Cooling of ground based telescope instrumentation, the LINC-NIRVANA cryostat

W. Laun[*], H. Baumeister, P. Bizenberger
Max Planck Institut fuer Astronomie, Koenigstuhl 17, 69117 Heidelberg, Germany

ABSTRACT

The MPIA in Heidelberg has built many instruments for IR observation over the years. While the previous instruments were moderate in size and could easily be enclosed in a liquid nitrogen (LN_2) dewar, future instruments will require different cooling concepts. The use of Gifford McMahon coolers was chosen for some instruments, but has the disadvantage of low frequency vibrations. The recently-developed pulse tube coolers have lower vibrations but other disadvantages. For the LINC-NIRVANA cryostat, we plan to build a cooling system with a constant flow of Helium through a heat exchanger inside the cryostat. This cooling concept could also be expanded to future instrumentation for the next generation of telescopes.

Keywords: IR instrumentation, cryogenics, GM cooler, PT cooler, closed loop cooling

1. INTRODUCTION

The cryostat remains an essential component of IR instruments. Different cooling systems are used and the choice is not always obvious. In the concept phase of an instrument, the cryogenic engineer has to establish the requirements of the cryostat. In most cases, there will not be a detailed specification with accurate values at the beginning of a project. These requirements include:

- The size of the instrument
- The mechanical stability
- The required temperature and stability
- The maximum local temperature
- The window size
- The number and cross section of the cabling from electrical feed-throughs
- The mechanical feed-throughs
- Internal heat dissipation by motors or electronics

Many values cited during the concept phase will change, so one must be careful not to choose a cooling concept which is already operating close to its limit.

2. COOLING WITH PELTIER ELEMENTS [1]

If only moderate cooling is required, i.e. for a CCD at –80°C Peltier cooling could be used. Some manufacturers provide CCD’s already packaged with cooling. The advantages of Peltier cooling include: small size, minimum operational support, easy temperature control. The limitations can also easily be seen: low cooling power, limited temperature range.

3. COOLING WITH DIFFERENT LIQUID CRYOGENS

The use of liquefied gases is a very common method of cooling. Depending on the required temperature, different gases can be used but mainly only nitrogen and for temperatures below 10 K helium are used. The application is restricted by various factors including availability, price, operational support and safety. Liquid hydrogen would be an ideal coolant for some applications but it is very reactive and therefore much too dangerous for frequent use at the telescope.

---

[*] laun@mpia.de

	Normal boiling point in K	Heat of vaporization in kJ/kg	Temp. at triple point in K	Cooling power of 1 ltr/h in W	Consumption of liquid from 1 W in ltr/h
Helium	4.224	20.73	-	0.72	1.4
Neon	27.09	86.6	24.56	29.0	0.035
Argon	87.28	161.6	83.8	63.0	0.016
Hydrogen	20.268	445.6	13.803	8.8	0.11
Nitrogen	77.347	198.3	63.148	44.6	0.022
Oxygen	90.18	212.9	54.35	67.5	0.015
Air	78.9	205.1	60	49.8	0.02

Table 1: Thermal properties of some liquefied gases[2]

3.1. Liquid nitrogen (LN_2)

The most convenient coolant is LN_2 because it is easy to handle, non toxic, inert and inexpensive. Cooling with LN_2 is very common in industry and research, and it is the standard liquid cryogen in astronomy. LN_2 is about as dangerous and difficult to handle as boiling water. As a rule of thumb, one liter per hour LN_2 will provide 45 W of cooling power at 77 K. The boiling temperature at 1013 mbar is 77.35 K, sufficiently low for the wavelength range of most IR instruments. The boiling temperature could be dropped down to about 64 K by reducing the pressure inside the vessel (i.e. pumping). At lower temperatures the Nitrogen freezes, raising difficulties with the thermal contact to the vessel and for refilling.

