DESY Summer Student Programme 2010

Performance testing of a Pulse Tube Cryo-cooler

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European XFEL
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Task

<u>Tests of pulse tube cryo-cooler</u>. The performance of an ultra-low vibrating pulse tube cooler has been tested in dependence of the applied thermal load, the mounting direction and other parameters. Data acquisition software has been developed in Labview environment.

1 Introduction

At the European XFEL GmbH the photon beam line group (Work Package 73) is currently involved in designing, testing and purchasing all the main components and apparatus for the future optical beamlines of this fourth generation light source. One important optical device is the monochromator. Its function is to selectively choose a narrow band of wavelengths from the wider range of wavelengths characterizing the input radiation. According with laws of physics like the Bragg's law; this result can be achieved by taking advantage of the atomic lattice properties of some materials like diamond and silicon. Nevertheless, when diamond or silicon monochromators are hit by the x-ray beam, the heat load deposited into their crystals will deform their atomic lattices, therefore affecting the device performance. It becomes then important to provide sufficient cooling power to the monochromators (fig. 2).

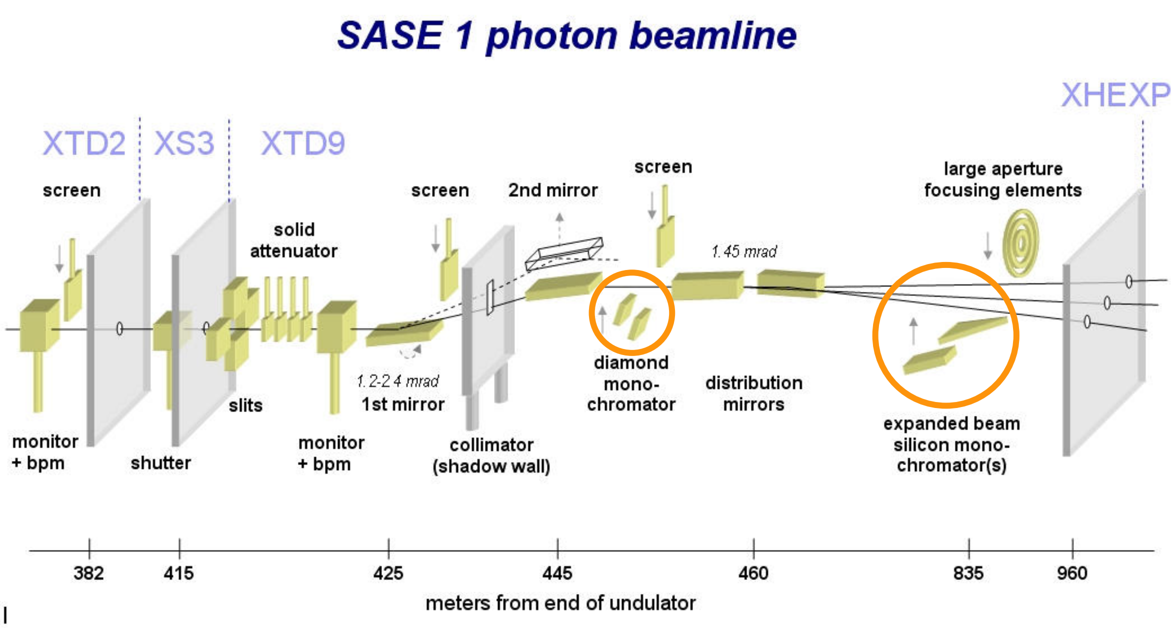


Fig. 1: SASE1 photon beamline with marked monochromators

As shown in Fig. 2 both diamond and silicon show their best thermal properties (higher thermal conductivity and lower thermal expansion) for a temperature of about 100 K. Among many cryocoolers available on the market, one interesting choice is certainly represented by the pulse tube cooler. This device is in fact capable of providing cooling powers above 40 W at 100K. Moreover this device is characterized by an extremely low level of vibrations on its cold side, due to the absence of a moving solid displacer. Relatively low cost, design simplicity and the fact that the cooler operates with helium gas and not nitrogen are all factors making this cooler the first choice candidate for cooling the XFEL monochromators.

The basic pulse tube cooler and the orifice pulse tube cooler are schematized respectively in Fig.3 and Fig.4. A basic pulse tube cooler simply consists of a compressor (generating a sinusoidal pressure wave) coupled with a closed end tube. The cooling mechanism of the basic pulse tube is based on the so called “surface heat pumping” process. The gas is adiabatically compressed and expanded inside the closed end tube by the sinusoidal pressure wave. When the gas is compressed its molecules get hotter while being simultaneously displaced towards the closed end of the tube. During the subsequent expansion process, the gas gets colder. Meanwhile its molecules are displaced towards the opposite side of the tube. A temperature gradient is then created between the cold end at on side of the pulse tube and the hot end at the other side. The net heat transfer between the gas and the pulse tube wall thus shuttles heat from the cold end to the warm end. However the net amount of heat transferred is relatively small and disappears when the temperature gradient in the wall becomes sufficiently large to match the temperature excursions developed in the gas during the compression and expansion processes.

