Nanopositioning with Unprecedented Low Heat Dissipation at milli-Kelvin Temperatures (Whitepaper A)

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Positioning at milli-Kelvin temperatures is a key enabling technology for studying novel quantum materials and devices. Most quantum states are only visible and controllable when the thermal energy k_BT is comparable or smaller than the energy difference ΔE between the quantum states. Therefore, to see the quantum properties of materials or devices, they often need to be cooled to and maintained at temperatures between 10 mK and 300 mK. In this field it is of great importance to have the ability of doing positioning of (quantum) sensors over materials, alignment of optical components, and other R&D tools, while preserving the low temperature conditions.
However, the cooling power at these temperatures is often in the order of micro-Watts, while most conventional large range positioning solutions produce milli-Watts of dissipation at their minimum operating frequency and as such increases the temperature of the refrigerator. In this white paper we show that arQtika, the cryogenic nanopositioner of Onnes Technologies, dissipates in the order of micro-Watts, resulting in a significantly more stable thermal milli-Kelvin environment while positioning, i.e. minimizing drift and thermalization times.
We measured the dissipation of an arQtika positioner while moving and measuring the absolute position continuously. The total dissipation is found to be below 10 μW when moving with 0.2 μm/s at 48 mK. Onnes Technologies' piezo based cryo-walking technology is able to dissipate so little due to a significant minimization of the heat dissipation linked to the (de)charging frequency of the piezo components and the avoidance of mechanical friction linked heat dissipation, while maintaining speed in the order of tens of micrometer per minute. Due to this low dissipation, the arQtika Linear Cryo-Walker enables the possibility of positioning during experiments without destroying quantum states or having to wait for long cooling times after movement. This helps researchers utilizing novel quantum sensors, enables non-destructible monitoring of single atomic structures, and significantly speeds up iterations of developing and testing quantum computing devices.

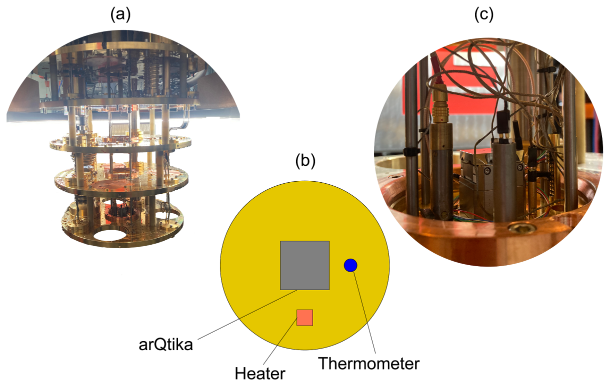

Figure 1: *a) The inside of the dilution refrigerator with the lowest plate being the mixing chamber plate reaching 20mK temperatures. b) Schematic layout of the experiment inc. an arQtika nanopositioning stage, thermometer, and heater. c) Setup is mounted on an insertable probe facilitating quick experimental cycles.*

Test setup

We measure the dissipation using a calorimetric measurement configuration as shown in figure 1. The RuOx thermometer is calibrated to measure temperatures in the 10 mK to 1K range. We use the thermometer-heater combination to keep the temperature of the probe base constant at 48 mK by means of a PID feedback loop. The power we send to the heater before we move the arQtika motor to maintain this temperature acts as a reference baseline. The difference between this reference and the power that is needed to keep the temperature constant when the positioner is working is the power that is being dissipated by the positioner. This approach yields a constant cooling power throughout the experiment, since the temperature is kept constant.

