UNIVERSITY OF SUSSEX

Towards Sideband Cooling and Thermometry on an X-Junction Surface Trap with Integrated Current Carrying Wires

Sahra Ahmed Kulmiya

July 9, 2024

III rd EARLY CAREER CONFERENCE in TRAPPED IONS

Overview

01. Introduction

The blueprint concept, the QCCD architecture.

02. The X-Junction Chip

The experimental setup, the x junction chip and its electrical testing.

03. Experimental Results 1

Preparing qubits, measuring the gradients generated, measuring coherence times.

04. Experimental Results 2

Demonstrating single ion entanglement, large spin-motion coupling parameter

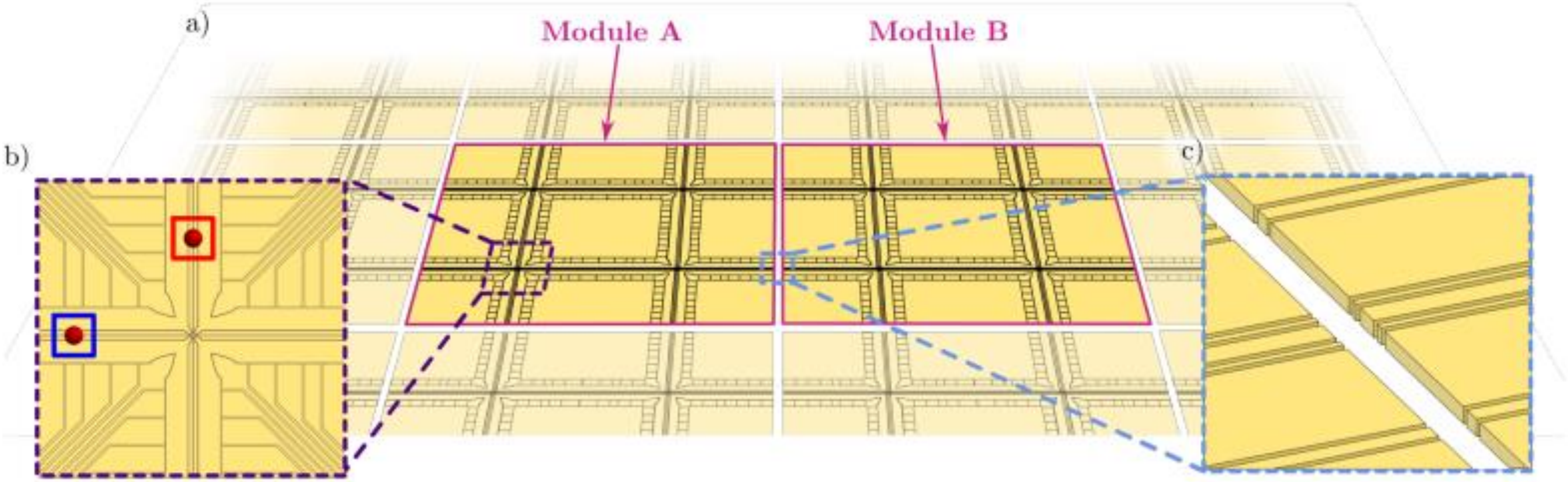
05. Outlook

Review the next steps for the experiment.

Introduction

A key requirement of a quantum computing architecture is the ability to scale to millions of qubits. If lasers are used to address each individual qubit, then it is required to have a high level of precision over millions of individual laser beams. This high level of precision is not required for qubits manipulated using long wavelength global radiation.

The blueprint paper [1] outlines an array-based design, like a QCCD type architecture.

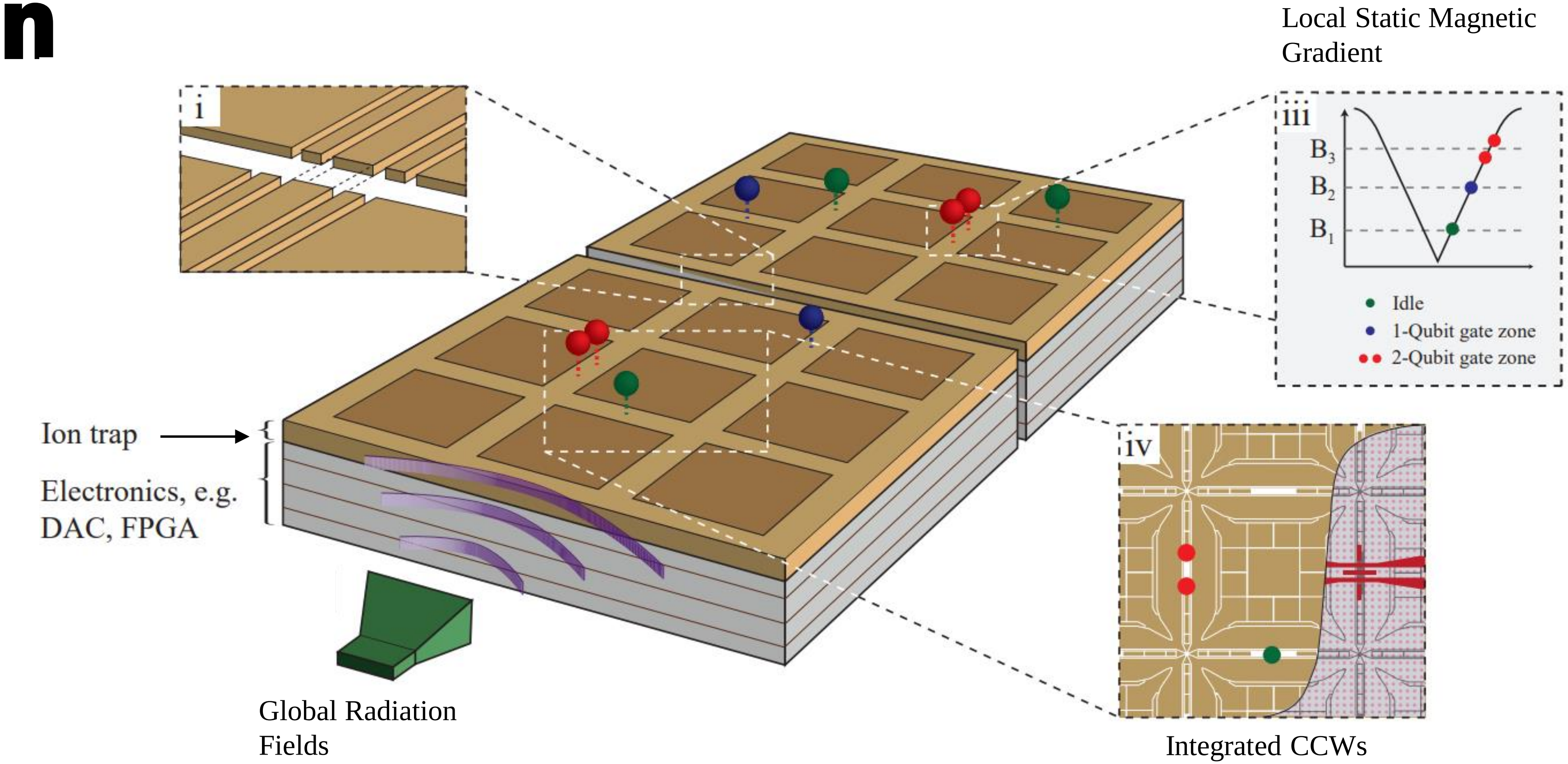


[1] B. Lekitsch, S. Weidt, A. G. Fowler, K. Mølmer, S. J. Devitt, C. Wunderlich, and W. K. Hensinger, Blueprint for a microwave trapped ion quantum computer, Science Advances, 3 (2017), p. e1601540

Introduction

Ions can then be transported between these different regions [4] to perform a quantum algorithm.

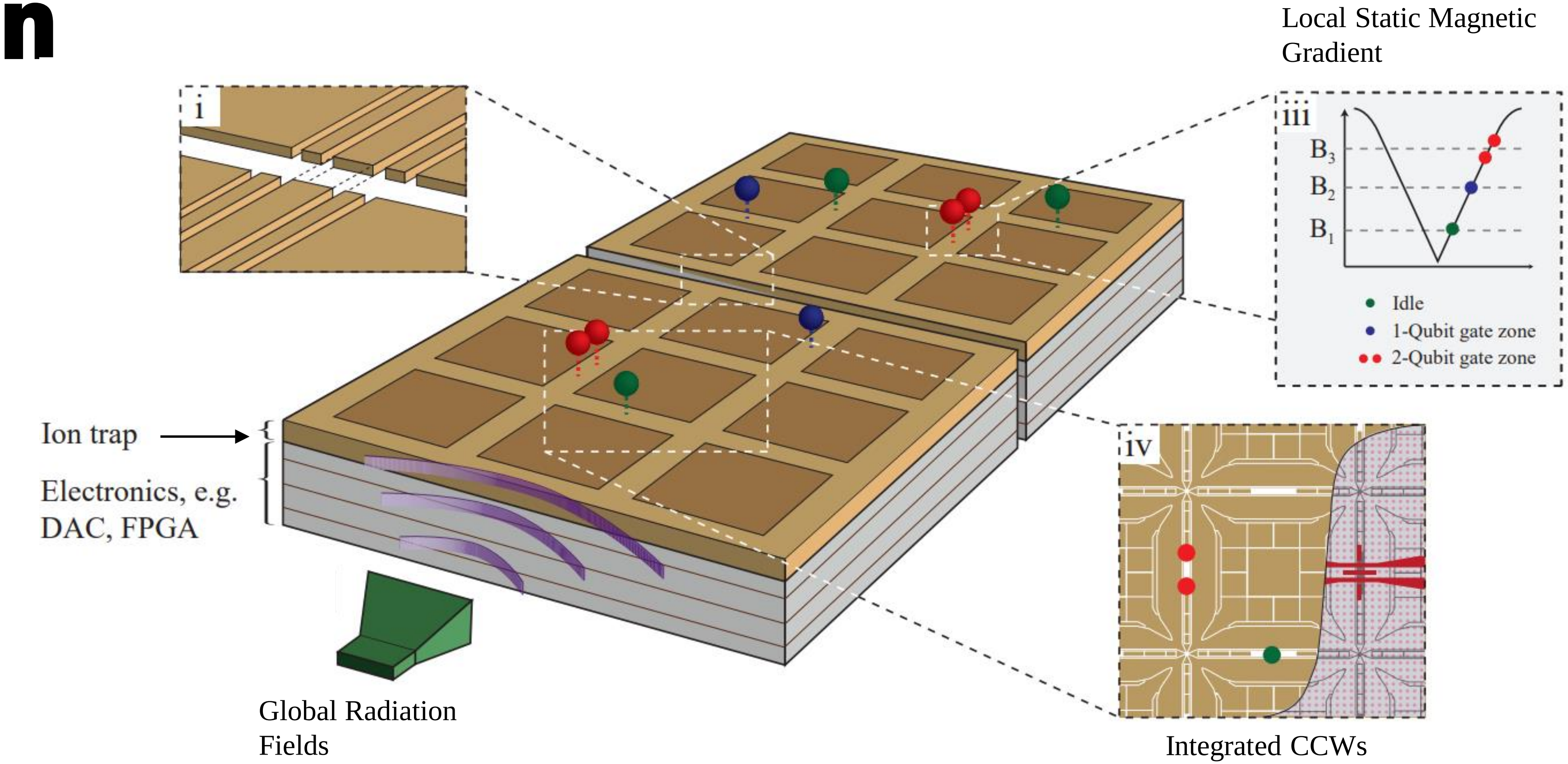
One major challenge of this approach, however, was that the number of radiation fields required increased with the number of ions.



