Primary thermometry and electron cooling: on the way to sub-mK temperatures

Yuri Pashkin

Lancaster University, UK

QT60 - 19 September 2018

International collaboration

Lancaster (UK)

Lancaster Quantum Technology Centre

Ian Bradley, Richard George, Tony Guénault, Rich Haley, Stephen Holt, Alex Jones, Yuri Pashkin, Jon Prance, Matthew Sarsby†

Aivon Oy (Finland)

aivon

Jari Penttila, Leif Roschier*

VTT (Finland)

VTT

David Gunnarsson*, Hannele Heikkinen, Leif Grönberg, Kestutis Grigoras, Mika Prunnila

(* Now at BlueFors Cryogenics)
(† Now at TU Delft)

Measuring temperature

- variety of thermometers
- based on physical effects
- ensure good thermal contact with medium
- secondary vs. primary
- lattice vs. electron temperature
- mK temperature range difficult

Physics | Lancaster University

Primary electron thermometry: Jukka's Coulomb Blockade Thermometer

VOLUME 73, NUMBER 21 PHYSICAL REVIEW LETTERS 21 NOVEMBER 1994

Thermometry by Arrays of Tunnel Junctions

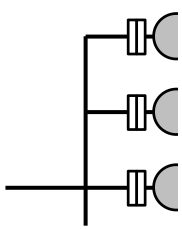
J. P. Pekola, K. P. Hirvi, J. P. Kauppinen, and M. A. Paalanen
Laboratory of Applied Physics, Department of Physics, University of Jyväskylä, P. O. Box 35, 40351 Jyväskylä, Finland
(Received 13 July 1994)

We show that arrays of tunnel junctions between normal metal electrodes exhibit features suitable for primary thermometry in an experimentally adjustable temperature range where thermal and charging effects compete. *I-V* and *dI/dV* vs *V* have been calculated for two junctions including a universal analytic high temperature result. Experimentally the width of the conductance minimum in this regime scales with *T* and *N*, the number of junctions, and its value (per junction) agrees with the calculated one to within 3% for large *N*. The height of this feature is inversely proportional to *T*.

$k_B T$

$E_C = e^2/2C_\Sigma$

Conducting islan ... on



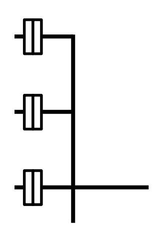
Primary thermometer:

$V_{1/2} \approx 5.44 N k_B T/e$

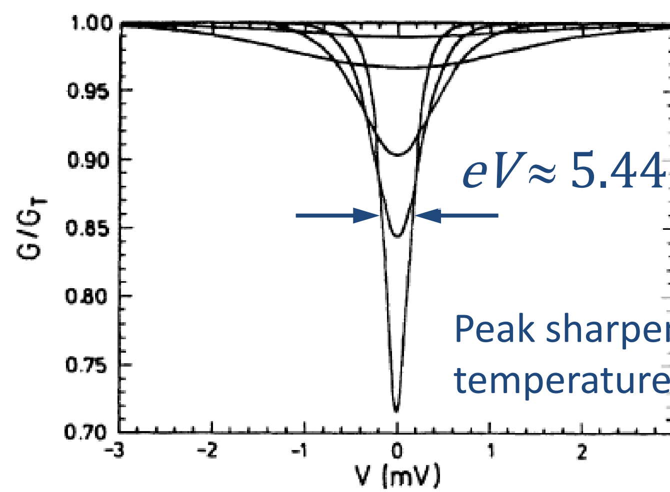
Secondary mode:

$G(0) = G_T(1 - u/6 + \dots)$

$u = (e^2/C_\Sigma)/k_B T$



Measure total conductance G of array as a function of bias voltage V



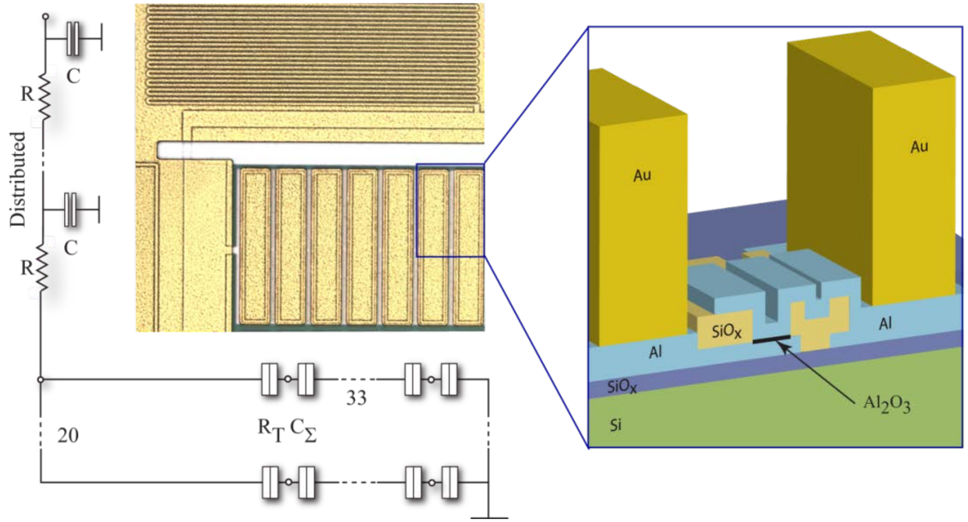
VTT/Aivon CBT design

Physics | Lancaster University

Optimised for sub-10mK operation:

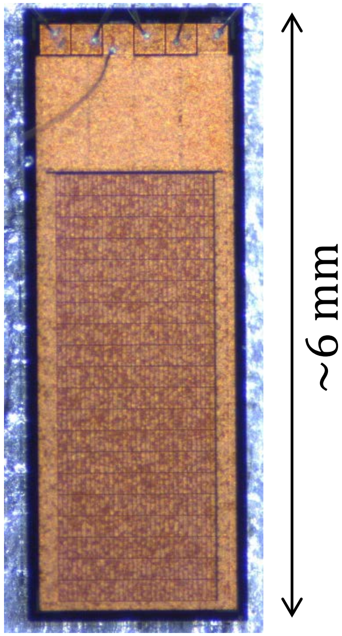
- **On-chip, distributed RC filters.**
- **Large cooling fins (≈ 205 x 40 x 5 μm^3) provide electron-phonon coupling**
- **32 × 20 arrays of Al islands**

