Towards High-Fidelity Microwave Entangling Gates on Microfabricated Surface Traps

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12/07/2024

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iQt ION QUANTUM TECHNOLOGY

III rd EARLY CAREER CONFERENCE in TRAPPED IONS

Outline:

1. Background
2. Motivation
3. Setup
4. Results
5. Future

Background

Why trapped ions?

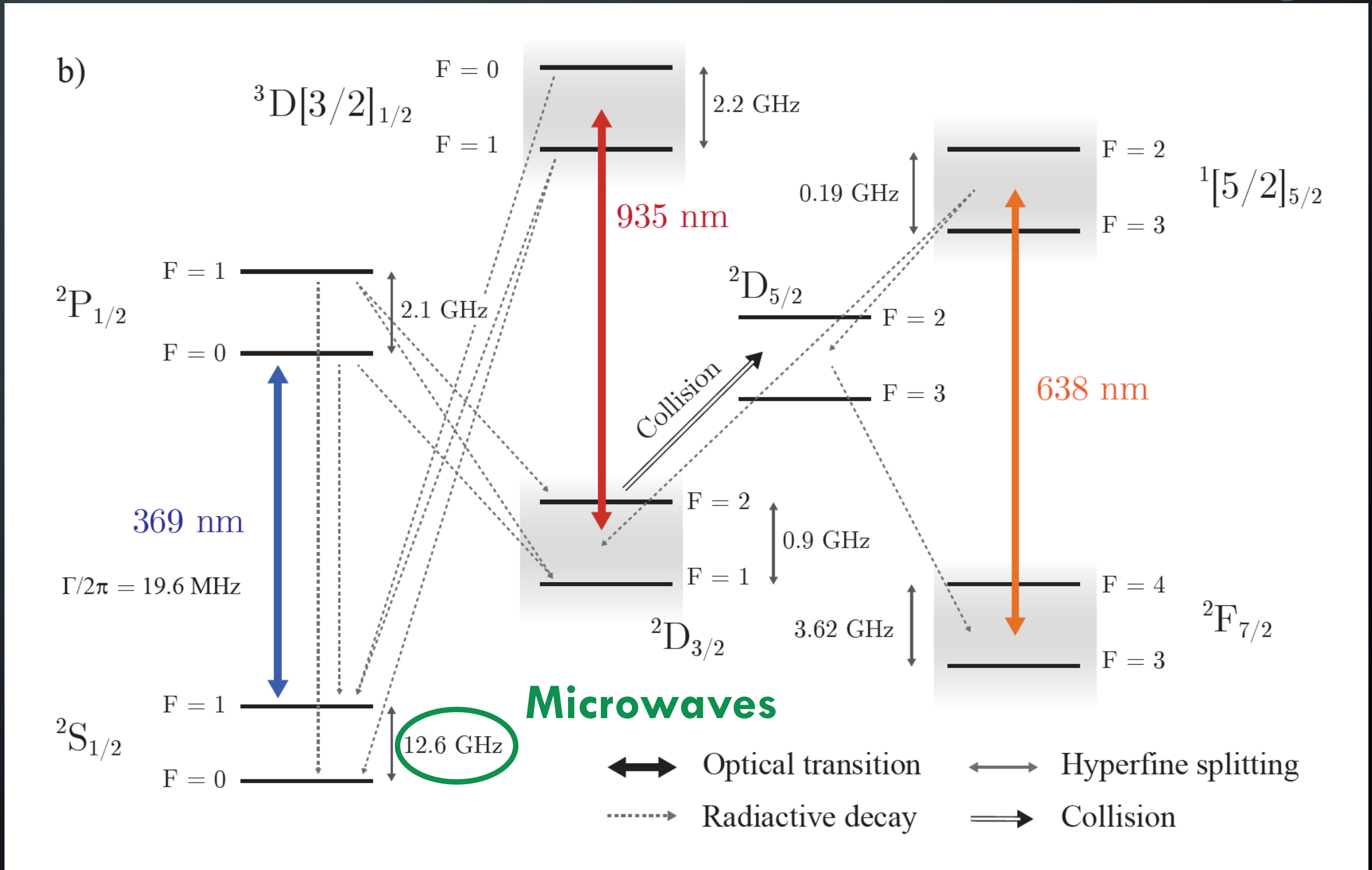
- Leading platform for **quantum computing**, because:
  - Natural reproducibility *(all ions are identical)*
  - High-fidelity *(two-qubit gates ~ 99.8 - 100%)**
  - Long coherence times
  - High connectivity *(all-to-all)***
  - Quantum Volume *(2^{20})***

** Srinivas R., Burd S.C., Knaack H.M. et al. "High-fidelity laser-free universal control of trapped ion qubits." Nature **597**, 209–213 (2021)*

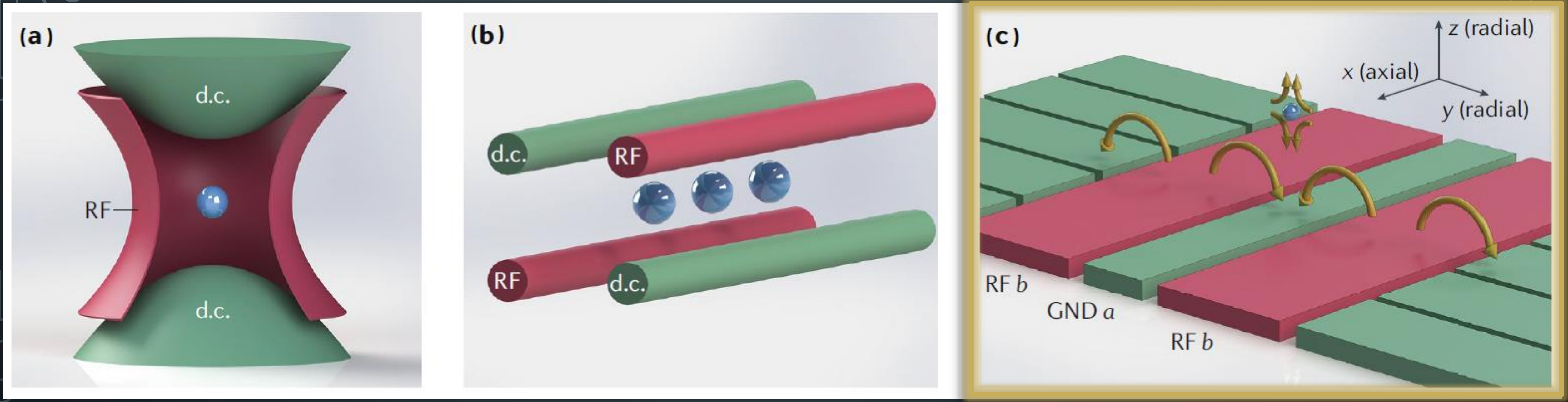
*** arXiv:2406.02501v3 **[quant-ph]***

$^{171}Yb^+$ Qubits

- Ground-state hyperfine manifold ($^2S_{1/2}$) of the $^{171}Yb^+$ ion → "clock" qubit
- **MW (12.64 GHz)** required to address these energy levels
- Also used in the Doppler cooling cycle



