Cryo design for the VLTI MIDI instrument

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ABSTRACT

The paper describes the cryogenic design of the 8-12 μm beamcombiner instrument MIDI for the VLTI. Because the instrument is very sensitive at the whole thermal wavelength region, all optics and mechanics inside the dewar have to be cooled to temperatures at 40K. The main contribution to the heat load is the radiation. We propose to use one liqiud Nitrogen cooled radiation shield and a second shield cooled by the first stage of a closed cycle cooler with a refrigeration capacity of 35W at 50K and 1.5W at 4.2K. The main problems by using a closed cycle cooler (CCC) are the vibrations which can disturb the interferometric measurements. We measured the vibrations during cooler operation and checked different vibration isolation possibilities.

Keywords: Interferometry, cryo design, closed cycle cooler

1. INTRODUCTION

The Very Large Telescope Interferometer (VLTI) uses in phase A coudé trains of two 8m-telescopes, two delay lines, two test siderostats and two auxiliary telescopes with the necessary control system. Two beam combining instruments are planned - a near infrared imaging instrument (AMBER) and the mid infrared instrument MIDI at 8-12 μm. The use of liquid Helium to achieve the requested temperature of the cold optics and the detector of MIDI at this operating wavelength is no option on Paranal.[1]

2. REQUIREMENTS AND COOLING OPTIONS

The major concern of the design of the MIDI instrument is the thermal insulation of the low-temperature parts from room temperature and the mechanical insulation of the instrument from vibrations introduced by the CCC.
Because the detector is very sensitive at the whole thermal wavelength region all optics and mechanics inside the dewar have to be cooled to temperatures at 40±5 K.
The main contribution to the heat load is the radiation. We propose to use one N_2 cooled radiation shield (77 K) and a second shield cooled by the first stage of a closed cycle cooler.
This heat load can be calculated:[2]

$$q = F\sigma A_1(T_2^4 - T_1^4)$$

with

$$F = \epsilon/2$$

$\epsilon = 0.04$
σ = Stefan-Bolzmann constant

The results for the different surfaces are:

→ First radiation shield (2 m^2, 295 K → 77 K): 17 W
→ Second radiation shield (1.4 m^2, 77 K → 40 K): 0.05 W

The heat dissipation of the detector is 0.065 W. The optical path inside the dewar should be well baffled. Then the heat load on the second radiation shield through the entrance windows is negligible.
Other contributions to the heat load are the heat conduction due to the cabling, the spacers and the motor shafts

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which we estimate at 2 W.
The main problems of cooling the cold bench (including the second radiation shield) and the detector by a closed cycle cooler (CCC) are the vibrations which can disturb the interferometric measurements.

We discussed the following options to avoid this problem:

1. The first stage of the CCC is connected to the second shield and the second stage is connected to the detector with passive vibration isolation. A vacuum bellow is the only connection between cold head and dewar. The cooler is mounted independently from the beam combining table.

2. The CCC works as a He-liquefaction system. We need a cooler with the highest available cooling power to realize this option. For an assumed heat load of 0.1 W in 12 hours we need 1.65 litre liquid Helium.

3. Use of a two-stage pulse tube cooler developed especially for sensitive experiments at the University of Giessen.[3] In contrast to the Gifford-McMahon cryocooler, a pulse tube cooler operates without moving cold parts. A disadvantage is the long development and delivery time of at least one year.

4. Use of a high power He-liquefaction system (5 litre per hour) in a closed cycle. These systems are very expensive (starting at 300 k$) and more service is necessary.

Option 1 gave very promising results which we will discuss later in this paper.
Figure 1 shows the cryo-system design for the MIDI instrument. The drawing gives an overview especially of the proposed equipment for the vacuum pumping and the liquid N_2 (LN2) cooling.

