Development of a closed-cycle miniature dilution refrigerator for a fast cooldown 100 mK detector wafer test cryostat

S Azzoni[a*], AJ May[a], ST Chase[b], G Coppi[a], LC Kenny[b], L Piccirillo[a], A Suzuki[c], J Wenninger[a]

[a]Jodrell Bank Centre for Astrophysics, University of Manchester, Manchester, M13 9PL, UK
[b]Chase Research Cryogenics Ltd, Sheffield, S3 8AG, UK
[c]Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
*susanna.azzoni@postgrad.manchester.ac.uk

Introduction

Motivation

- The forthcoming generation of CMB polarization observatories are developing large format detector arrays [1]
- The scaling up fabrication of high performance detectors requires timely feedback testing capabilities operating at 100 mK

Approach

- Retrofit Chase ^{4}He/^{3}He/^{3}He systems [2] with a miniature dilution refrigerator (MDR) stage to repurpose existing 250 mK cryostats
- The MDR provides a 100 mK stage for rapid feedback testing of single detector wafers fabricated for the Simons Observatory [3]

Benefits

- By confining the circulation of cryogens to the cold stage, MDRs require very little ^{3}He and no external connections or gas handling systems
- The architecture design will modify the existing APEX test cryostat at UC Berkeley in order to reduce development time and costs

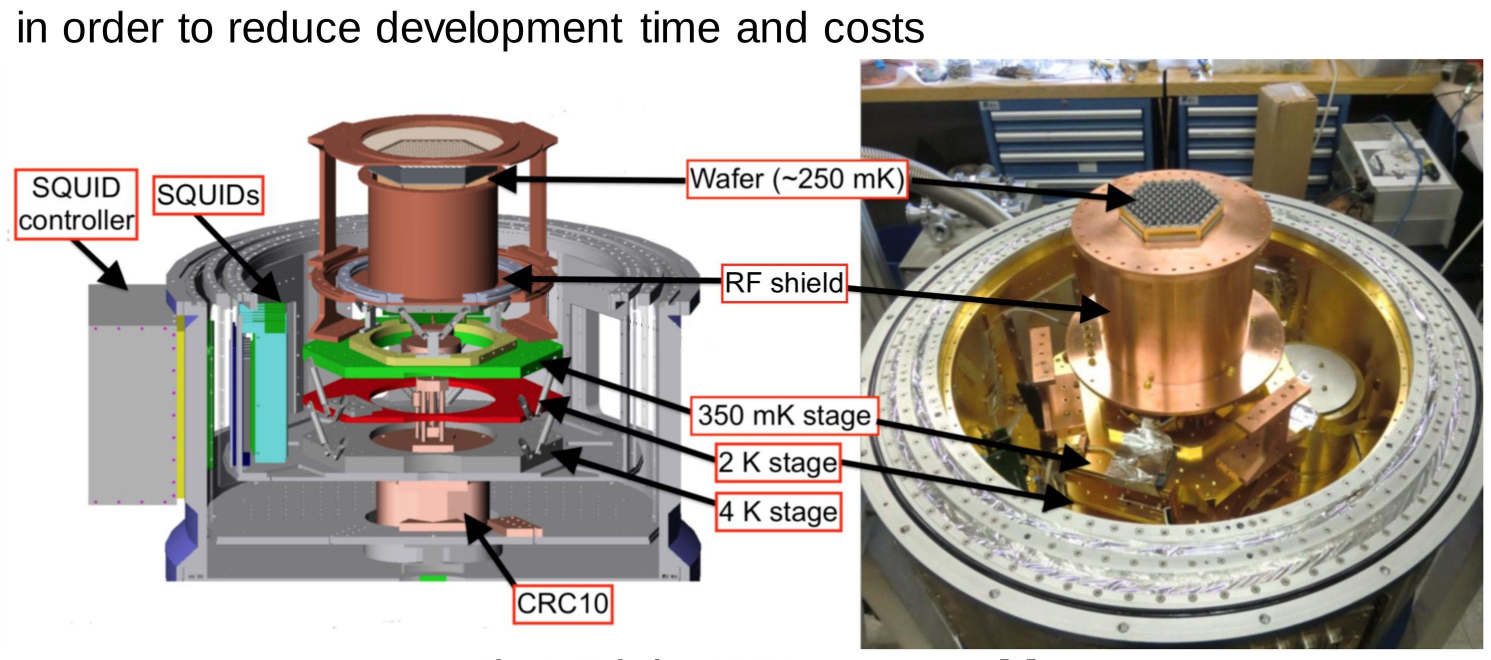

Fig. 1: Existing APEX test cryostat [6]