[2] S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Trapped-Ion Quantum Logic with Global Radiation Fields, (2016).
[3] F. Mintert and C. Wunderlich, Ion-Trap Quantum Logic Using Long-Wavelength Radiation, Physical Review Letters, 87 (2001), p. 257904.
[4] Akhtar, M., Bonus, F., Lebrun-Gallagher, F.R. *et al.* A high-fidelity quantum matter-link between ion-trap microchip modules. *Nat Commun* **14**, 531 (2023)

Introduction

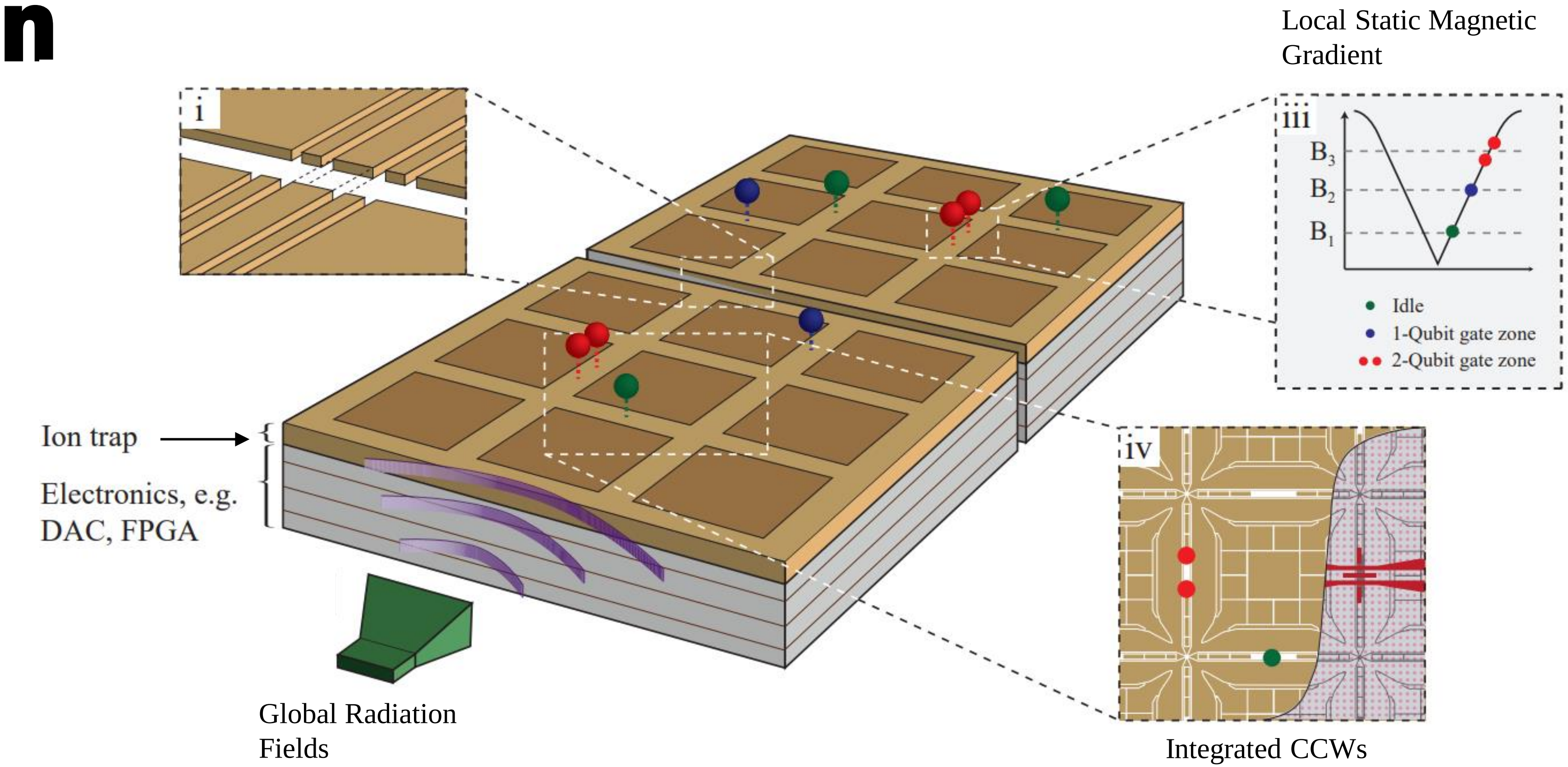
This requirement was removed when in 2016 [2], high-fidelity quantum logic using long wavelength radiation was successfully demonstrated for the first time, following the scheme proposed by Mintert et. Al. [3] in 2001.



[2] S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Trapped-Ion Quantum Logic with Global Radiation Fields, (2016).
[3] F. Mintert and C. Wunderlich, Ion-Trap Quantum Logic Using Long-Wavelength Radiation, Physical Review Letters, 87 (2001), p. 257904.

Introduction

In conjunction with a local static magnetic gradient generated at specific positions on the chip, the ions are separated in frequency space, a single global microwave field can be used to address each ion and perform quantum logic.

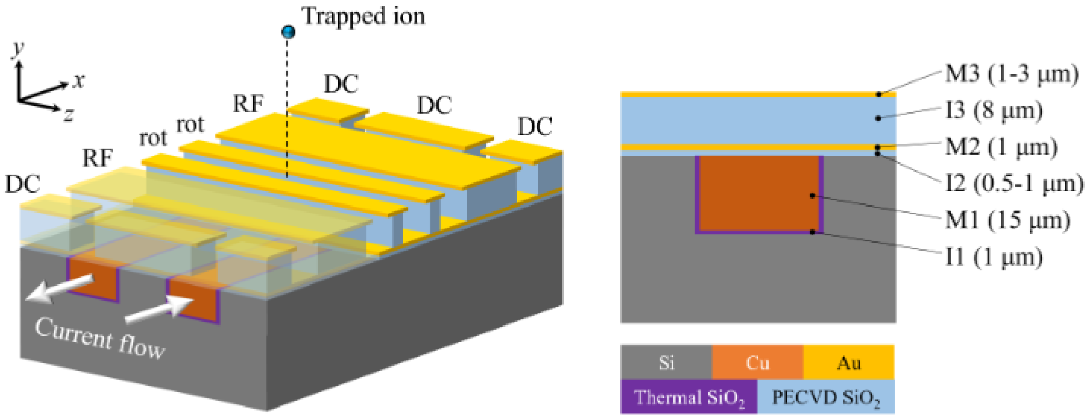


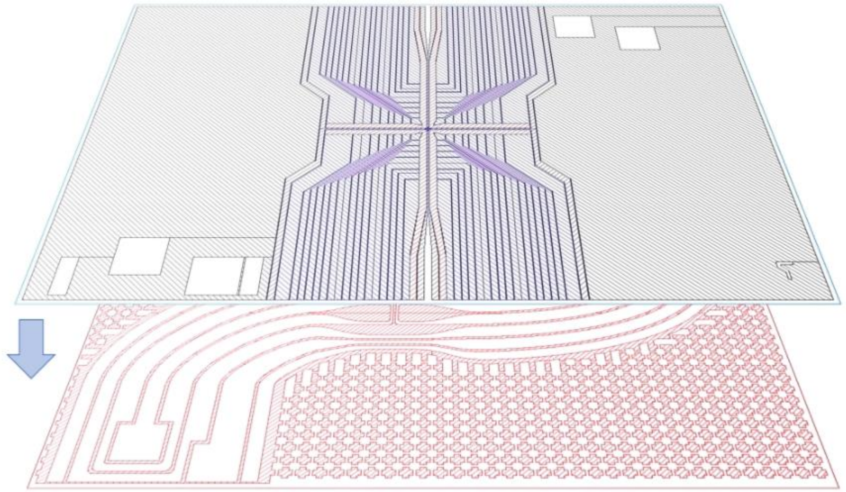
[2] S. Weidt, J. Randall, S. C. Webster, K. Lake, A. E. Webb, I. Cohen, T. Navickas, B. Lekitsch, A. Retzker, and W. K. Hensinger, Trapped-Ion Quantum Logic with Global Radiation Fields, (2016).
[3] F. Mintert and C. Wunderlich, Ion-Trap Quantum Logic Using Long-Wavelength Radiation, Physical Review Letters, 87 (2001), p. 257904.

The X-Junction Chip

To demonstrate a unit cell of the blueprint, a surface ion trap is designed [4] with integrated current carrying wires embedded underneath the RF and DC trapping electrodes.

Ion traps with CCWs in the top layer have demonstrated static axial magnetic gradients up to 23 T/m [5]. Oscillating radial magnetic gradients of up to 152 T/m [6] have also been demonstrated at ion heights of 30 um.





RF/DC electrodes

Integrated CCWs

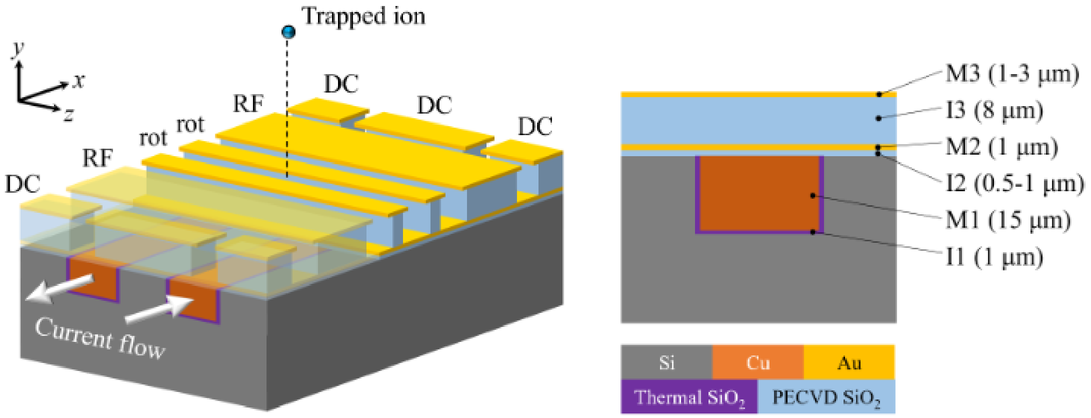
[4] M. Siegele-Brown, S. Hong, F. Raphael Lebrun-Gallagher, S. James Hile, ¨ S. Weidt, and W. Karl Hensinger, Fabrication of surface ion traps with integrated current carrying wires enabling high magnetic field gradients, (2022)
[5] Kunert P, Georgen D, Bogunia L, Baig M, Baggash M, Johanning M and Wunderlich C 2014 Applied Physics B 114 27–36
[6] Srinivas R, Burd S, Knaack H, Sutherland R, Kwiatkowski A, Glancy S, Knill E, Wineland D, Leibfried D, Wilson A C et al. 2021 Nature 597 209–213

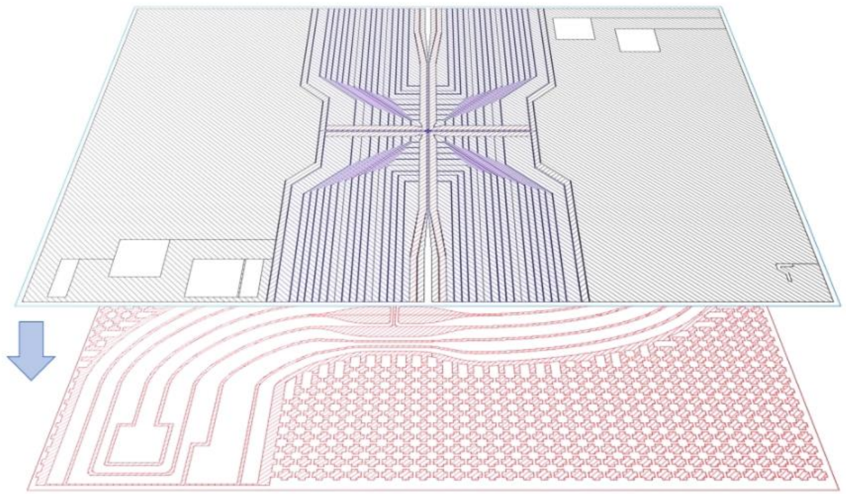
The X-Junction Chip

In this concept:

- the design of the CCWs is completely independent from the design of the top electrode layer.
- The CCWs are not moved significantly further away from the ion.
- Low sheet resistance copper is utilised for the wires to allow management of thermal dissipation.