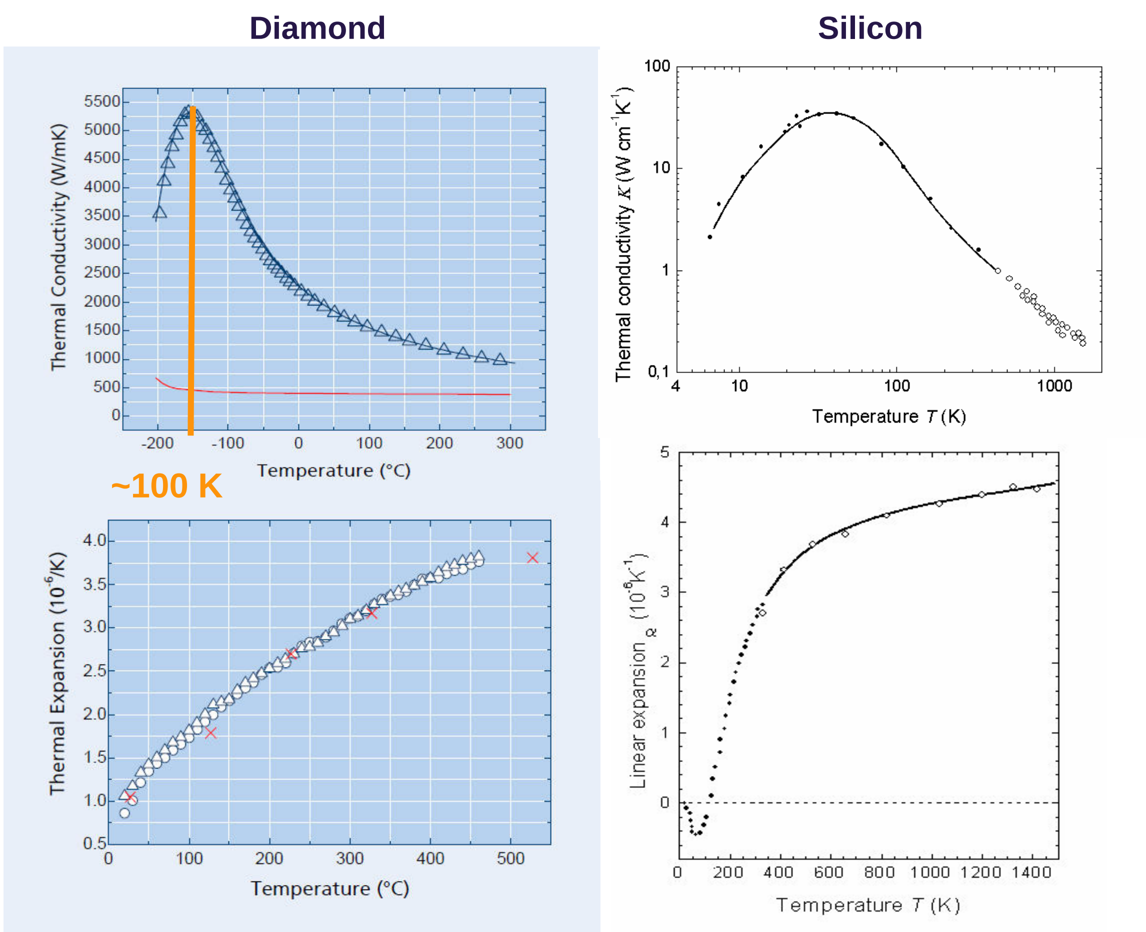


Fig. 2: Thermal properties of diamond and silicon

The cooling mechanism of a basic pulse tube is only based on the interaction between cooling gas and pulse tube walls. In the case of the basic pulse tube, the mass flow wave, which is driven by the pressure wave, is 90° out of phase with respect to the pressure wave. This implies that the temperature wave, being proportional to the pressure wave, will be 90° out of phase with the mass flow wave. This explains why the net enthalpy over one full working cycle will be 0, meaning that no P-V work is produced. P-V cooling work can be obtained introducing "inertia" effects on the mass flow rate, by putting an orifice valve and a reservoir on the closed end of the pulse tube. The orifice will force the phase difference between pressure and mass flow to be less than 90°. In this case the pulse tube working principle is similar to the more famous stirling refrigerator, with the only difference that the solid displacer of the stirling cooler is replaced by the column of gas in the pulse tube.

The orifice pulse tube creates refrigeration through PV-work as well as surface heat pumping. The gas column in the orifice pulse tube acts exactly like the solid displacer in a Stirling cycle refrigerator (fig. 4). This PV-work is transferred from the compressor through the regenerator to the cold heat exchanger. It is continuously delivered from the cold end to the hot end by changing the volume of the gas column in the pulse tube with associated pressure changes. Then, this PV-work is dissipated in the orifice and transferred as heat in the hot heat exchanger. An orifice single stage pulse tube system has been tested in the European XFEL assembly Lab.