3. FIRST VIBRATION TESTS WITH THE SUMITOMO CLOSED CYCLE COOLER

We described in chapter 1.1. that the main problem of using a CCC are the vibrations introduced by the moving parts of the cooler. The maximal allowed path length variation due to vibration is defined to be less than 100 nm.
Therefore we bought a cooler to start early with the first tests[4] on the vibration properties and the resulting design options for mounting the CCC. To have the option to use this cooler as a He-liquefaction system, high cooling power was necessary. The SRDK-415D from Sumitomo Heavy Industries was selected as the best choice for our purpose. Figure 2 shows the CCC with the first and the second stage and connected helium lines. This cooler has a refrigeration capacity of 35 W at 50 K and 1.5 W at 4.2 K.
Figure 3 shows the test setup in our lab. The CCC is mounted on the right table, the vacuum pipe on the left table. The only connection between the two parts is the vacuum bellow. In the foreground we see the Laser interferometer ZLM 500 from Jenaer Messtechnik. We used a radial and an axial measuring setup. Axial setup means in the direction of the displacer movement of the CCC. The figure shows the radial measuring setup. Both tables are placed directly on the floor; if the tables are mounted on long legs, the vibrations are higher. Therefore we propose to use for the final experiment a table with large thickness ($\geq$610 mm) mounted only on short adjustment spacers.
We tested three different vacuum bellows in our experimental setup. The bellow from Witzenmann (figure 4) gave the best results. We achieved vibration amplitudes at the vacuum tank of max. 87 nm p-v in axial direction and max. 48 nm p-v in radial direction. Figure 5 shows the power spectrum measured in axial and radial direction. Please note, that this is the vibration of the outside tank and not the movement of the cold bench with the cold optics. The cold bench is connected to the outside with spacers and to the CCC with copper braids. We expect smaller values for the vibration of the cold bench.

4. MIDI TEST DEWAR

4.1. Necessity for a Test Dewar

Before we build some important parts of the MIDI instrument it is necessary to do some tests to get experience of their properties at working conditions.
The following items we want to check with our test dewar:

- Vibrations due to connection between CCC and outside tank
- Vibrations due to copper braid connection between first stage of CCC and cold bench

- Vibrations due to copper braid connection between second stage of CCC and detector
- Stiffness of spacers
- Test of feedtroughs
- Minimum temperature of different positions on the cold bench
- Cooling down time

4.2. Principle Set Up of the Dewar

The test dewar is round in shape with a flat flange at the top and the bottom. Figure 6 shows a drawing and Figure 7 the real dewar in the lab. Several KF flanges (12) are at the sides and in addition there is a flange for the CCC and the turbo molecular pump (TMP). At the top flange are two LN2 feedthroughs (7). Inside there are three temperature stages. The warmest is a large LN2 reservoir (8) with an attached Aluminium shield. The shield with the reservoir is supported by three thermally isolated spacers. The two neck tubes to the feedthroughs are made with bellows to compensate thermal shrinking. The next temperature stage is an Aluminium plate (6) at about 40 K which is cooled by the first stage of the CCC. The aluminium plate has a grid of tapped holes with M 4 thread. The plate has a covering shield of polished aluminium (9). The plate rests on three isolating spacers. Inside the 40 K space is a little block of Aluminium with a heating and temperature sensor. The block is supported by isolating spacers and cooled by the second stage of the CCC (5) to a temperature of about 5-8 K. A heat switch can connect the LN2 shield with the 40 K shield for faster cooling down.

4.3. Connection of the Closed Cycle Cooler

The CCC rests on a heavy separate table (14) with a rigid mount (1). The vacuum connection is made by a flexible edge welded bellow (2). The thermal contact at the first stage is made by some flexible copper braids (11) to a bracket which is directly connected to the 40 K plate. The second stage is connected by a single copper braid to the 5 K Aluminium block.
Figure 8 shows the open test dewar.

5. MIDI FINAL DEWAR

5.1. Principle Set Up

The final dewar will be made in a cubic shape which has several advantages compared to a round dewar. The side where the entrance window is will be free from other flanges, connectors and feedthroughs. This side is here defined as the front side. On each side, right and left, there will be four rotary drives with encoders for the movement of the optomechanics on the cold bench. On the back there will be the mounting flange of the closed cycle cooler (CCC) and the vacuum flange for the turbo molecular pump (TMP). Inside the dewar we have three different temperature stages. The warmest stage is a shield at 77 K, cooled by LN2. The next stage is the cold bench with a surrounding shield at 40 K, cooled by the 1st stage of the CCC. The coldest part is the detector at 5-8 K, cooled by the 2nd stage of the CCC (figure 9).