Therefore, currents up to 10 A can be applied, generating static axial magnetic gradients of up to 100 T/m at ion heights of 125 um [4].





RF/DC electrodes

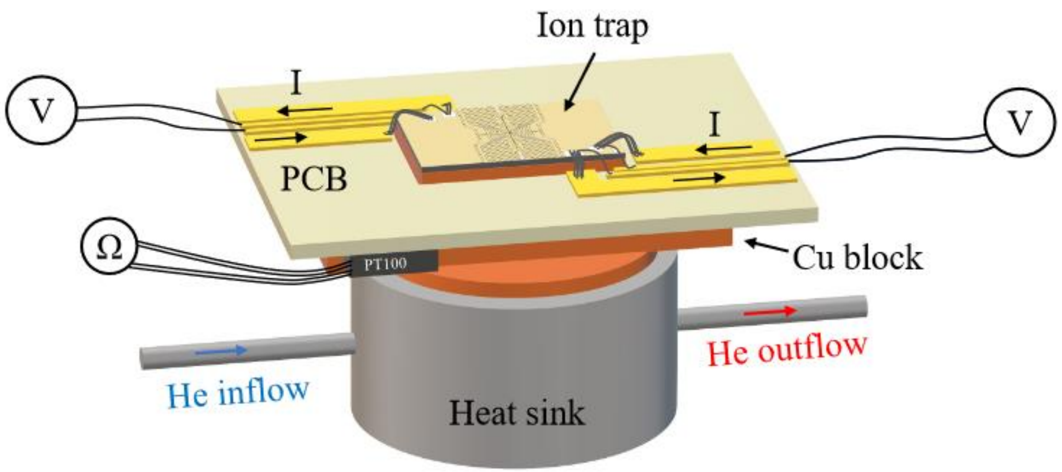
Integrated CCWs

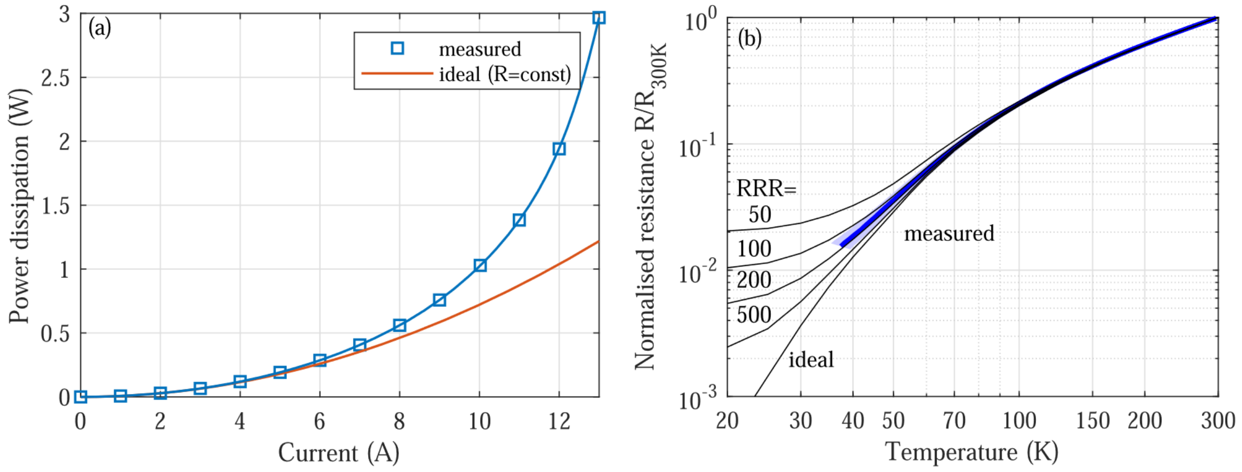
[4] M. Siegele-Brown, S. Hong, F. Raphael Lebrun-Gallagher, S. James Hile, ¨ S. Weidt, and W. Karl Hensinger, Fabrication of surface ion traps with integrated current carrying wires enabling high magnetic field gradients, (2022)

Testing the X-Junction Chip

The following UHV experiment was set up to evaluate the chip's electrical performance. The device was mounted on a heatsink supplied by a custom closed-loop cryogenic system [5].

The power dissipated was measured for continuous currents from 0 A to 8A, and pulsed currents from 10 A to 13 A. The power dissipated reached 20 W, which is well within the cooling power of the cryogenic system [5].



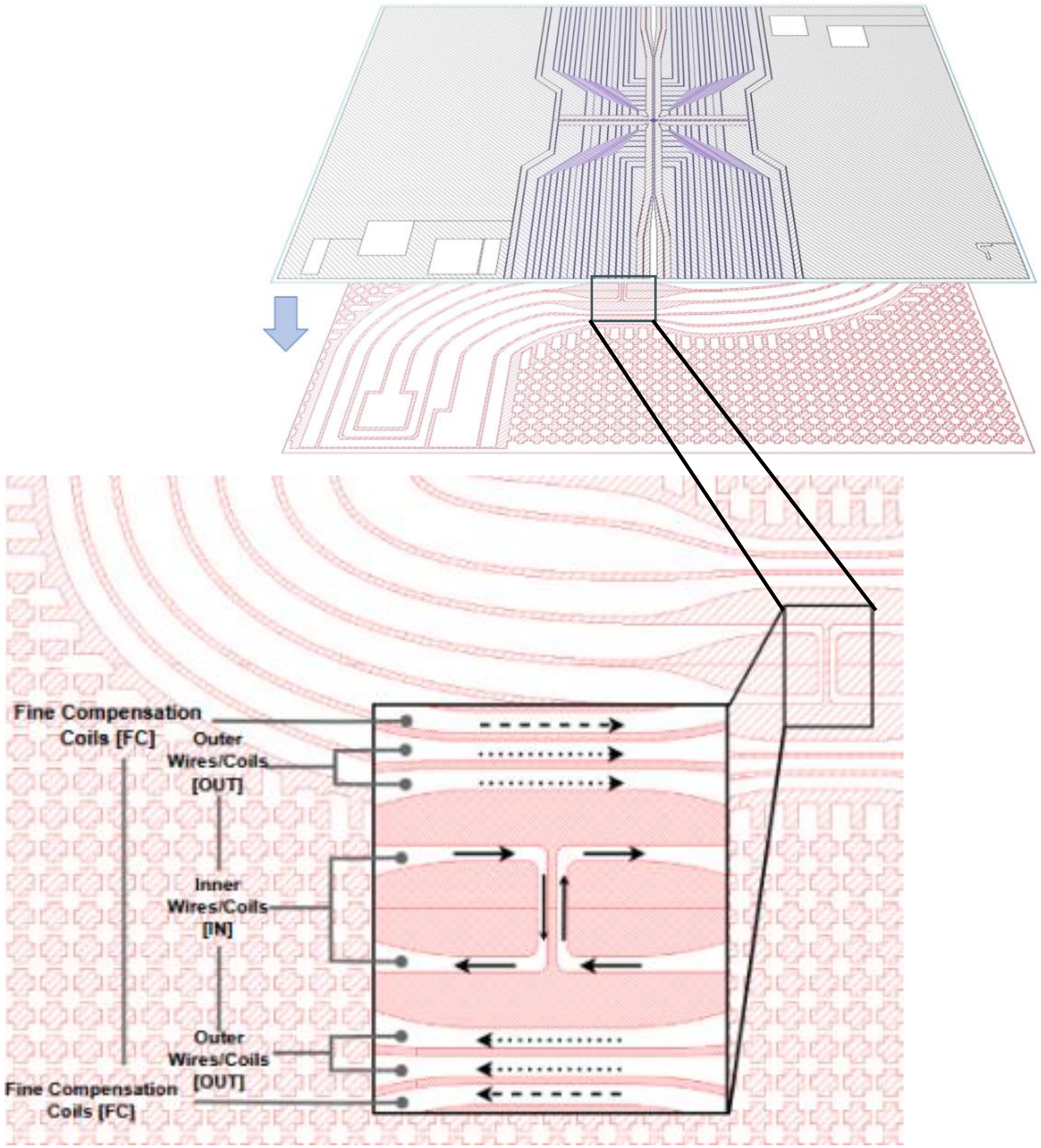


[5] F R Lebrun-Gallagher et al 2022 Quantum Sci. Technol. 7 024002

Simulating the X-Junction Chip

We now take a closer look at the design of the CCWs. In our CCW geometry, there are multiple wires, as labelled in the figure on the left. They were designed and optimised to generate the highest axial magnetic gradient.

In total there are 10 wires that have been optimised in an anti-parallel wire pair geometry [6]. The inner wire pair, in combination with the outer wire pair generates a magnetic quadrupole nil at the desired ion height, with the fine compensation coils allowing finer resolution adjustment to the position of the quadrupole nil in one axis.