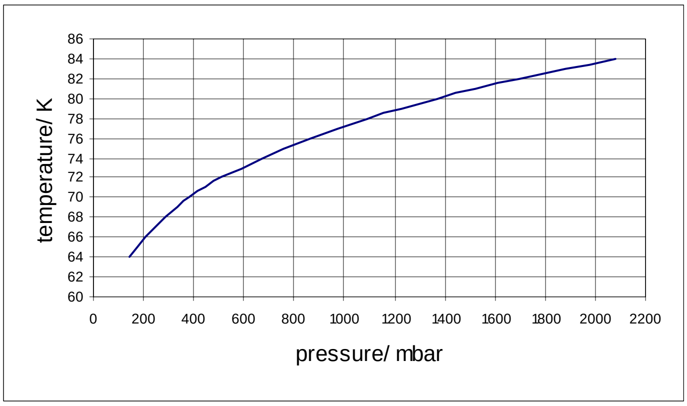

Fig. 1. Boiling point of LN2 depending on the pressure[3]

Advantages of LN_2
- High amount of stored cooling power
- Constant temperature
- Fast cooling down
- Easy handling
- Available at most telescopes

Disadvantages of LN_2
- Limited temperature range
- For high accuracy temperature stability additional control is needed
- Additional volume for the tanks needed
- Frequent refilling
- Changing weight of the instrument when full and empty
- Vibrations from boiling
- Venting of the cold boil off gas at the telescope
- Ice building

Example for a large LN_2 cryostat

Scaling up the traditional bucket-sized LN_2 cryostat resulted in the largest LN_2 cryostat ever made for the MPIA, the cryostat of **OMEGA2000**[4]. This instrument is a prime focus camera at the Calar Alto 3.5 m telescope in Spain. The size of the vacuum can is about 1.65 m long and 0.56 m in diameter. The liquid nitrogen is stored in two vessels that can be filled from the rear side of the cryostat. One of the nitrogen tanks is directly connected to the inner radiation shield, the optics, and the detector. The second tank is connected to a second, outer shield which completely encloses the inner tank and shield. This arrangement reduces the temperature gradient on the inner shield and the temperature variation due to movement and changing outside temperatures. Because of the large surface area, radiation is the major contribution to the heat input. We added a third baffle cooled by the exhaust gas at the fill necks, which takes away almost half of the radiation. The size and holding time of the cryostat appears in Table 2: Main dimensions of the Omega 2000 cryostat.

	Diameter	Height	Volume	Used volume	Holding time
LN_2 inner tank	488 mm	260 mm	48.6 l	24.3 l	34 h
LN_2 outer tank	511 mm	355 mm	72.8 l	36.4 l	50 h

Table 2: Main dimensions of the Omega 2000 cryostat

The overall LN_2 consumption of OMEGA2000 is about 34 liters a day. About a third of the inner volume is used for storage of nitrogen. The cryostat must be refilled every day.

3.2. Helium

In some cases helium is used to reach temperatures below 10 K but handling is difficult and the price is high (up to $100 per liter at observatory sites). If helium must be used the heat input should be reduced as much as possible. The most common method is to place the helium environment inside a nitrogen cooled environment. Alternatively, one can construct system, where the shielding is cooled by a Gifford McMahon cooler. This scheme is used in NMR (nuclear magnetic resonance imaging) superconducting magnets. This cooling system is used in the **MAX camera**[5].

Other cryogenic liquids are rarely used in ground based instrumentation. Some satellite instrumentation use alternate cryogens[1].

4. COOLING WITH GIFFORD MCMAHON COOLERS [6]

Different types of Gifford McMahon (GM) coolers are available, from high power at 100 K (up to 300 W) to about 1 W at 4 K. Depending on the application, one can use powerful single stage coolers in the 77 K range or 2 stage coolers which provide high power in the 77 K range for shielding, and low power at lower temperatures. With the development of 4 K coolers, the use of helium is no longer really necessary, except (a) if very low vibration at 10 K or less is required or (b) for temperatures below 2 K. With the growing size of instruments, the use of GM coolers has become more and more common. For larger size instruments, more than one cooler may be necessary. A conceptual design has to answer at least two major questions:

- How does one connect the cooler with the cold structure, and what is the resulting temperature distribution?

Experience shows that the temperature difference inside the structure and due to the thermal connection is very often underestimated. Depending on the power flow, the connection from the cooler to the structure can itself cause a gradient of more than 10 K. Finite element calculations are necessary but may be quite uncertain.

- How does one damp the vibrations of the cooler?

Sensitive optical instruments can suffer from the low frequency vibrations introduced by coolers. Damping with lage masses or flexible mounting in a passive damping structure are used. Active damping would be the next step, if other strategies do not suffice. In the case of LINC-NIRVANA, the vibrations were the main reason why we decided not to use GM coolers.