Evolution of Ion Traps



a) Mechanically manufactured 3D hyperbolic trap

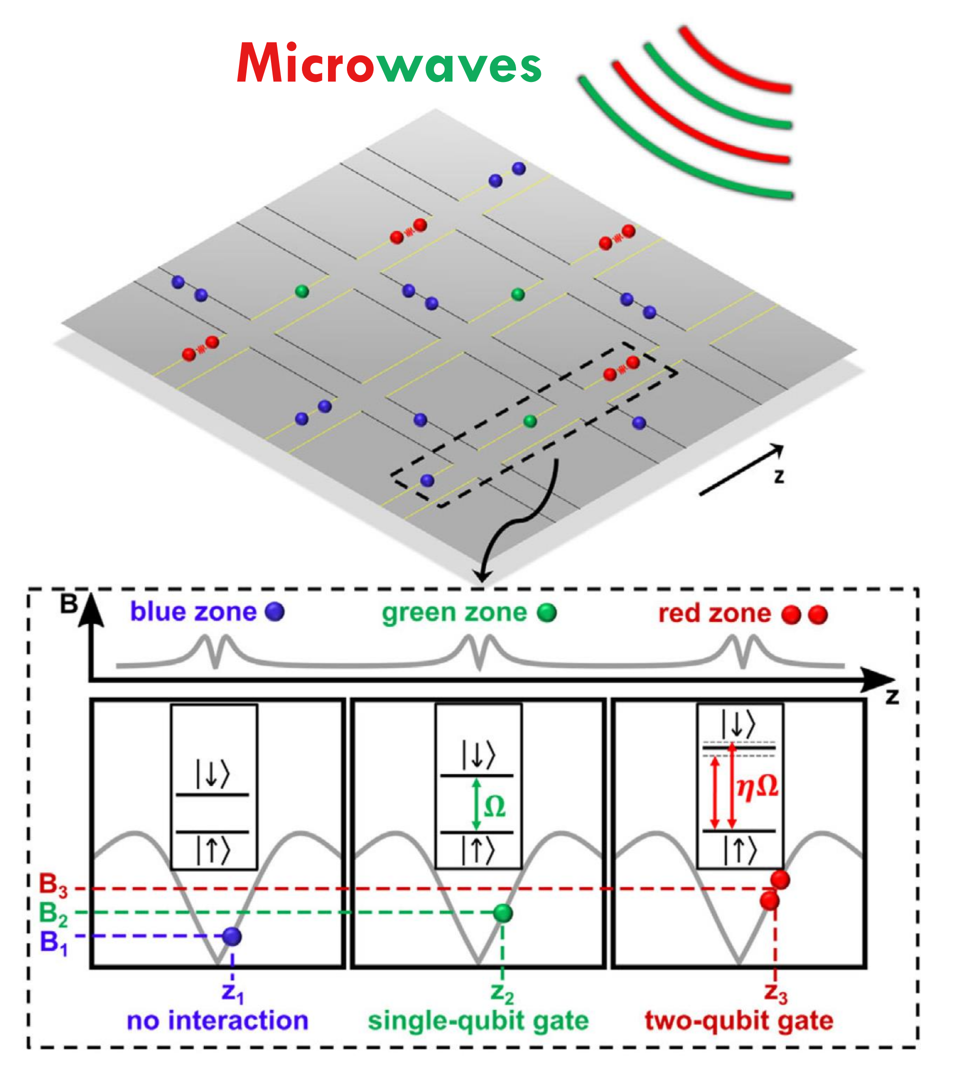
b) Linear Paul trap – four machined rods (+ endcaps not shown)

c) **Microfabricated surface trap – miniaturised, planar and modular!**

Microwave Trapped-Ion Quantum Computer

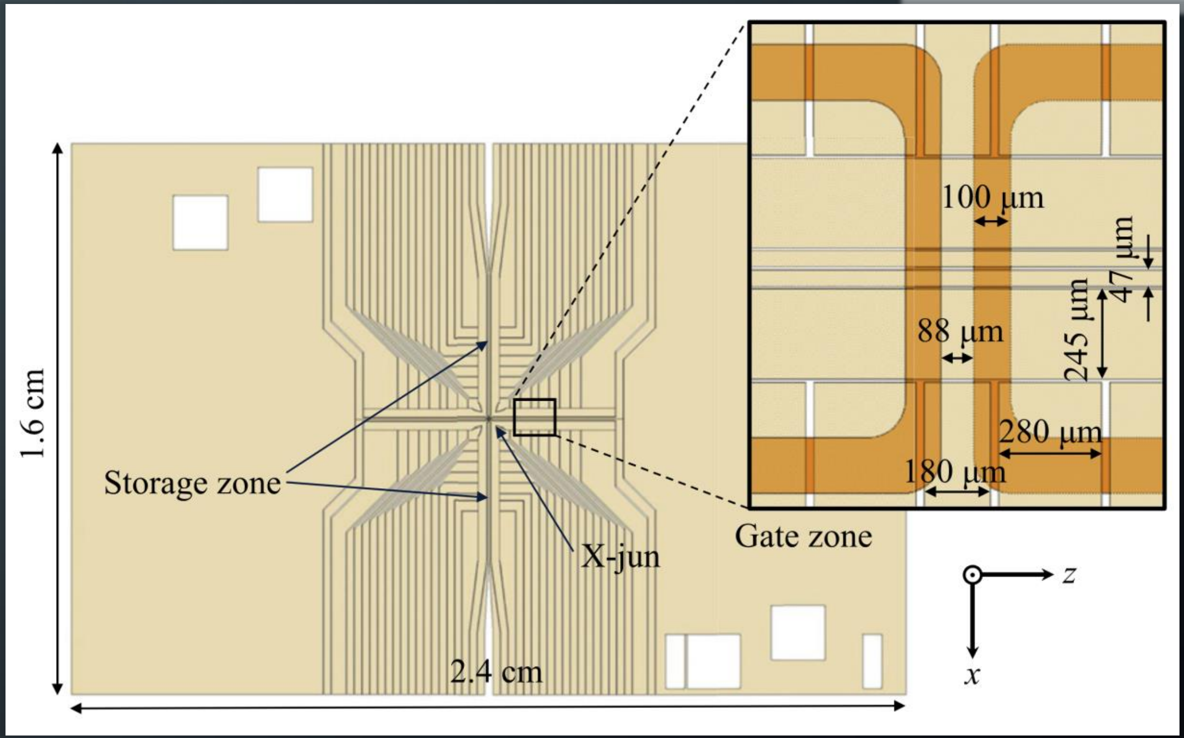
Bjoern Lekitsch et al,
Sci. Adv. **3**, *e1601540 (2017)*

- Distinct readout and gate zones within an array of **X-junctions**
- Based on long-wavelength radiation
  → Global **microwave** fields
- Local magnetic field gradient, generated by **current-carrying wires**, required for gate operations

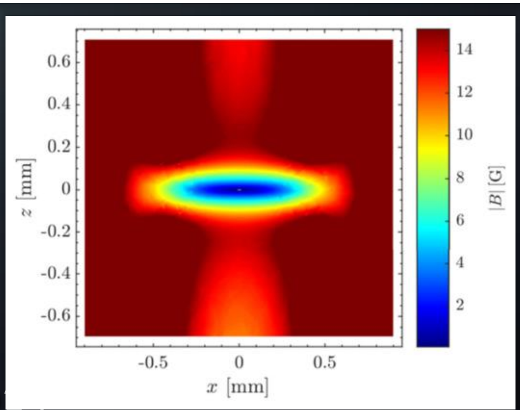


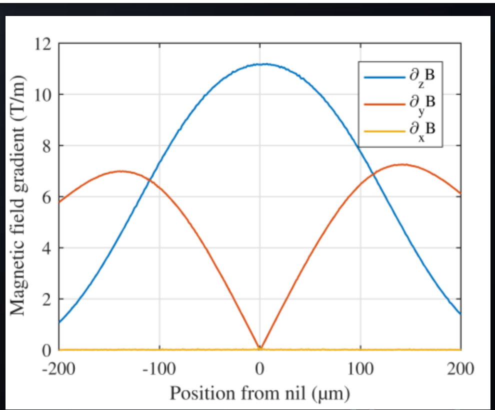
X-junction chip with embedded CCWs

Martin Siegele-Brown et al,
2022 Quantum Sci. Technol. 7 034003



- Low power dissipation
- $\sim 11\, T\, m^{-1}$ per 1 A of input current
- Continuous currents up to 13 A can be applied
- Maximum achievable B-field gradient $\sim 144\, T\, m^{-1}$ (with $h_{ion} = 125\, \mu m$)