VTT aivon

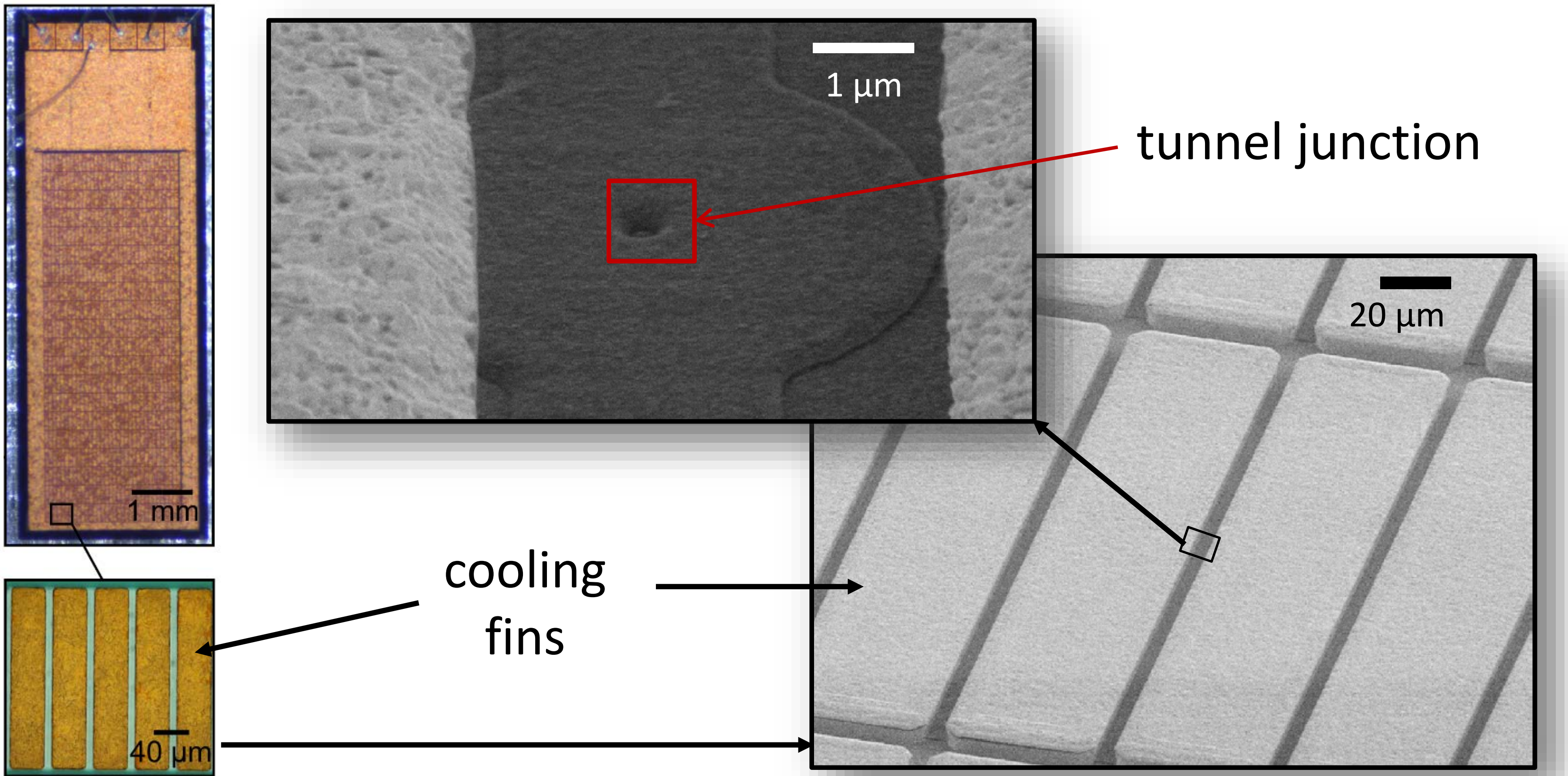


Some measurements were made with products from Aivon (Finland)

- PA-10 current source and voltage preamplifier
- Low-temperature RC filters



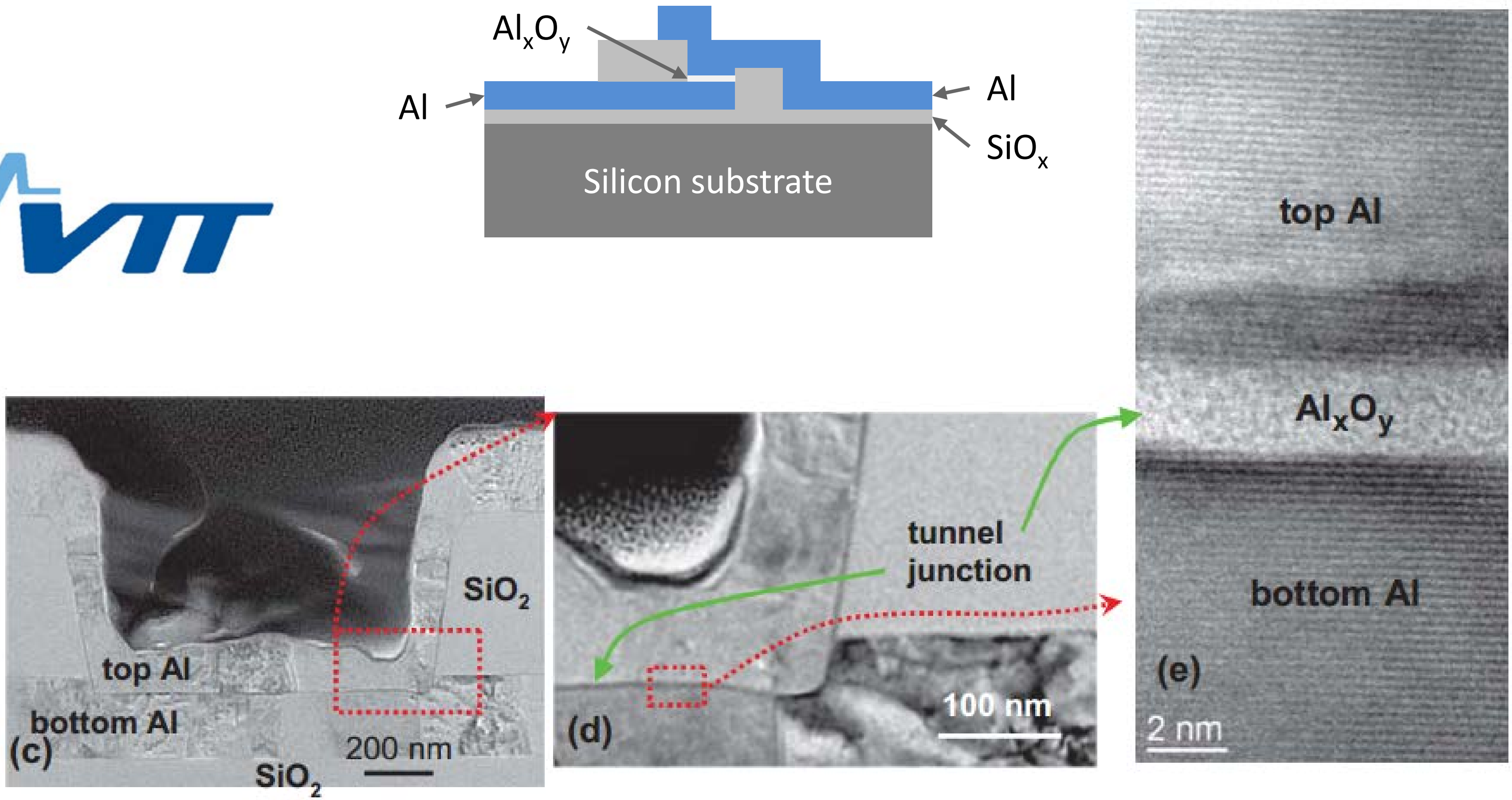
CBT fabrication



CBT fabrication

Physics Lancaster University

Instead of the commonly used angle deposition, a multi-layer ex-situ process was used



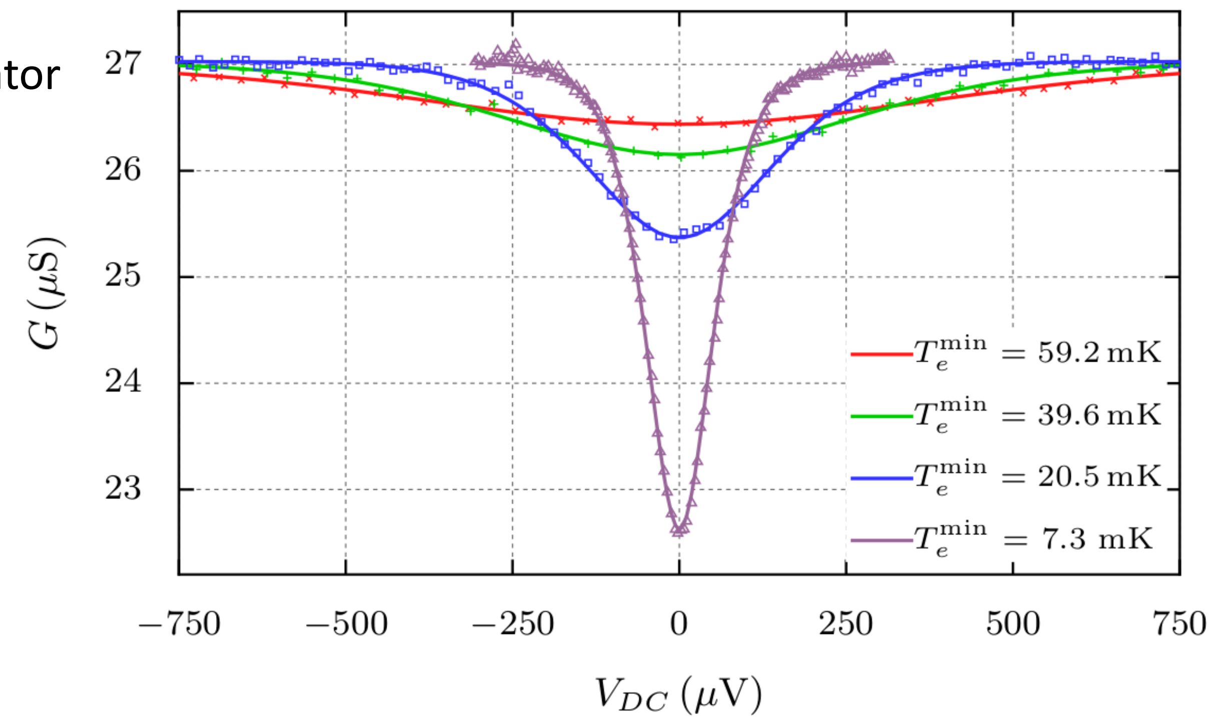
Prunnila et al., J. Vac. Sci. Tech. B **5**, 1026 (2010)

CBT performance down to 7 mK

Physics | Lancaster University

Bradley et al., Nat. Commun. **7**, 10455 (2016)

Measured in a commercial, cryogen-free dilution refrigerator (BlueFors Cryogenics LD250)



Warmest three isotherms are fitted (simultaneously) to calibrate the CBT. The fit gives $C_\Sigma = 236.6$ fF and $R_T = 22.42$ kΩ

The actual temperature of the measurements does not need to be known because the CBT is a primary thermometer.

