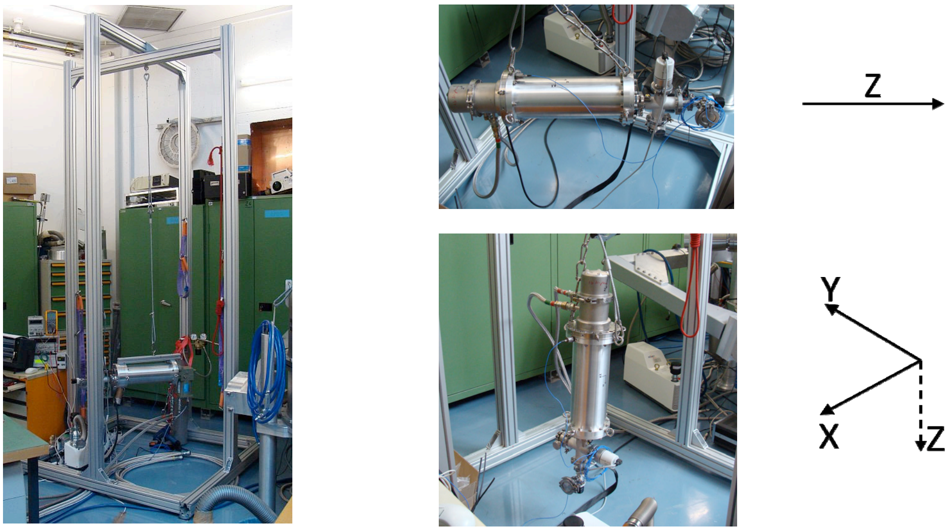

Figure 3: aluminum framework with free oscillating cold head vacuum assembly (left), definition of cold head coordinates (right)

3. COOLING POWER

For cooling power evaluation different levels of electrical dissipations were applied to the power resistors. 1st and 2nd stage temperatures were read out by using Pt100 and fully calibrated Cernox sensors. For practical reasons most of the measurements were performed without shield. For those an ambient radiation load of 5-10 W depending on dimensions and reflectivity factors may be added to the presented cooling capacities of both stages. In order to reach the lowest approachable 2nd stage temperature, some of the 4 K coolers were equipped with shield. It is mounted on the 1st stage, enclosing the 2nd stage completely. The shield reduces the radiation load on the 2nd stage from 5-10 W to some mW depending on the actual 1st stage temperature and it has influence on the cool down behavior of both cold head stages.

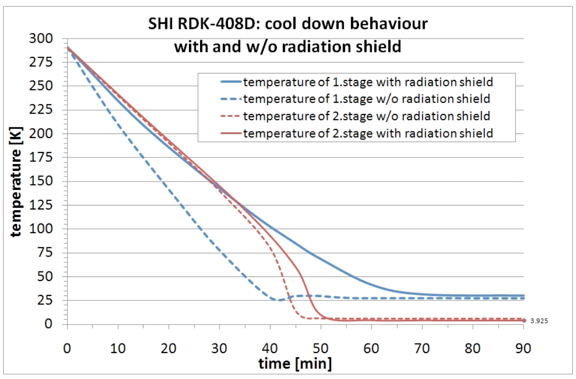

Figure 4: cool down of unpowered cold head with and without radiation shield

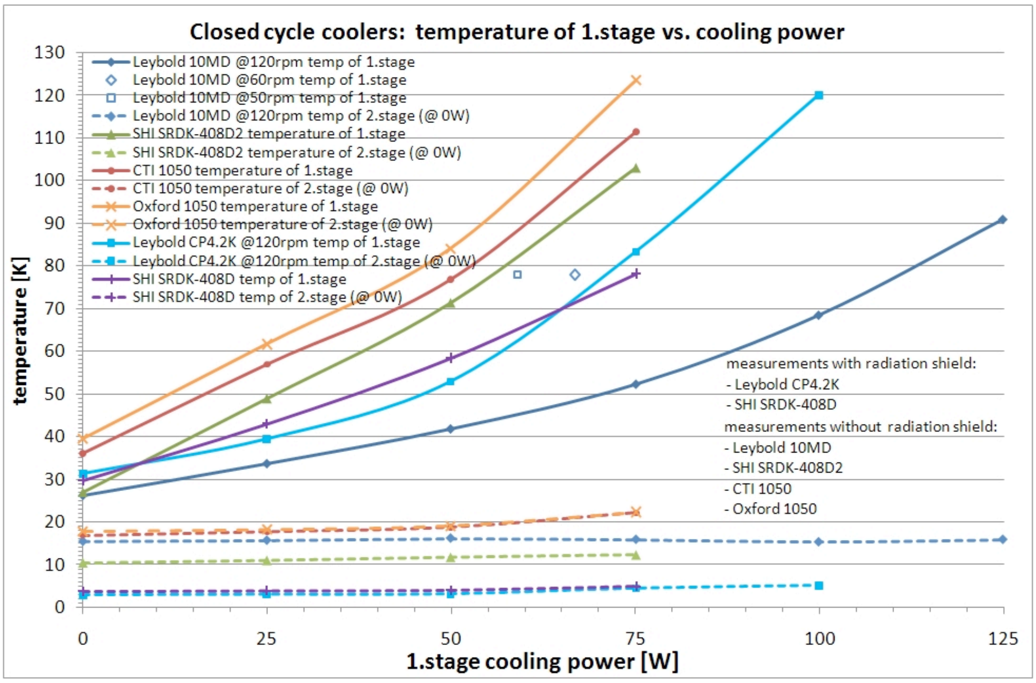

Figure 5: 1.stage cooling power of different GM closed cycle coolers

Figure 5 illustrates the 1st stage cooling power of investigated cooler systems. The **Leybold 10MD** cryocooler, operated at nominal motor revolution of 120 rpm, has a much higher 1st stage cooling power than the other machines. The measured 110 Watt @ 77 Kelvin meets easily the ESO requirement of 100 Watt @ 80 Kelvin. It is the only 20 K system offering adjustable motor revolution. This can be executed within the range of 20-160 rpm by increments of 10 rpm. How the cooling power is depending on the selected motor speed is shown in figure 6. The motor speed influence on vibration levels is presented later.