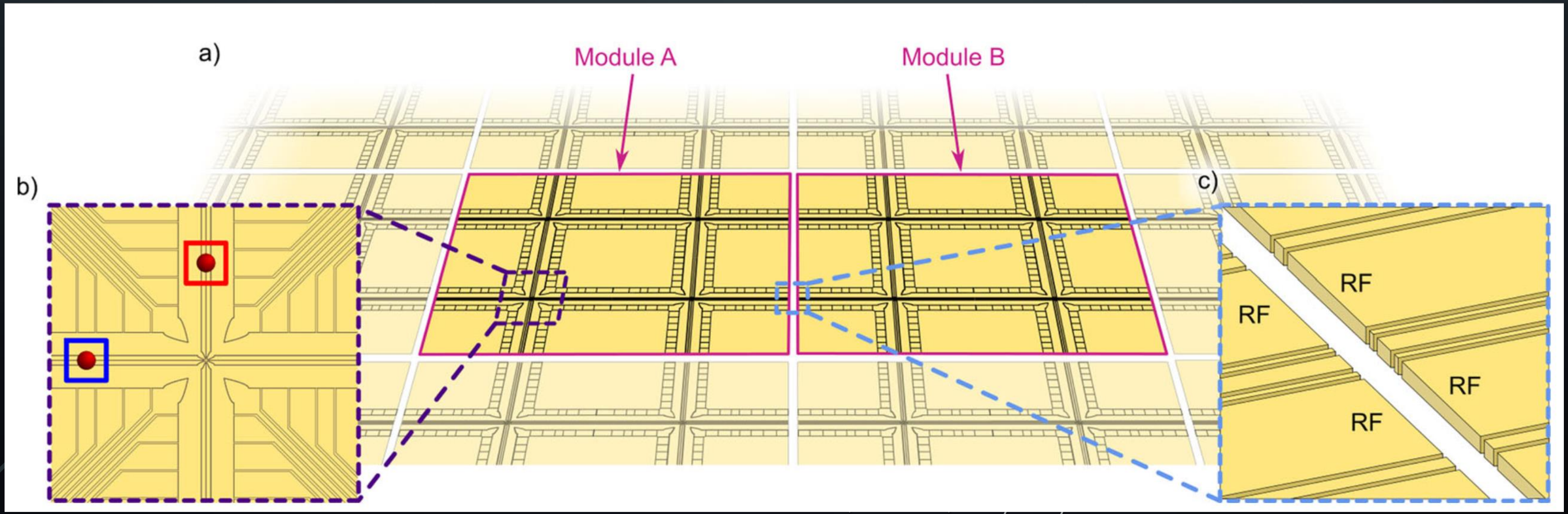


Approach to Scalability

- Laser beams for photoionisation, Doppler cooling and repumping. These are global *(all ions)* → no more scaling with qubit number

- Individually controlled DC voltages facilitate **ion shuttling**

- Module alignment for ion transport between different modules

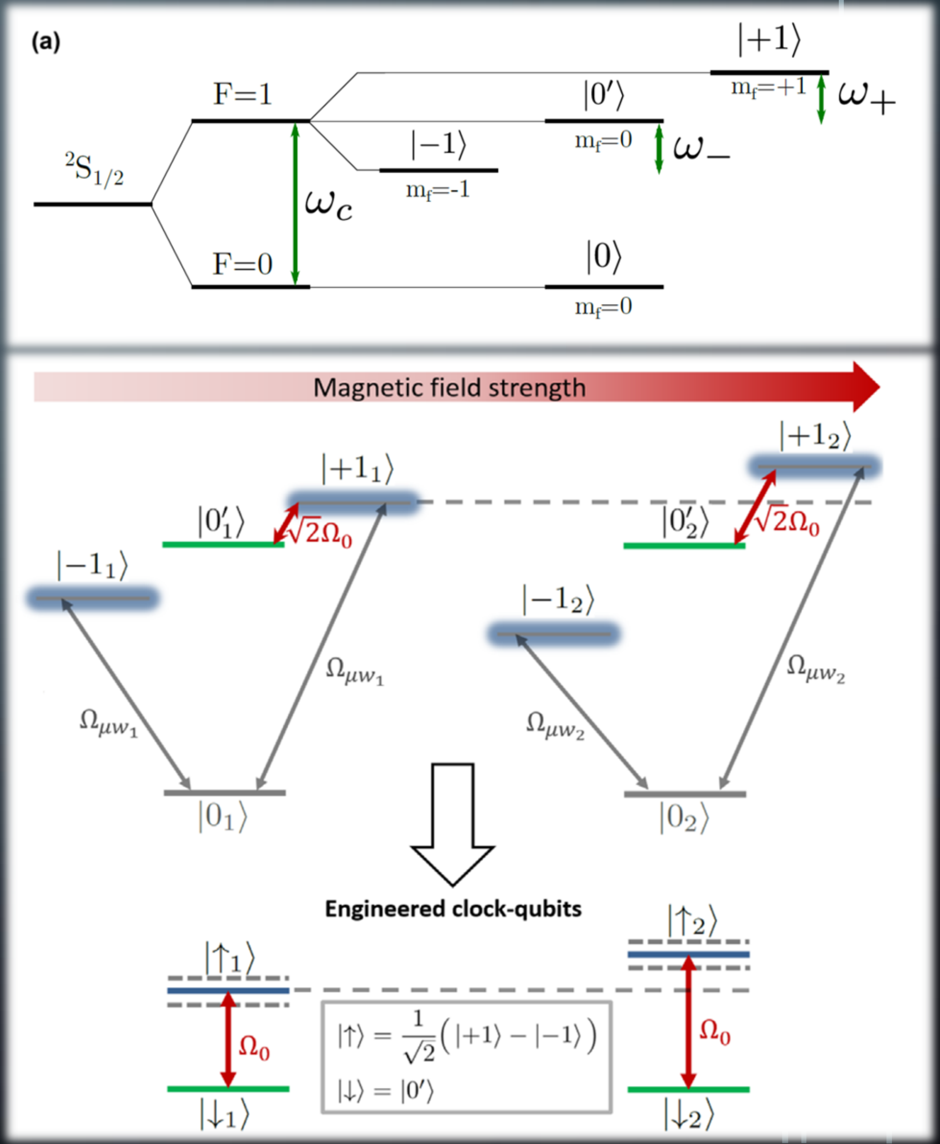


Akhtar M. et al, A high-fidelity quantum matter-link between ion-trap microchip modules. Nat Comm 14, 531 (2023)

Zeeman States

- Exhibits Zeeman-split states in an external magnetic field
- These magnetically sensitive states are susceptible to decoherence from ambient field noise *(fluctuations)*
- Static $\vec{B}$ **field gradient** $\rightarrow$ position-dependent resonances
- Tuneable transition frequency