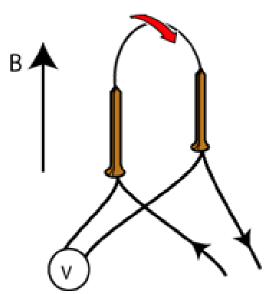
The fitted C_Σ and R_T are used to relate peak height to electron temperature.

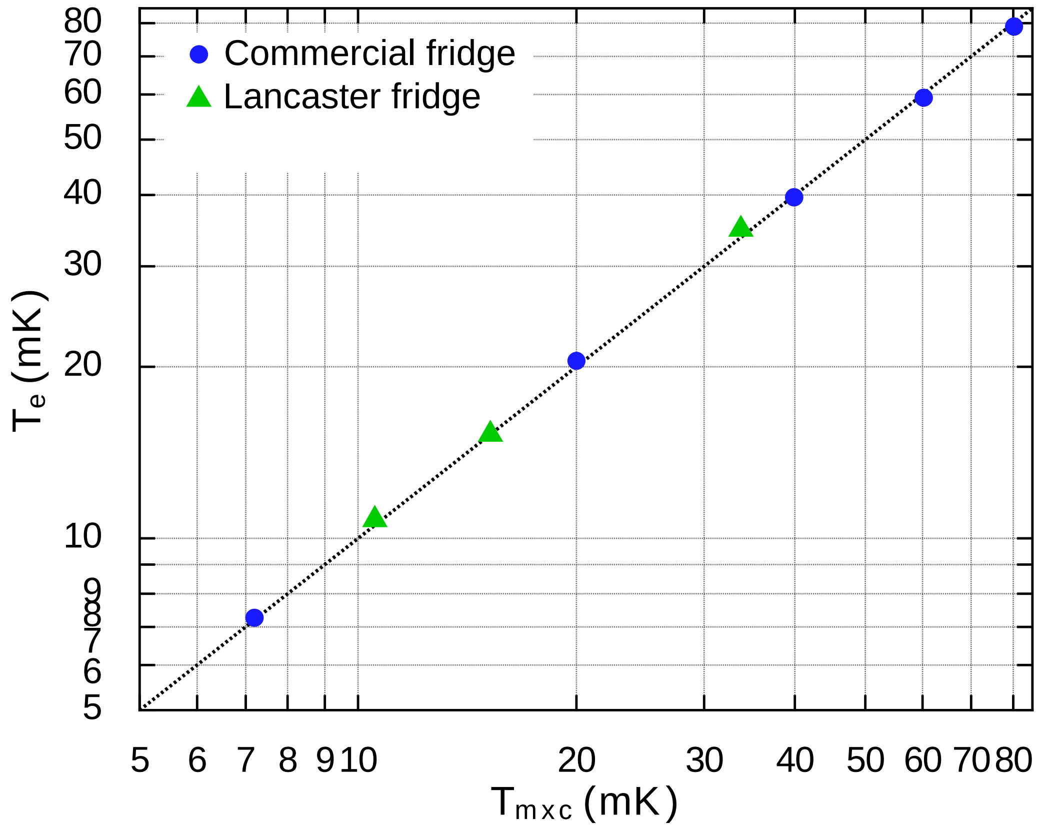
CBT performance down to 7 mK

The same CBT was also measured in a custom dilution refrigerator (Lancaster design)

In the commercial fridge, base temperature (T_{mxc}) is measured using a calibrated RuO_2 resistor.

In the custom fridge, T_{mxc} is determined from viscosity of the refrigerant, measured using a vibrating wire loop.



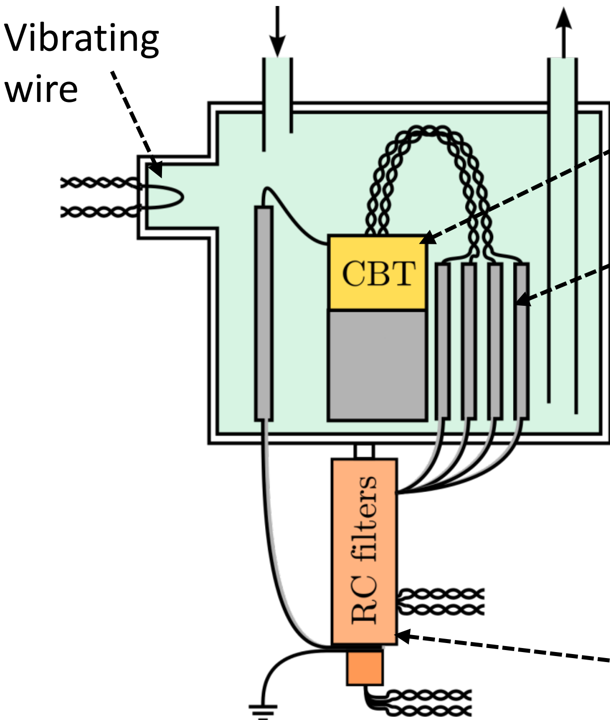


The CBT temperature T_e matches the refrigerator temperature T_{mxc} down to ≈ 7 mK

Physics | Lancaster University

CBT immersed in $^3He/^4He$ mixture

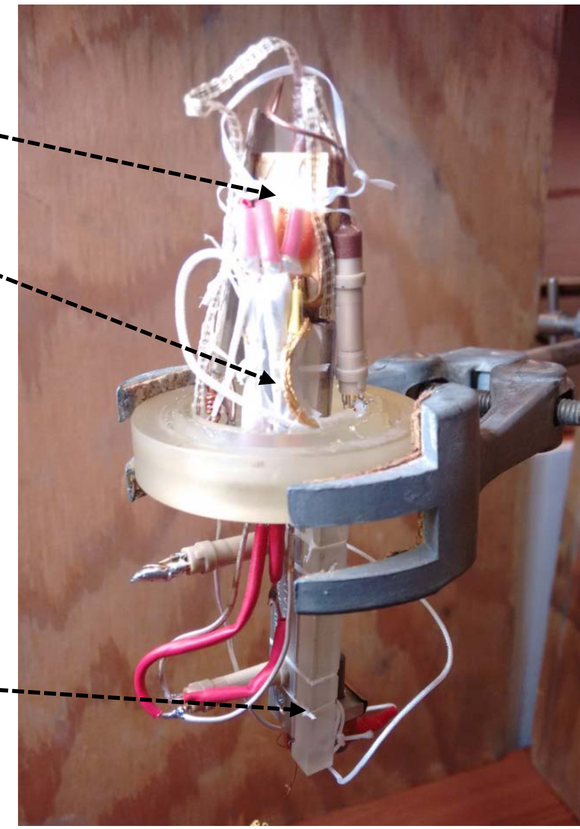
A cell was built to immerse a CBT in the mixing chamber of a dilution fridge



CBT package

Sintered silver heat-sink (x 6)

RC filters, connected to sinter pad inside mixing chamber.

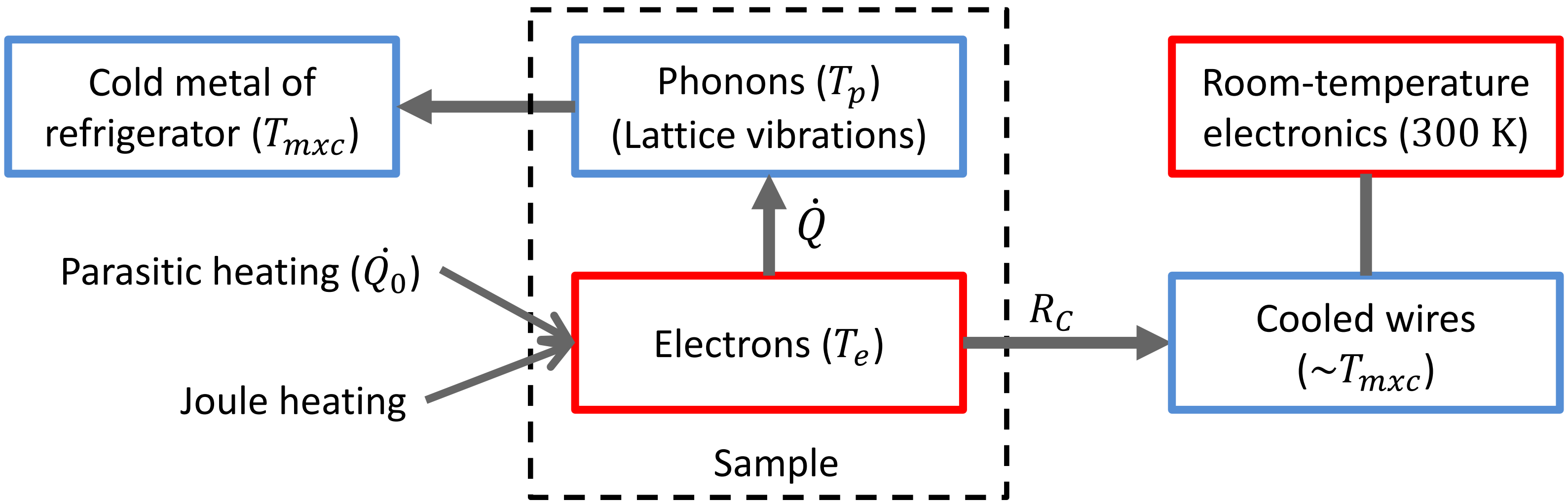


Blocks of sintered silver powder make excellent thermal contact with the refrigerant due to their high porosity and immense service area.