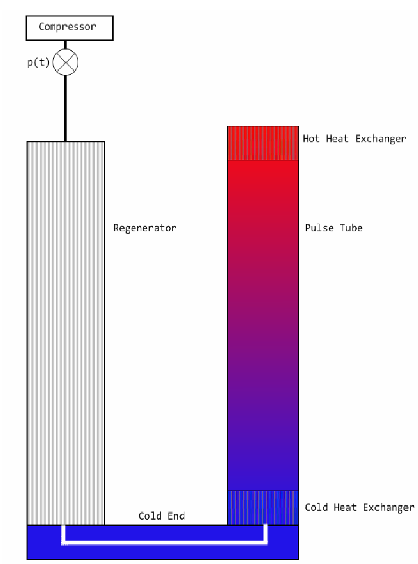


Fig. 3: Basic pulse tube

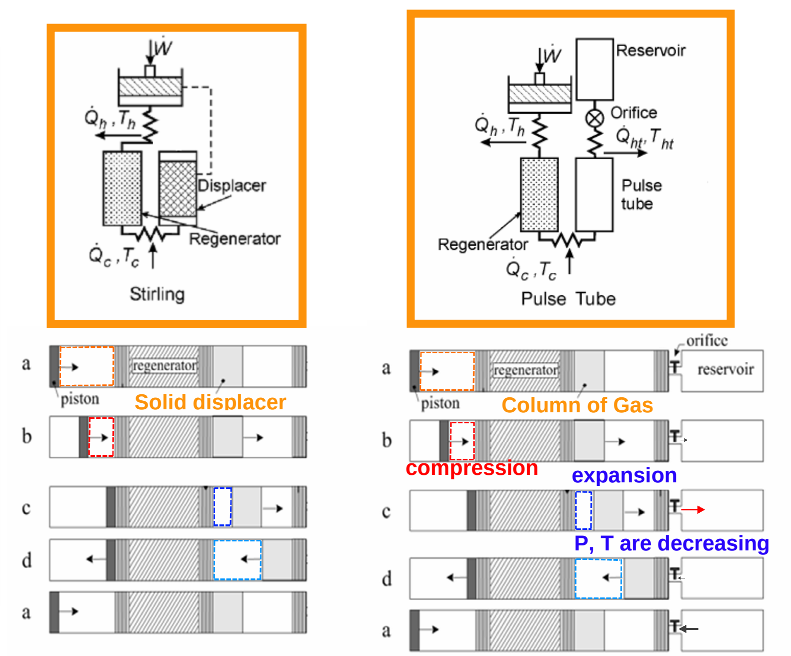


Fig. 4: Orifice pulse tube (right) working cycle compared with Stirling cooler (left) working cycle

2 Measurement

As schematically shown in fig. 5, the cryogenic temperature produced by the pulse tube cooler is recorded by means of two temperature sensors (Pt-100) placed in two adjacent spots on the cold tip. The resistance fluctuations of the Pt-100 sensors are measured using a Keithley multimeter and then converted in the equivalent temperature scale. On the cold tip a 50 Ohm resistor is mounted as well. In this way it is possible to apply a variable heat load by powering the resistor with an external power supply. The cooler is inserted in a double cross ISO 200 vacuum chamber, necessary to provide the proper thermal insulation. According with the vendor's specifications a vacuum of 10-5mbar would be sufficient to provide a good thermal insulation. Therefore, a cold cathode vacuum pressure sensor was used in the setup as well. All the sensors were interfaced to a PC and read by the data acquisition commercial software Labview. (See fig. 6, 7, 8, 9).