  $\rightarrow$ Individually addressable qubits

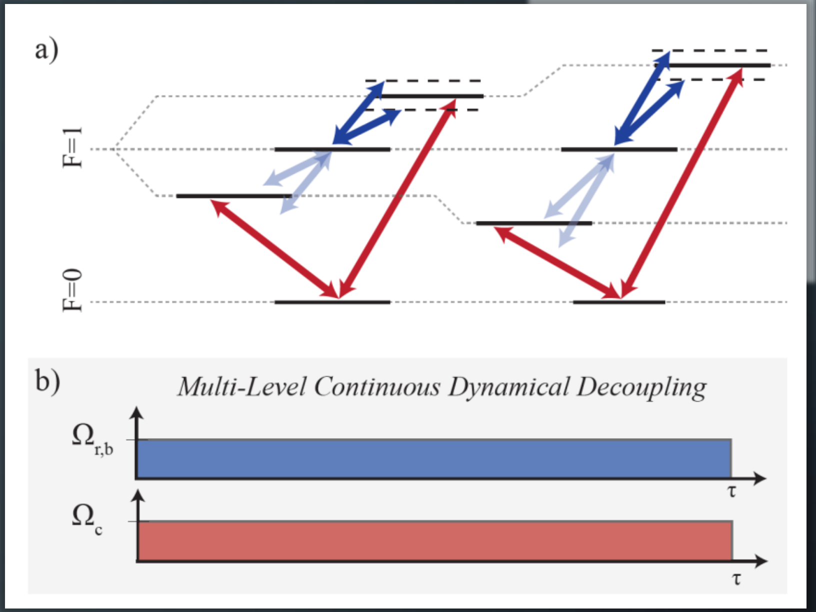


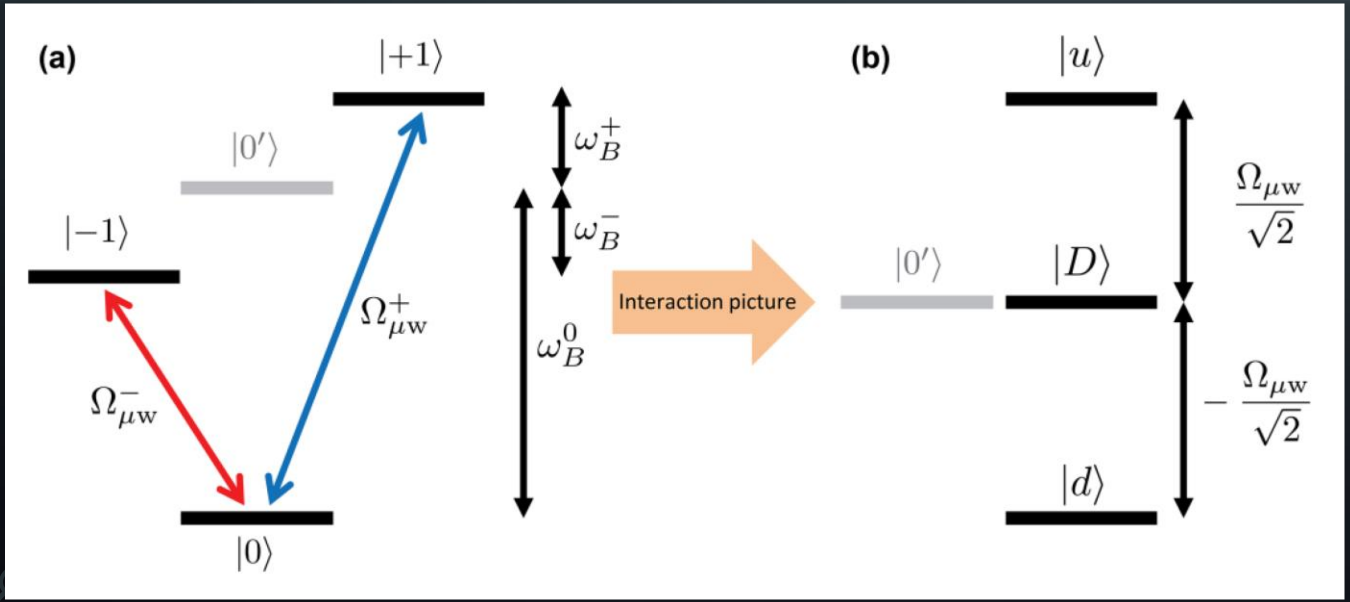
Microwave Dressed States

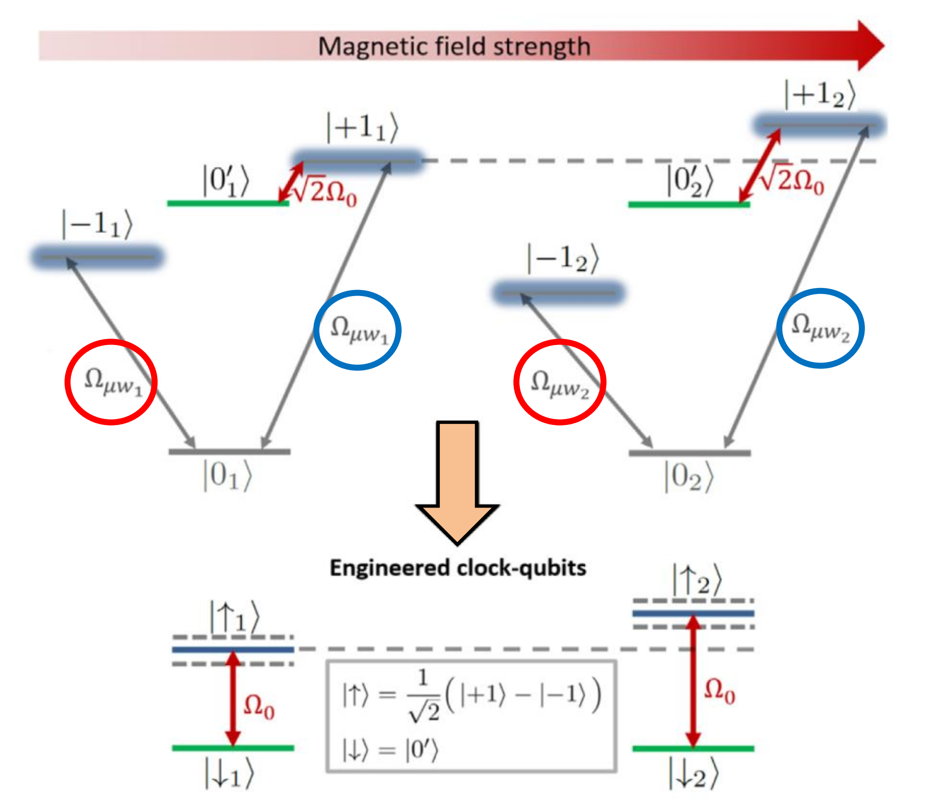
- Encode qubits in **microwave-dressed states**

  (**a.k.a.** Multi-level continuous dynamical decoupling)