Cooling a nanoelectronic sample

Physics | Lancaster University

Normal method: attach your sample to the coldest point of the refrigerator.



Problem: electron-phonon coupling is very weak in small structures at low temperatures.

Heat flow from the electrons to the phonons:

$$\dot{Q} = \Sigma\Omega\left(T_e^5 - T_p^5\right)$$

F.C. Wellstood et al., PRB **59**, 4952 (1994)

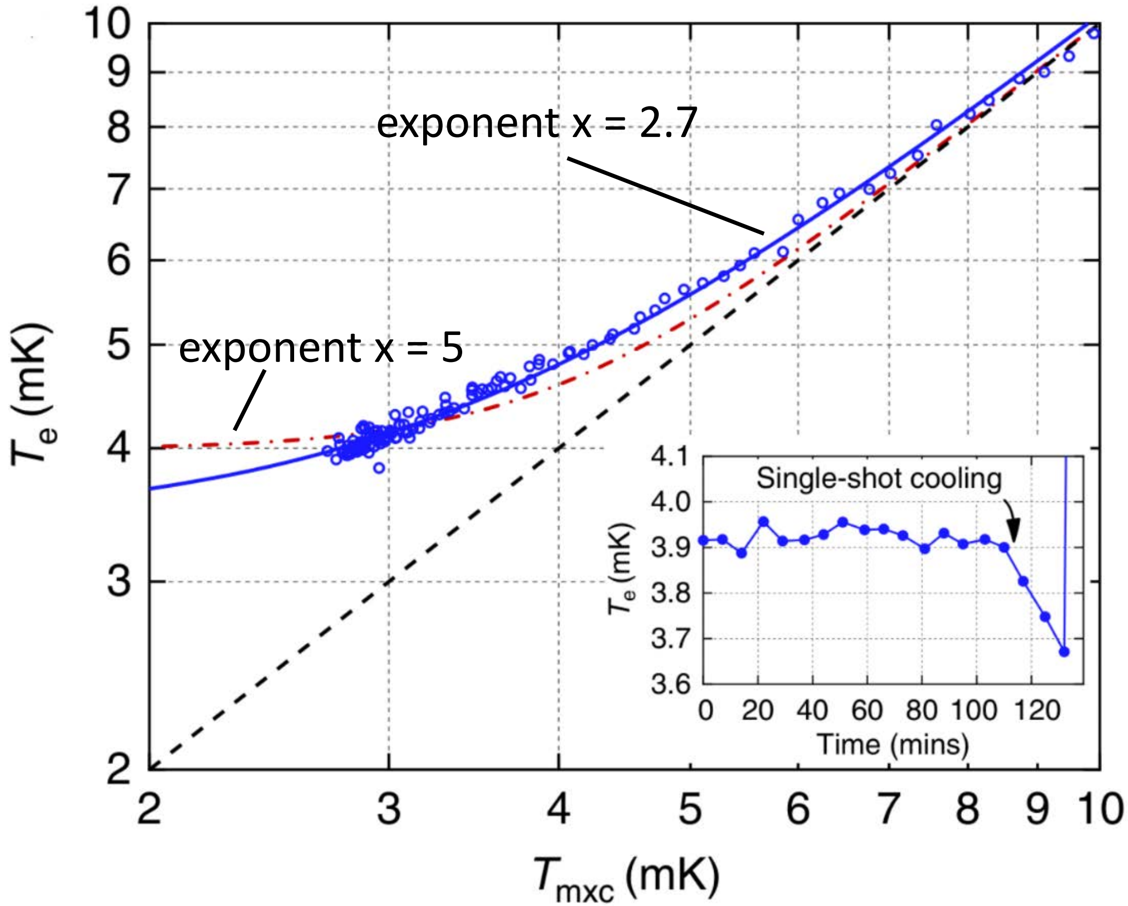
Electrons in the sample are often at a different temperature to the phonons

= **hot-electron effect**

CBT immersed in $^3He/^4He$ mixture

Physics | Lancaster University

Bradley et al., Nat. Commun. **7**, 10455 (2016)



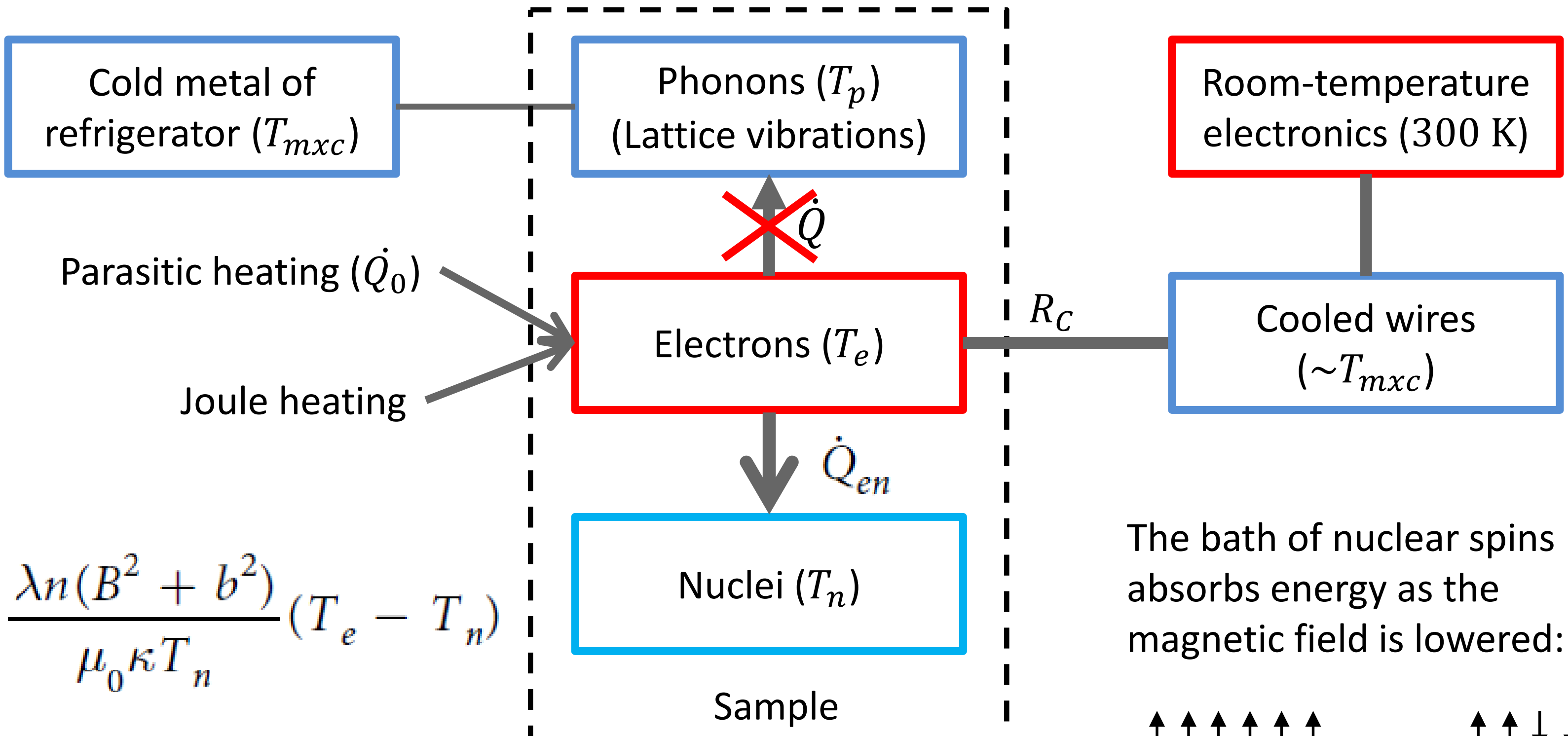
Below 7 mK, the electron temperature reported by the CBT no longer agrees with the temperature of the refrigerator (as measured by a vibrating wire viscometer)

⇒ Electrons and phonons not in thermal equilibrium.
Cooling through direct contact is insufficient.

