Solvay Cryocooler for a Quantum Material Characterization Cryostat

Ravi Bains

Advanced Research Systems, Inc.
Allentown, Pennsylvania, USA 18062

ABSTRACT

Quantum applications of the future will require high performance cryocoolers. Quantum computing, quantum sensors and quantum transmission will require low vibrations for maximum performance. These applications are sensitive to noise on an atomic scale and vibrations must be managed to a sub nanometer level.

In collaboration with Prof. Markus Raschke of the University of Colorado, ARS has demonstrated the capability of the ARS-Solvay cryocooler to deliver such performance.

INTRODUCTION

ARS manufactures Solvay cryocoolers for laboratory cryogenic research. These cryocoolers have been popular in the fast-growing quantum technology applications where ultra-low vibrations are necessary, such as Scanning Tunneling Microscopes (STM's) and Atomic Force Microscopes (AFM's).

ARS collaborated with Prof. Raschke to cool an AFM to study quantum properties such as quantum defects using nano-optics techniques. The results are reported in this paper.

Three levels of vibration isolation are needed for atomic imaging. The first and most important level is the use of a Solvay cryocooler which has inherently a low vibration, making it suitable for such demanding applications.

- 1^{st} Level vibration management, Solvay Cryocooler: +/-10 µm of vibrations (displacement).
- 2^{nd} Level vibration management, Gas gap heat transfer: 3 to 5 nm of displacement.
- 3^{rd} Level vibration management, Spring and Damper: <100 pm of displacement.

CONSTRUCTION OF THE SOLVAY CRYOCOOLER

The Solvay cryocooler offers some advantages to manage and achieve low vibrations at the experimental platform.

Firstly, it has a pneumatically driven displacer which does not utilize a mechanical coupling between the motor and the reciprocating displacer. The elimination of the mechanical coupling simplifies the vibration frequencies to be managed, as the displacer motion is controlled and buffered by the bubbles of helium gas at the two ends of the displacer. The helium softens the landing at the end of each stroke, shown in Figure 1.

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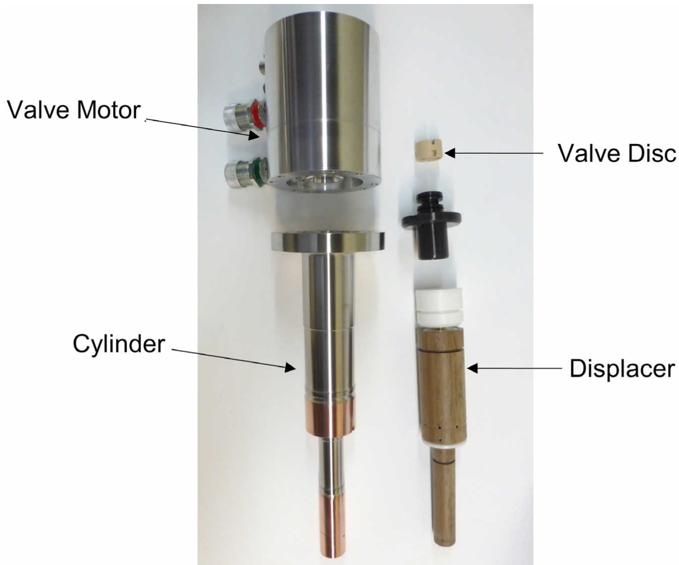

Figure 1. Solvay Cryocooler disassembled to show the internal components.

Secondly, the valve motor spins at a constant speed with uniform torque. There is no ratcheting which could be caused by uneven loading of the motor during its rotary cycle. This uniform and low torque is achieved through minimizing the friction between the valve disc and the valve stem.

Finally, the axial arrangement helps keep the motors vibration contribution at a minimum. There are no forces in the X and Y axis, as most vibrations are in the Z axis along the axis of the cryocooler. This simplifies the task of managing the vibrations at the experimental stage.