The cooling power of the **Brooks / CTI 1050** cooler was measured being insensitive to different helium pressures to be used for optimal 60Hz or 50Hz operation, resulting for both helium pressure options in a 1st stage cooling power of 50 W @77 K, which is even with the radiation correction (plus 5-10 W) somewhat below manufacturer's specification (65W @77 K). An optional 60 Hz frequency converter increases the 2nd stage cooling power slightly, while the 1st stage is nearly uninfluenced.

The **SHI SRDK-408D2** 4 K-cooler has also a rather low 1st stage cooling power but is with 55 W @77 K still ~ 10-15% higher than the CTI 1050. The older version of that cooler type, the **SHI SRDK-408D**, which was used for ESO's TIMMI-2 experiment, showed with 75 W @78 K better performance.

The 1st stage cooling power of the **Oxford Instruments / Austin Scientific 1050 CS** cooler was measured to be the poorest of all tested machines (45 W @77 K) and is more than a factor of 2 too low to meet the ESO requirement. Even when regarding a maximum value for the effective initial radiation power (10 Watt), the manufacturer's specification of 65 Watt @ 77 Kelvin could not be reproduced.

The **Oerlikon Leybold CP4.2K** is a new developed 4 K-cooler with quite high 1st stage cooling power. It is the only 4 K system offering adjustable motor revolution. Manufacturer's specifications can be confirmed for higher motor revolution operations. At 120 rpm values of 50 W @55 K or 70 W @77 K can be achieved. Below 90 rpm the cooling power is decreasing appreciably (figure 6).

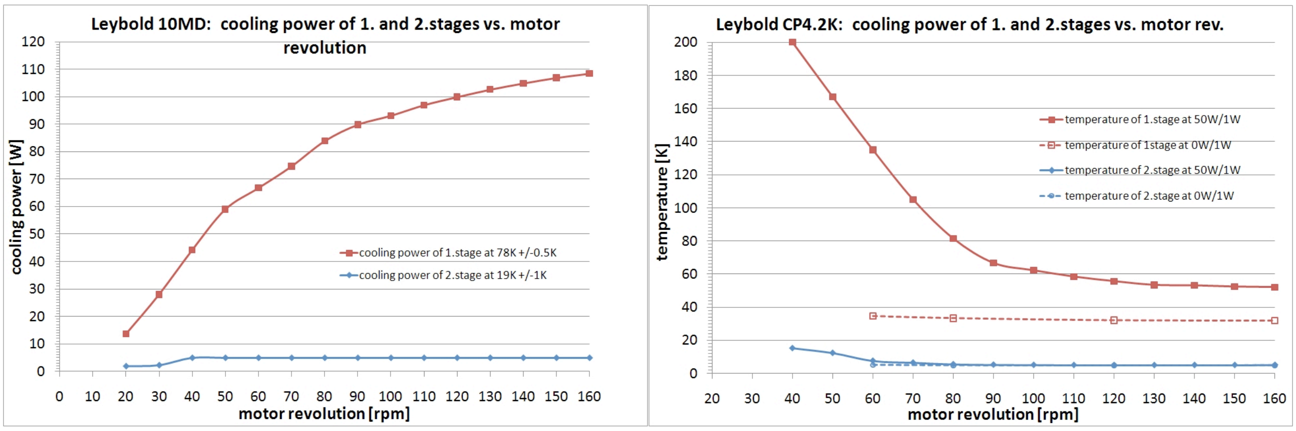

Figure 6: Oerlikon Leybold CP10MD cooling power at variable motor revolution, compared to operation at nominal motor speed 120 rpm the 1st stage cooling power decreases at 80 rpm by 16% and at 60 rpm by 33% (left); Oerlikon Leybold CP4.2K cooling power at variable motor revolution for two 1st / 2nd stage load cases 0 W /1 W and 50 W / 1W (right)