- Larger coherence times ⟶ Longer-lived qubits







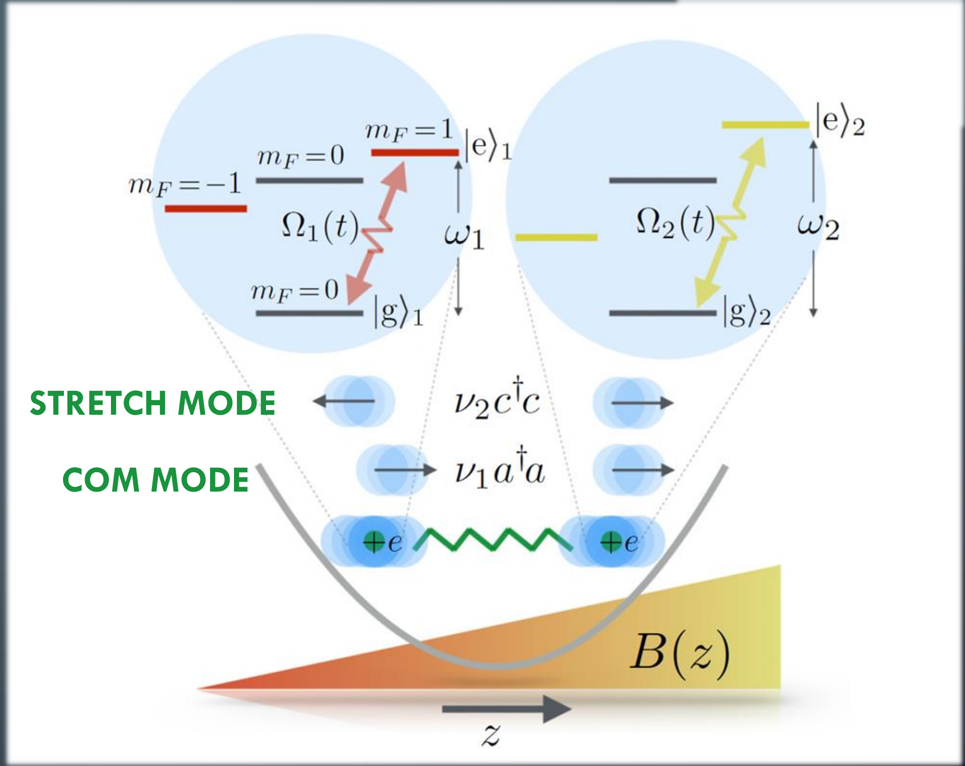
Entanglement Gates with Trapped Ions

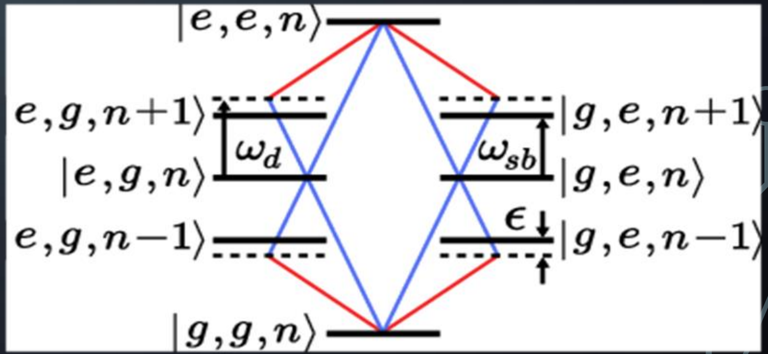
➢ Two-qubit entangling gates operate via **shared motional modes** of the ions

→ Information bus coupling their internal **electronic spin states**

➢ MS gate scheme uses fields detuned close to the upper and lower **motional sidebands,** and is insensitive to the ions' motional state

F. Mintert and C. Wunderlich, "Ion-trap quantum logic using long-wavelength radiation"

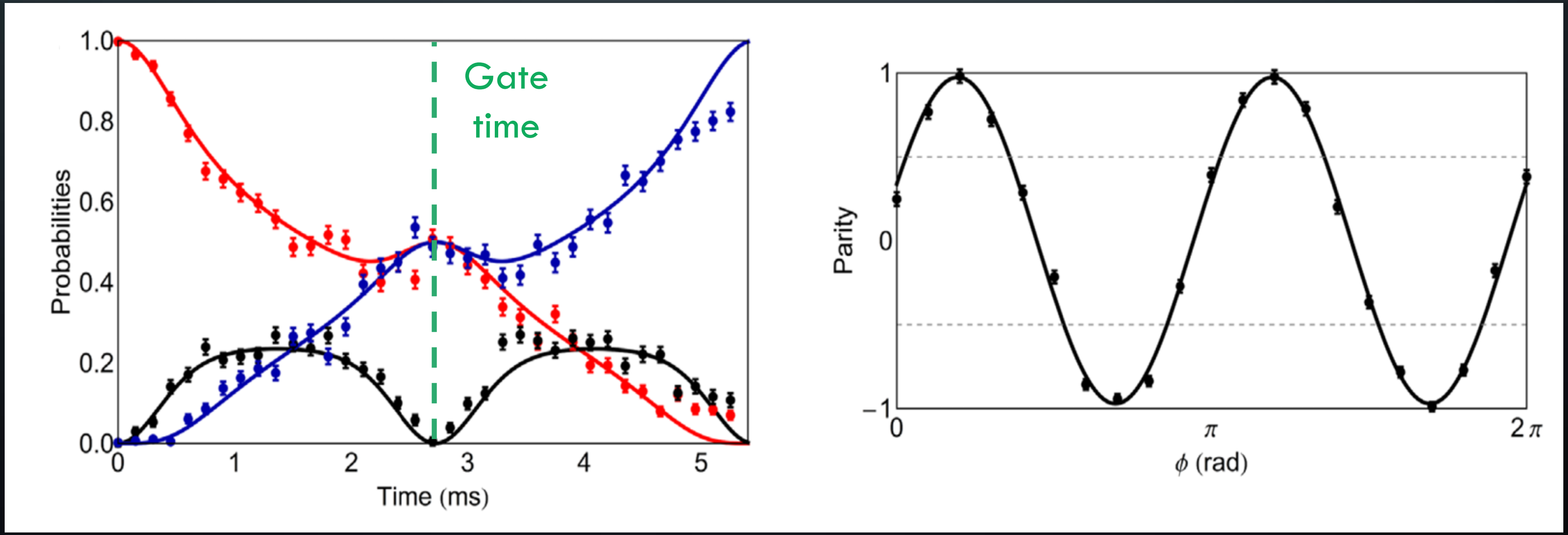




A. Sørensen and K. Mølmer, "Entanglement and quantum computation with ions in thermal motion"

Mølmer-Sørensen Gate

- Experimentally measure **state populations** and **parity scan** at the gate time → Calculate final **gate fidelity**
- Fidelity limited by miscalibrations and drifts, but mostly environmental noise coupling to the ions → **spin and motional decoherence**



Motivation for High(er)-Fidelity Gates

Petros Zantis, ECCTI, 12/07/2024

Motivation

Quality >> Quantity

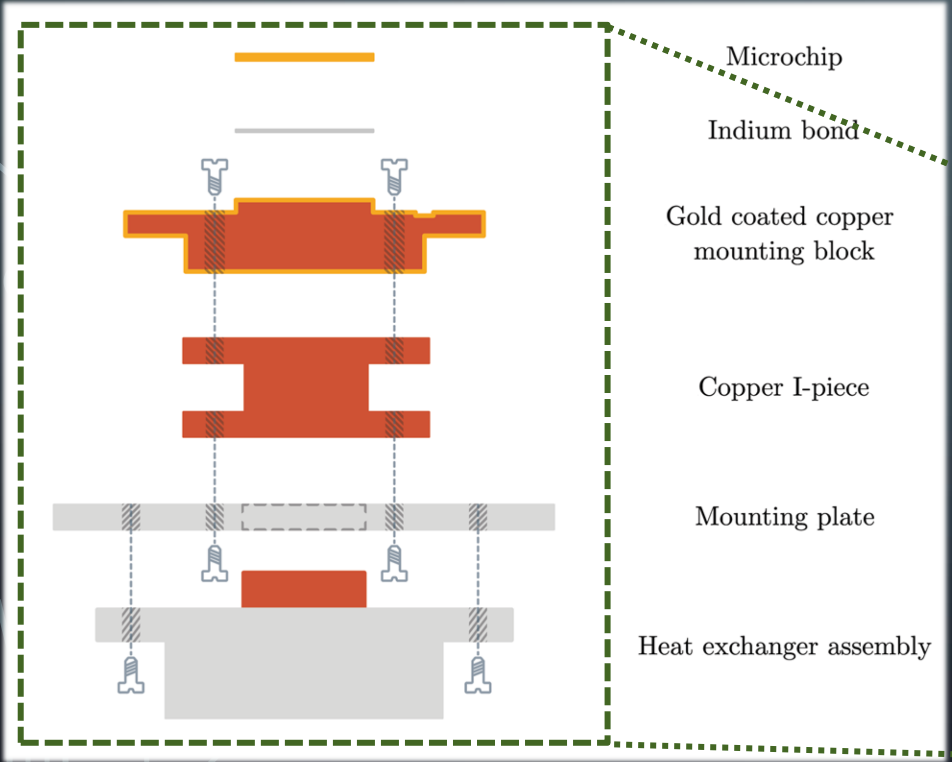
- Why **Q**uantum **E**rror **C**orrection?
  - Qubits inherently suffer from environmental noise → **decoherence**
  - Best platforms currently achieve **99 – 99.9%** gate fidelities → 1 – 0.1 % error
  - Useful algorithms (Shor's, Grover's, Quantum Chemistry) require ~ $10^9 - 10^{10}$ gates
- Why **higher** Fidelities?
  - Each QEC scheme results in a threshold - if **gate errors < threshold,** QEC works
  - Overhead is the price to pay (more physical qubits per logical qubit)
  - **A factor of 10 decrease in gate error rate ≈ factor of 10 decrease in overhead (and thus QC size) !!!**