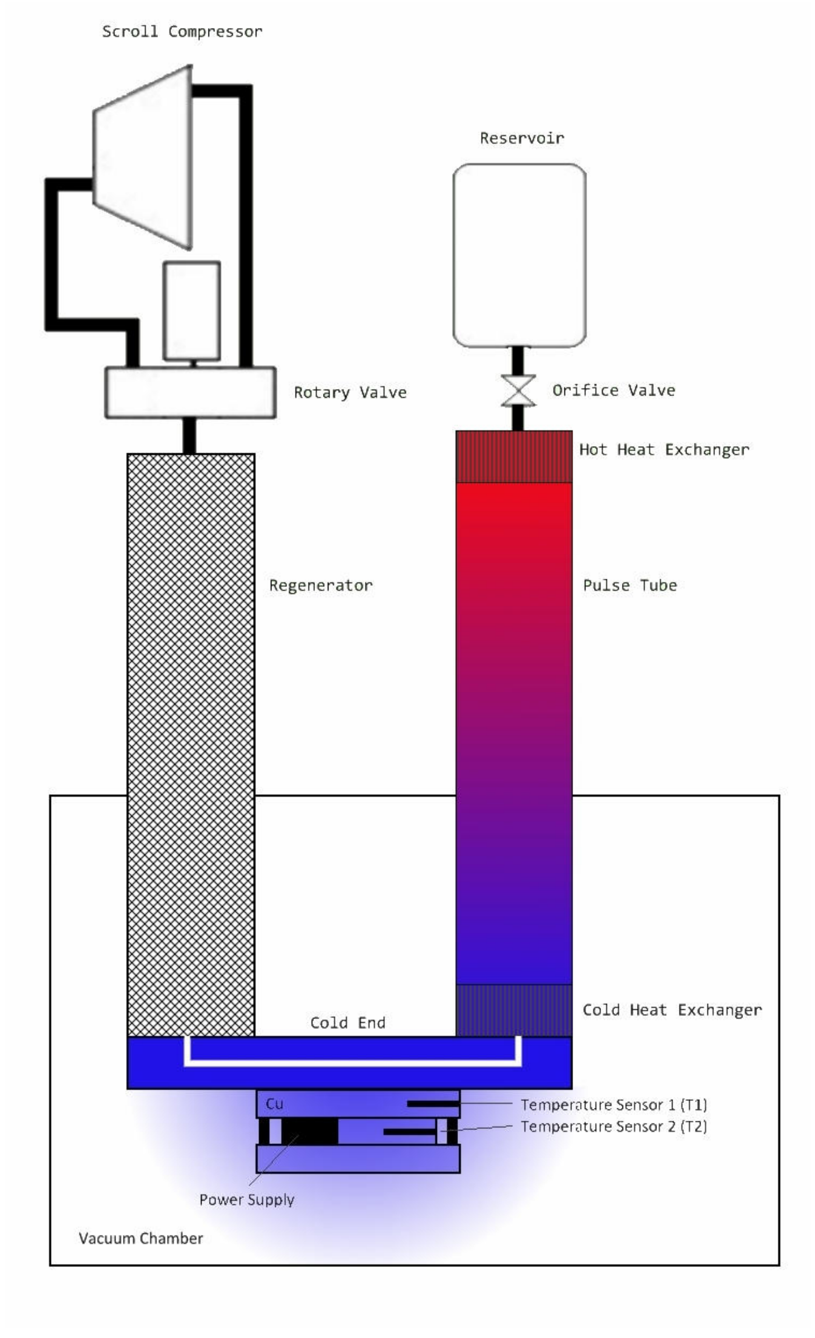


Fig. 5: Orifice single stage pulse tube cooling system scheme with marked sensors and power supply