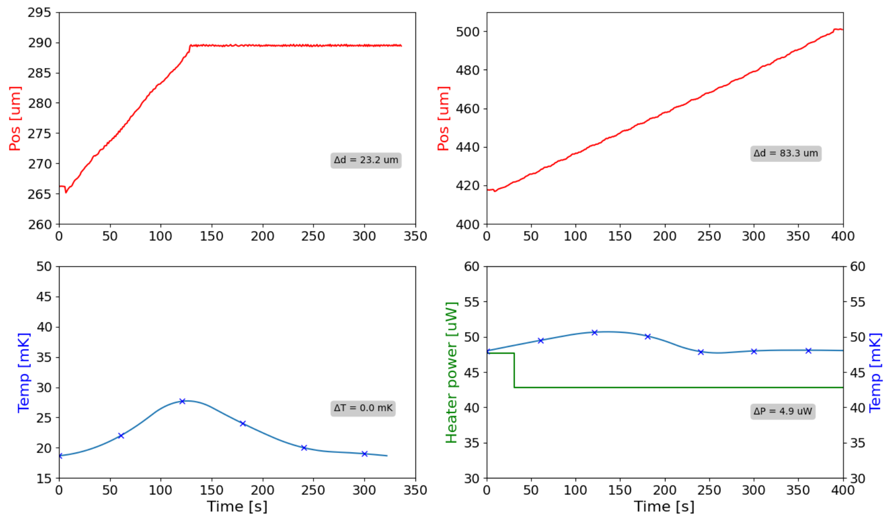

Figure 2: *Left: Demonstration of unprecedented low heat dissipation over micrometers long displacement at base temperature. Right: Calorimetric determination of the heat dissipation.*

The setup is mounted on an insertable probe in an Leiden Cryogenics dilution refrigerator with a base temperature of $\sim$ 17 mK.

Results and discussion

We moved the positioner with 1 step per second leading to a speed of 0.2 μm/s at cryogenic temperatures. The capacitance-based absolute position readout measures the position once per second using an Andeen-Hagerling AH2500 capacitance bridge. The left side of figure 2 shows that we moved 23 micron within 120 seconds and restabilize temperature a few minutes later. The dissipation during positioning with these settings is 4.9$\pm$2.3 μW and measured with a calorimetric measurement at 48 mK, shown on the right side.
Positioning is done by repeated (de)charging of the piezo material, generating small dissipative currents and losses. At these temperatures the total capacitance that needs to be charged and uncharged by 50Vpp, is approximately 0.3 μF. At 1 step per second the total I_{RMS} = 34 μA. The standard cryogenic wiring has a resistance of 100 Ω, giving an expected ohmic dissipation of 0.1 μW. We assume that the rest of the measured heat dissipation comes from the loss in piezo material and the mechanic inefficiencies. We can calculate this combined loss factor as $\tan(\delta) = \frac{\text{loss}}{\text{total energy stored in piezo}}$. This yields approximately $\tan(\delta)$ = 0.6% $\pm$ 0.3% which is a typical value for piezos at cryogenic temperatures and operated at these low frequencies and voltages.
We notice that within a couple of minutes, after stopping the motion, the base temperature is reached again. This demonstrates the very high efficiency of displacing by cryo-walking technique and it shows that the positioner is well thermalized, i.e. there is no heat reservoir that keeps on leaking heat long after operation. These two characteristics verify the use case of arQtika as an effective tool to speed up low temperature research.
There are many positioning systems available on the market, even for cryogenic purposes. They all have their own travel range, travel speed, stiffness, maximal payload, and principle of operation, and therefore it is very difficult to compare different stages in general. However, we claim that among the positioners with more than 0.1 mm range the heat dissipation of the arQtika is several orders of magnitude lower than what has ever been demonstrated: a world record regarding positioning efficiency in a milli-Kelvin environment. Additionally, this is done by posing no special requirements to the cabling and offering compatibility with high payloads, all included in a robust, stiff and non-magnetic design.

Conclusions

We demonstrate unprecedented low heat dissipation in an arQtika Linear Cryo-Walker. Through a calorimetric measurement strategy, we measured a heat dissipation below 10 μW while moving with 0.2 μm/s and continuously measuring the absolute position. At temperatures around 20 mK, this yields tens of micrometers displacement per minute while minimally affecting the temperature of the milli-Kelvin plate of the dilution refrigerator. The heat dissipation is dominantly linked to the loss in (de)charging piezo material. As such, we demonstrated arQtika to be an effective tool to do cryogenic positioning with minimal thermal impact on experiments and minimizing cooling times after movement.