The lack of mechanical drive components and mechanisms also gives the added advantage of keeping the cryocooler light and compact, and it also allows the cryocooler to work in any orientation.

Two stage Solvay cryocoolers are available in three sizes shown in Figure 2, and each size is available with a selection of regenerator beds to suit the experimental requirements for optimization of temperature, cooling power, and cost. Table 1 provides typical performance values.

Figure 2. ARS Solvay Cryocoolers for low vibration applications.

Table 1. Typical Performance Specifications

	202S	204S	210S	110
Temperature. Min	4.2K	3.8K	2.9K	20K
Cooling Power at 4.2K. Watts	0.1	0.2	1.0	
Vibrations, Microns	+/- 5	+/- 10	+/- 15	

THEORY OF OPERATION

The displacer motion is controlled by the bubbles of helium at the two ends of the displacer. The helium pressure above the displacer, at the warm end, is regulated to an intermediate pressure, approximately 200 psi; the gas is stored in a constant pressure reservoir at the warm end which supplies this gas as needed, as shown in Figure 3.

The pressure below the displacer, at the cold end, is controlled by the supply pressure (high) and the suction pressure (low) of the helium compressor. The timing and duration of this pressure is controlled by the rotating valve disc.

When the high-pressure helium gas flows through the valve stem into the bottom of the displacer the displacer moves upwards, and the high-pressure gas expands in the displacer further cooling the regenerator bed.

As the valve disc rotates, the helium is exhausted to the suction side of the compressor, the cold side pressure drops, and the displacer moves downwards as the helium expands and is exhausted back to the compressor.

The displacer is always cushioned between the two bubbles of helium gas and its motion and change of momentum is cushioned by the helium at the end of each stroke. A typical vibration motion at the cold end of the cryocooler is shown in Figure 4.

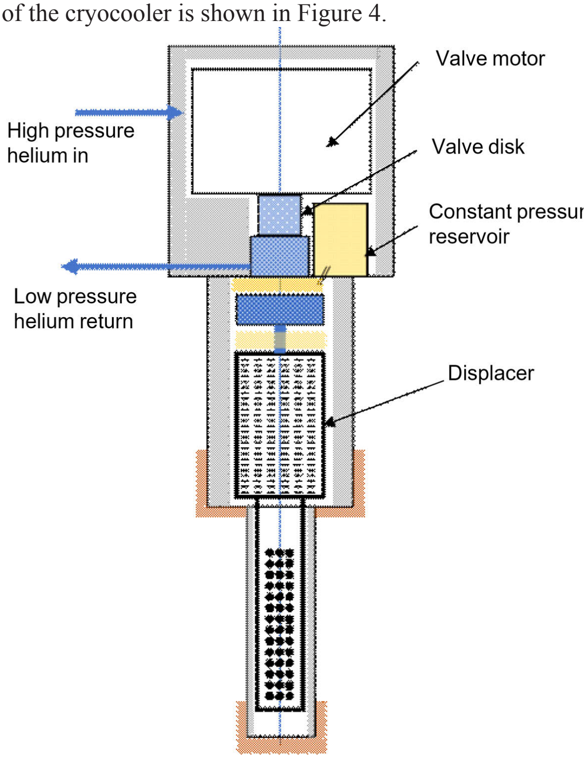

Figure 3. Schematic of Internal components

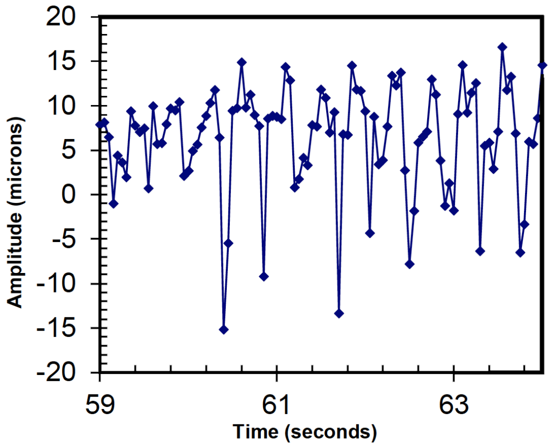

Figure 4. Vibrations of a 202 Cryocooler.