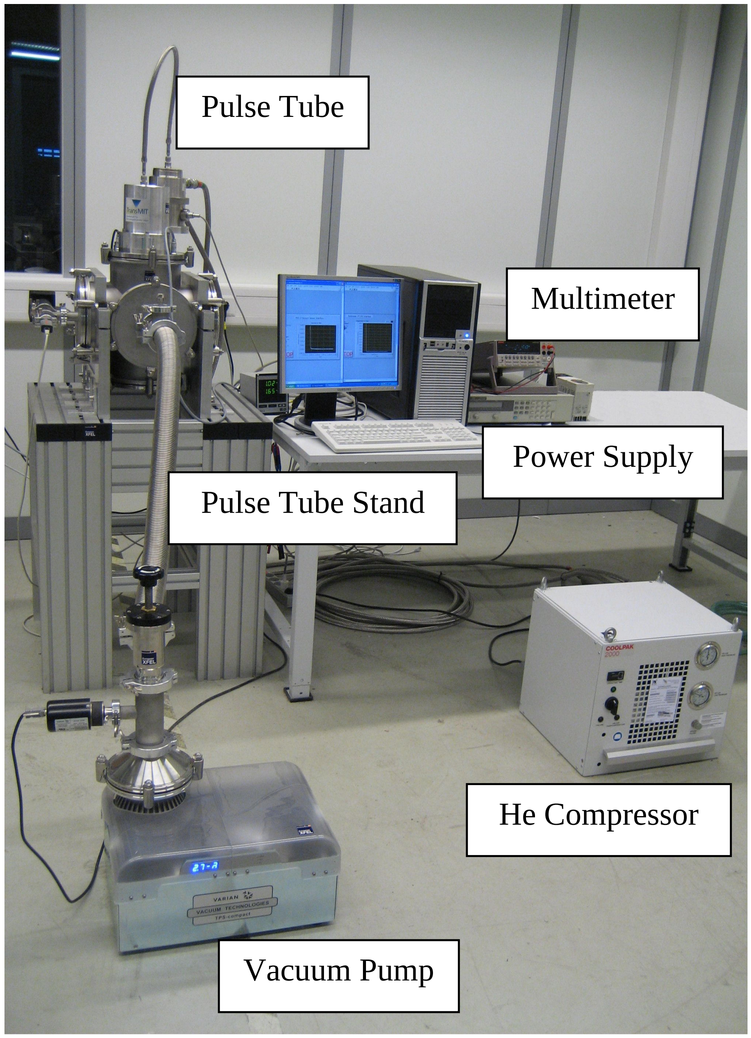


Fig. 6: How it looks in the real

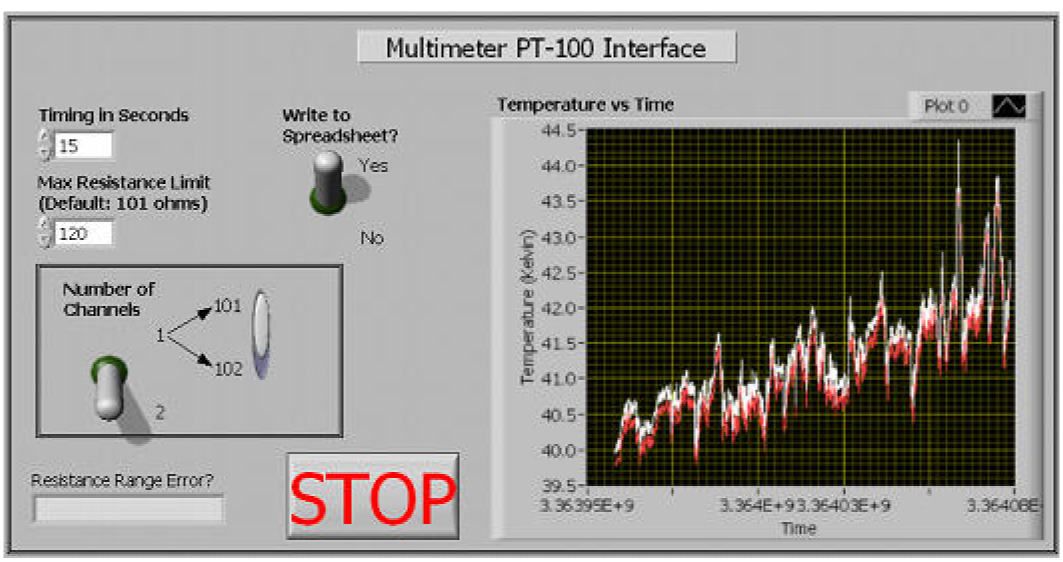


Fig. 7: Labview temperature data acquisition software

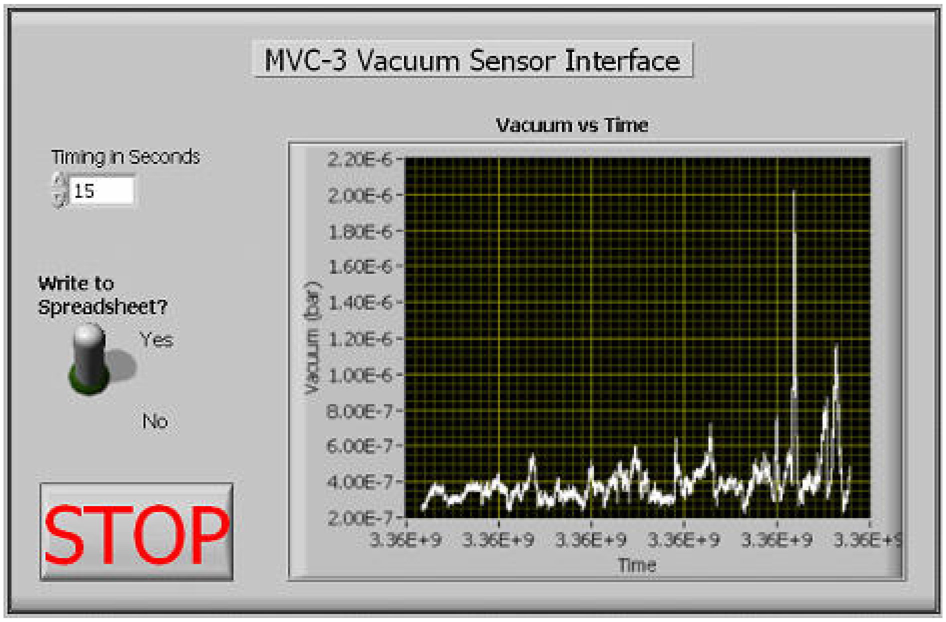


Fig. 8: Labview pressure data acquisition software

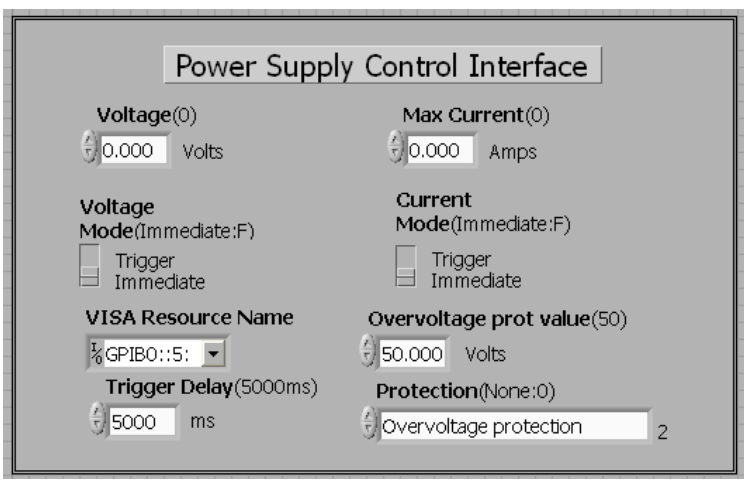


Fig. 9: Labview software for controlling power supply

2.1 No Thermal Load

Since the pulse tube that has been tested does not have any temperature regulation system, it produces cooling until the cold end reaches a minimum temperature of 36 K. According to the vendor's specifications, the system should stay stable at its minimum temperature for an almost unlimited time. Nevertheless, after few days of measurements the temperature started to show a pretty unstable trend (fig. 10).