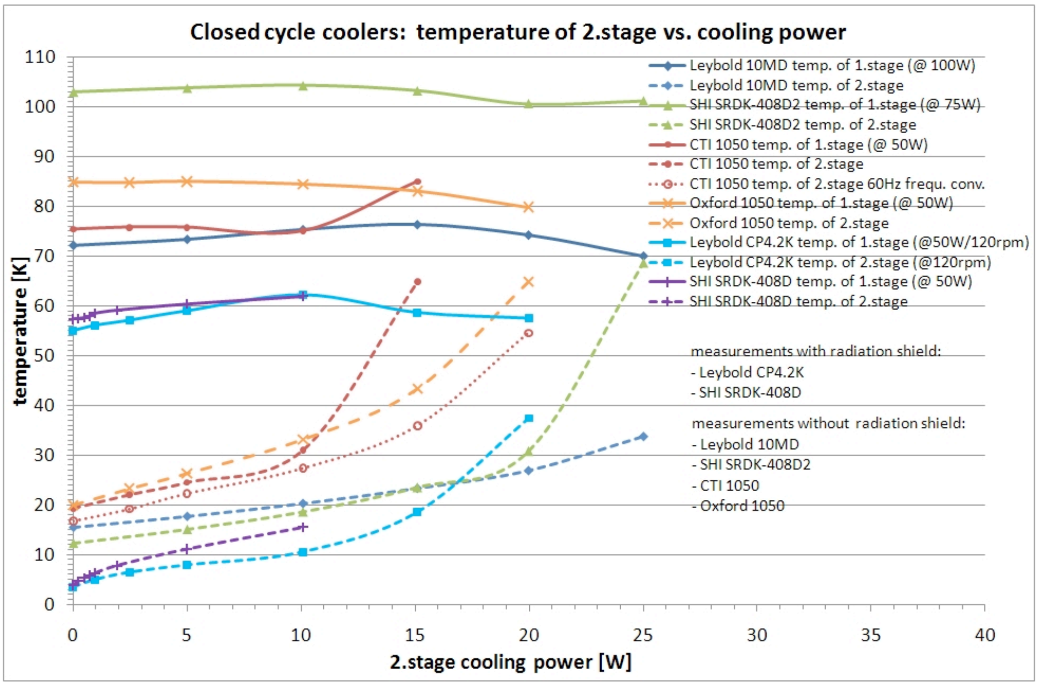

Figure 7: 2.stage cooling power of different GM closed cycle coolers

Figure 7 illustrates the 2nd stage cooling power of investigated cooler systems for certain 1st stage load cases. In principle all tested coolers fulfill the ESO requirement of 5 W @20 K when assuming the initial radiation load of 5-10 W. The 20 K-cooler **Leybold 10MD,** the 4 K-coolers **SHI SRDK-408D2, SHI SRDK-408D** and the **Leybold CP4.2K** are powerful systems with sufficient margins.

None of the 4 K-coolers was found to have a 2nd stage cooling power of 1 W @4.2 K as specified by their manufacturers. The **Leybold CP4.2K** showed with 1 W @5 K the best value, followed by the TIMMI-2 cooler **SHI SRDK-408D** with 1 W @6.2 K. All the others are to be radiation corrected.

4. CRYOCOOLER VIBRATION LEVELS

With this set-up absolute measurements of the vibration levels are practicably hard to achieve. In principle the free oscillating cold head mount is similar for all cooler types, but is practicably influenced by the stiffness, position, length, shape etc. of the attached helium lines (damping) and by weight, shape etc. of the cold heads themselves. It was aimed to keep these perturbations as low as possible in order to get comparative results. Nevertheless, numbers on absolute vibration levels have to be handled with care, but the spectral energy distributions are well suited to compare the different cryocooler vibration spectra.

Measurements were performed in two frequency ranges 0-63 Hz and 0-1 kHz although the lower frequency range is of main interest. For all tested cryocoolers the main vibration excitation is generated in Z-axis, which is the rotation symmetric axis of the cold head, respectively the direction of the displacer stroke. Measured PSDs and amplitudes in X- and Y- axes, which are mainly caused by motor and valve movements, are by about one or two magnitudes lower, except for the Leybold CP 5/100. Typical time signals are shown in figure 8. Compared to the pneumatic system CP 5/100 the signals of all mechanical systems are more sine like. The according spectra in the 0-63 Hz range are shown below.

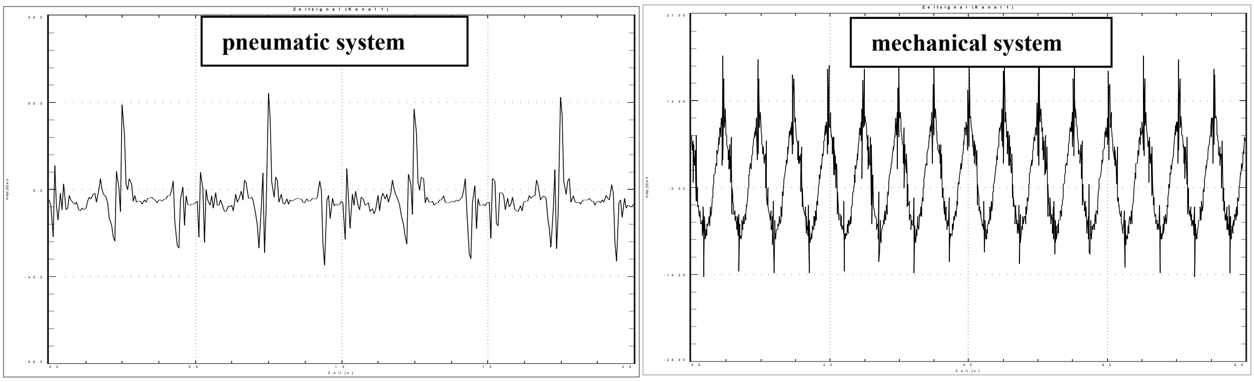

Figure 8: typical Z-axis time signals of a GM system with pneumatically driven displacer COOLPOWER 5/100 (left) and the mechanical driven system COOLPOWER 10MD (right)

The **Leybold Coolpower 5/100** has the most "unclean" spectrum of all tested machines. Amplitude levels of the harmonics are in the same range or even higher than the 1st frequency levels. Damping or elimination of all resonance frequency peaks can be very complex.

The **Leybold Coolpower 10MD** has a quite pure sine spectrum with a moderate peak at the 1st frequency and quite low amplitudes at the harmonics. Operated at 60 rpm motor revolution, this cooler has even the lowest amplitude at the 1st frequency peak of all investigated 20 K coolers. Also at nominal motor speed of 120 rpm the 1st frequency peak amplitude is competitive to the other coolers, but is offering almost twice as much cooling power.