Advantages of cooling with GM coolers

- Wide range of temperatures
- No refilling
- No change in weight due to filling level

Disadvantages of cooling with GM coolers

- Low frequency vibrations
- Flexlines and compressor needed
- Very local cooling on the cold structure with a resulting temperature gradient
- For the 4 K machine changing cooling power with orientation
- Low cooling power for initial cooling, so additional cooling power for cooling down is needed
- Annual service of the cold head
- Significant power and cooling water requirement (about 5 kW/ compressor)

Example for typical instrument with GM cooler
The MPIA has built several instruments with GM coolers. **CONICA**[7] is cooled by a two stage Leybold RGD 580 cooler. The first stage is used to cool the camera structure to about 80 K. The second stage of the cooler keeps the detector at a temperature of about 25 K. Initial calculations predicted that no additional shielding would be needed to reduce the heat radiation on the cold structure. Nevertheless, the emissivity was higher than expected and it was necessary to add a passive radiation shield to reduce heat input. This resulted in a lower thermal gradient over the shield and the required temperature could be reached.

5. COOLING WITH PULSE TUBE COOLERS [2]

Several years ago the MPIA began examining pulse tube (PT) coolers to use in the MIDI[8] interferometer. Unfortunately, at that time, PT coolers were not commercially available. Nowadays, several companies provide different types of PT coolers, most of them very small and with low cooling power. As with the GM coolers, single stage and two stage coolers are available.

Advantage of PT coolers compared with GM coolers

- Low vibrations
- Easy service

Disadvantage of PT coolers compared with GM coolers

- Strong orientation dependence of the cooling power
- Lower cooling power, approximately half that of GM coolers

Test with PT coolers

a) Orientation dependence of the cooling power

For the LINC-NIRVANA cryostat, we tested the performance of the PT60 single stage cooler from Cryomech. The nominal cooling power is about 60 W at 77 K. By using two cooling heads, we power would be sufficient to reach LN_2 temperature. Unfortunately, current PT coolers are very orientation dependent. The optimum cooling is only in the vertical position with the cold surface pointing down. Even in this orientation, the nominal cooling power could not be reached. Additional heat input from radiation and the reduced power by using 50 Hz mains power is the reason.

The LINC-NIRVANA cryostat only moves from horizontal to the vertical orientation. It does not rotate. An early concept was to mount the cooler with a tilt of 45° to have it moving in a range of ±45°. We therefore needed to know the cooling power as a function of orientation in the range of 0 to 45°. The result is shown in Fig. 2. A tilt of 40° already drops the cooling power significantly. To have a constant temperature in all orientations, we must add a heater to compensate when the cooler is vertical. This reduces the cooling power more than 30%. The concept with two coolers at a certain angle to each other also did not provide enough cooling power over the entire range of movement. Finally, we did not find a practical solution to cool the LINC-NIRVANA cryostat with PT coolers.

b) Vibrations of the cooler[9]

The main advantage of a PT-cooler over a GM-cooler is low vibrations. We performed some tests with the PT60 cooler. The movement of the cold surface was measured with an interferometer from Jenaer Messtechnik. A mirror was mounted on the cold surface. The cold surface moves about 3 – 4 µm in the axial direction due to the pressure change inside the tube.