In the attempt of improving the situation, it as been decided to wrap the cold part of the pulse tube with insulating aluminium foil, as the vendor suggested. Measurements of this setup were taken for five days as shown in Fig. 11 and 12. In this case the minimum temperature of 36K was reached in 45 minutes remaining almost stable over the 5 days period (the temperature drifted up of only 1 K over 5 days).

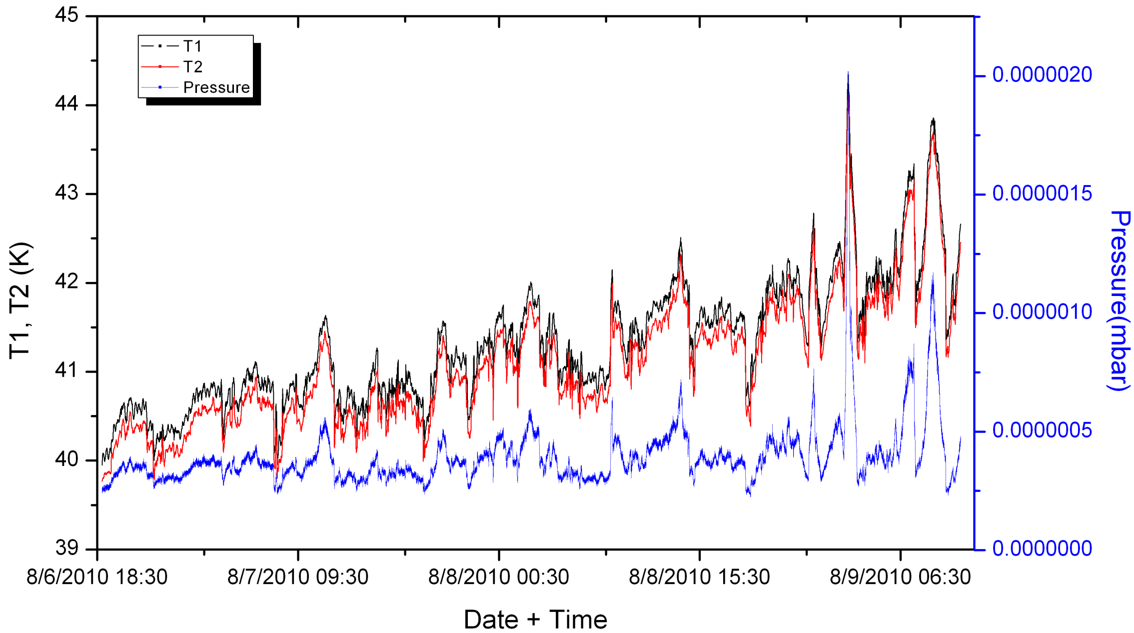


Fig. 10: Results of measurement of the temperature and pressure of the vacuum at the PT system with no applied heat load during app. 36 hours

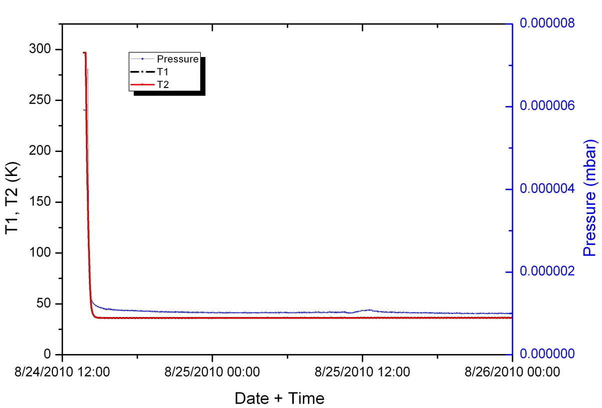


Fig. 11: Foil applied, cooling down

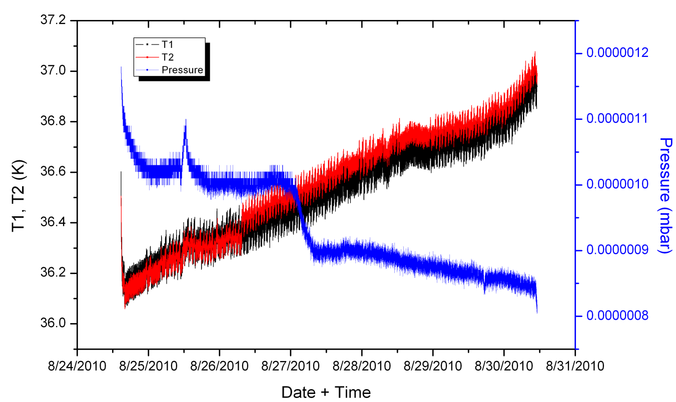


Fig. 12: One week of measuring without heat load, zoomed part of fig. 12 after cooling down

2.2 Applied Thermal Load

As shown in Fig. 12, the temperature stability of the system greatly improved by just wrapping the cold tip of the pulse tube with aluminium foil. It was then decided to apply three different heat loads by powering the resistor mounted on the cold tip of the pulse tube. 10 W, 20 W and 30 W have been applied for at least 24 hours. The results of the measurement are shown in fig. 13.