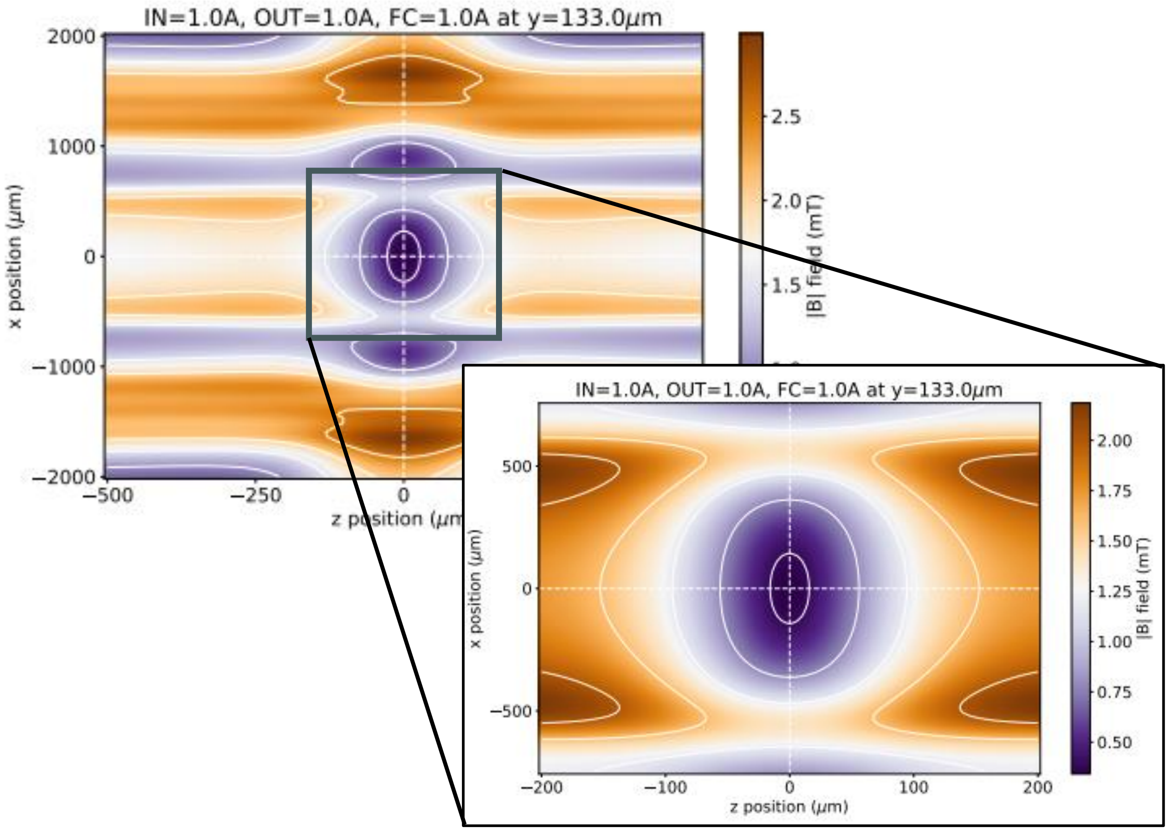
[6] F R Lebrun-Gallagher PhD Thesis (2022)

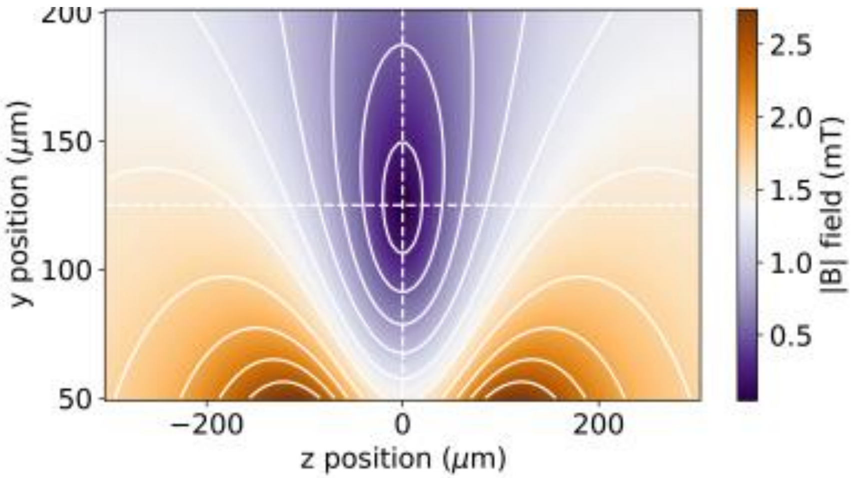
Simulating the X-Junction Chip

In this scheme utilising global microwave radiation, only the gradient of the magnetic field magnitude is of interest [3].

$$\eta_{\text{eff}} = \frac{\mu_B \partial_z |B|}{2\omega_z \sqrt{m\hbar\omega_z}}$$

This parameter is directly proportional to the strength of the effective Lamb Dicke parameter which defines the strength of the spin-motion coupling in our qubits.



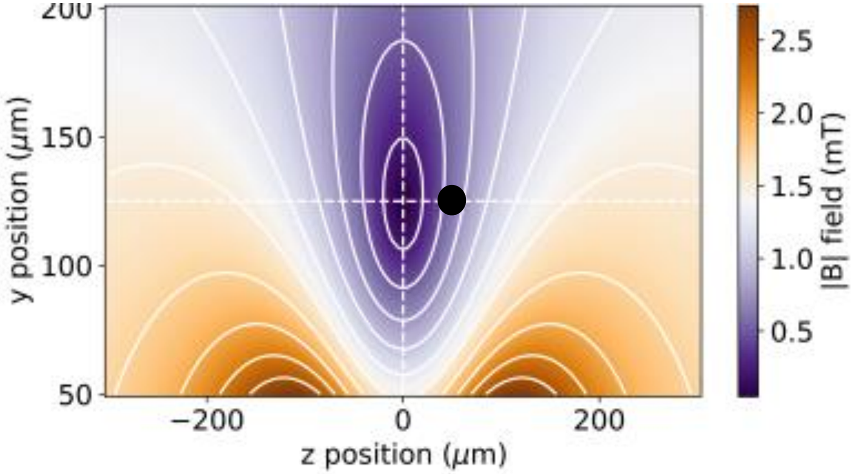


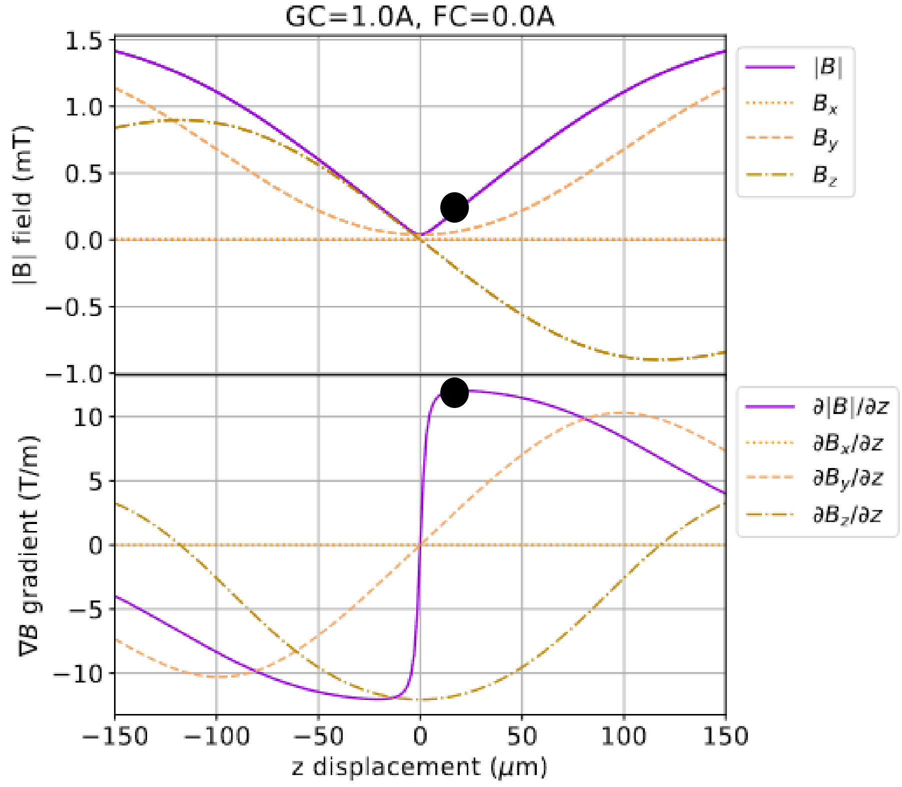
[3] F. Mintert and C. Wunderlich, Ion-Trap Quantum Logic Using Long-Wavelength Radiation, Physical Review Letters, 87 (2001), p. 257904.

Simulating the X-Junction Chip

- At 1A on the gradient coils we should generate approx. 11T/m along the axial direction, and approx. 5T/m along the radial y direction.
- There is no magnetic field or magnetic field gradient from the x-axis at all. This is a consequence of the design geometry [5].
- The ion should not sit at the centre but displaced some amount from the zero of the magnetic field, allowing a small zeeman splitting, but a large gradient.

[5] F R Lebrun-Gallagher et al 2022 Quantum Sci. Technol. 7 024002

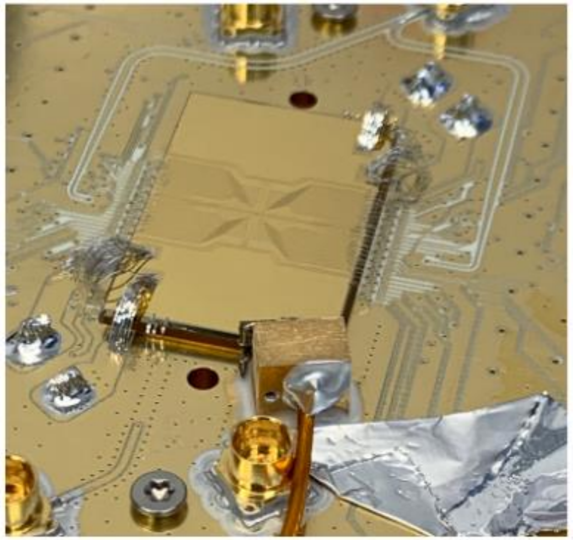


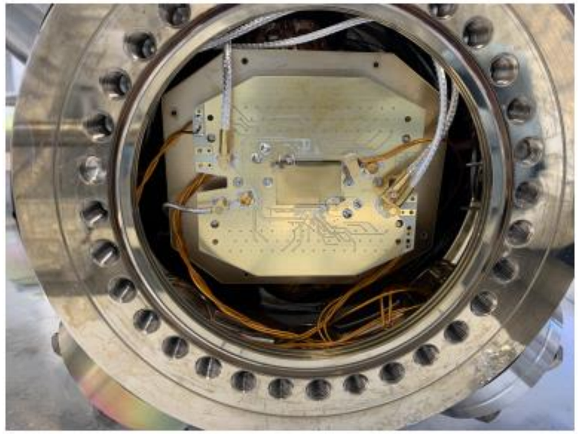


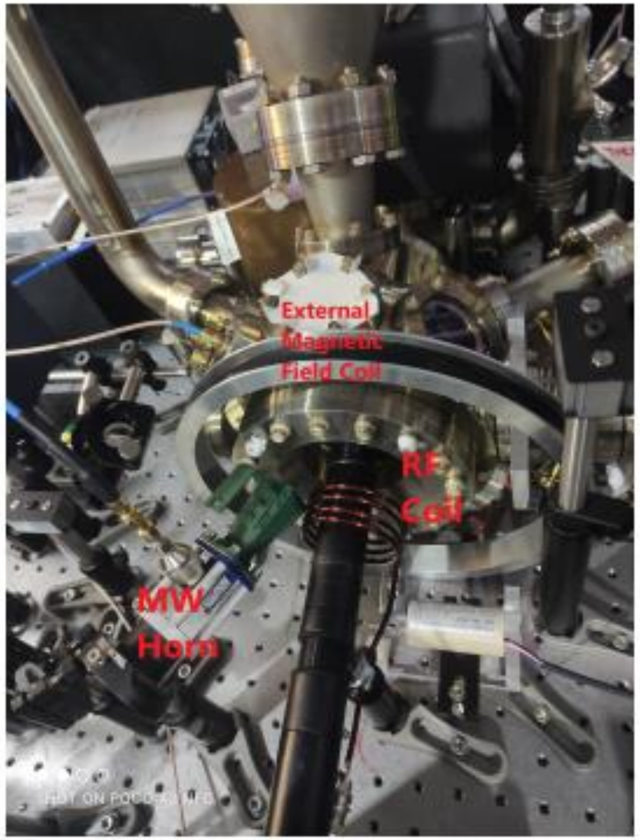
The Experimental Setup

The results and data shown in this presentation were taken using an ultra-high vacuum chamber containing electrical equipment to provide the relevant signals and fields at the ion. An FPGA using the ARTIQ framework is used to perform almost all experimental work.