VIBRATION MANAGEMENT

In the second level of vibration management a gas gap vibration isolation technology is utilized. In this design the cryocooler is inserted into a coaxial cylinder (Low Vibration Interface) slightly larger than the diameter of the cryocooler, and the space between the cryocooler and the interface is filled with helium gas, see Figure 5. To contain the helium gas in the confined area, a soft rubber bellows is hermetically installed between the cryocooler and the LV Interface. When the cryocooler

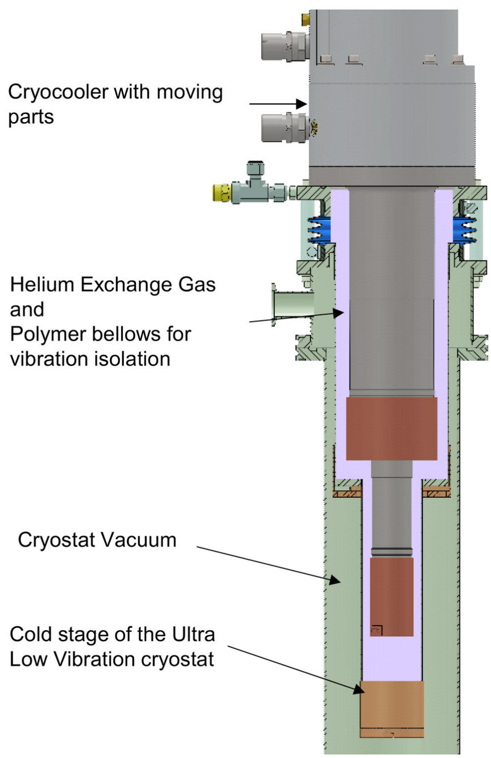

Figure 5. Schematic of the Gas Gap isolation technology.

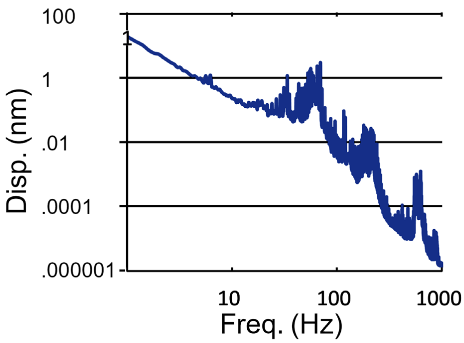

Figure 6. Vibration Spectra of a Model 204 cryocooler with gas gap interface. Vibration level of 3-5 nm at 2.4 Hz is common.

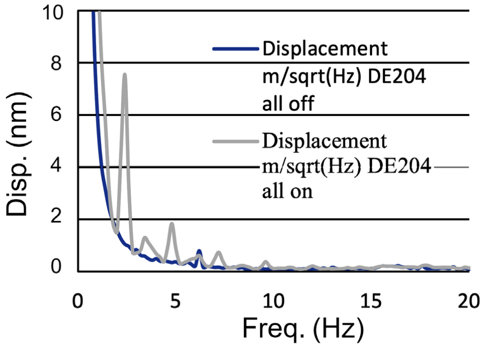

Figure 7. Vibration Spectra in the 0-20 Hz range.

is mounted on the ceiling or on the floor of the laboratory the vibrations at the tip of the interface have been measured at 3-5 nm. Figures 6 and 7 show example vibration spectra for the ULV interface tip with the cryocooler on and cryocooler off.

In the third level of vibration management the cryocooler is disconnected from the research table by suspending it from the ceiling or mounting it to the floor, see Figure 8.

The cryogenic platform is suspended from the vacuum chamber by multiple springs and any periodic motion is dampened. The thermal path from the low vibration interface to the platform is via a soft copper braid or a stack of copper foils. High purity copper works best for high conductivity and soft contact for vibration isolation. The goal is to get the platform as close to 4K as possible using good cryogenic practices.

