Cryogen-free Dilution Refrigerator Systems as Environments for Quantum Computation

Dr A J Matthews
Oxford Instruments NanoScience
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Classical Vs Quantum Computation

Classically, information is processed using binary encoding.

Each ‘bit’ has two possible states: 0 or 1.

In a quantum computer quantum bits (qubits) can be 0 or 1, but they can also be both at the same time!

\[ \alpha |0\rangle + \beta |1\rangle \]

\[ |\alpha|^2 + |\beta|^2 = 1 \]

Quantum algorithms process information stored on qubits prepared in a superposition of their basis states in a way that evaluates both possible input values. For multiple qubits the computation is evaluated for all possible input states simultaneously.

Quantum computers have the potential to massively outperform classical computers for certain classes of problems. But…
We need to build a quantum computer!

The first step is to identify a suitable qubit – there are many options being pursued: in the solid state the two most actively researched are single electron spins in quantum dots and superconducting circuits with Josephson junctions.
Solid state qubits are fragile

To ensure the fidelity of the quantum superposition of states we prepare, any thermal fluctuations must be small compared to the energy gap between our quantum states.

Typically we need temperature below a few tens of milli-Kelvin.

And we need lots of them

To outperform classical computers, a quantum computer will need > 100 qubits – each of which will needs to be addressable.

We’ll need lots of wiring.

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Traditional Dilution Refrigerator Technology 1

Isotopic mixture of 3He and 4He used to obtain cooling.

Continuous process providing cooling powers up to \(~ 1 \text{ mW at 100 mK}\).

Minimum temperatures \(~ 5 \text{ mK}\).
Traditional Dilution Refrigerator Technology 2

The cold environment for the dilution refrigerator is generated by evaporating liquid cryogens.

4He at 4.2 K

(N2 at 77 K)

Helium is a scarce, diminishing and, therefore, expensive resource.

Use as little as possible and make it last as long as possible.
Traditional Dilution Refrigerator Technology
- Weaknesses for QIP 1

Even “low-loss” dewars require filling every few days:
- Manpower
- Infrastructure
- Experimental uptime
- Health and safety considerations
Traditional Dilution Refrigerator Technology

- Weaknesses for QIP 2

The need for a narrow neck in the helium dewar to keep the boil off to an acceptable level means that the space available for experimental wiring and other experimental services is limited.

The cold vacuum seal also means hermetically, sealed, cryogenically compatible wiring feed-throughs are required in addition to the room temperature fittings. This also makes heat-sinking of wiring difficult.

Traditional dilution refrigerator technology enables the generation of cold environments, but is not necessarily well suited for generating useful experimental (computational) platforms.
The alternative to “wet” technology

Two stage pulse tube coolers to provide the cold environment for dilution refrigerators.

Room temperature helium compressor.

No moving parts at the cold stages.

Typically ~ 1 W cooling power at 4.2 K
    ~ 40 W cooling power at 45 K

Service interval ~ 20 000 hours.

Removes the need for liquid cryogens.

No boil off considerations to dictate the platform design....
The Triton concept

- Turbo Pump
- Still pumping line
- Condenser line
- PTR 1st stage HX
- PTR regenerator HX
- PTR 2nd Stage HX
- Still pumping line HX
- Impedance
- Still / still HX
- Continuous HX
- Step HX
- Mixing chamber
- L.E.C.S.H.
- Magnet
- PTR
- Vacuum can
- Pre-cool line HX
- 50 K plate / shield
- 4K plate / shield
- Still plate / shield
- 100 mK plate
- MC plate
- Magnet support plate
- Demountable still shield extension
The Triton cryogen-free dilution refrigerator

- No liquid cryogens
- Base temperature < 10 mK
- Cooling power 400 μW at 100 mK
- Temperature control possible > 30 K
- No IVC (only room temperature o-ring)
- 240 mm diameter mixing chamber plate
- Open structure for easy experimental access
- Fully automated cool down from room temperature in < 24 hours

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Experimental services, heat sinking and available cooling powers...

- 50 K : 10s of W
- 4 K  : 100s of mW
- 1 K  : 10s of mW

60 mm central access, 50 mm LoS, 2 x 40 mm LoS plus non-LoS ports.

Space on fridge plates for bulkhead feedthroughs and wiring clamps for thermal anchoring.
Open structure allows easy access to fit and to thermally anchor effectively all experimental services.
24 off UT85 coax
40 GHz connectors
40 GHz attenuators
Integrated superconducting magnets
Sample exchange

Allow cold loading of samples for rapid turnaround.

Top or bottom loading available.
Top load through the central access of the fridge.

Use rotating baffles to shield from thermal radiation.

8 off UT-85 coaxial lines and 24 off DC lines heat sunk on the fridge.

Sample temperatures below 10 mK when puck is cold loaded into the system.
MultiQubit Systems Based on Electron Spins in Coupled Quantum Dots

Special bottom loading sample holder (loaded directly into magnet bore)

14 off SMP coaxial connectors (40 GHz) and 51 DC connectors
Integration of superconducting magnets with cryogen-free dilution refrigerator systems

G. Batey, M. Buehler, M. Cuthbert, T. Foster, A.J. Matthews *, G. Teleberg, A. Twin

Oxford Instruments NanoScience, Tubney Woods, Abingdon, Oxon OX13 5QX, UK

ABSTRACT

There has been much recent research interest into “cryogen-free” dilution refrigerators. Cryogen-free systems have some advantages from a safety and convenience point of view as liquid cryogens are unnecessary. However, this also makes integrating the low-temperature system with a high magnetic field environment much more challenging. Here we shall describe recent successes of integrating superconducting magnets and dilution refrigerators into one system requiring a single pulse tube cooler. The resulting environment provides experimental temperatures between 7 mK and 30 K and magnetic fields up to 12 T. We shall describe the effects of AC loss heating in such systems on the pulse tube refrigerator when the field is ramped and also the effects of eddy current heating on the mixing chamber in sweeping fields.

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