On-chip magnetic cooling

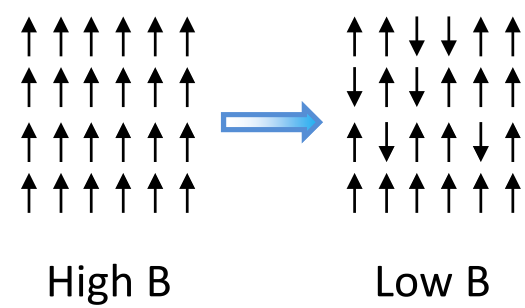
Physics | Lancaster University

New method: cool on-chip electrons directly through the magnetocaloric effect



$$\dot{Q}_{en} = \frac{\lambda n (B^2 + b^2)}{\mu_0 \kappa T_n}(T_e - T_n)$$

The bath of nuclear spins absorbs energy as the magnetic field is lowered:

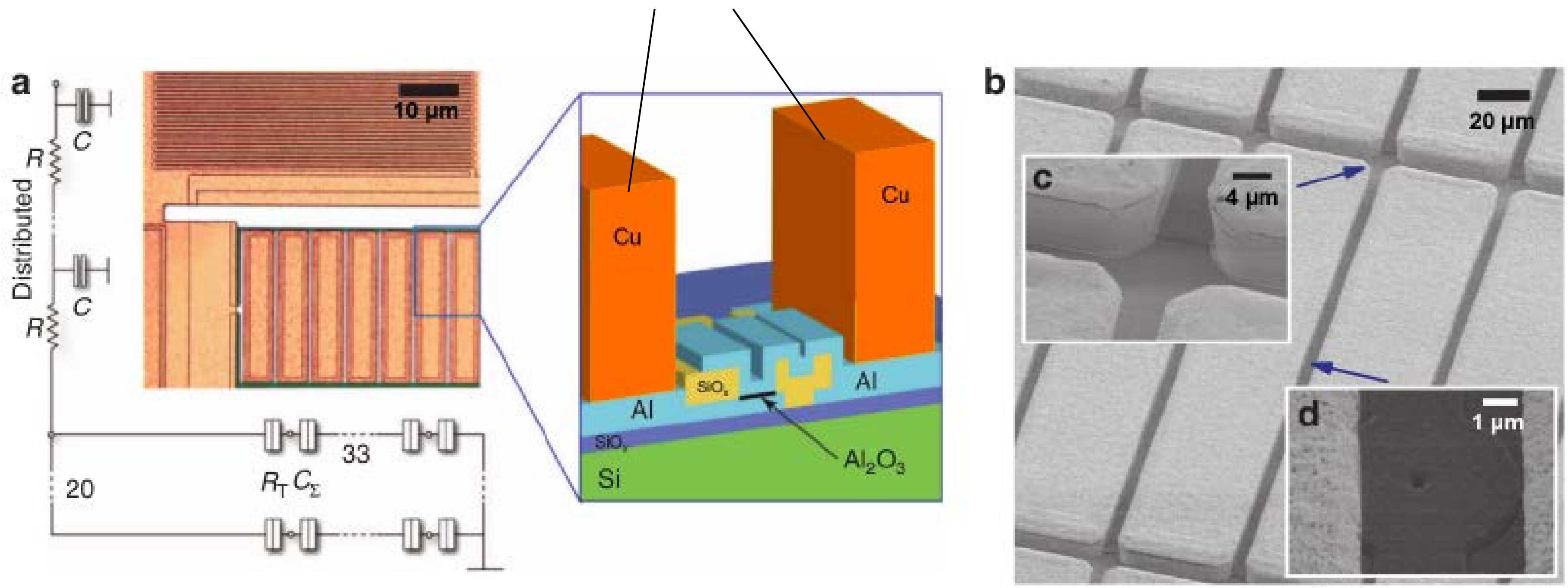


Weak electron-phonon becomes an advantage: electrons are isolated from their host lattice.

CBT design for on-chip cooling

Same an ex-situ tunnel junction process used

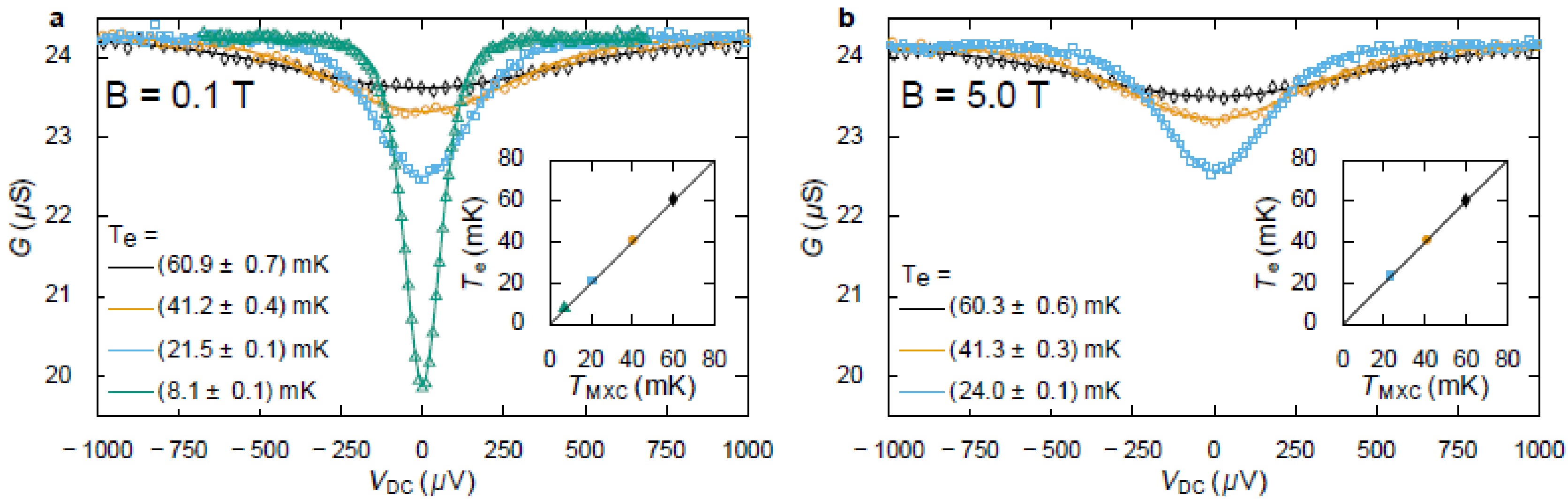
Cu nuclei used as refrigerant for electrons



Prunnila et al., J. Vac. Sci. Tech. B **5**, 1026 (2010)

Sample calibration with and w/o magnetic field

Physics | Lancaster University



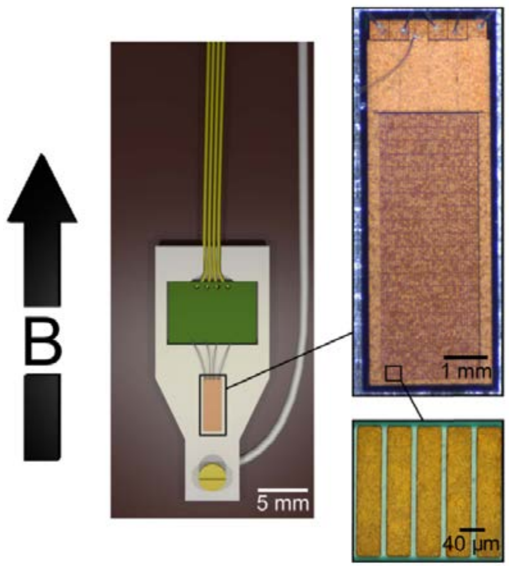
Field (T)	C_Σ (fF)	R_T (kΩ)
0.1	192.4 ± 0.9	24.99 ± 0.06
5.0	191.9 ± 0.8	25.10 ± 0.06