The microfabricated surface chip shown is glued to a heatsink, and mounted inside the UHV chamber.


BONDED X JUNCTION TRAP


INSIDE VACUUM CHAMBER



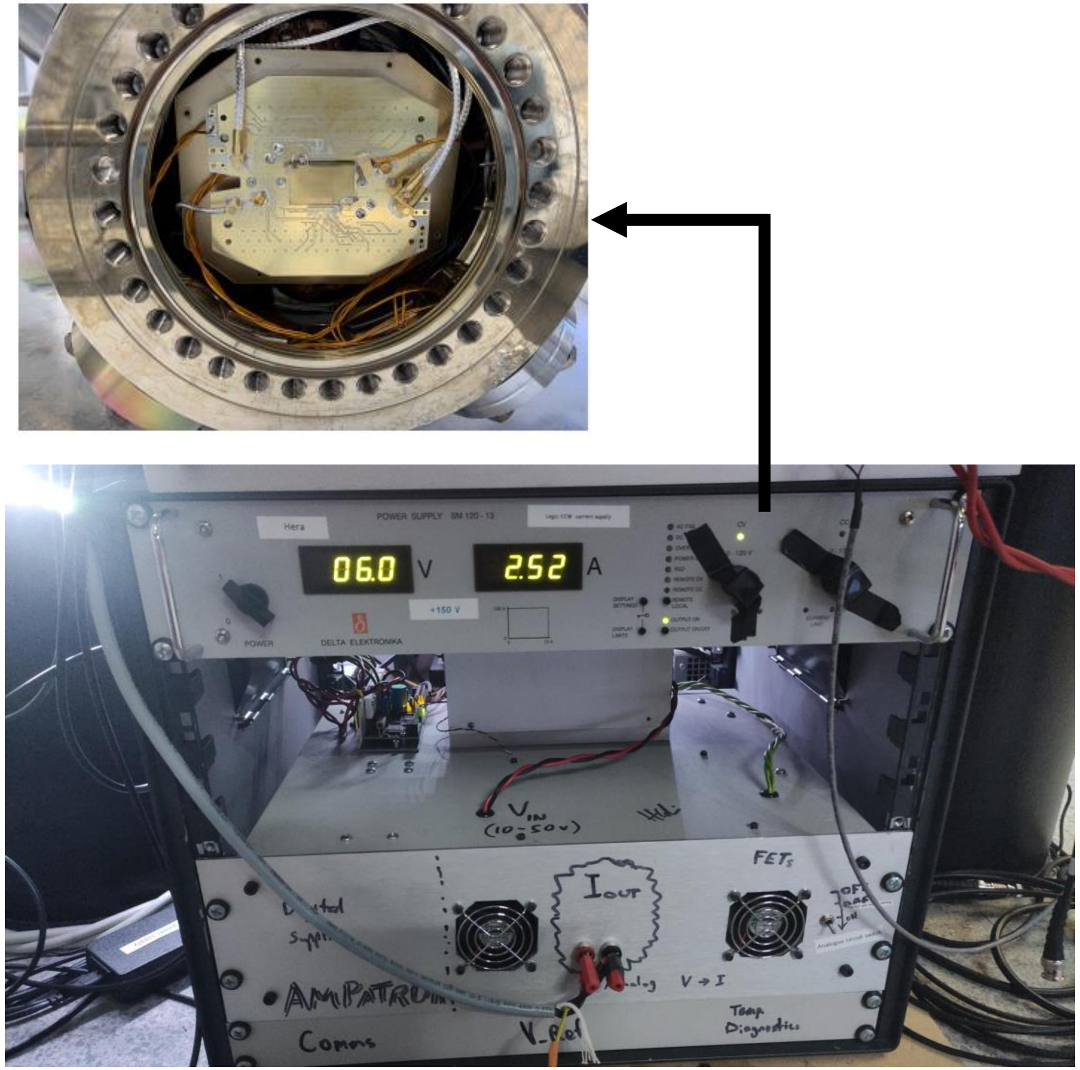
UHV CHAMBER

The Experimental Setup

We utilise a home-built ultra-low noise current source to power the CCWs. It can go up to 10A.

- Builf for very low current noise.
- Can switch on and off very quickly in order to interleave ion transport operations for scalable architecture.

INSIDE VACUUM CHAMBER

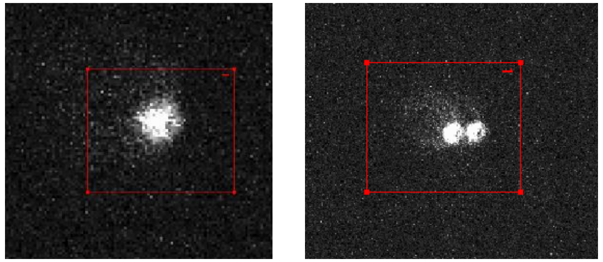


System built by Harry Godwin [Universal Quantum] et. Al.

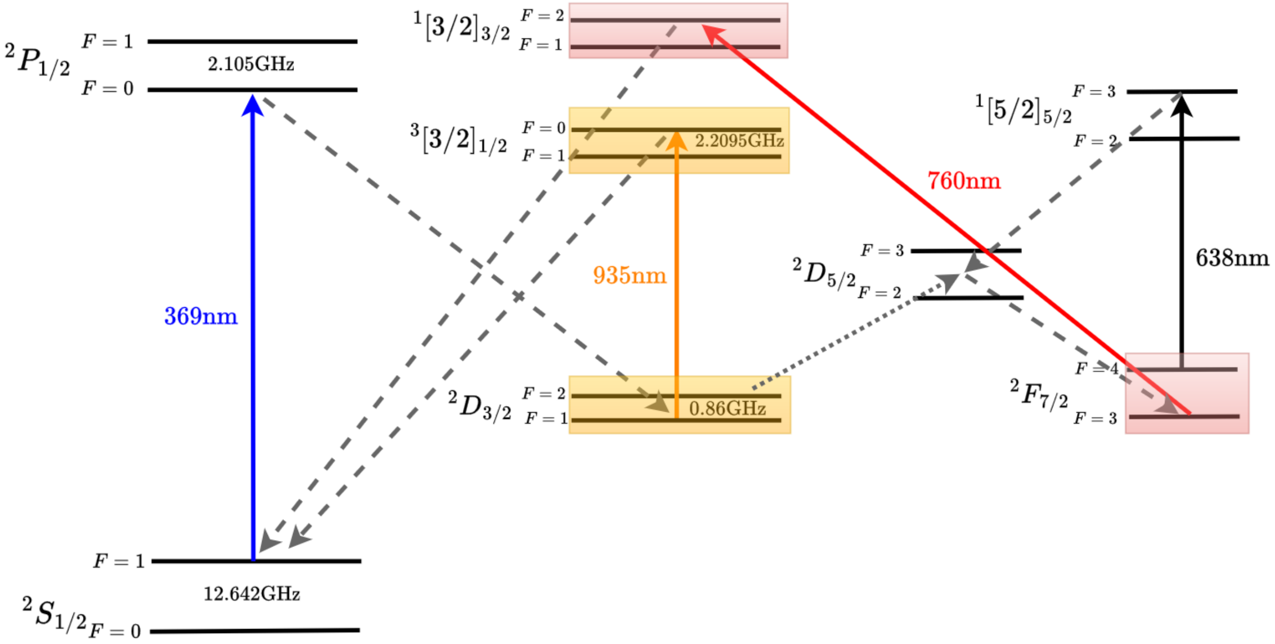
Initial Trapping

Initial experimental characterisation of the chip starts by trapping a single Yb 171+ ion. The experiment temperature is 130 K, and sits at a base pressure of 2.8e-11 mbar. Ion lifetimes are over 30 hours on average.

A magnetic field of approximately 1 mT is typically applied to the ion trap. The transition frequencies of the 2S[1/2] sub-manifold were then measured.



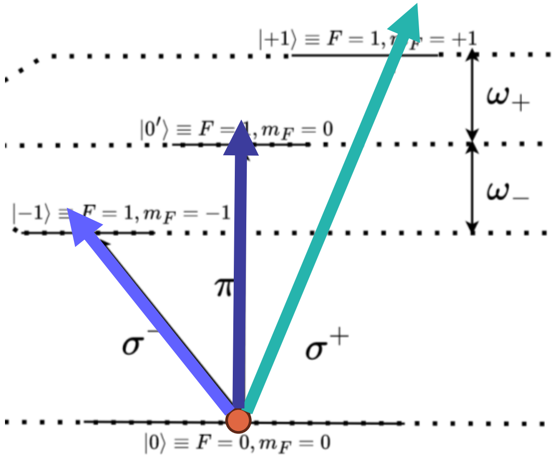
A single Yb ion, and multiple Yb ions taken using an EMCCD camera.