5.2. Vacuum Can

The cubic vacuum can is made out of stainless steel sheets, welded at the edges. For good access to the cold bench the cube can be dismounted by O-ring sealed flanges, one at the bottom and one at approximately half the height of the vacuum can. So we will have a vacuum can mainly consisting of 3 parts, the base plate, the lower part and the upper part or cover. All feedthroughs and connection flanges except the LN2 feedthroughs will be placed at the lower part. There will be eight flanges for the rotary feedthroughs which will be O-ring sealed, four on each side. Another two flanges will be placed on the left hand side looking in direction of the beam. There will be the electrical feedtroughs for the detector signals. On the right hand side there will be a flange plate with several electrical feedthroughs for sensors, heaters and switches. On the front there is an O-ring sealed plate which can be removed for direct access to the detector unit. There are corresponding covered holes in the shields as well.

5.3. Liquid Nitrogen Shield

The first shield will be cooled by LN2 which is placed in a cubic reservoir above the cold bench. The volume of the reservoir will be about 35 litres. Three feedthroughs will go through the top plate of the vacuum can, one for filling, one for exhaust gas and a safety valve and one for a level sensor. The three connection tubes to the feedthroughs have bellows to compensate stress due to the thermal contraction. The shield below the LN2 reservoir can be dismounted similarly to the vacuum can into three parts, the base plate, the lower shield and the upper shield, which is permanently connected with the LN2 reservoir. All shields and the reservoir are made out of polished Aluminium. The complete LN2 shield is supported from the base plate which is fixed by thermally isolated spacers to the base plate of the vacuum can. There will be a heater of about 200 W at the LN2 reservoir for warming up the system and for the heating of the getter material .

5.4. Coldbench

The cold bench is cooled by the CCC. The thermal contact is made by copper braids which connect the base plate of the coldbench with the first stage of the CCC. The cold bench is covered by a shield of polished Aluminium. The shield can be separated into two parts, like the LN2 shield. The base plate is connected by thermally isolating spacers on the baseplate of the LN2 shield and supports the complete optical set up. The spacers have a thermal connection to the base plate of the LN2 shield.

5.5. Detector

The detector is cooled to about 5-8 K by the 2nd stage of the CCC but the optimum temperature has to be found out. The thermal contact is made by a copper braid. The detector is supported by thermally isolating spacers placed on a 40 K linear stage on the coldbench. The detector has a heater and temperature sensor for temperature control and warming up.

5.6. Feedthroughs for Axes

The axes go through the wall of the vacuum can and the two radiation shields. The vacuum feedthroughs will be from Ferrofluidics, flanged and O-ring sealed to the vacuum can. The feedthroughs at the shields will use ball bearings for easy rotation. The axis will be thermally anchored to the shield by a number of little sapphire balls. The light baffling will be done by a labyrinth. The coupling of the different bearings will be done by bellows which can compensate radial and axial misalignment due to thermal shrinking.

5.7. Feedthrough and Connection for Closed Cycle Cooler

The CCC will go into the vacuum can and through the two radiation shields. The connection to the vacuum can is made by a flexible edge welded bellow. At both shields there will be light tight optical labyrinths. The first stage will be connected with a copper tube which reaches to a place above the cold bench. Here a number of copper straps will be connected and lead to the connector bracket which is mounted on the cold bench. The second stage will be connected by a single copper strap to the cooling bracket at the back of the detector.

5.8. Heat Switch

There will be a mechanical heat switch to thermally connect the cold bench and the LN2 shield. The switch will be actuated by a hand driven rotating axis. The place of the switch will be in the gap between the two base plates. The heat switch is only closed for initial cooling down and optionally for warming up. The switch is open during normal operation.

5.9. Molecular Sleeve

There will be a package of getter material placed under the bottom of the LN2 reservoir.

5.10. Vacuum

At the back there will be a flange DN 160 CF for the vacuum pump. At the tube of this flange there will be 3 KF flanges in radial direction. Two are used for the vacuum measurement with two vacuum gauges and one is used for a solenoid valve for venting the complete vacuum system. Between the vacuum chamber and the turbomolecular pump there will be a high vacuum gate valve with flange DN 160 CF.

6. MOUNTING OF DEWAR AND CLOSED CYCLE COOLER

The CCC will be mounted on a heavy separate table with a very rigid mount. The table does not have any direct contact to the optical table with the dewar. The vacuum connection is made by a flexible edge welded bellow of stainless steel. The thermal contact at the first stage is made by flexible copper braids and an extension tube of copper. A bracket is mounted to the cold bench. All the copper braids are mounted on this bracket. The second stage of the CCC has a single copper braid which is mounted on the cooling bracket at the back of the detector. All flexible parts are so dimensioned that they could be installed without stress to give a maximum of flexibility.
The MIDI dewar is mounted on a 5-axes adjustment platform with 10 mm range for the translation axes and 0.5^o range for the rotation axes. Figure 10 shows the principle setup already built for the motor-driven adjustment of a 200 kg infrared camera. We also want to use this principle for MIDI.
The lever system (three at 120 degrees) is responsible for the rotation round the x- and z-axis and the translation along the y-axis. A big ball-bearing makes the rotation round the y-axis possible. An additionally needed translation stage (perpendicular to the input beams) is not shown in this figure. A translation parallel to the input beams is not necessary.