The three heat loads applied wanted to simulate the real case scenario of x-ray beam hitting the monochromator's crystal. The amount of heat that the cryocooler should be able to remove has to be equal to the steady state power deposited by the x-ray beam into the crystal. Diamond monochromators absorb only a little amount of the beam power, usually up to 5 %. A silicon monochromator instead absorbs almost the 90 % of the power carried by the x-ray beam. In general the typical amount of heat that should be removed from a monochromator at XFEL can vary from few Watts up to 40 Watts.

From fig. 13 we can notice that the system was pretty stable for an applied heat load of 10 W, maintaining a temperature of about 54 K over one full day. With a heat load applied of 20 W the system showed a slightly temperature increase, rising from 66.5 K to 68 K in 24 hours. After increasing the heat load to 30 W, the system became clearly unstable and the temperature increased at the rate of 10K/day over a measurement period of 72 hours (from 89 K to 123 K in three days). Because of the high instability of the system, the measurement was stopped.

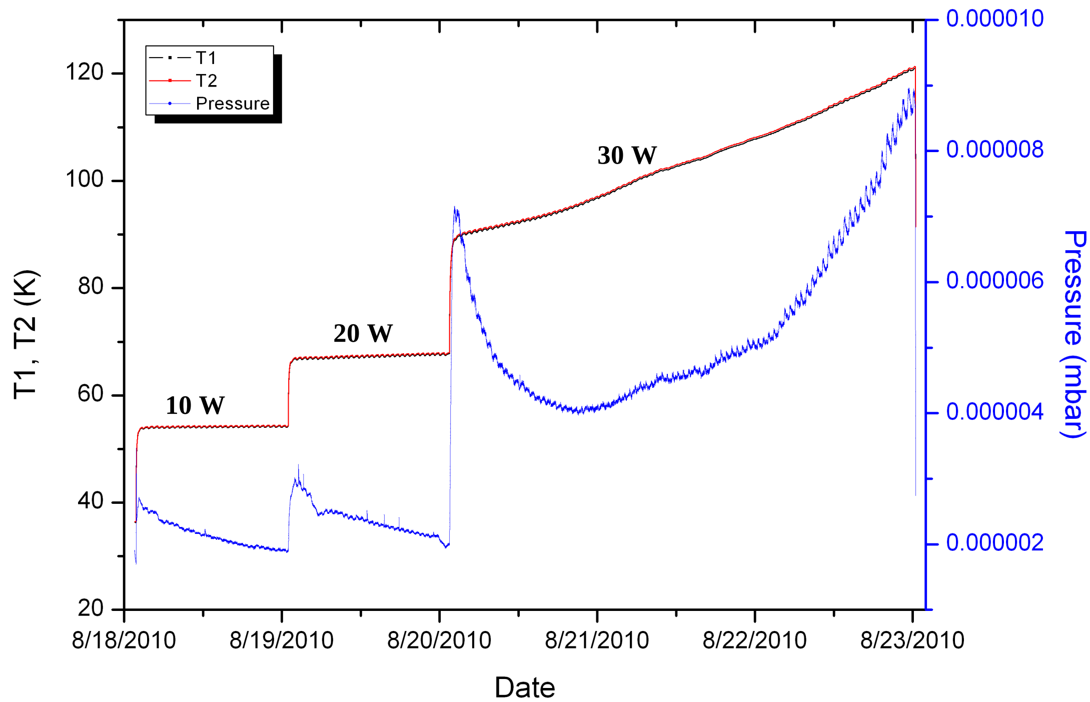
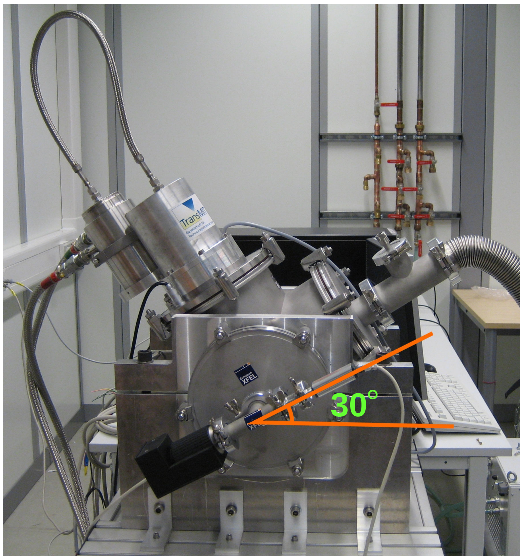


Fig. 13: Temperature and pressure measurement after applying heat load of 10 W, 20 W and 30 W

2.3 Different mounting directions

The pulse tube maximum efficiency is obtained for a perfectly vertical mounting direction, with cold tip pointing down. Its cooling capabilities were tested also by considering two different mounting directions (Fig. 14, 15). Each measurement was performed for 48 hours. The results obtained are shown in fig. 16. It appears clear that the system was instable also at these two different mounting directions. A temperature drift was observed in both cases, becoming more evident for higher mounting angles.