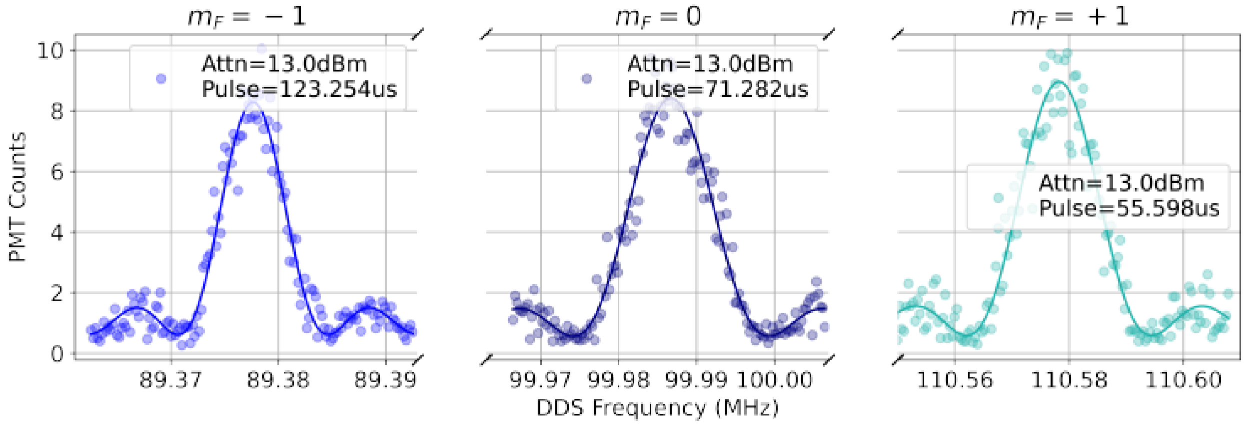


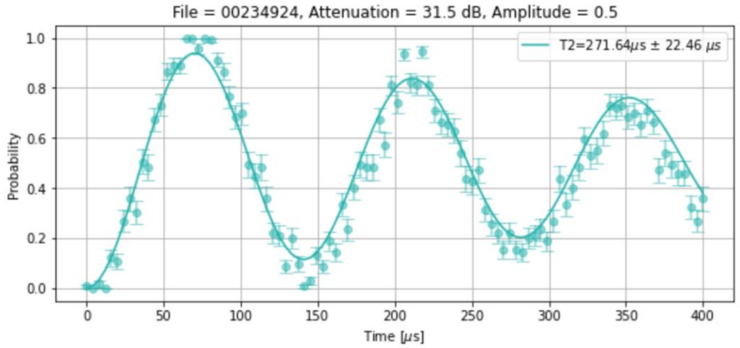
Experimental Results 01

By preparing the ion in the ground state, a microwave pulse with either a fixed duration or fixed frequency can be applied, measuring the centre frequencies and rabi frequencies of each transition.

Qubits can be encoded in bare hyperfine ground states by applying pulses to prepare either ground, excited or superposition states.

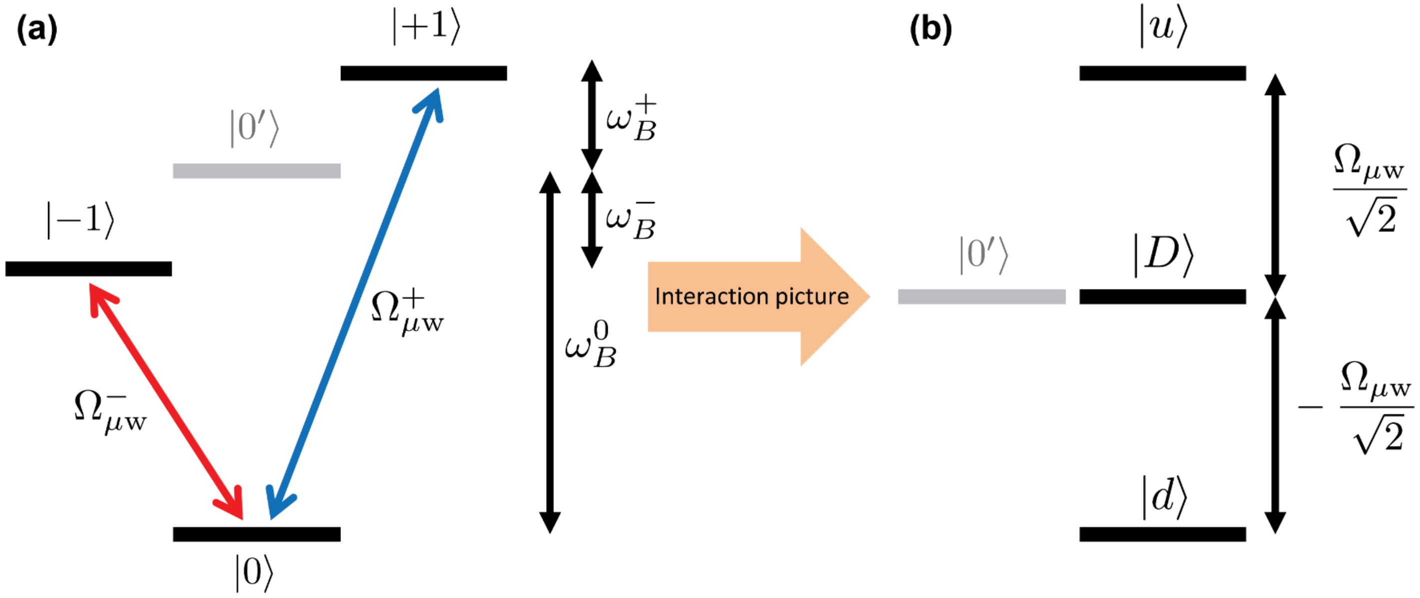






Moving into the Dressed State Picture

Instead of encoding the qubit in the bare atomic transitions, it can be advantageous to instead encode quantum information in the states formed when the ion is dressed by continuous application of a microwave or laser field, known as dressed states [6].

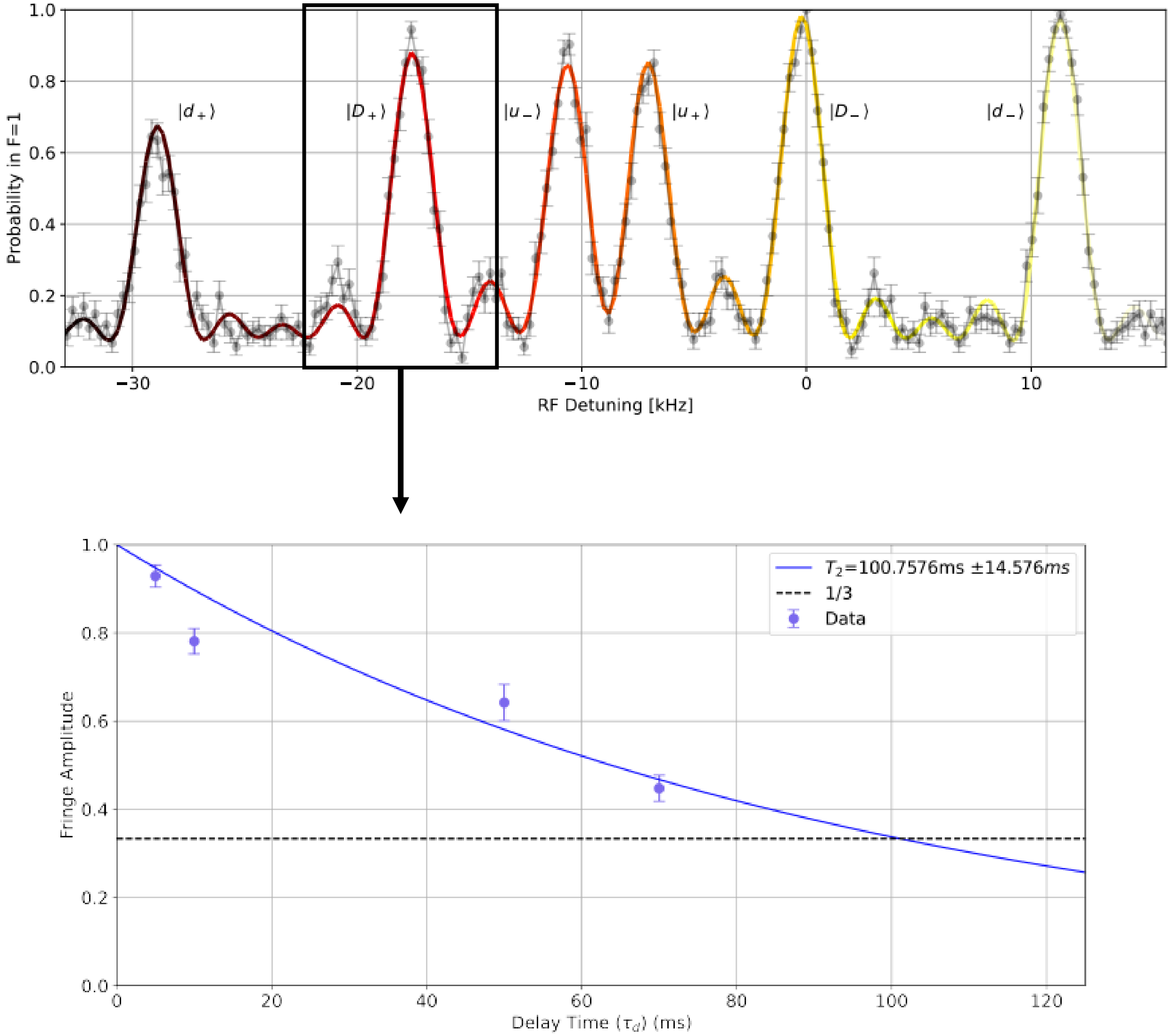


[6] N. Timoney, I. Baumgart, M. Johanning, A. F. Varon, M. B. Plenio, A. Retzker, and C. Wunderlich, Nature 476, 185 (2011).

Experimental Results 02

We prepared a dressed state qubit over both zeeman sensitive transitions in Yb171.

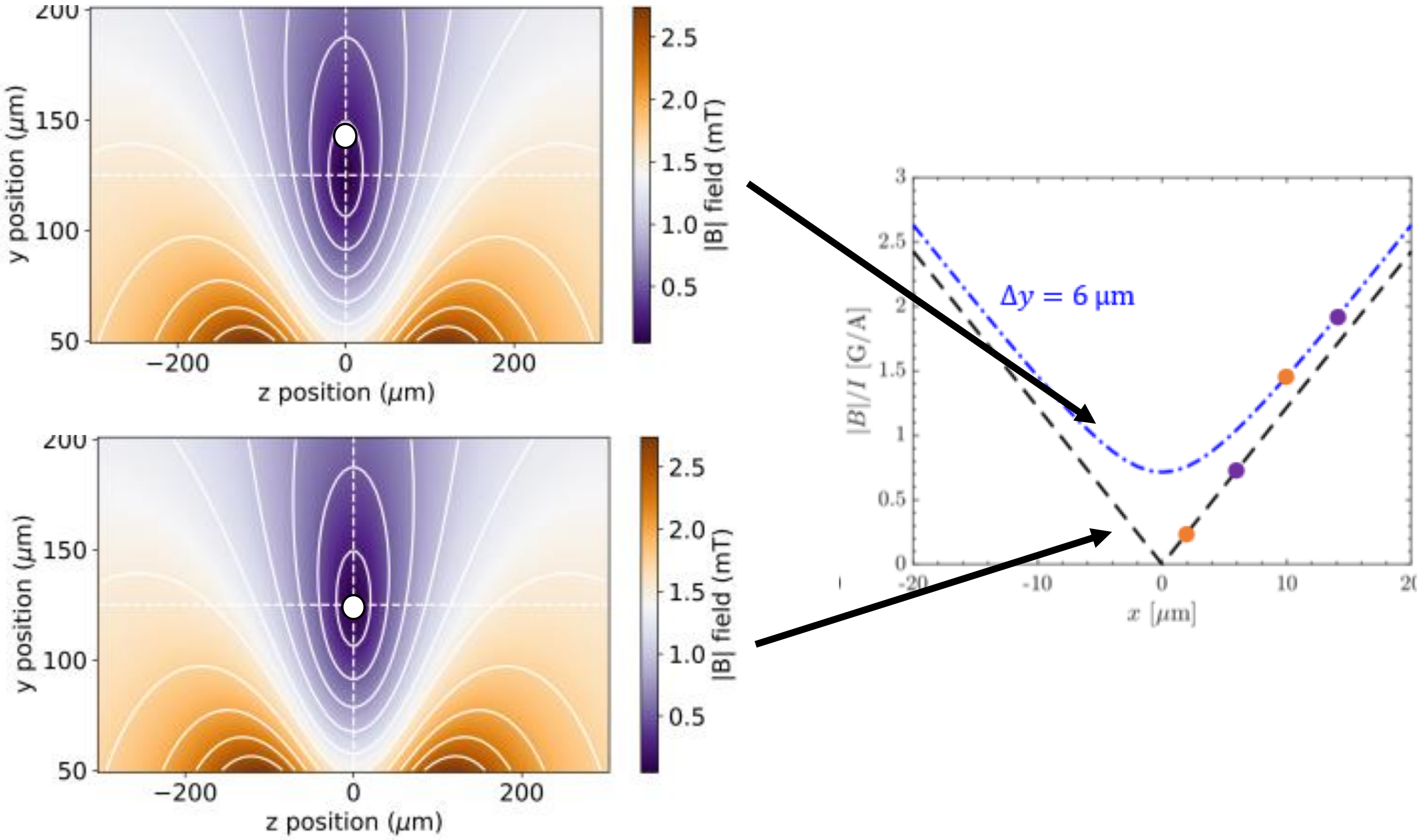
The |D⟩ state transitions are utilised as it is protected from both magnetic field noise and any microwave amplitude noise in the dressing fields. Coherence time was measured to be approx. 100 ms at 20 kHz dressing field rabi frequencies.