7. CONCLUSION

Cooling an interferometric instrument with a closed cycle cooler is not an easy task because the vibrations can destroy the scientific signal, but MIDI has the advantage that it does not move with the telescope. Therefore the only connection between CCC and dewar is the vacuum bellow. Mounting of the CCC directly on the outside housing is not necessary.
The experiments with the test dewar are underway and the final dewar is now in the design phase and can thus be altered based on the test results.

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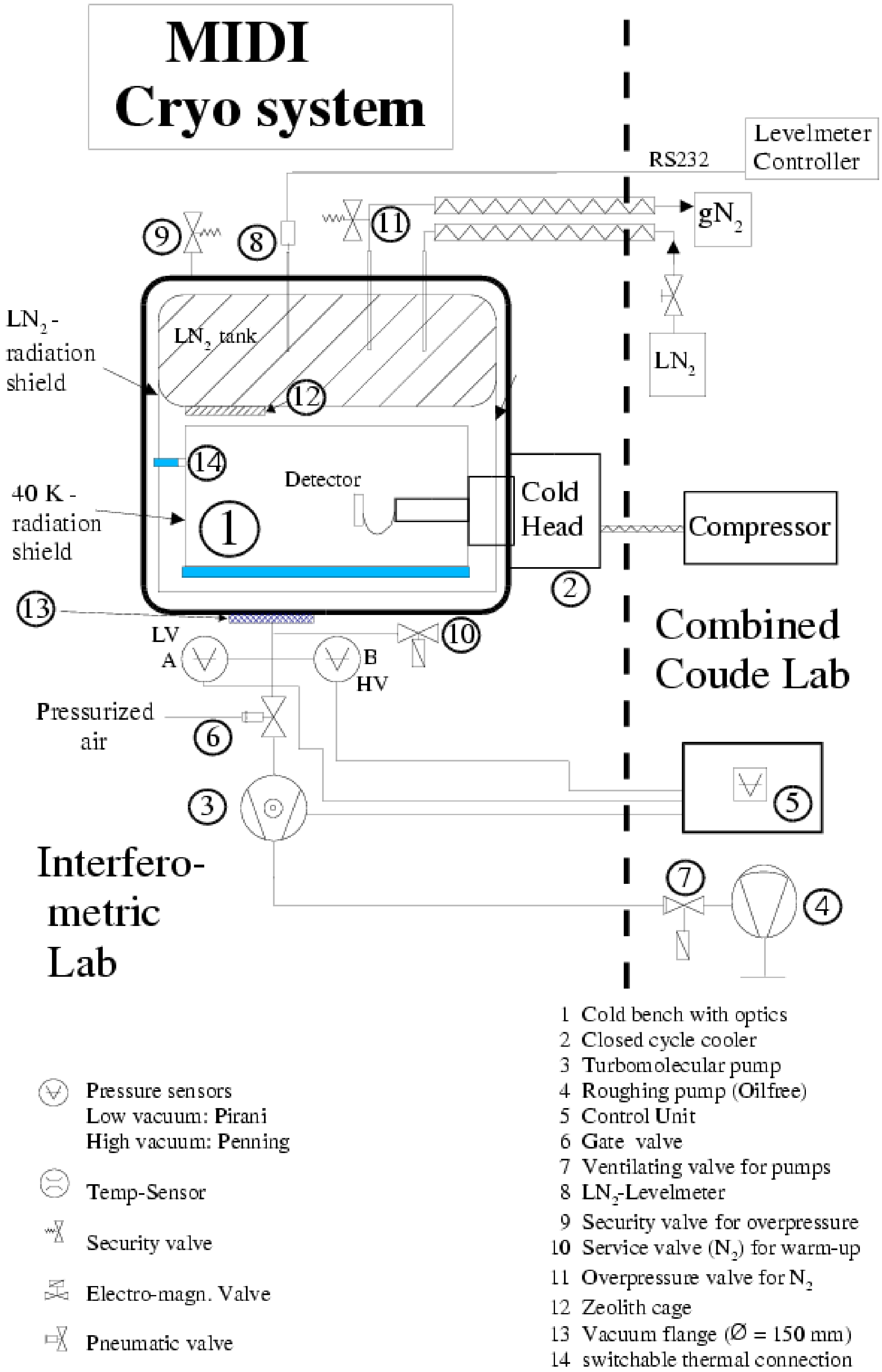