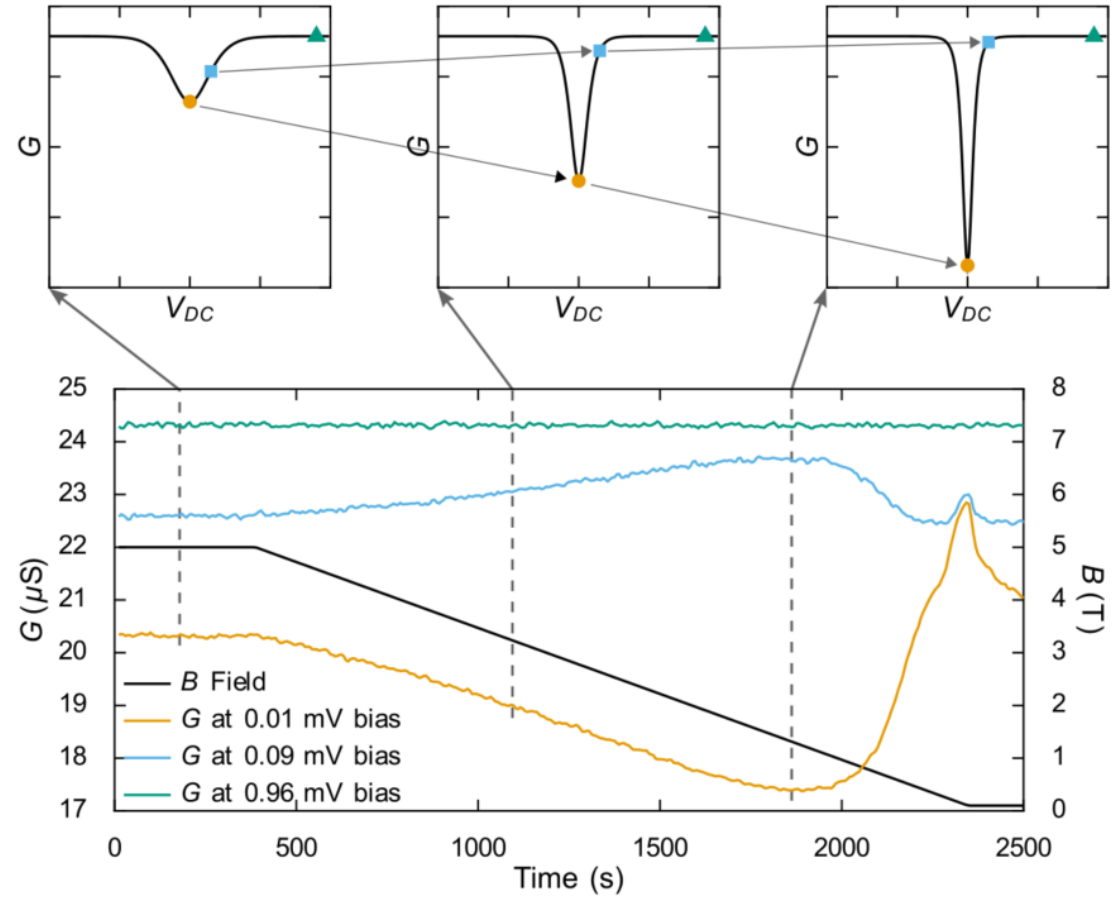
Physics | Lancaster University

Magnetic cooling of a CBT

Bradley et al., Sci. Rep. **7**, 45566 (2017)

Demagnetisation of a CBT in a commercial, cryogen-free dilution refrigerator:





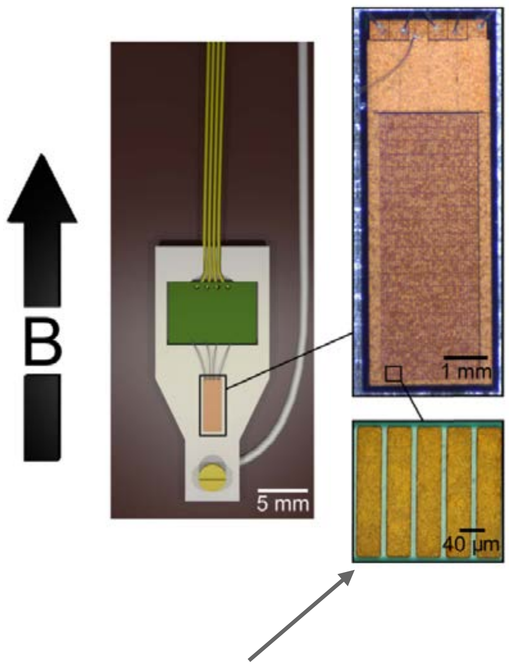
CBT islands are electroplated with copper (refrigerant)

Magnetic cooling of a CBT

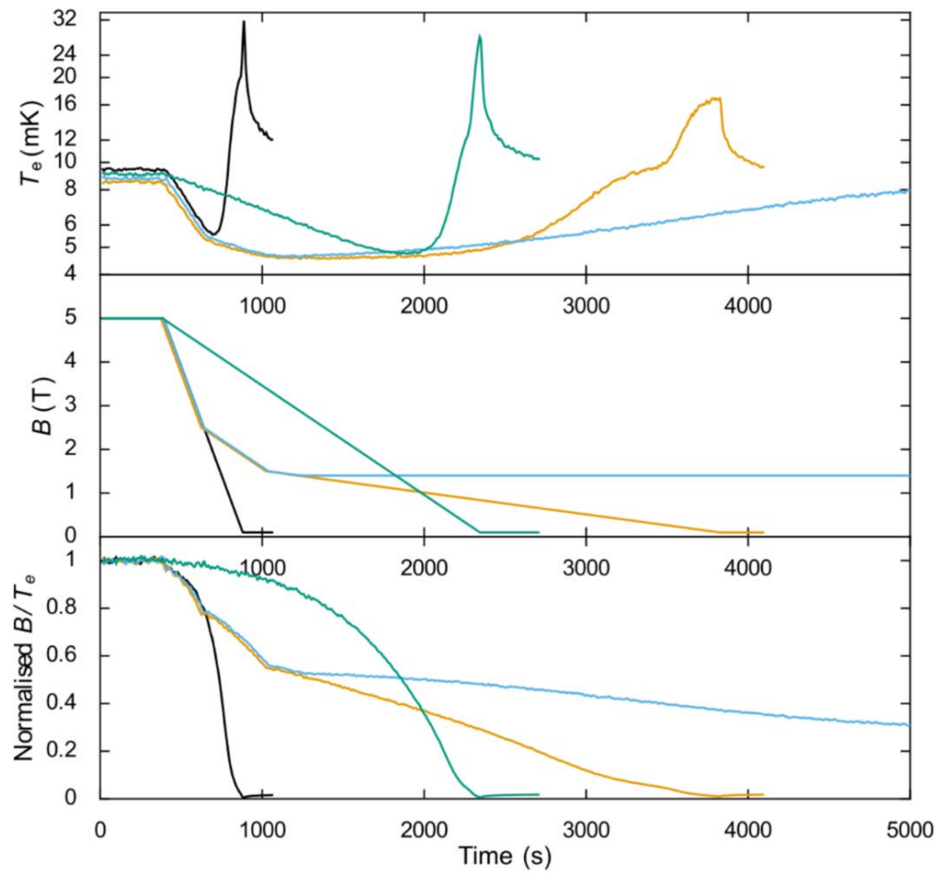
Physics | Lancaster University

Bradley et al., Sci. Rep. **7**, 45566 (2017)

Demagnetisation of a CBT in a commercial, cryogen-free dilution refrigerator:



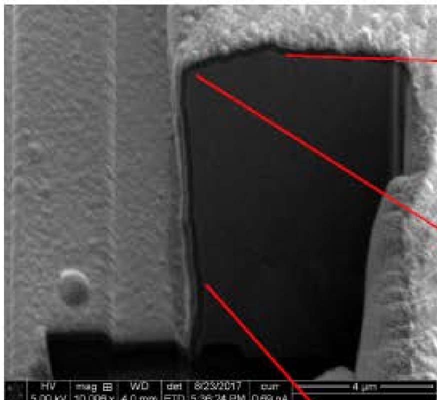
CBT islands are electroplated with copper (refrigerant)

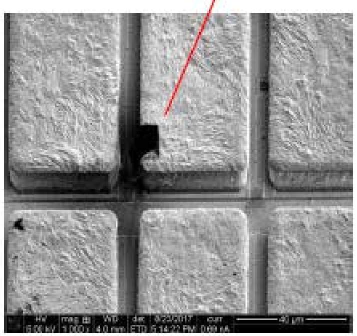


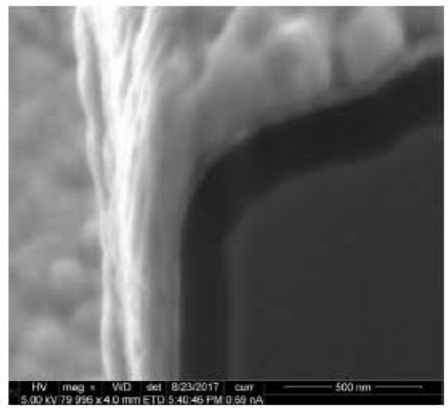
Best result: CBT cooled from $9\ \mathrm{mK}$ to below $5\ \mathrm{mK}$ for over 1000 seconds.
Next step: target $< 1\ \mathrm{mK}$ by starting colder and in a larger magnetic field