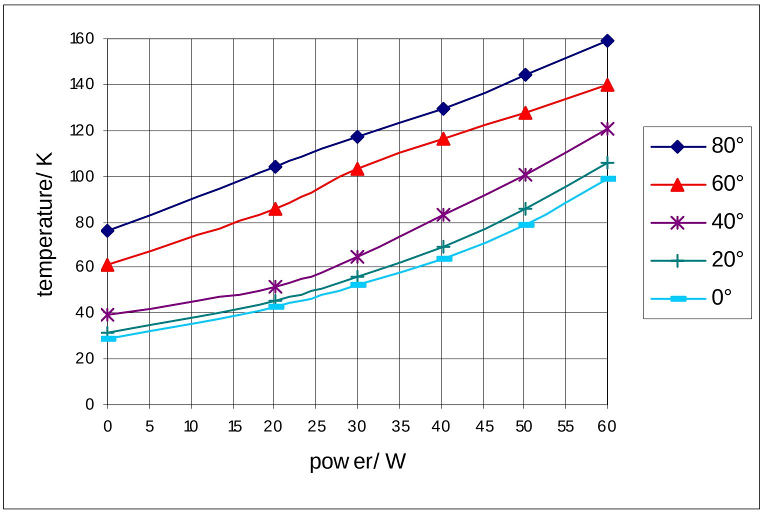

Fig. 2: Cooling power of a PT60 cooler depending on the angle of tilt

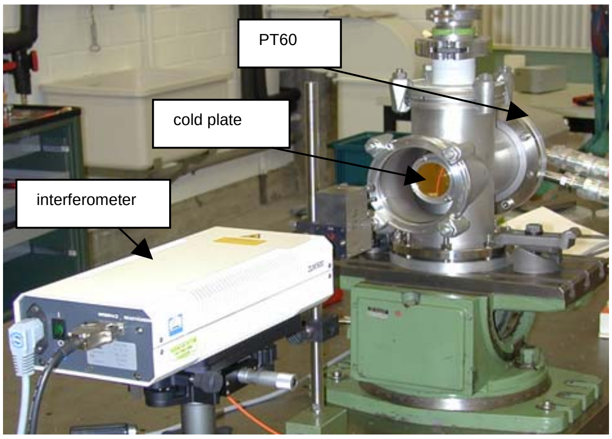

Fig. 3:Lab set up with mirror on the cold surface of the cooler

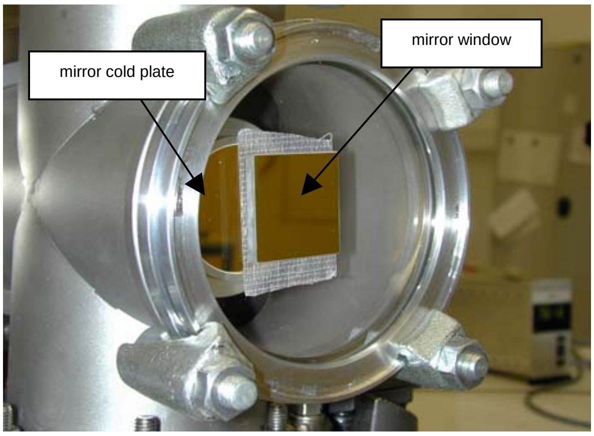

Fig. 4: Mirror on the vacuum window

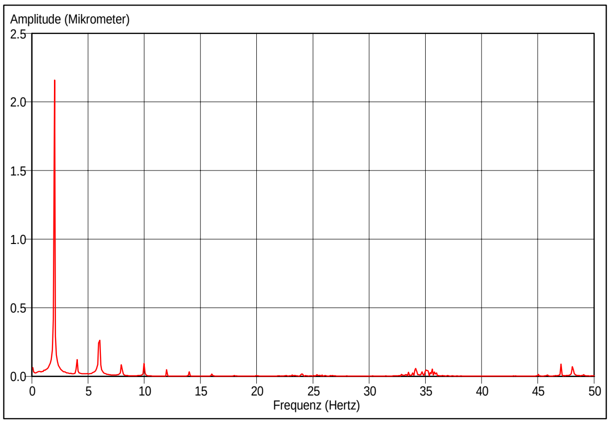

Fig. 5: Vibrations measured on the cold surface

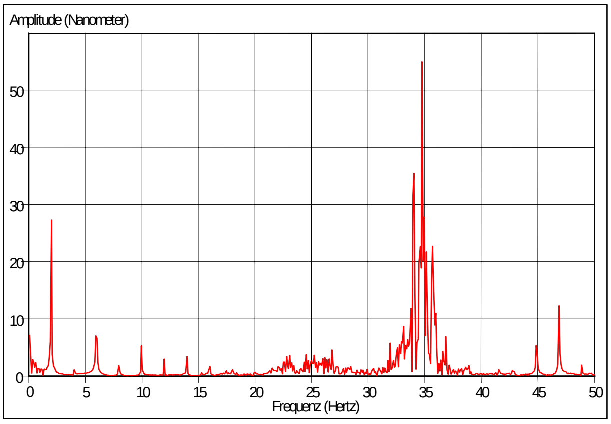

Fig. 6: Vibrations measured on the vacuum window

The amplitude of the vibrations on the cold surface dropped below 30 nm on the vacuum window without any damping. The background vibrations of the building were much higher than the cold head vibrations.

The PT cooler is clearly a good choice for a fixed instrument which is sensitive to vibrations. With the use of an additional damping system, it should be possible to reach the highest requirements of vibration stability.