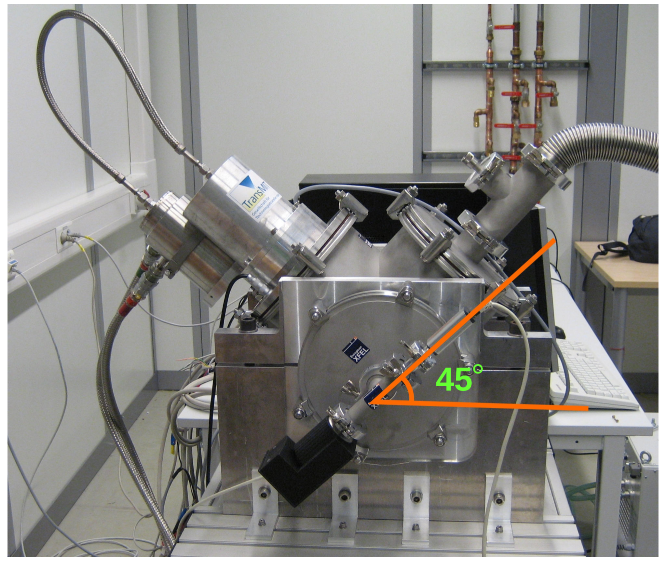


Fig. 14: Mounting direction changed by the angle of 30°

Fig. 15: Mounting direction changed by the angle of 45°

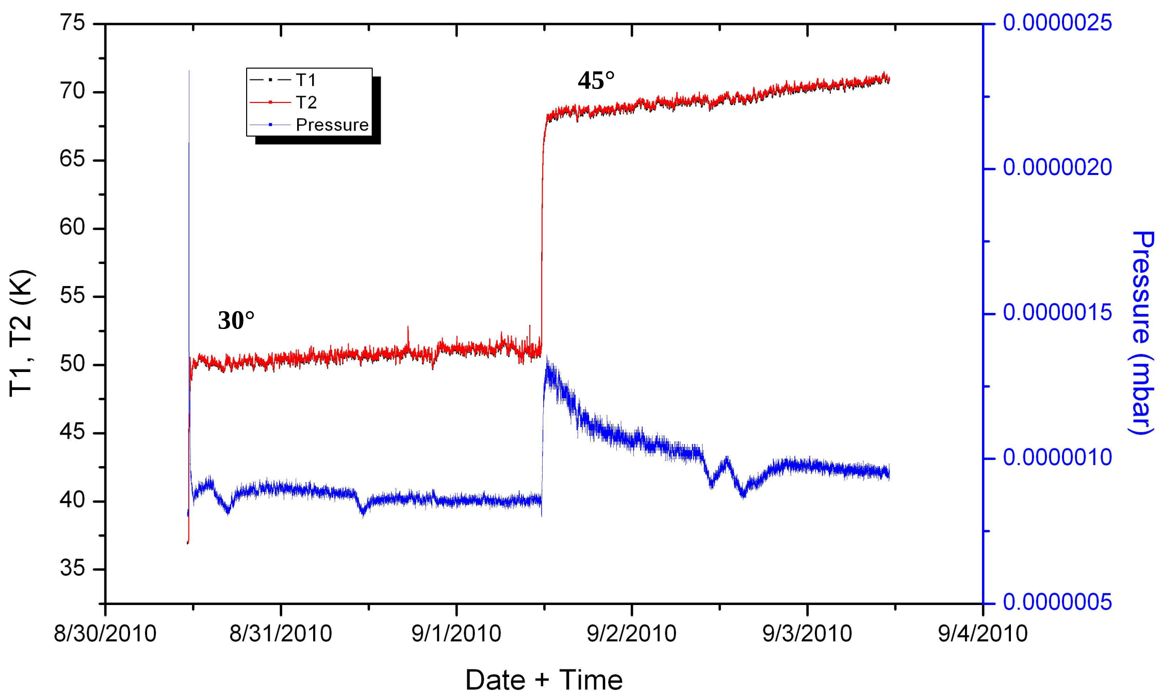


Fig. 16: Results obtained from measuring at conditions from fig. 14 and 15

3 Conclusions

A full set of tests was performed in order to verify the technical specifications of a pulse tube cryocooler. A final report will be submitted to the pulse tube vendor. The document will summarize the results that have been obtained, pointing out all the instabilities observed for different working conditions (long time operation, heat loads applied and different mounting orientations). The huge instabilities observed for high heat loads applied and high mounting angles are an indication that the helium gas may be contaminated. A lot of experience in data acquisition and controlling has been gained.

Acknowledgement

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