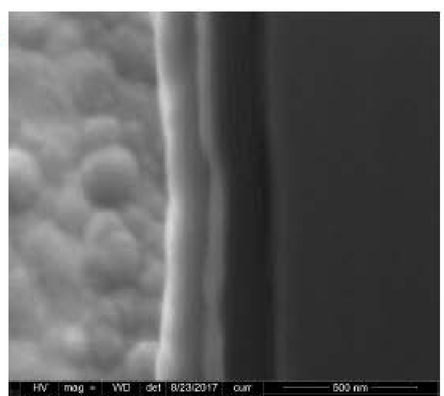
Modification to CBT design for on-chip cooling

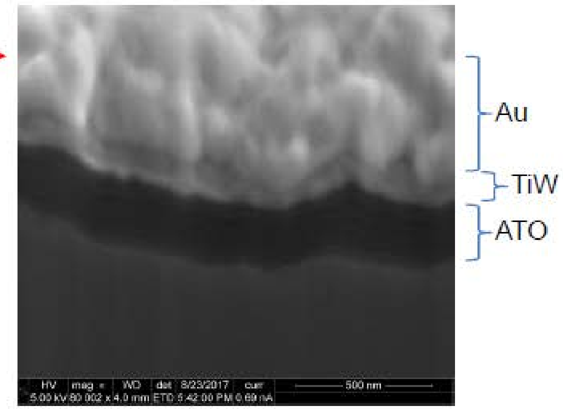
Issue: capacitance too small for ~ 1 mK operation, CBT fully blockaded
increase by adding an extra metal layer











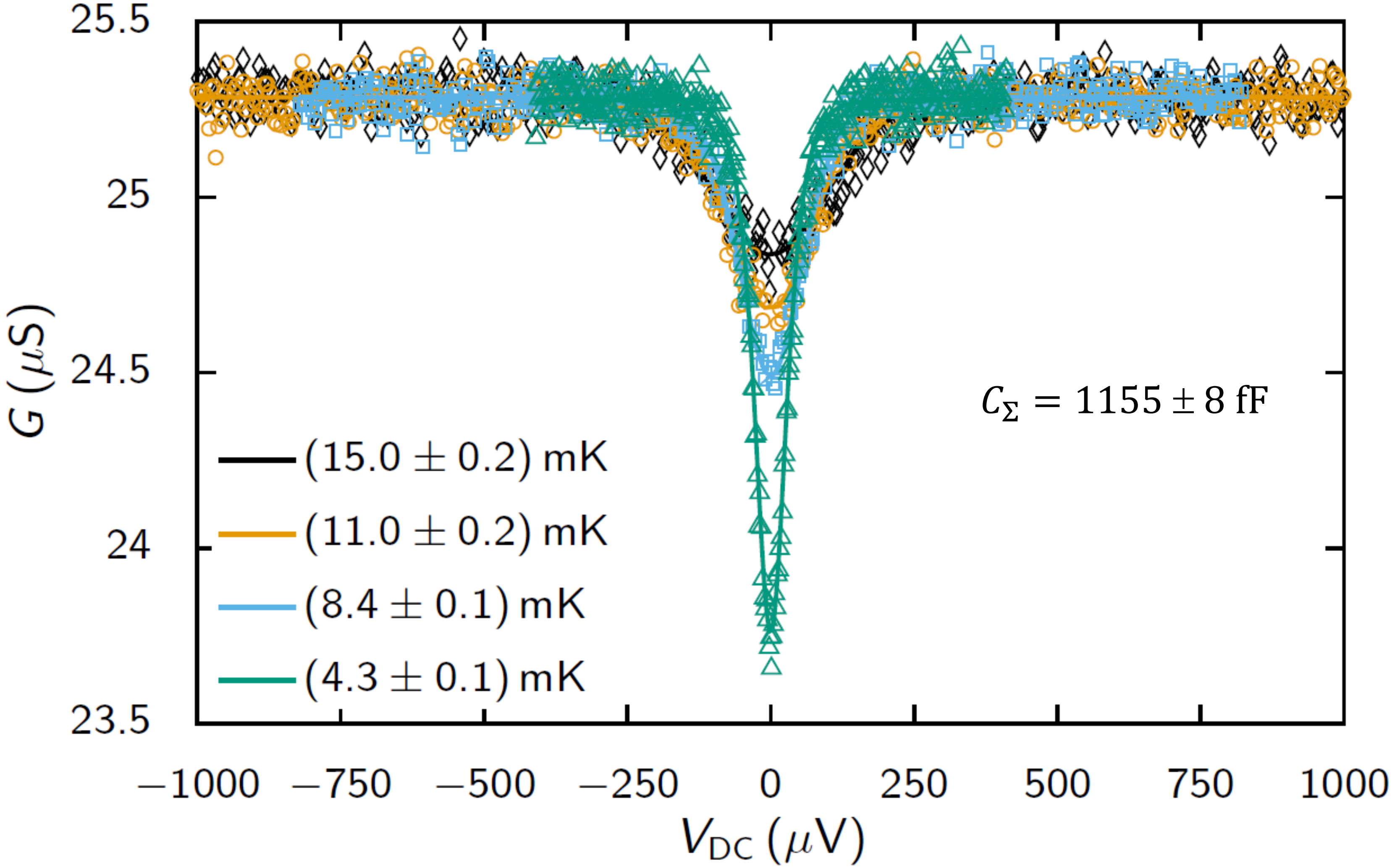
SEM pictures of 52° tilted sample

conformal layers

bottom: 150 nm Al_2O_3/TiO_2
top: 35 nm AuW and 160 nm Au

Calibration with large C

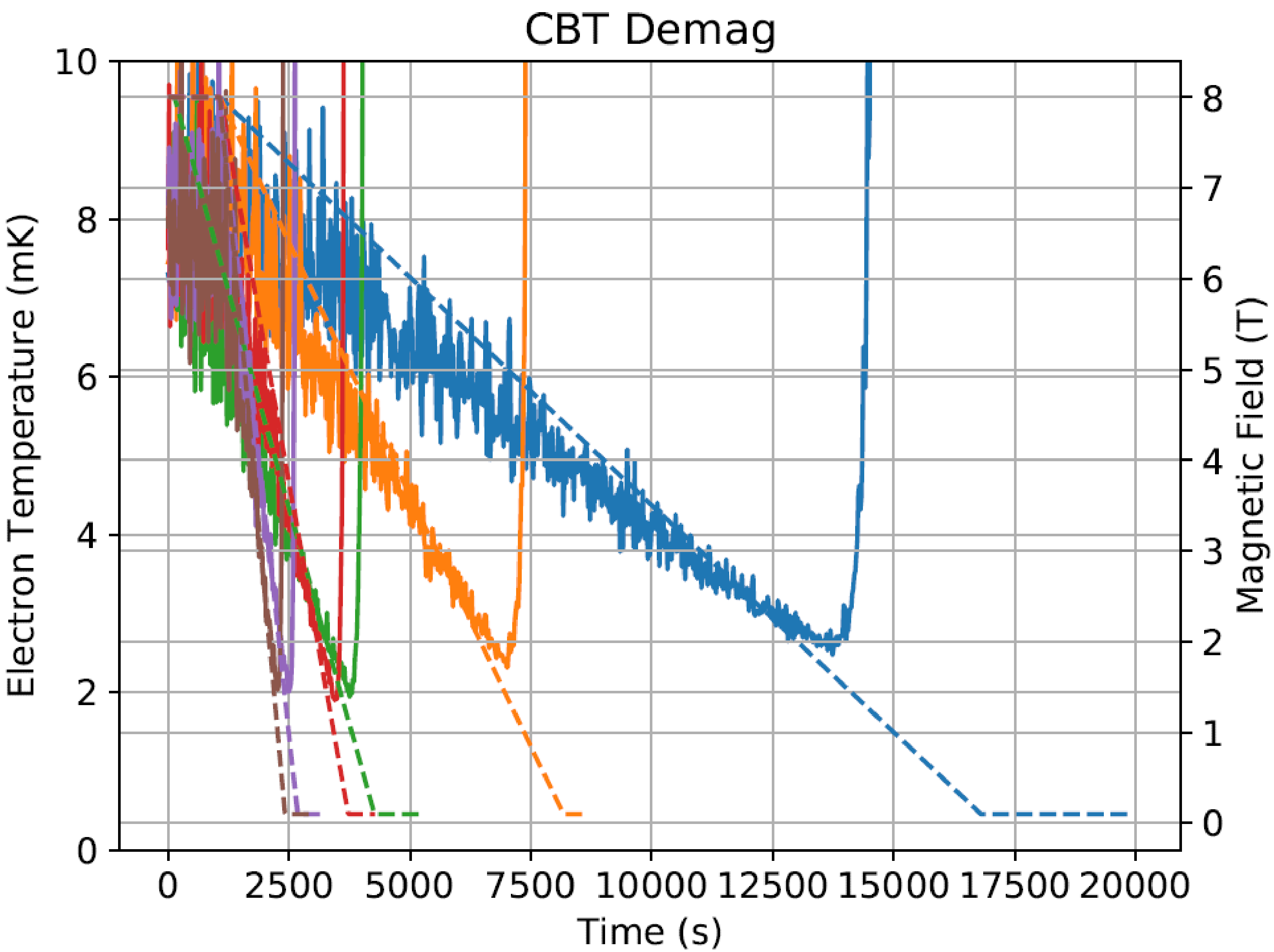
taken in a home-made dilution refrigerator