Testbed cryostat architecture

- A dry (cryogen free) cryostat is used, based around a mechanical cryocooler providing pre-cooling stages to 40 K and 4 K
- Mounted on the 4K stage, a Chase CRC7 ^{3}He/^{4}He sorption cooler [2] provides cooling down to 350 mK
- The 350mK stage precools the MDR and operates the condensation pump which runs the MDR

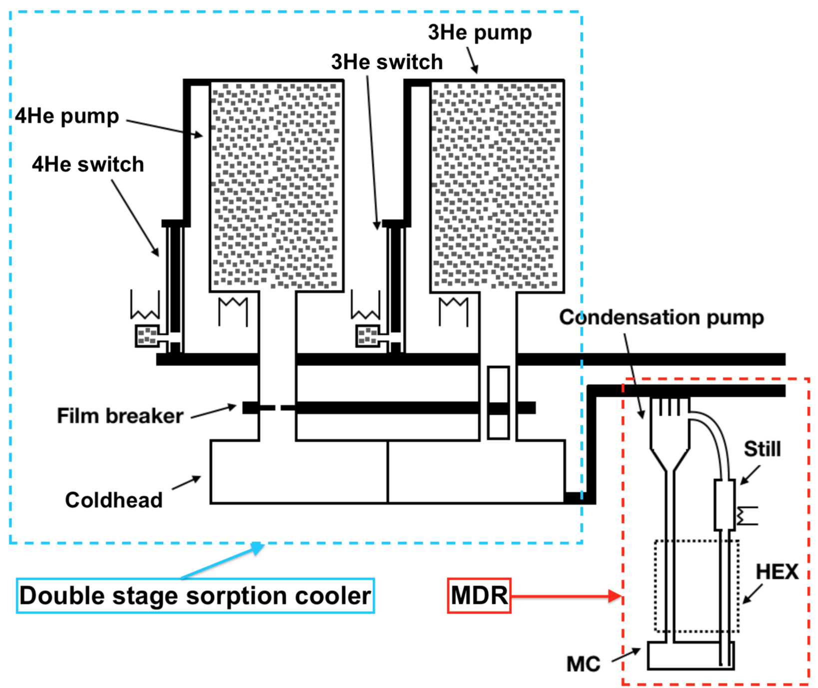

Fig. 2: Schematic figure of CRC7 and MDR [4]

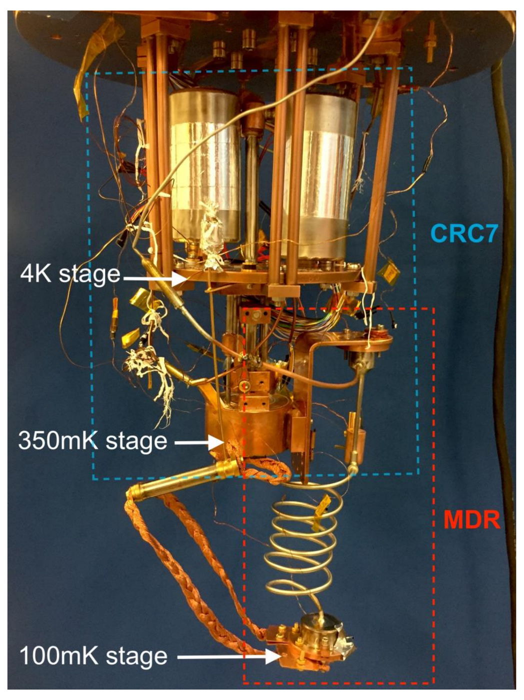

Fig. 3: CRC7 and MDR mounted in test dewar

^{3}He/^{4}He sorption cooler (350 mK stage)

Design

- ^{3}He and ^{4}He charcoal-loaded cryopumps are operated by gas-gap heat switches linked to the 4K stage
- Pumping lines run from the cryopumps down to a condenser block, connected by thin-walled stainless steel tubes to an evaporator
- ^{4}He stage is used to condense ^{3}He in the second stage

Cooler performance

i. System in thermal equilibrium at ~4K (charcoal adsorbs gas)
ii. Cryopumps are heated up to ~50K (gas desorbs)
iii. ^{4}He pump cooled down to pump on liquid ^{4}He in the coldhead (which cools to 900 mK)
iv. Once ^{4}He is exhausted, the ^{3}He side is run (the coldhead goes to 308mK)
v. ^{3}He completely exhausted after ~13 hours