The 1st frequency can be shifted within a range of 0.33 Hz to 2.67 Hz, depending on the selected motor speed of 20 rpm to 160 rpm. At 20 rpm the spectrum is almost flat. The option to shift the 1st frequency is beneficial when adapting the cooler to a mechanical system with known eigenfrequencies in the critical region. Compared to other coolers, which have the 1st frequency fixed at 1 Hz (and harmonics at 2 Hz, 3 Hz, 4 Hz etc.), this cooler produces only half of the excited harmonics when operated at 120 rpm (1st frequency at 2 Hz -> harmonics at 4 Hz, 6 Hz, 8 Hz etc.).

The Sumitomo cooler **SHI SRDK-408D2** has a rather pure spectrum with a quite strong peak at the 1st frequency of 1 Hz. The 1st frequency amplitude is comparable to the Leybold 10MD cooler at 120 rpm, but compared to this the Sumitomo cooler it is offering only about half of the cooling power. Also the amplitudes of the harmonics are higher than for the Leybold 10MD or the CTI cooler.

The **Brooks / CTI 1050 Cryodyne** cooler has one of the purest spectra of all tested machines with a strong peak at the 1st frequency of 1 Hz. The amplitude level of the 1st frequency is higher than the one from Leybold's 10MD at 60 rpm, but a little lower than 10MD operated at 120 rpm. The peaks of the harmonics are the lowest of all machines.

The **Oxford Instruments / Austin Scientific 1050 CS** shows similar characteristics than the CTI 1050, but the 1st frequency amplitude level in Z-axis is even higher than of CTI1050, although having ~10% less cooling power.

The 4K-cooler **Leybold CP4.2K** when operated at 120 rpm creates a similar spectra than the 20 K cooler Leybold CP 10MD. But when operated at 60 rpm it has by far the lowest 1st frequency amplitude at 1Hz out of all tested machines. In combination with its high cooling powers on both levels, this 4 K cooler might be of interest for vibration sensitive 10K/20K-systems as well.

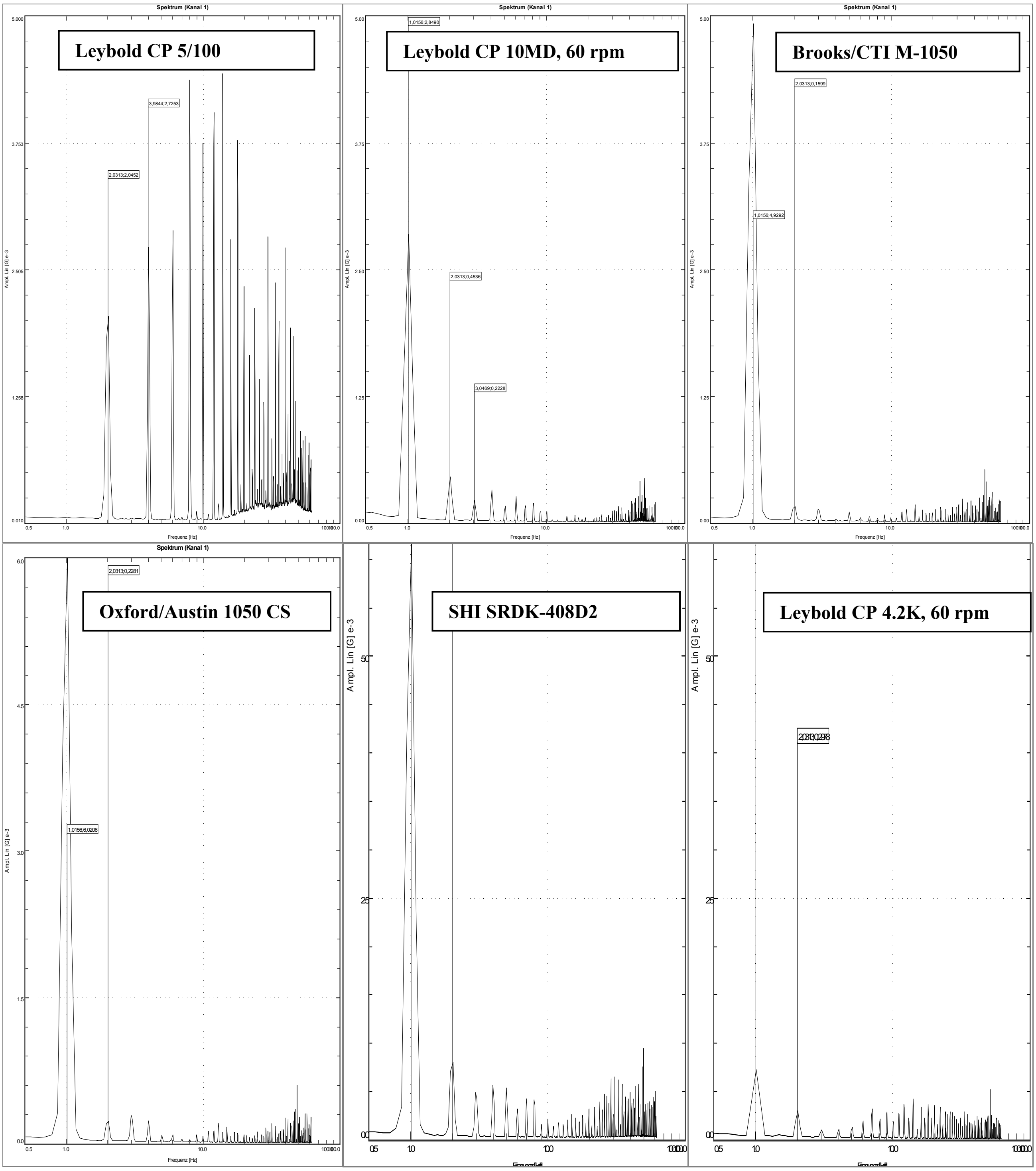

Figure 9: linear vibration spectra of different GM coolers in Z-axis, abscissa 0-100 Hz, ordinate 0-5 mg (resp. 0-6 mg)