The AFM is installed on the cryogenic platform and enclosed in a ~4K radiation shield; this ensures the lowest temperature at the sample under test. For the AFM to have the highest resolution drift the vibrations must be in the sub 100 pm. This means the temperature stability and the mechanical motion must be in the 100 pm range.

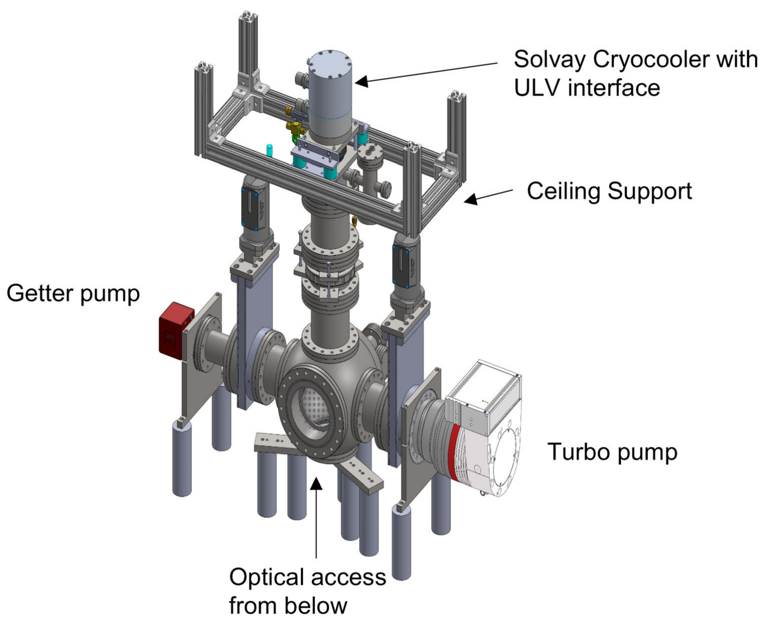

Figure 8. Experimental apparatus at the Raschke Lab.

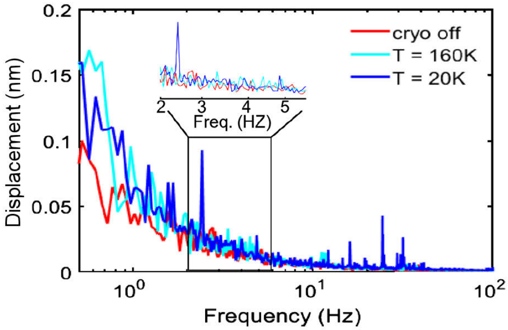

Figure 9. Third level of vibration isolation. The AFM is installed on this platform. Vibration from the cryocooler at 2.4 Hz is 100 picometers.

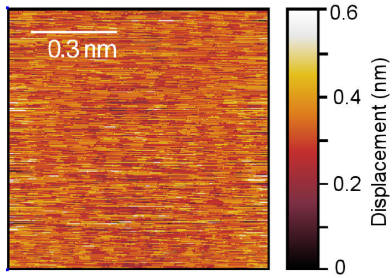

Figure 10. Surface scan using a low temperature AFM. Sample at 15 K.

TEST RESULTS

Referencing Figures 9 and 10.

Experimental Conditions:

- Variable temperature of cryostat: T=4-350K
- Variable temperature of the AFM: T=15-350K

- Vibrations at the cryocooler, Level 1: 10 Microns
- Vibrations at the ULV Interface, level 2: 3-5 Nanometers
- Vibrational noise at 2.4Hz. at AFM tip, Level 3: < 100 picometers

- Precise optical (Beam) control for AFM.
- Vacuum level: < 10^{-10} Torr

DISCUSSION

With liquid helium becoming more expensive or unavailable for the research scientists world-wide, and with the growing interest in quantum technologies research and commercial applications, further development in cryocoolers and cryostats will be important.

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