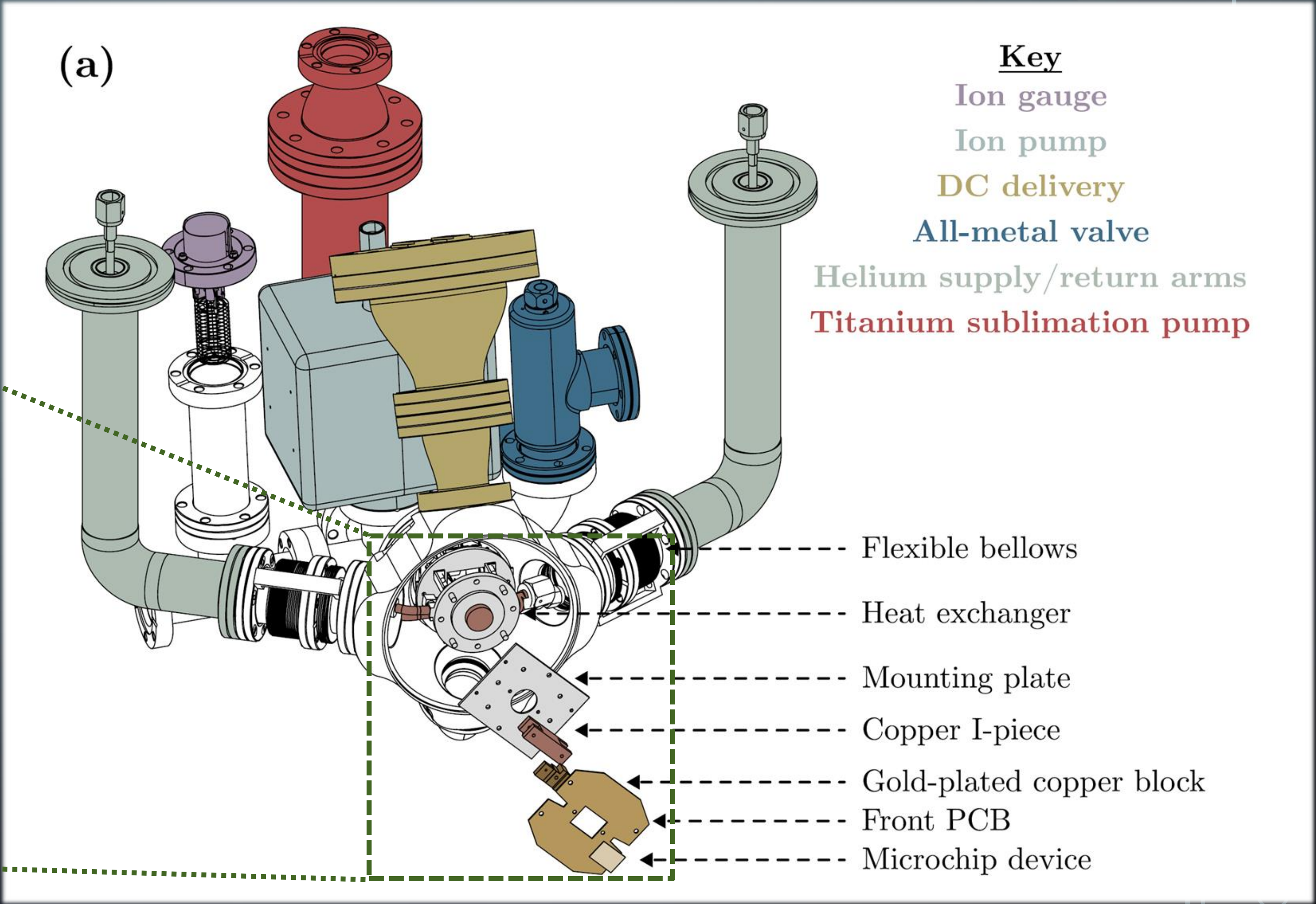
Experimental Setup

UHV chamber

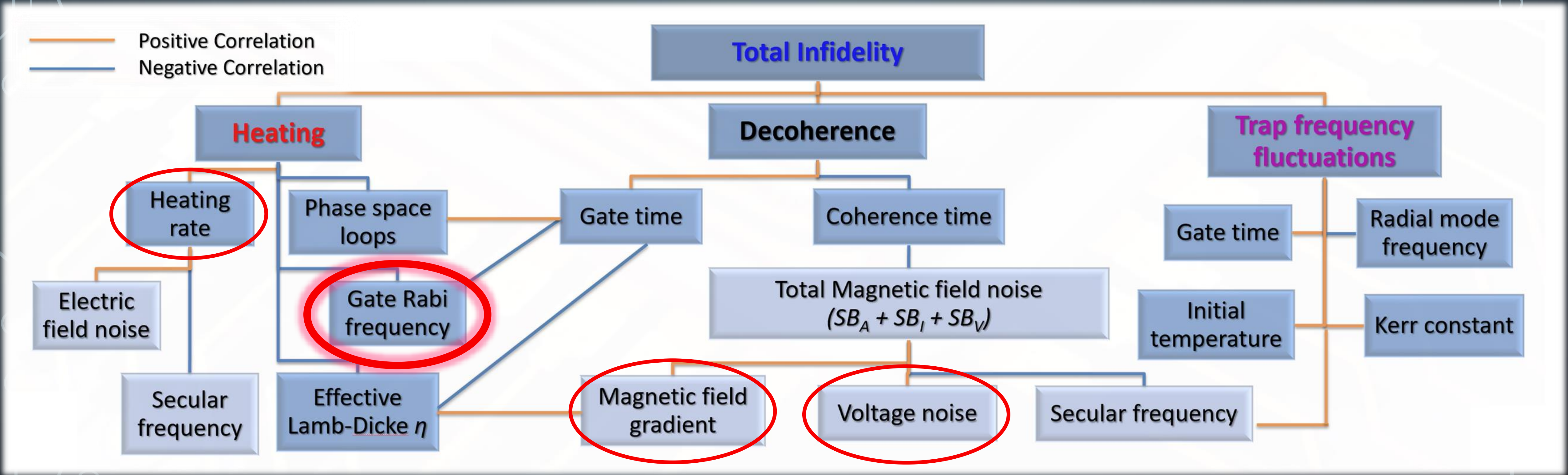
$\sim 10^{-12}\ mbar$

$\sim 50 - 70\ K$





Error Modelling & Parameter Dependencies



- More MW power at the ion → higher oscillating $\vec{B}$ field amplitude → larger Rabi frequency → lower gate time → less gate error → **higher gate fidelity!**