Both mechanical driven cryocooler systems from Oerlikon Leybold the 20 K and the 4 K system offer adjustable motor speed. The influence on vibration levels in Z-axis and the shift of the frequency is shown in figures 10-13 as outcome for the CP 10MD and CP 4.2K power spectral density (PSD) measured in the 0-63 Hz range for different motor revolutions. Below 80 rpm (1st frequency $\leq$ 1.33 Hz) the acceleration amplitudes respectively PSD levels are decreasing exponentially which are of great advantage for low vibration applications.

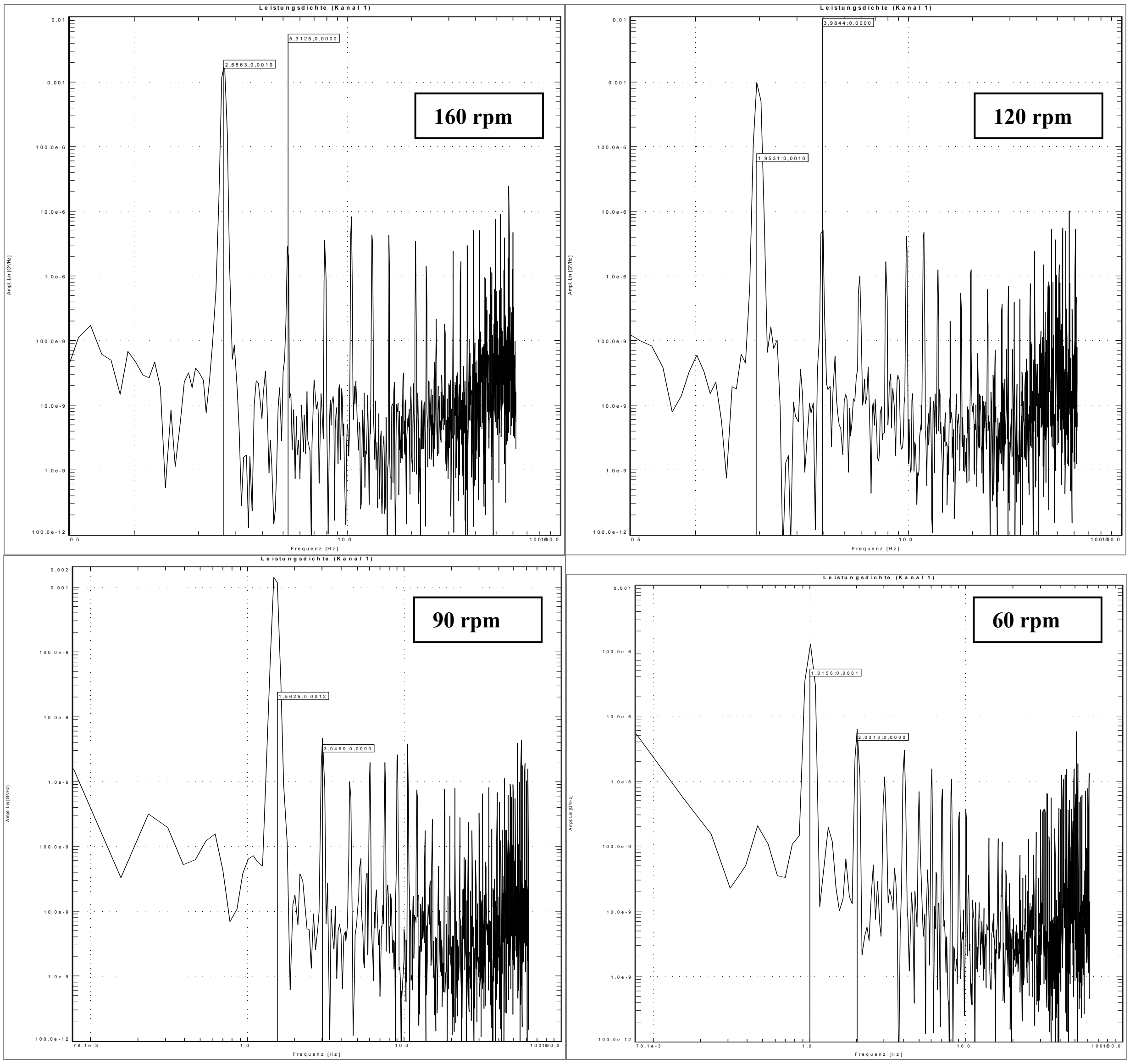

Figure 10: power spectral densities of CP 10MD at different motor revolutions

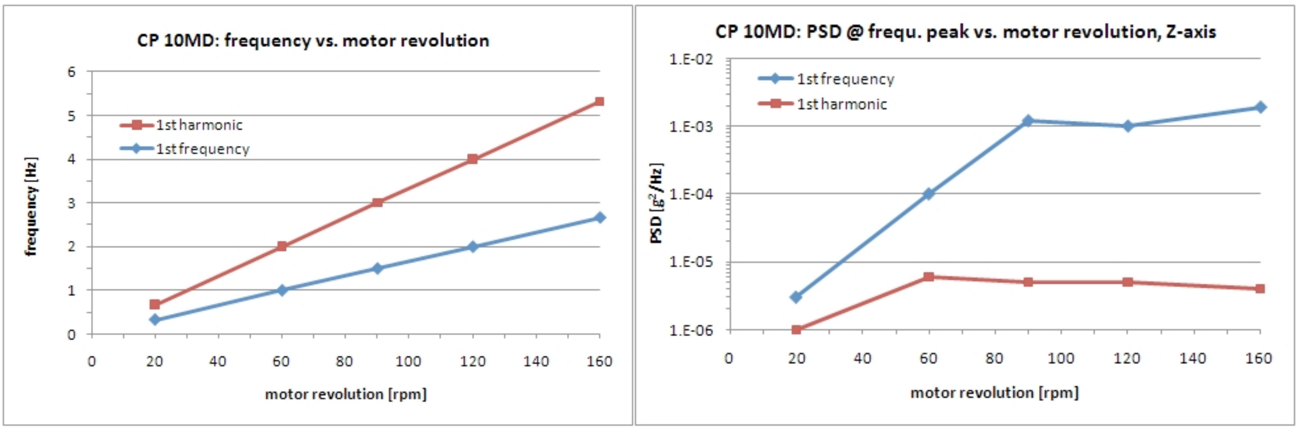

Figure 11: COOLPOWER 10MD frequency shift and vibration levels against motor revolution