Beside the high power single stage PT60 cooler there are also coolers with two stages available with a minimum temperature below 10 K. One should carefully study the different types to find the right one for the application. Some companies also offer special customized coolers which are not much higher in price than the standard.

6. COOLING WITH A FLOW OF CRYOGEN

Using a flow of gas or liquid to transport heat away from an object is a standard procedure in many every day applications. Cooling to cryogenic temperatures with a flow of helium or nitrogen in an open line is a common way of cooling small lab cryostats. Some large experimental facilities use a cryogen in a closed loop going from a cooler to the consumer and back. For example, it is used at the ESRF synchrotron radiator to cool the monochromator crystals[10] or cooling of superconducting cables[11].

Advantages of a closed loop cooling system

- High cooling power available
- Good thermal contact to the instrument with low thermal gradient
- No additional precooling needed
- Low vibrations at the instrument

Disadvantages of a closed loop cooling system

- Large size
- Vibrations at the cooler
- Vacuum isolated transfer lines are needed.
- Only one base temperature provided
- High price
- Significant power and cooling water requirement depending on the type of cooler

6.1. Closed loop with Nitrogen[6]

Its high cooling capacity and easy handling make nitrogen the first choice as a coolant. Plenty of configurations are possible. Here are two examples

A flow of liquid Nitrogen which evaporates inside the experiment cryostat.
The nitrogen will return as gas and must be recondensed at the cooler. The gas could either be pumped as a gas in the warm, or by a special LN_2 pump in the cold. To pump it in the warm requires a heat exchanger. The heat exchanger warms up the cold gas to room temperature and cools down the warm gas in the return line. There are also pumps available which can pump LN_2. In this case a heat exchanger is not required. The temperature range of such a system is determined by the boiling temperature of the gas at the working pressure. The cooling power of such a system can be enormous. The disadvantage in this scheme flow is (a) the large change in volume (a factor of 700) when changing from liquid to gas, and (b) the vibrations from the boiling liquid.

Cooling LN_2 below its boiling point
The intention is, to keep the temperature of the cryogen always some Kelvin below the boiling point (subcooled nitrogen), to prevent it from bubbling in the instrument. In a closed loop system, the pressure will drop with the temperature. There for one needs a mechanism to keep the pressure high while the temperature is dropping. One also needs to compensate the volume change due to temperature. The temperature range of such a system is from about 64 to 80 K. The cooling capacity of the subcooled nitrogen is about 56 W for a flow of 100 l/h and a temperature increase of 1K. This corresponds to less than 1.5 l/h boil off for a conventional LN_2 cryostat.