Figure 1. *MIDI cryo-system*

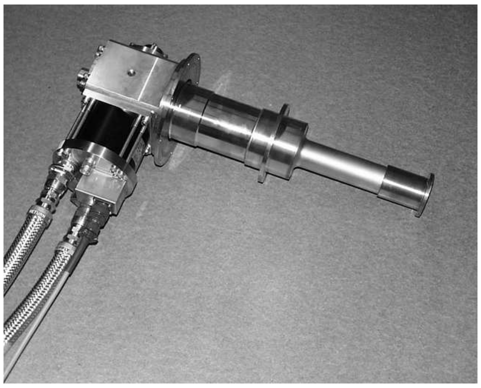

Figure 2. *Closed cycle cooler SRDK-415D with first and second stage*

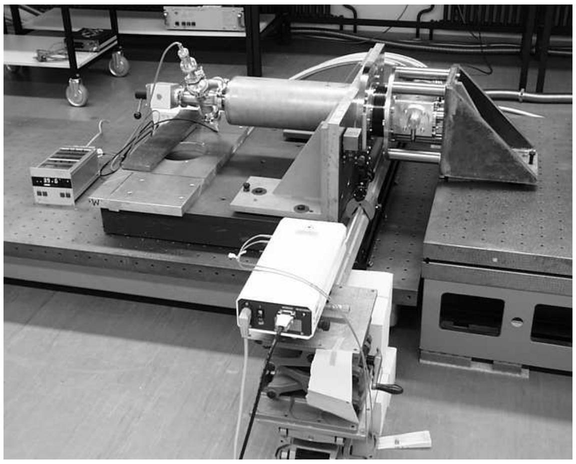

Figure 3. *Experimental setup in lab at MPIA*