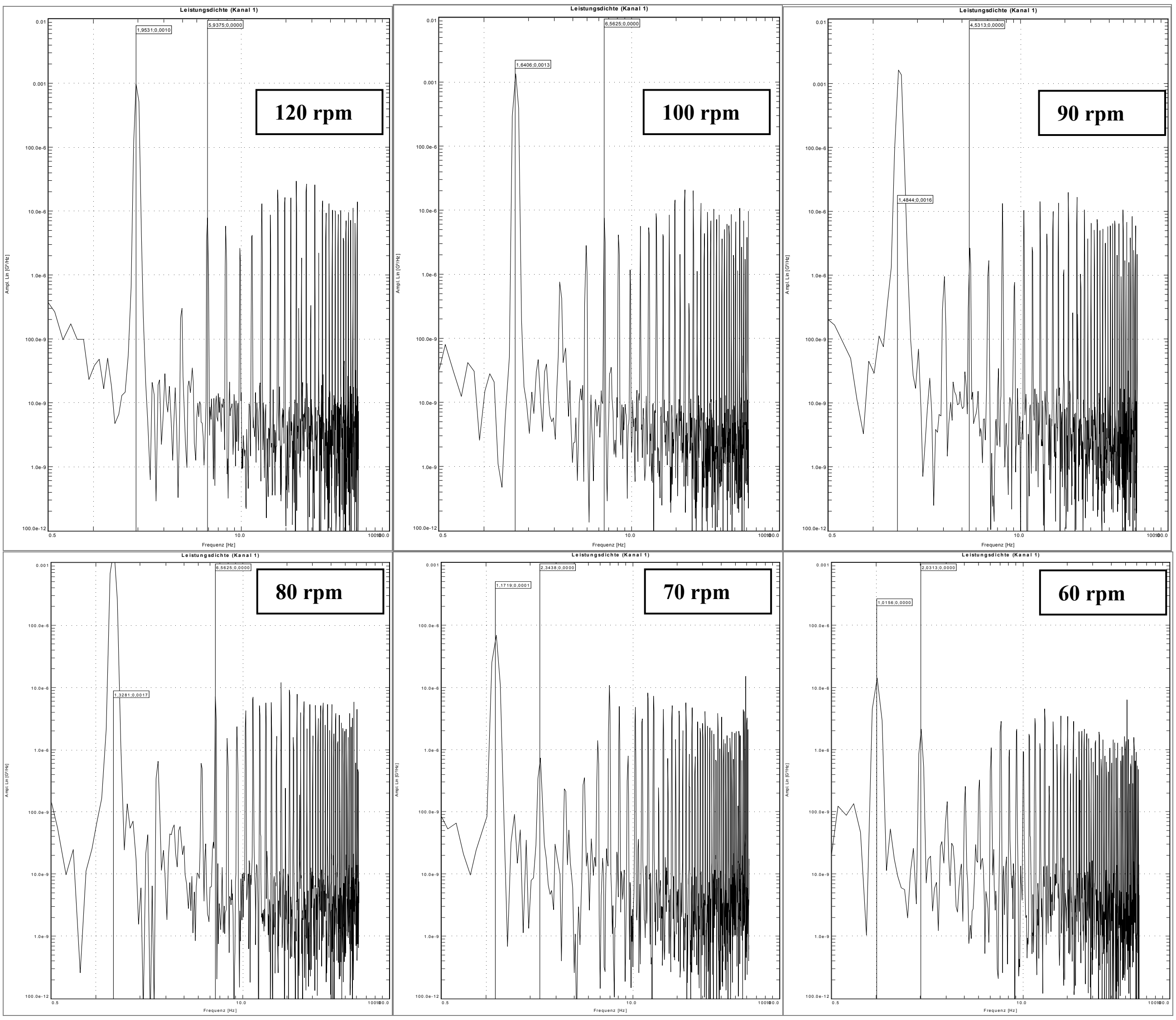

Figure 12: power spectral densities of CP 4.2K at different motor revolutions

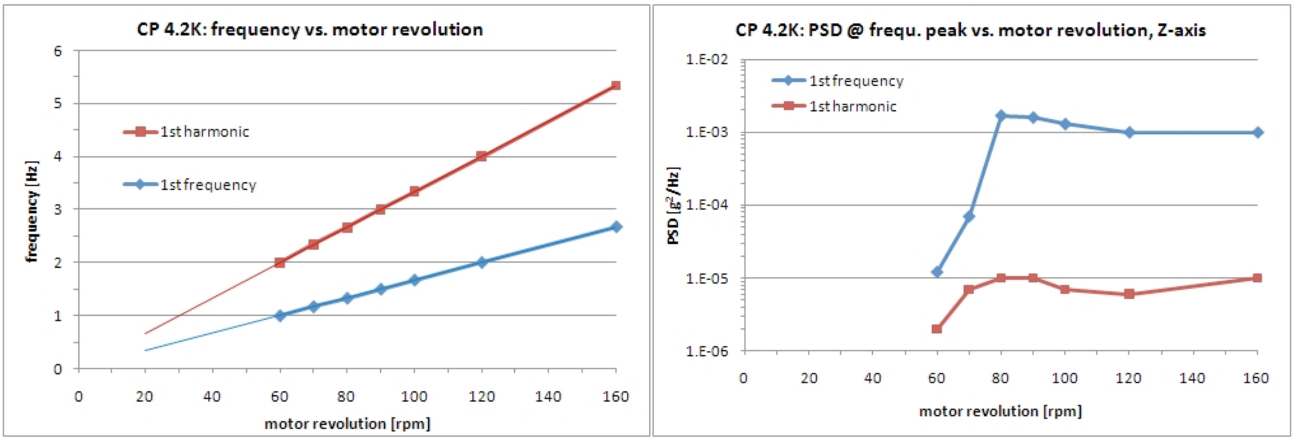

Figure 13: COOLPOWER 4.2K frequency shift and vibration levels against motor revolution

5. DISTURBANCE FORCES

For an even more appropriate comparison normalized values of disturbance forces are considered. This is obtained by multiplication of measured accelerations a in excitation direction with the oscillating mass M.

$$F = M_{asy} * a \tag{2}$$

Figure 14 and table 1 illustrate the induced forces of all investigated GM cryocoolers each in three space-coordinates.

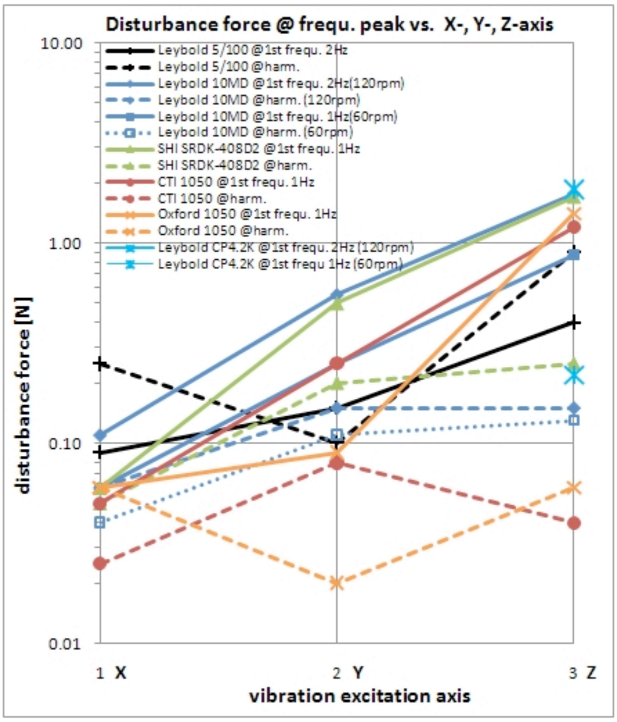

Figure 14: disturbance forces of tested GM cryocooler systems in three space-coordinates

Table 1: induced forces F of tested GM cryocoolers

Cryocooler type	Leybold CP 5/100	Leybold CP 10MD @ 60 / 120 rpm	SHI SRDK-408D2	Brooks / CTI M-1050	Oxford / Austin 1050 CS	Leybold CP4.2K @ 60 / 120 rpm
$M_{cold\ head}$ (kg)	13.0	22.6	18.2	13.0	13.5	16.8
M_{asy} (kg)	20.5	31.0	28.8	23.5	24.2	31.0
$F_{1st\ frequ.,\ X}$ (N)	0.09	0.06 / 0.11	0.06	0.06	0.05	n.a.