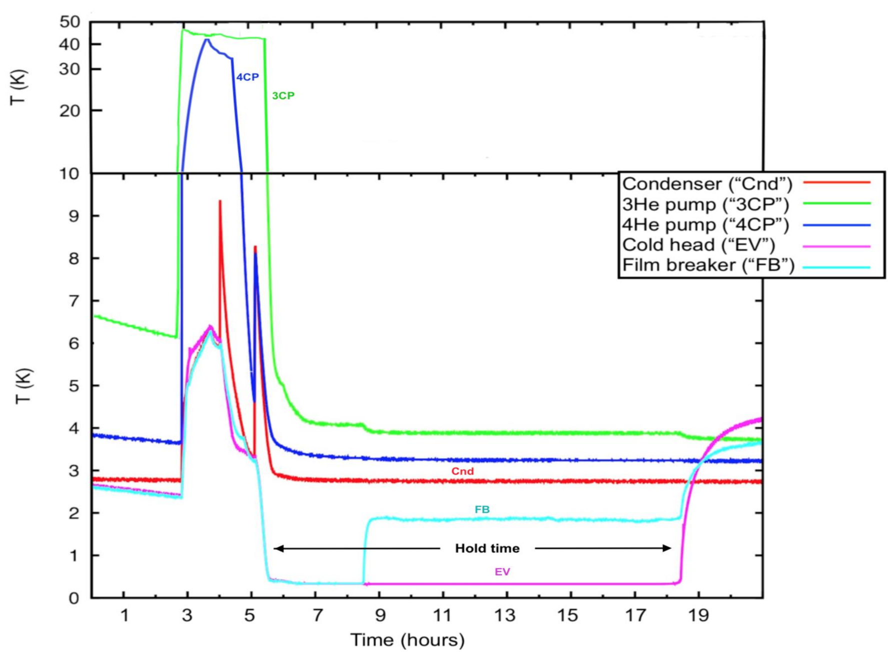

Fig. 4: Experimental cycle of the cooler

Miniature Dilution Refrigerator (100 mK stage)

Design

- Helium is circulated using a condensation pump chamber is mounted to the CRC7 coldhead
- Stainless steel tube-in-tube heat exchanger ("HEX") design is used [7]
- A return line connects the chamber with the mixing chamber ("MC")
- A second tube runs from the MC bottom up to the still
- An active gas-gap heat switch couples the coldhead and the MC to ensure effective precooling of MC

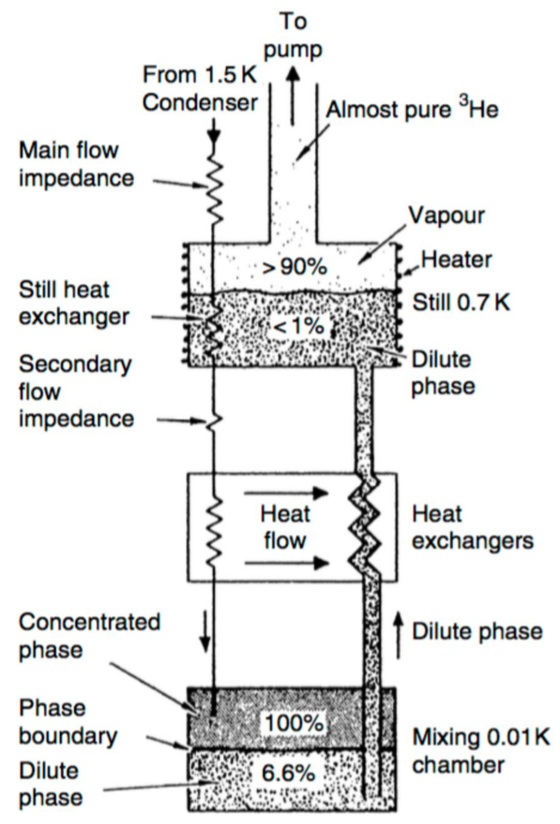

Fig. 5: Diagram of dilution refrigerator [5]