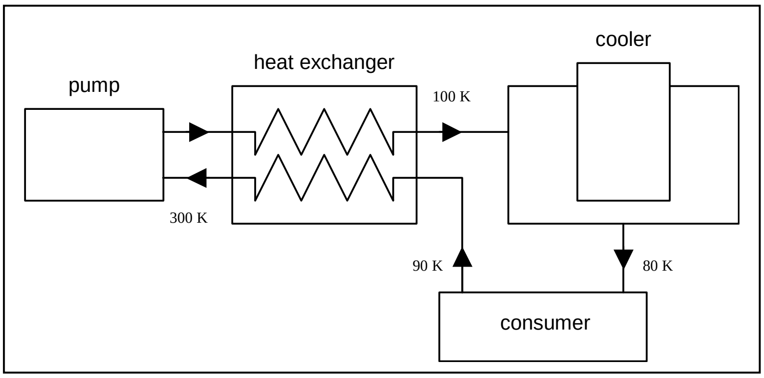

Fig. 7: Closed loop nitrogen cooling with evaporating liquid and warm pump

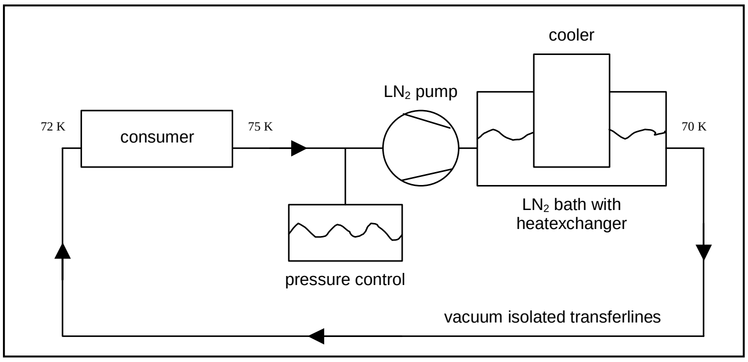

Fig. 8: Closed loop LN_2 cooling with cold pump

6.2. Closed loop with helium[6]

Helium does not seem to be the ideal medium to transport significant amounts of heat. Nevertheless, it does have major advantages. The boiling point of Helium is at 4.2 K. This means that most applications are well above the boiling point. The loop can therefore use gas. Instead of an expensive liquid cryogen pump, one can use a suitable fan blower. Any change in temperature changes only the pressure but not the volume. Another advantage is that one is not limited by the triple point of the gas. Therefore, cooling below 64 K freezing point of nitrogen is possible.

A closed loop helium system is simpler than one with LN_2, because no pressure control is needed. An additional buffer volume is required. This volume of gas is always warm, so it can be a gas cylinder and does not have to be thermally isolated. There is only a gas transfer when pressure and temperature of the gas in the loop changes, and the buffer volume keeps the pressure change small.

The heat capacity of Helium is about 5.23 kJ/kg K. At 60 K and 1 K temperature increase 1 m^3/h, 20 bar helium gas has cooling power of 23.6 W.

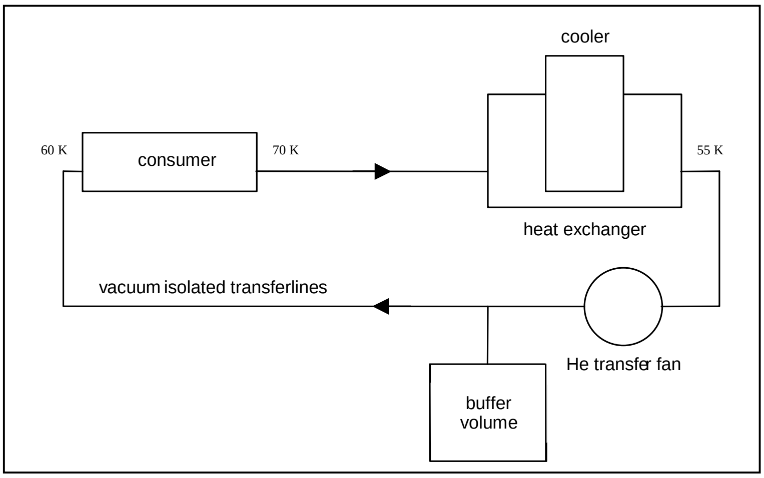

Fig. 9: Closed loop with Helium gas

6.3. Types of coolers for a closed loop system

A number of conditions drive the selection of a cooler for a closed loop system. These include cooling power and temperature range, vibration, space requirements, reliability, price, efficiency, etc. Large industrial coolers with several kW of cooling power are available. This is often may be overkill for telescope applications. Smaller lab coolers need less space, but sometimes have insufficient cooling power.

Cooling LN_2 with LN_2 [12]

This can be a clever solution for a subcooled closed loop of LN_2. A pressure reduced cold bath of LN_2 with refilling system could provide the cooling. The advantage of the subcooled LN_2 is the absence of vibrations from boiling LN_2 in the loop.

Cooling with GM or PT coolers [11]

In such a set up typically powerful single stage coolers would be used. Depending on the power dissipation of the system itself (transferline and pump), the cooling power of one cooler is not sufficient.

Cooling with industrial coolers [13]

Industrial liquefiers use large coolers. The most common is the Stirling cooler which is available as a small lab cooler or as a powerful machine. One such powerful machine, the smallest unit produced by Stirling (Netherlands) provides 1000 W of cooling power at 80 K, dropping to 500 W at 60 K. This unit requires approximately 10 – 15 kW of input power. The function principle of the cooler is described in [2]

7. THE LINC-NIRVANA CRYOSTAT

The LINC-NIRVANA cryostat needs a base temperature of about 80 K, and a detector temperature of about 70 K. The dimension is about 70 cm in diameter and 160 cm long for the cold volume. As an interferometer the cryostat will be very sensitive to vibrations. Bending due to changing tilt angle must be below the 10µm range.
The cryostat will consist of a central Aluminum tube which will perform several functions:

- central mounting structure
- radiation shield
- heat exchanger

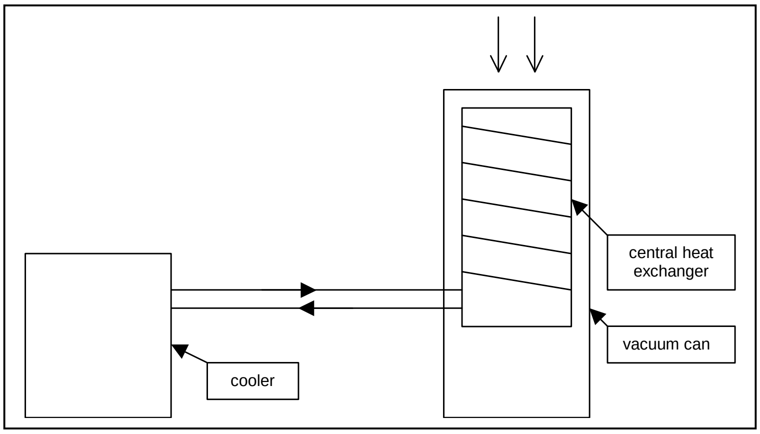

Fig. 10: Principal set up of the LINC cooling system

Cooling unit

The cooling unit consists of a 1-cylinder Stirling cryocooler with a vacuum insulated cold head. This head has an integrated helium transfer fan and a helium heat exchanger. Connectors to the vacuum insulated transfer lines for inlet and outlet are included, a Helium buffer tank and all required safety equipment. The motor is water cooled and has a vibration reducing subframe. The cooling unit has its own control hardware with interfaces to the instrument control electronics.

Temperature control

For temperature control, we can change the helium flow rate. Also, the cooler itself could be reduced in speed and therefore its cooling power. Without fast changes in the heat load, thermal variations will be less than ±1 K. The temperature set point can be changed from 50 – 80 K. During cool down we avoid large thermal gradients and therefore stress from a rapid cool down by setting the temperature drop rate at the control unit.

Position of the cooling unit

The cooler will be placed far from the instrument to reduce noise and vibrations. The resulting length of the transfer lines will be 50 m in one direction. There was no solution for shorter lines.

8. FUTURE INSTRUMENTS

Future IR instrumentation will require more and more cooling power because of growing size. The step from scaled up lab cryostats to industrial cooling plants should be done soon. The cooling gas or liquid could be standard infrastructure on giant telescopes, providing simple cooling at the instrument focus. The base temperature of 80 K could be reached by a LN_2 flow. Locally, lower temperatures can still be reached by additional small coolers e.g. to cool a detector.
In addition, helium flow coolers could be provided in 1 or 2 different temperatures using 1 or 2 stage Stirling coolers. The available cooling power could be in the range of several kW.

REFERENCES

1. W. L. Wolfe, *The infrared handbook*, IRIA Center, Washington, DC, 4th Printing, 1993
2. T. M. Flynn, *Cryogenic engineering,* Marcel Dekker, New York, 1997
3. W. Schreckenberg, *Gase Handbuch*, Messer Griesheim GmbH, 1990
4. H. Baumeister, *Cryogenic engineering for Omega2000*, Proc. SPIE 4841, p. 343 (2002)
5. M. Roberto, T. Herbst, *MAX: The New MPIA Thermal Infrared Imager,* Proc. SPIE 3354, p. 711 (1998)
6. H. Frey, R. Haefner, *Tieftemperaturtechnologie,* VDI-Verlag, Düsseldorf, 1981
7. R. Lenzen, *CONICA: the high-resolution NIR camera for the ESO VLT,* , Proc. SPIE 3354, p. 606 (1998)
8. R.-R. Rohloff, *Cryo design of the VLTI MIDI instrument*, Proc. SPIE 4006, p. 277 (2000)
9. T. Tomaru, *Vibration analysis of cryocoolers,* Cryogenics 44 (2004) 309 – 317
10. G. Marot, *Cryogenic cooling of monochromators,* Rev. Sci. Instrum. 63 (1), January 1992
11. Y. Suzuki, *Subcooled liquid nitrogen refrigerator for HTS power systems*, Cryogenics 43 (2003) 597 – 602
12. *Product data sheet*, Messer Cryotherm GmbH, Kirchen, Germany
13. *Product data sheet,* Stirling Cryogenics & Refrigeration BV, Eindhoven, Netherlands