$F_{harmonics,\ X}$ (N)	0.25	0.04 / 0.06	0.05	0.025	0.06	n.a.
$F_{1st\ frequ.,\ Y}$ (N)	0.15	0.25 / 0.55	0.5	0.25	0.09	n.a.
$F_{harmonics,\ Y}$ (N)	0.1	0.11 / 0.15	0.25	0.08	0.02	n.a.
$F_{1st\ frequ.,\ Z}$ (N)	**0.4**	**0.87 / 1.75**	**1.7**	**1.2**	**1.4**	**0.22 / 0.1**
$F_{harmonics,\ Z}$ (N)	0.5 – 0.9	≤ 0.13 / ≤ 0.15	≤ 0.2	≤ 0.04	≤ 0.06	0.16 / 0.1
Remarks	high forces at harmonics	cooler with the biggest mass and highest cooling power	heavy 4K cold head, moderate cooling power	light weight cooler with moderate cooling power	light weight cooler with low cooling power	4K cold head with highest cooling power

The pneumatic system CP 5/100 produces relatively high forces of almost the same level at 1st frequency and harmonics, while for the mechanical systems the induced forces at the harmonics are by magnitudes lower and therefore easier to control. Main disturbance is induced in Z-axis, which is defined as the axis of the displacer movement. For the mechanical driven cooler systems the forces induced by the other two axes are suppressed by factors of 10-100.