Figure 4. *Vaccum bellow as the only connection between CCC and vacuum tank*

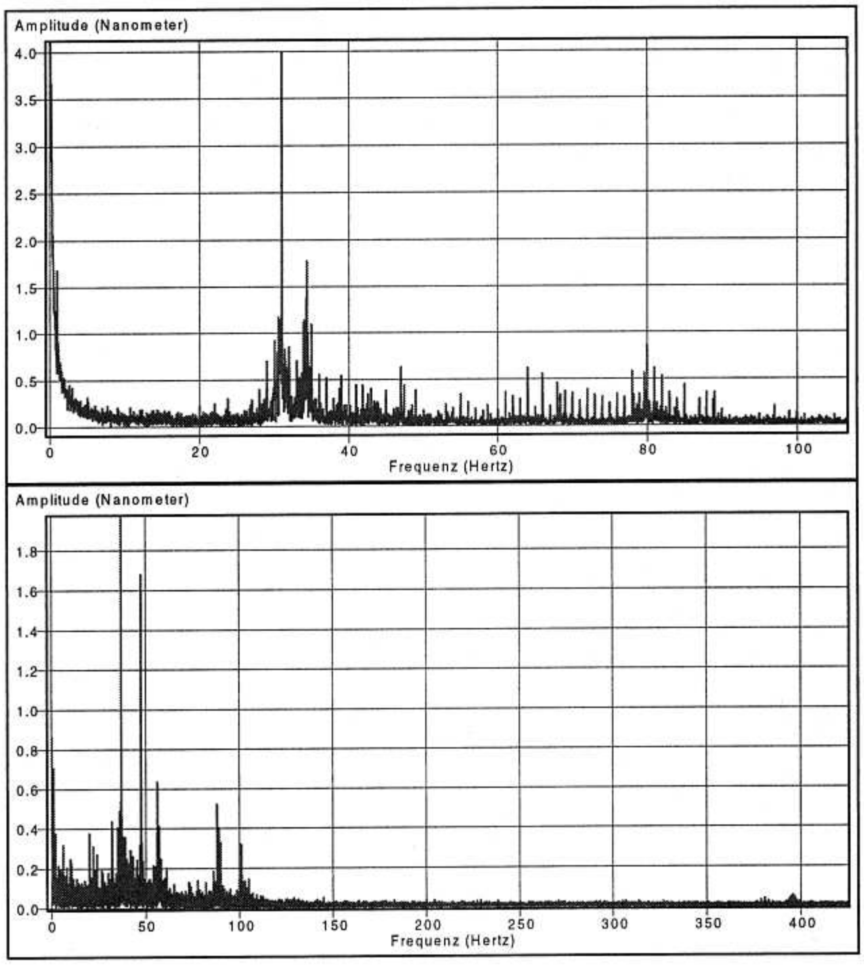

Figure 5. *Power spectrum in axial (top) and in radial (bottom) direction*