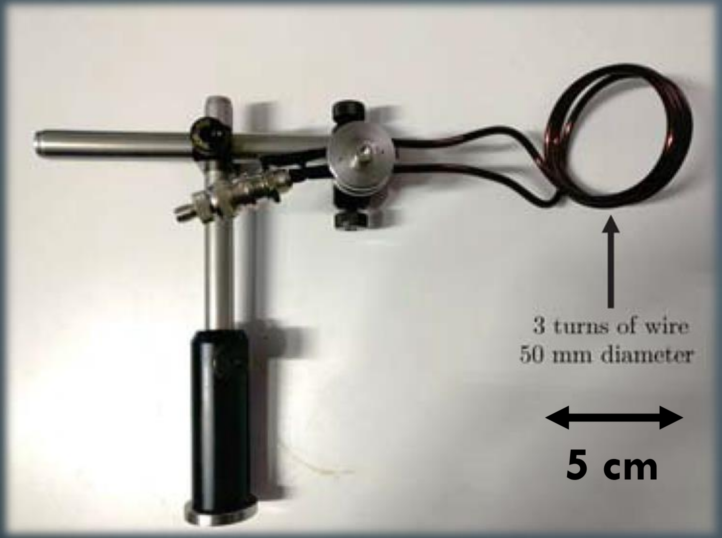
Microwave Delivery

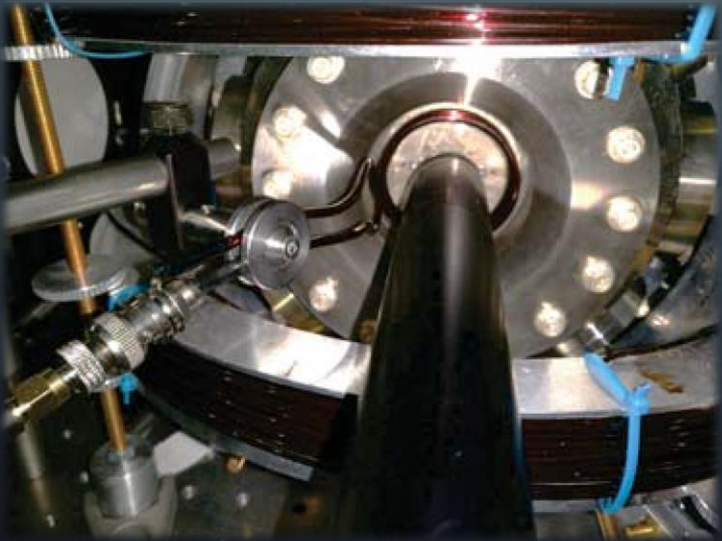
From this :

(external

RF coil &

MW horn)



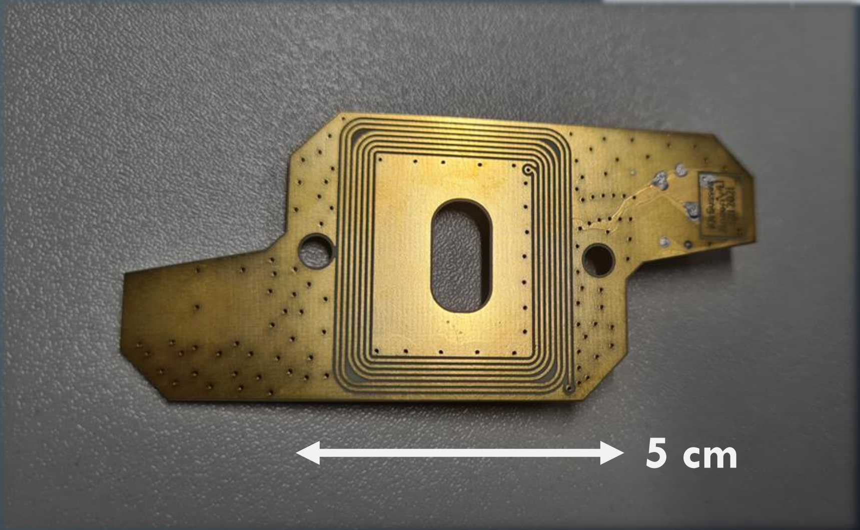


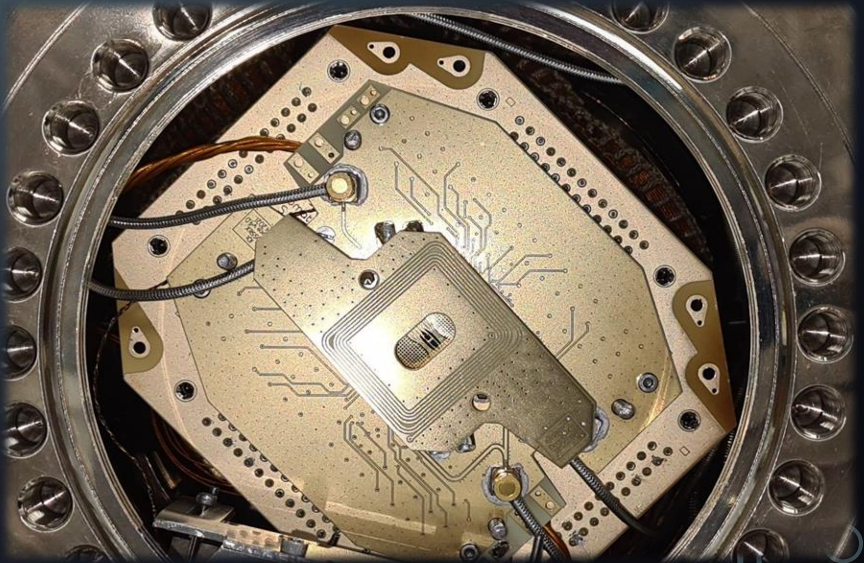
To this :

(in vacuum

patch

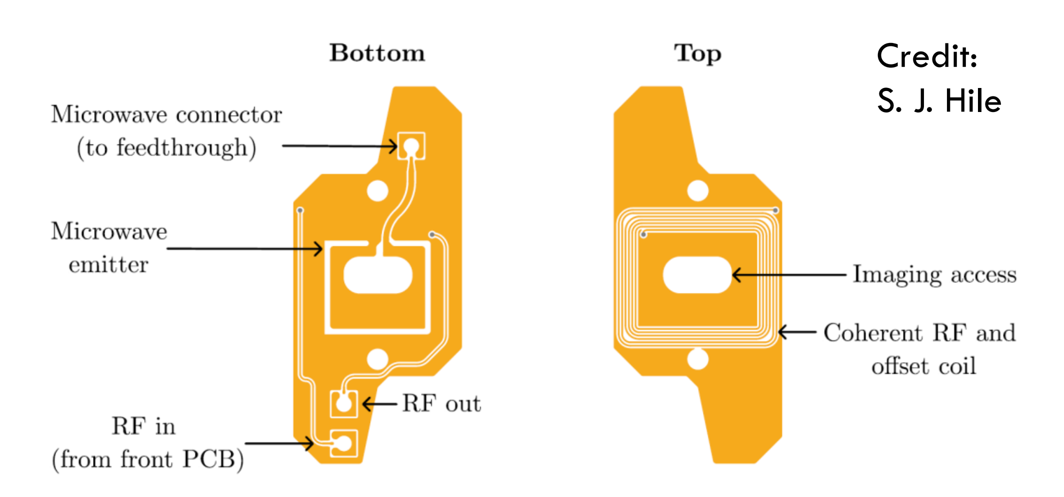
antenna)