Spin Echo (T_2)
Measure |0'⟩ -> |D+⟩

Mapping the Magnetic Gradient using Transport

To demonstrate the design and behaviour of the CCWs, we study how the magnetic field changes at different positions. Depending on the overlap of the nil with the PS nil, we get a different shape of the magnetic field.

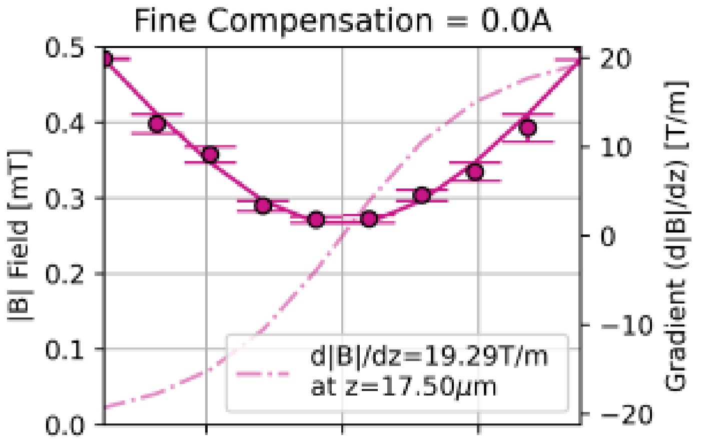


Experimental Results 03

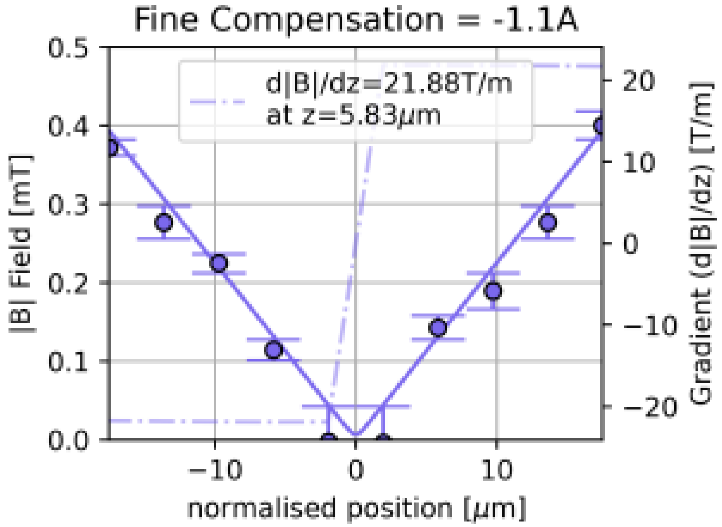
The ion was transported +- 20 um either side of the simulated nil, and the +1 transition was measured at 10 points, with a current of 2A applied to the coils.

By utilising the fine compensation coils, we are able to overlap the ions position with the quadrupole nil, optimising the gradient, and demonstrating full y-axis compensation, and absence of x-axis magnetic field

BEFORE COMPENSATION



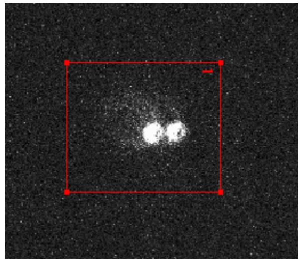
AFTER COMPENSATION

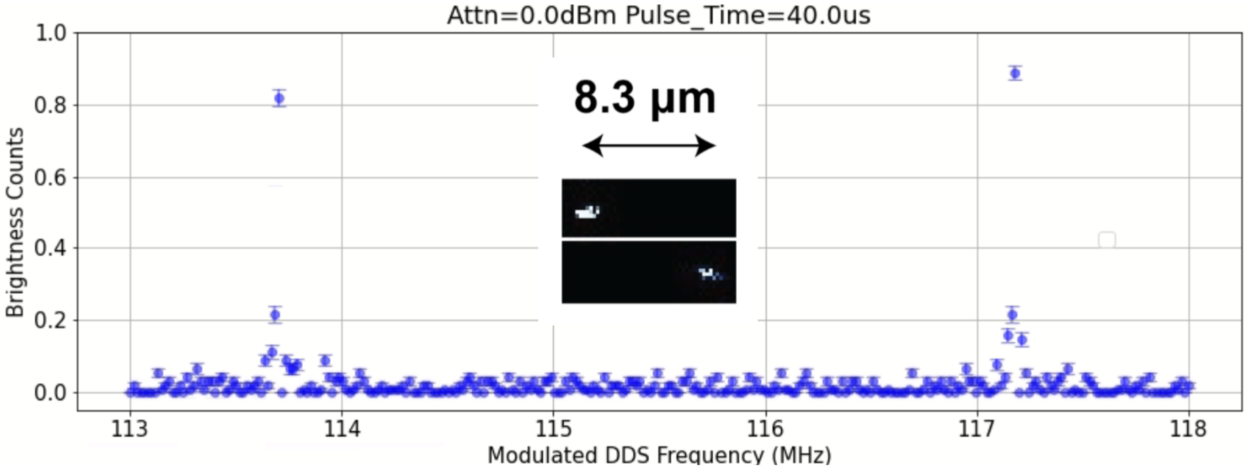


Experimental Results 04

We perform a frequency scan over the +1 zeeman state, with two ions present in the system, allowing us to distinguish each chosen transition.

We can also use this to verify the previous gradient measured. At 2.5A on the CCWs, and an axial secular frequency of 230 kHz, we find the expected 3.5MHz splitting indicating a gradient of 27.5T/m.

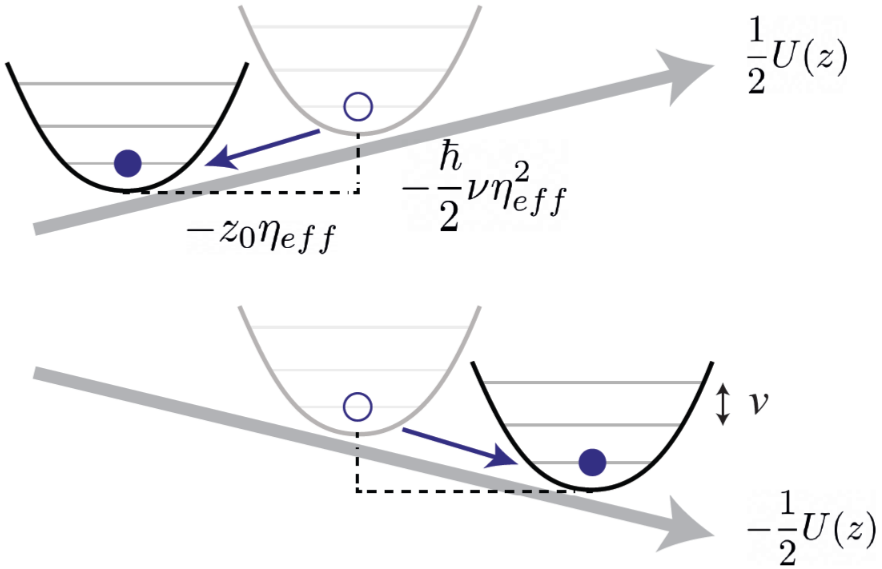




Spin-Motion Coupling

A magnetic-field gradient at the position of the ions can create a state dependent force which increases the coupling of the radiation to the ion’s motional state. Coupling of the spin states to the motional states allow us to address transitions to the motional state which allow ground state cooling, and the implementation of multiple gate schemes [8].

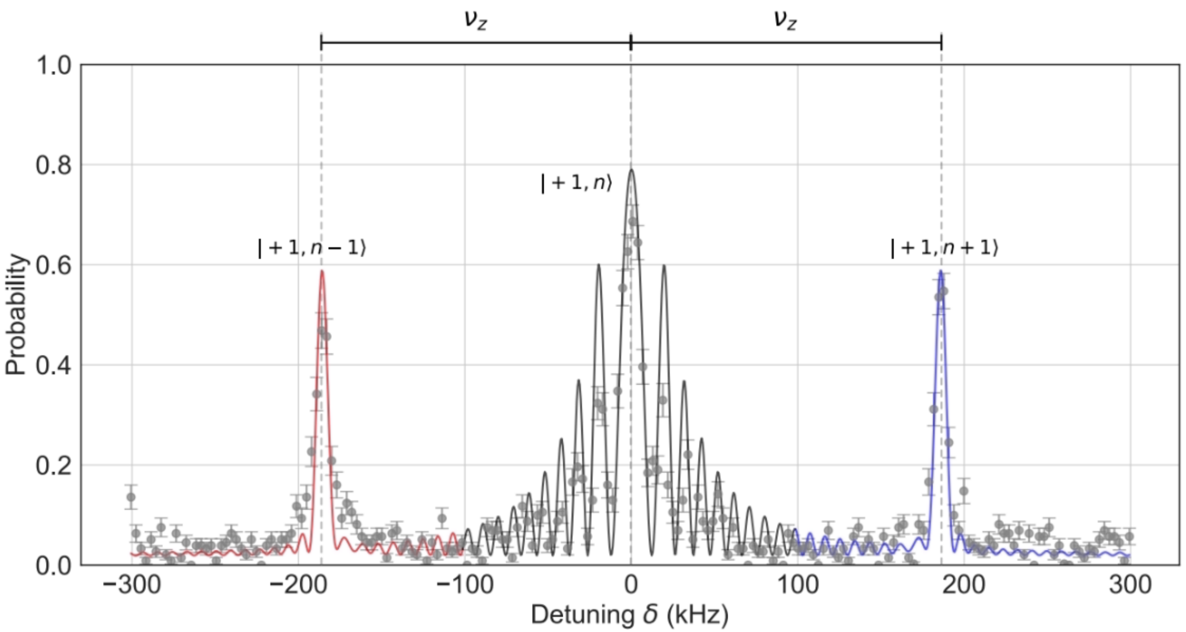
We can also address ions in a chain using frequency space.