Sweeps with various rates

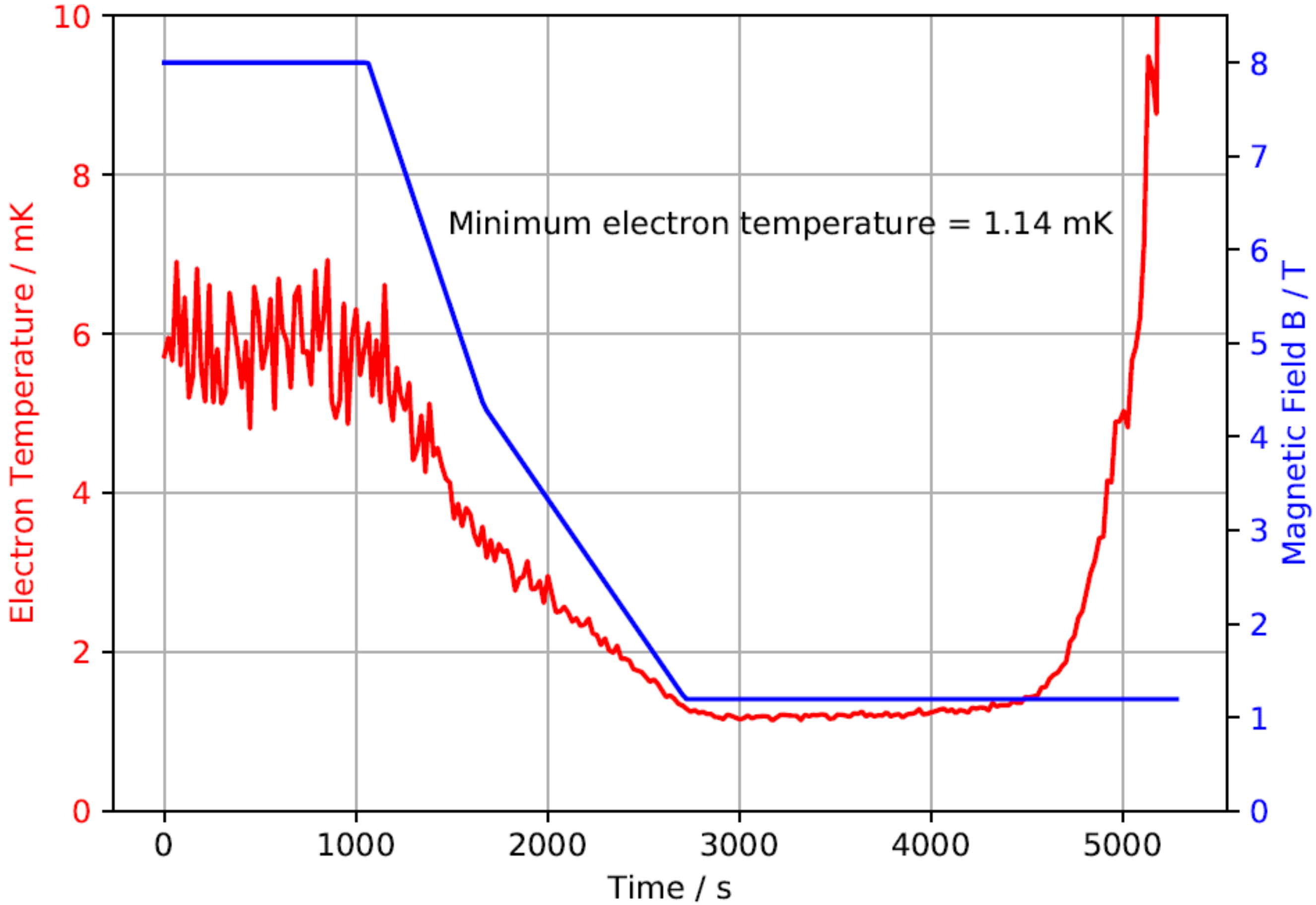
Physics | Lancaster University

taken in a home-made dilution refrigerator



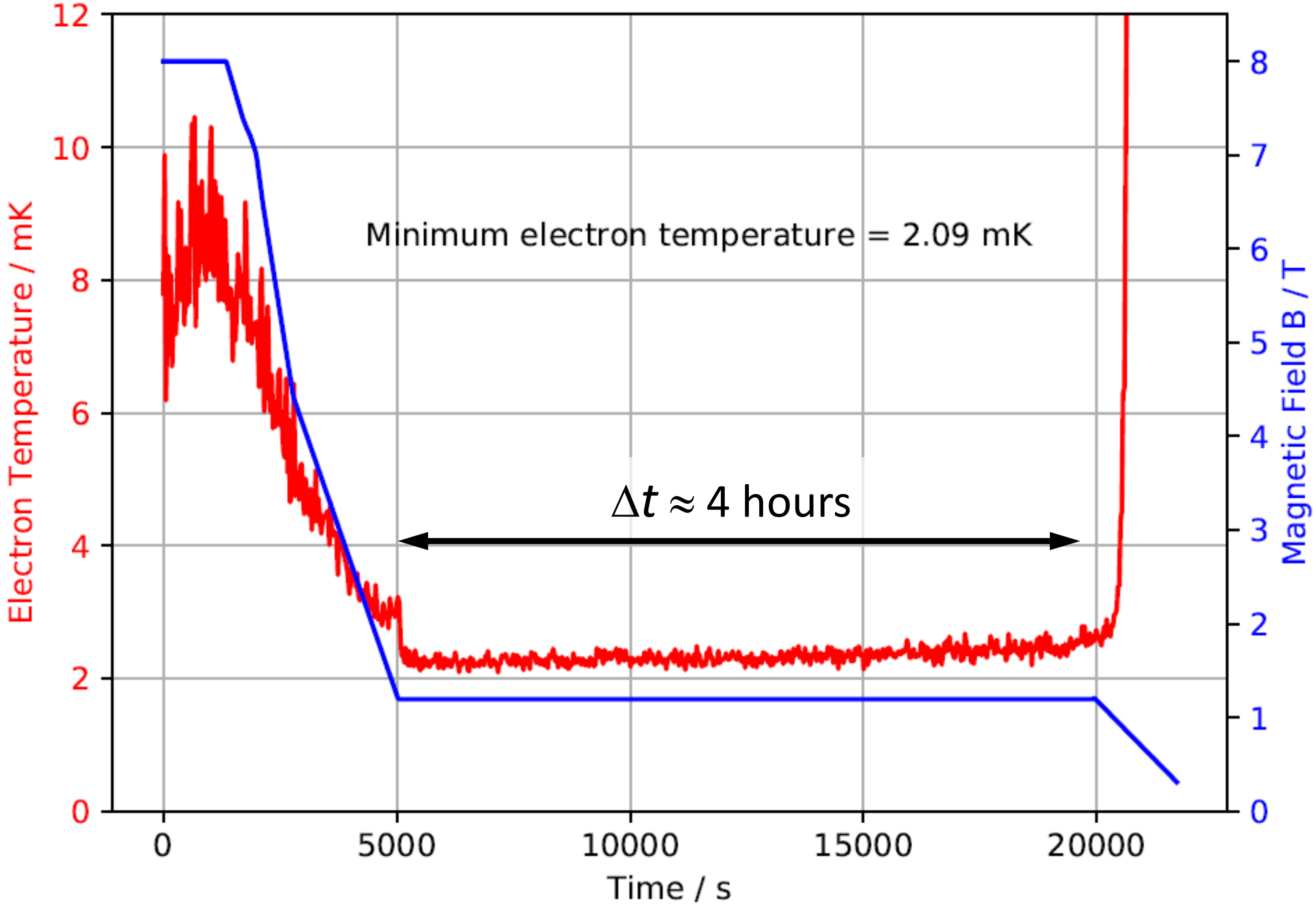
Most recent data

taken in a home-made dilution refrigerator



Most recent data

taken in a home-made dilution refrigerator
thermally decoupled sample stage



Summary

CBT works down to $\sim 1\,\mathrm{mK}$

Passive electron cooling down to $3.6\,\mathrm{mK}$
fridge temperature 2.4 mK

On-chip demag cooling down to $1.14\,\mathrm{mK}$

Cooled to $2\,\mathrm{mK}$ for $\sim 4\,\mathrm{hours}$