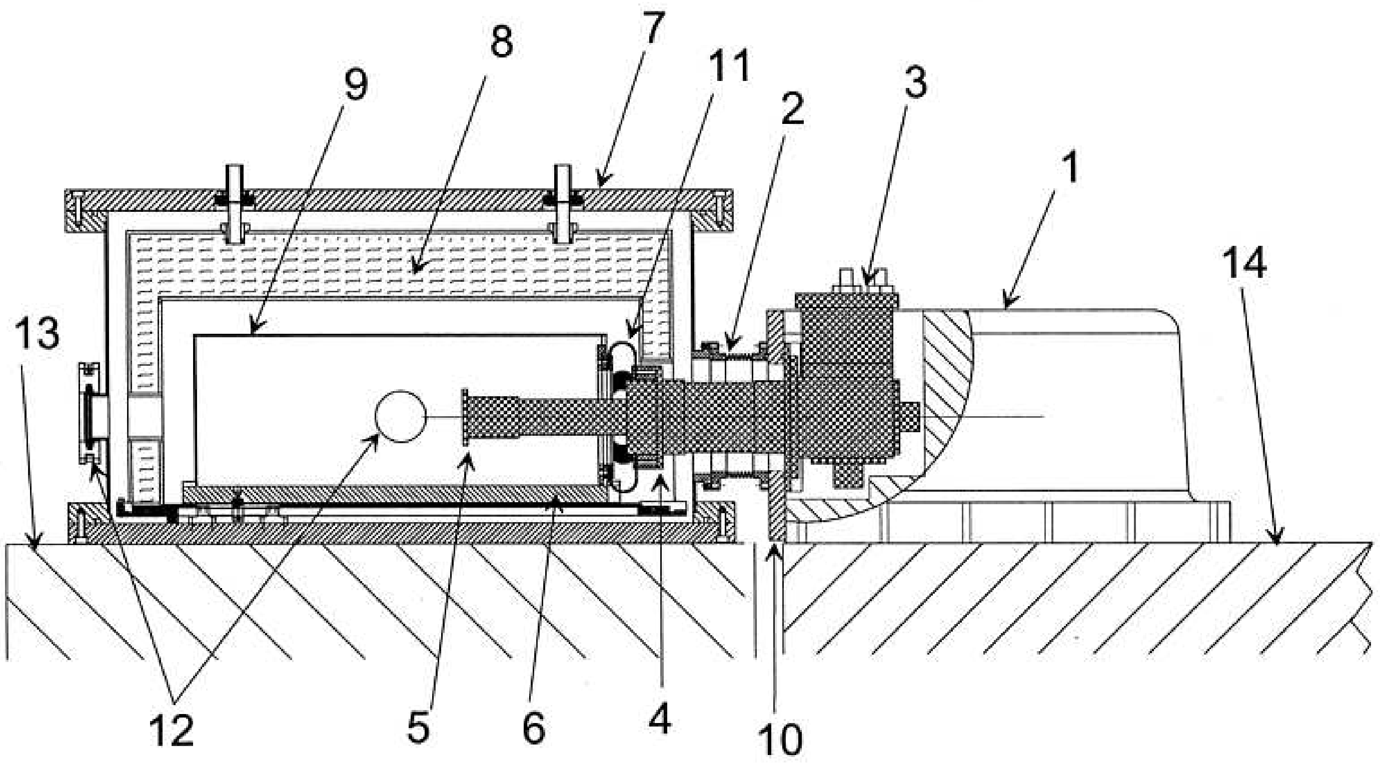

Figure 6. *MIDI test dewar*

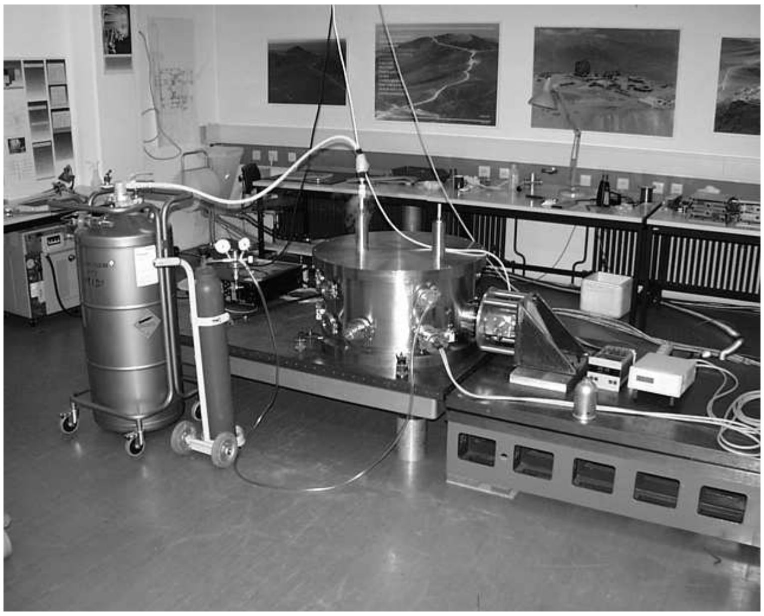

Figure 7. *MIDI test dewar in the lab*

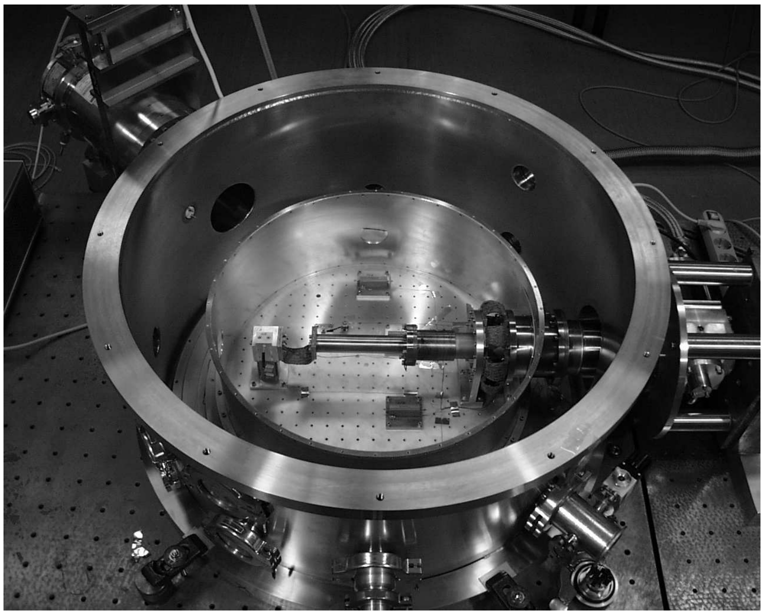

Figure 8. *MIDI test dewar open*