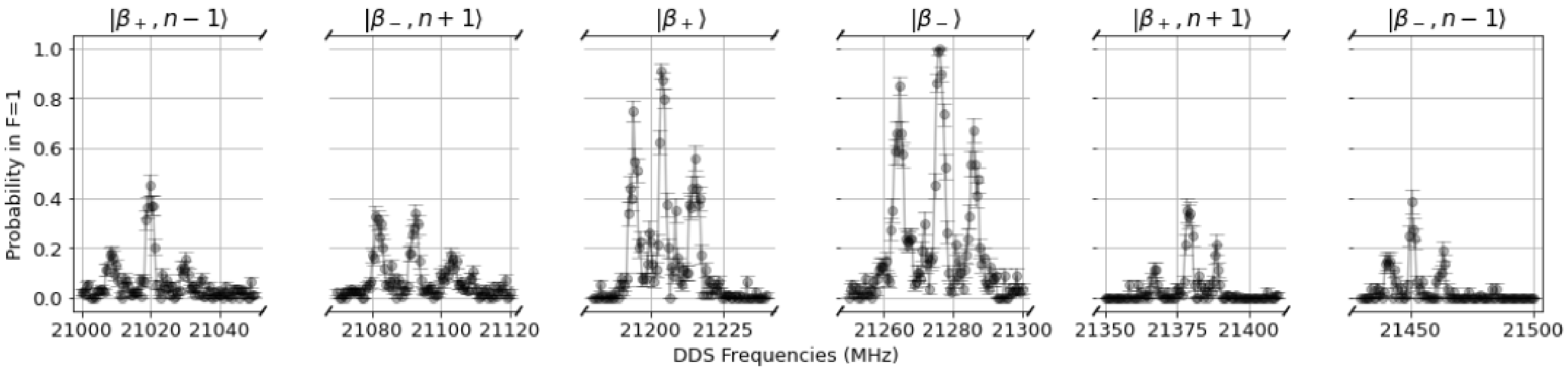
[8] K. Lake, S. Weidt, J. Randall, E. D. Standing, S. C. Webster, and W. K. Hensinger Phys. Rev. A 91, 012319

Experimental Results 05

In order to demonstrate spin-motion coupling we also perform a frequency scan over the range encompassing the axial secular frequency of the |0⟩ -> |+1⟩ , we can address transitions to the motional states.



A similar experiment is performed for our dressed state qubits as well.

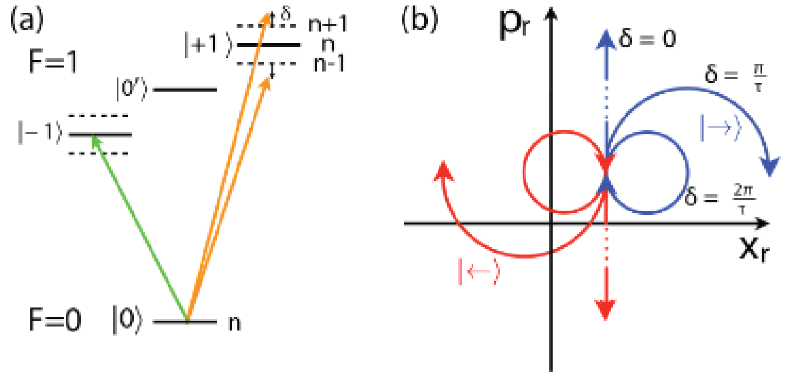


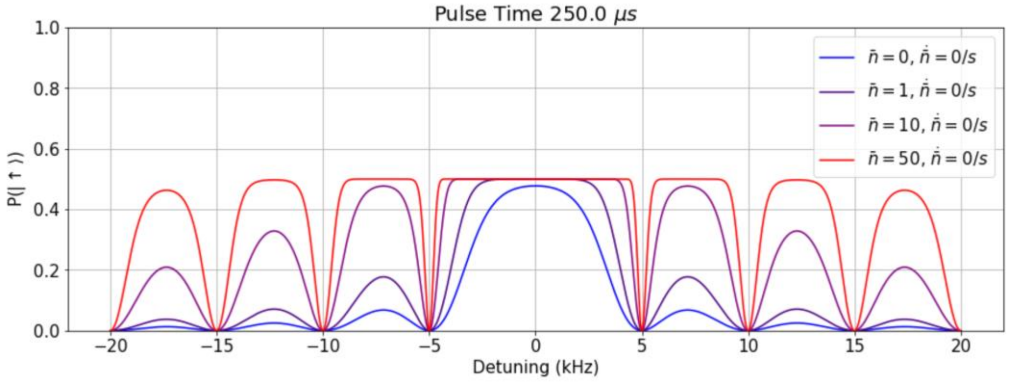
[8] K. Lake, S. Weidt, J. Randall, E. D. Standing, S. C. Webster, and W. K. Hensinger
Phys. Rev. A 91, 012319

Single Ion Entanglement (CAT State)

By using microwave radiation in conjunction with a large static magnetic-field gradient, we can generate a coupling between the internal and motional states of a trapped ion to demonstrate spin-motion entanglement [8].

We demonstrate this coupling by using it to produce entanglement between the internal spin state of a single trapped ion and its external motional state (a Schrodinger cat state), a single-ion version of the multi-ion Mølmer-Sørensen gate.





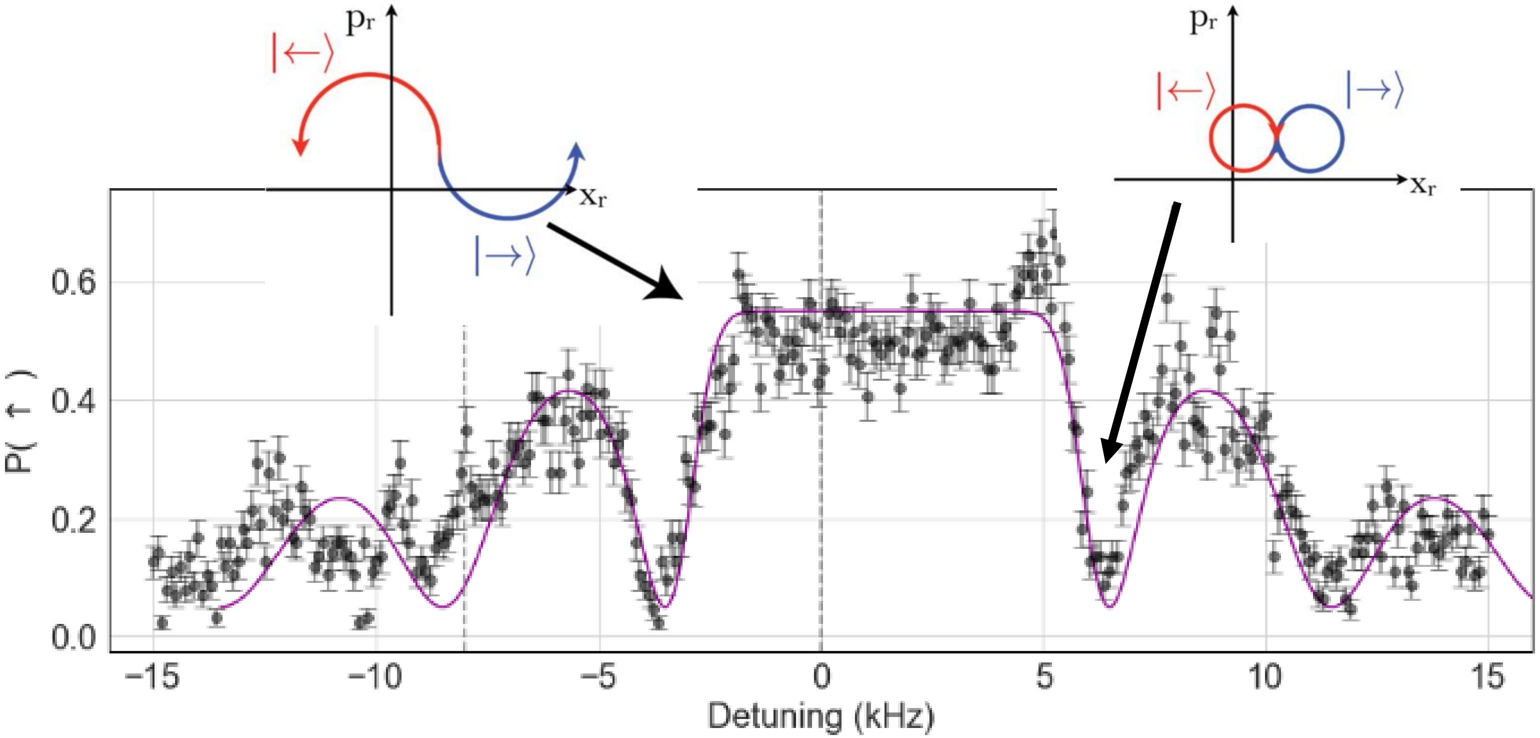
[8] K. Lake, S. Weidt, J. Randall, E. D. Standing, S. C. Webster, and W. K. Hensinger Phys. Rev. A 91, 012319

Experimental Results 06

We perform a frequency scan with two fields oppositely detuned from the red and blue motional sidebands of a single ion, with a pulse time of 200us, and initial nbar of 58.

The maximum distance between the two motional states in phase space occurs when δ = 2 kHz, and the minimum at δ = +-6 kHz.

Pulse Time = 200us,
Initial nbar = 58



Summary and Outlook

- Designed and fabricated a surface trap that can generate a high gradient with a relatively large ion height.
- Trapped and characterise the static magnetic gradient and addressed two ions in frequency space.
- Utilised the high magnetic gradient to demonstrate a large spin motion coupling parameter with global microwave fields and created a single ion entangled state (CAT) state.

OUTLOOK:

- Uitlised the dressed state motional sidebands to cool to the motional ground state using microwaves.
- Test two qubit entangling gates such as the Molmer Sorenson Gate.

Head of group:
Prof. Winfried Hensinger

Senior Scientist:
Dr Sebastian Weidt

MSc/UG:
Joe Swainston
Suraj Lokesh
Wallace Collins

Administrator:
Emily Crozier

PDRAs/ENGINEERS:
Dr Sam Hile
Dr Foni Raphaël Lebrun- Gallagher
Dr Martin Siegele
Dr Pedro Taylor-Burdett
Sahra Ahmed Kulmiya
Andrew Betts

PhD Students:
Vijay Kumar
Madalina Mironiuc
Petros Zantis
James Urquhart
Parsa Rahimi
Scott Mason
Toby Maddock
Matthew Aylett

We gratefully acknowledge funding from:

QUANTUM FLAGSHIP
Quantum Computing & Simulation Hub
Office of Naval Research GLOBAL Science & Technology
Fonds National de la Recherche Luxembourg
DQT
Government Office for Science
UK IC Postdoctoral Research Fellowship Programme
Universal Quantum
ROYAL ACADEMY OF ENGINEERING
UNIVERSITY OF SUSSEX
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME
UKRI Engineering and Physical Sciences Research Council
QSE Quantum Systems Engineering
Controlled Quantum Dynamics
Innovate UK