6. INSTRUMENT VIBRATION LEVELS

As reported earlier the cryocooler vibration disturbances of VLT instrumentation can have serious influence on VLT-I operations. ESO's vibration reduction program includes another comprehensive test campaign at the VLT with the goal to be able to define admissible vibration spectra for present and future VLT instruments. A so called vibration dummy instrument (VLTDI) was designed and built which is foreseen to replace a typical 1 ton Cassegrain instrument. It is also planned to install it at different Nasmyth foci and platforms. The dummy instrument comprises six cold heads COOLPOWER 10MD mounted in different axial configurations, a cold structure with power resistors, temperature sensors, vacuum equipment and it is mounted in a supporting rack allowing rotation for assembly and mounting (figures 15-16). It will be equipped with a grid of accelerometers to monitor the instrument-sided vibration spectra. Our plan is to operate in parallel the VLT-I, the VLTDI in different foci configurations and with different cooler arrangements (different combinations of horizontal / vertical cold heads), and the VLT Manhattan system which consists of a set of accelerometers mounted on telescope mirrors M1, M2 and M3. Aim is to find optimized low vibration cooler arrangements and to get transfer functions between vibration levels generated by a multiple cold head instrument on one hand and VLT-I compatible or incompatible levels on the other hand. In a final step future cryogenic instruments should be assessed by appraising their generated vibration spectra. This will be accomplished by suspending them similarly a free oscillating pendulum and simultaneous vibration acquisition during cryocooler and instrument operation. A comparison with admissible spectra obtained with our identical suspended VLTDI should judge compliance.

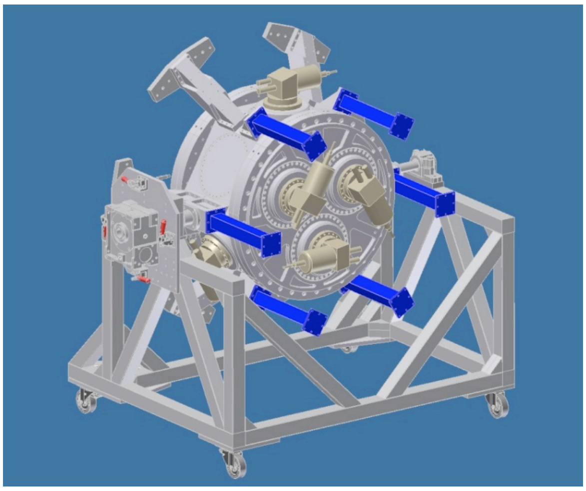

Figure 15: CAD design of vibration dummy instrument with six closed cycle cooler cold heads

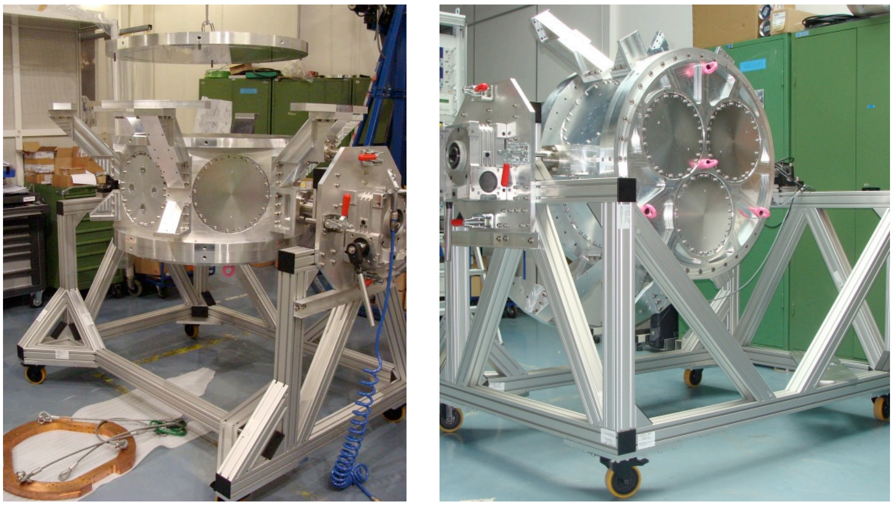

Figure 16: 1 ton vibration dummy instrument during assembly phase

7. CONCLUSION

ESO started an extensive mechanical vibration reduction campaign. As part of this program a comprehensive survey of state-of-the-art low vibration 2-stage cryocoolers was initiated. Potential candidates were selected for further characterization tests with particular emphasis on vibrations and refrigeration power capabilities. A dedicated test-bed was set up for comparative measurements on different cryocooler systems. Five alternatively Gifford-McMahon closed cycle cooler systems were tested in comparison to ESO's formerly used standard 20 K cryocooler. As a result one of the systems could be chosen as our new standard 2-stage 20 K cooler. The selected Oerlikon Leybold COOLPOWER 10MD is offering substantial advantages in flexibility (variable motor frequency) and orientation insensitivity along with best compromise for a low vibration device combined with high cooling power. As a consequence three machines of these type were integrated with the VLT high resolution infrared spectrograph CRIRES replacing its former pneumatically driven coolers with their problematic vibration spectra. A drastic reduction of mechanical vibrations could be verified [4]. The new 20 K cryocooler is also used for developing promising advanced 2-stage refrigerator systems in view of upcoming multiple cold head instruments and in terms of innovative E-ELT cooling concepts [5]. Next the new cooler is part of a presented concept comprising a comprehensive VLT vibration test program for defining admissible vibration spectra for future instrumentation.

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