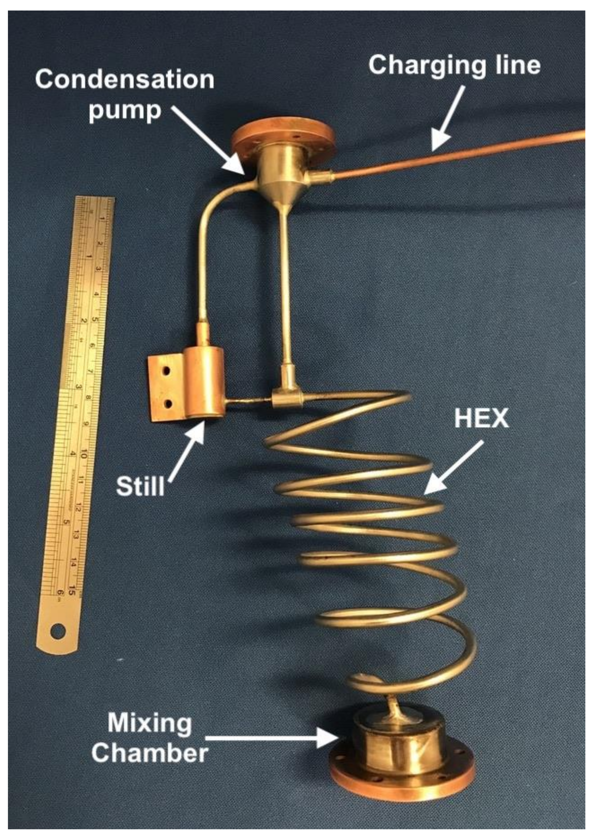

Fig. 6: MDR prototype

Performance

- Need heat lift of 5 µW for 8 hours to support preliminary testing
- Cooling power (assuming perfect HEX): $\dot{Q}_{MDR} = 82\dot{n}T_m^2$ [7]
- Flow rate: $\dot{n}$ = 6 µmol/sec
- Efficient operation of the condensation pump when its temperature is well below that of the still (^{3}He driven by vapour pressure differential)
- Required still power: 144 µW, corresponding to a condenser temperature of 360 mK as shown by the measured load curve

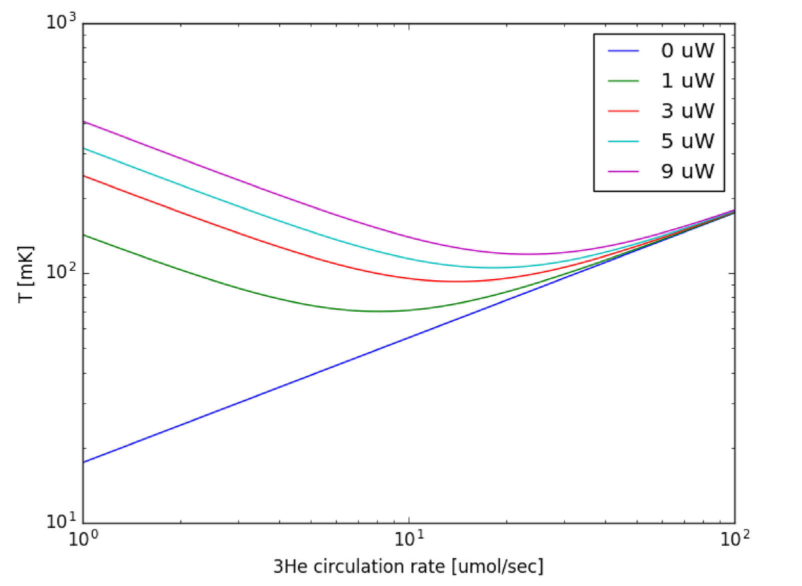

Fig. 7: Lowest achievable temperature as a function of ^{3}He circulation rate for various heat loads

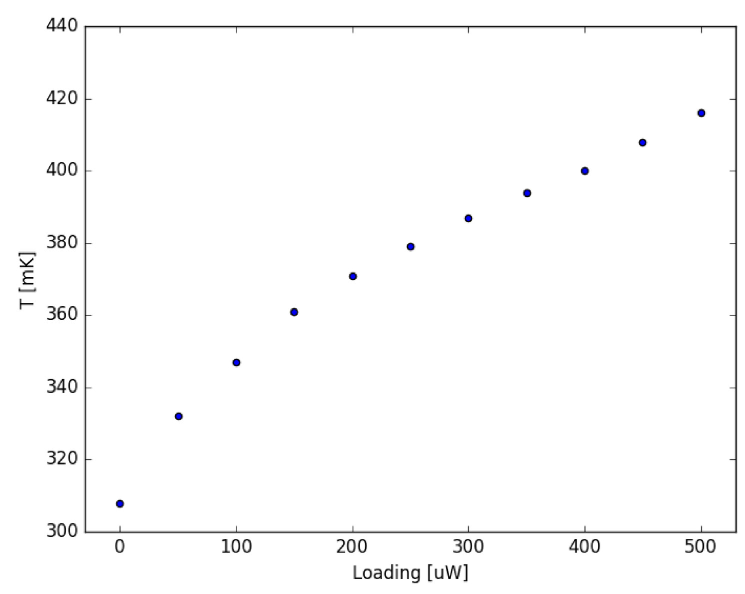

Fig. 8: CRC7 coldhead load curve

- The system will confortably support a flow rate suitable to provide a heat lift at the mixing chamber of up to 10 µW at 100 mK
- The turnaround time for detector wafer testing is minimised by automation of the precooler and MDR cycling down to 100 mK

Future developments

- A prototype has been manufactured, full characterisation awaiting to be reported
- A second version of this MDR as a self-contained unit will be shipped to UC Berkeley to retrofit the CRC10 in the APEX dewar
- Other 250 mK cryostats could be retrofit in the same way

References

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