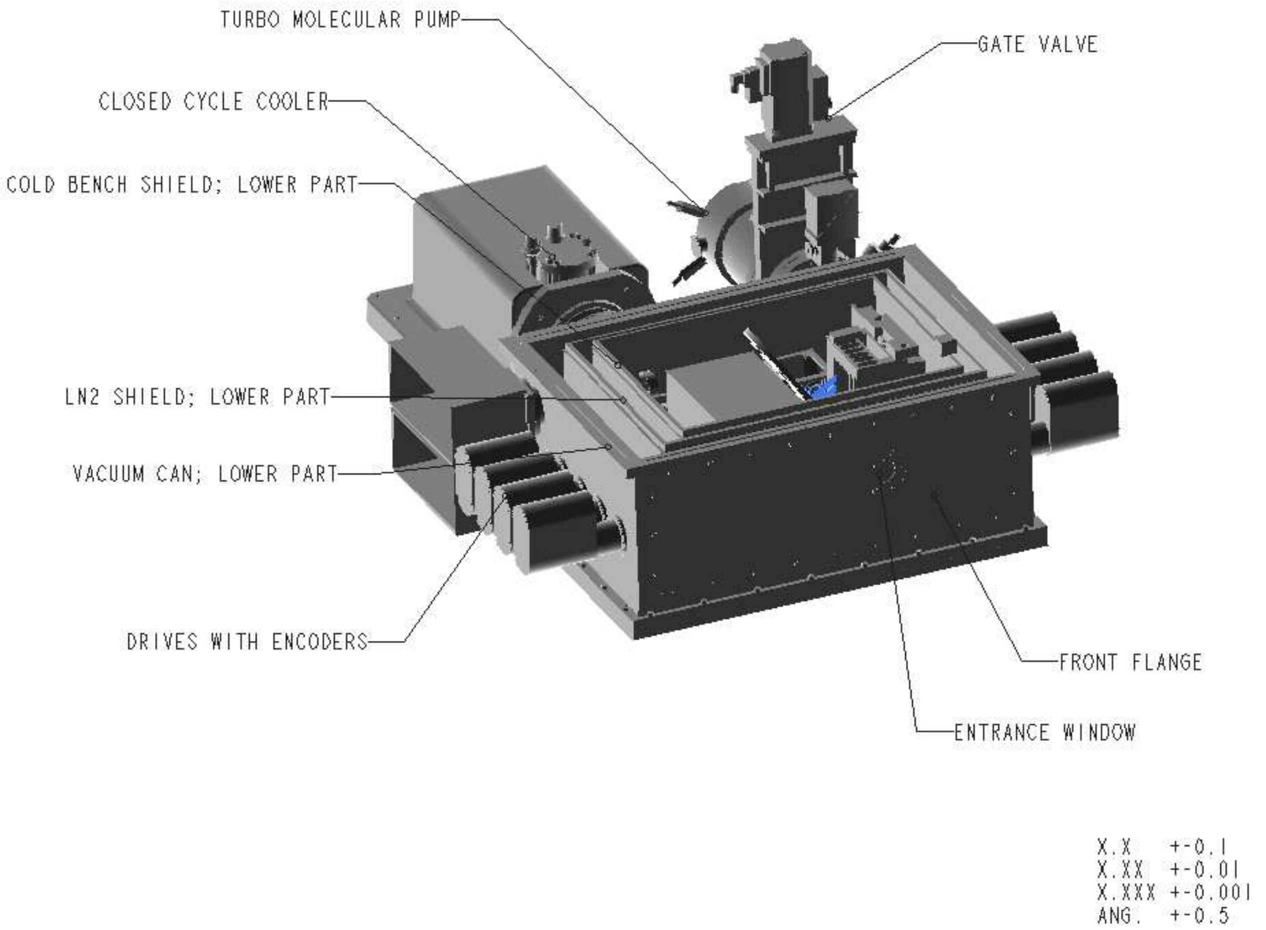

Figure 9. *MIDI final dewar - outer dimensions are 850x598x804mm*

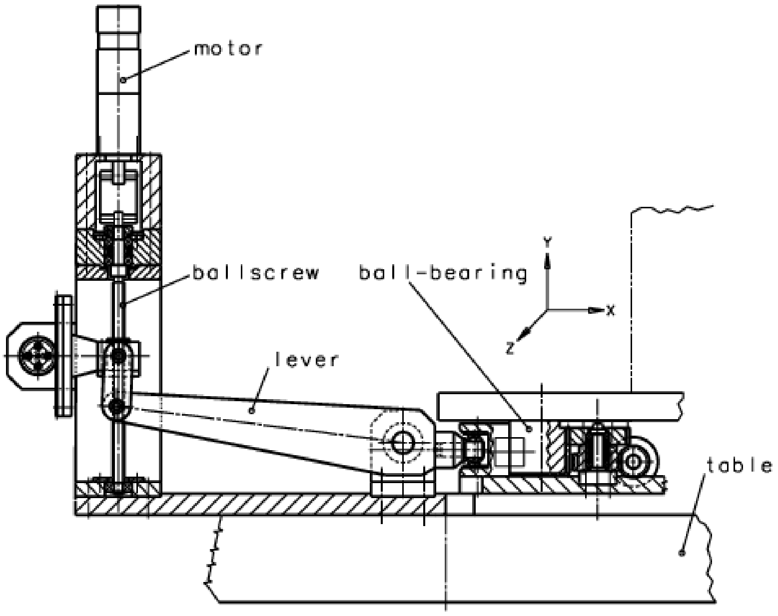

Figure 10. *Principle of MIDI dewar adjustment*