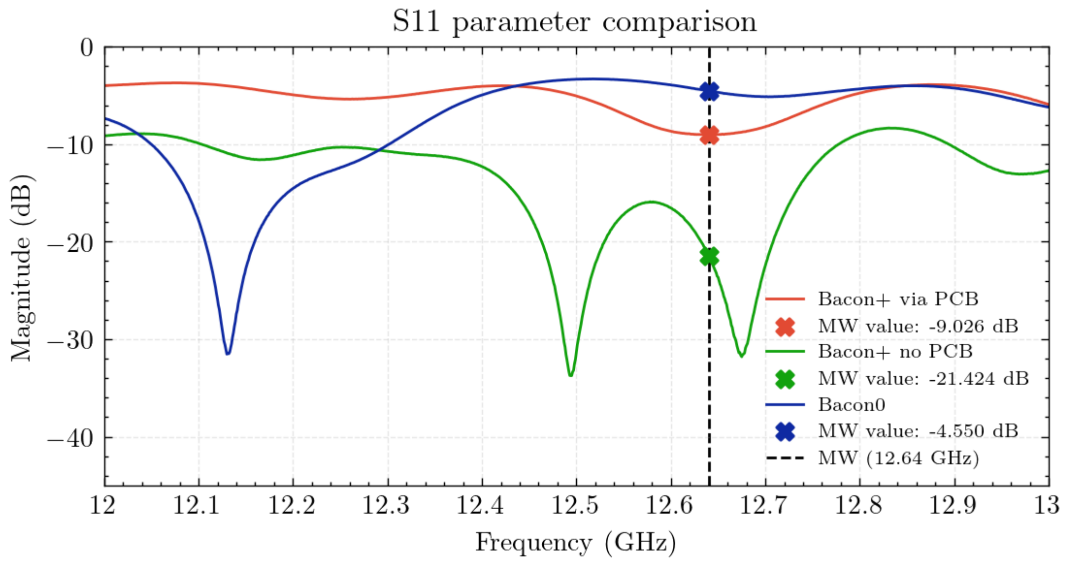


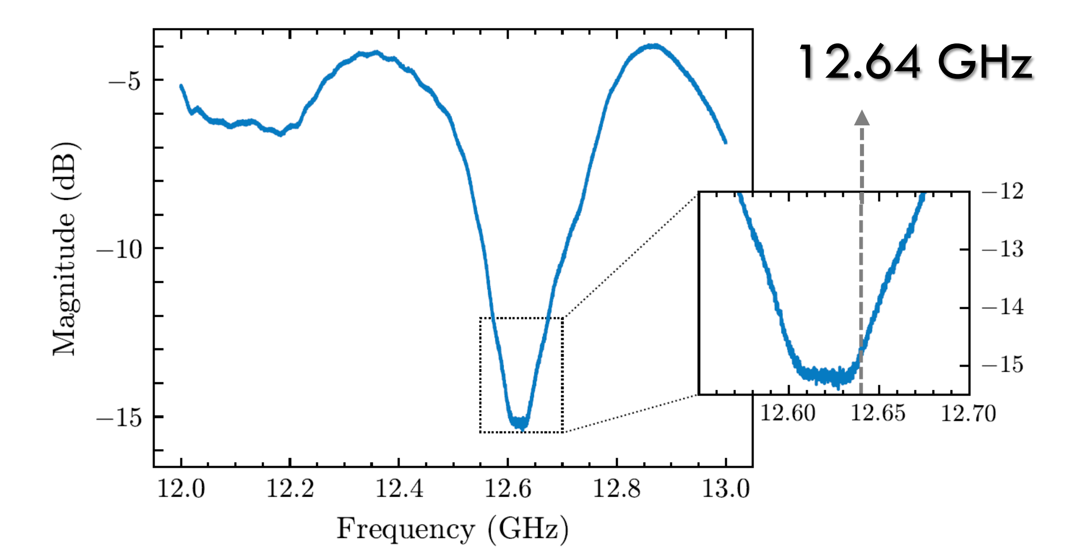


Antenna Characterisation

- Numerical simulations guided design
- Compared various prototypes
- S11 reflection parameter measured on VNA *(Rohde & Schwarz ZNB20)*
- Final iteration shows healthy resonance dip!



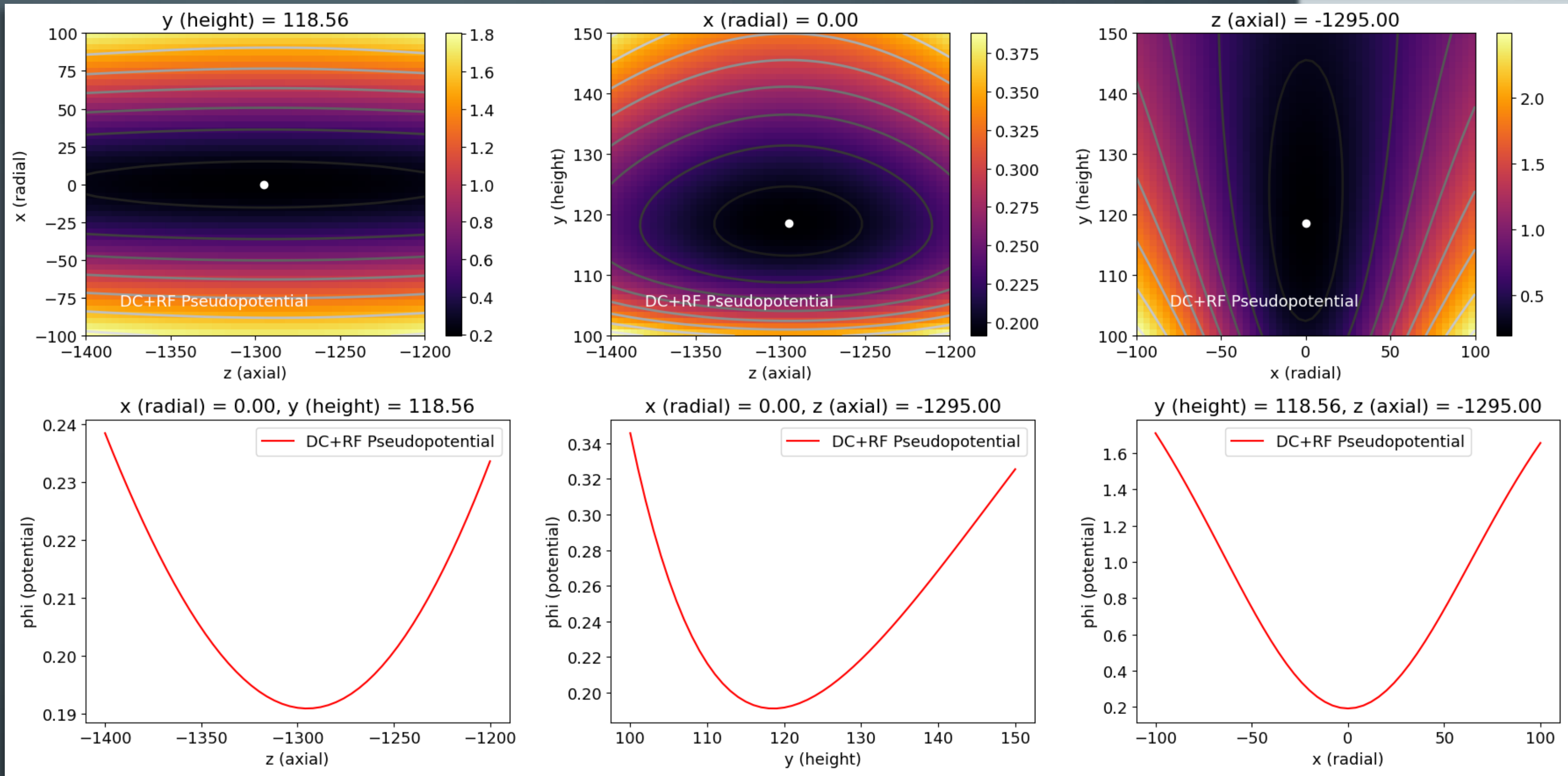


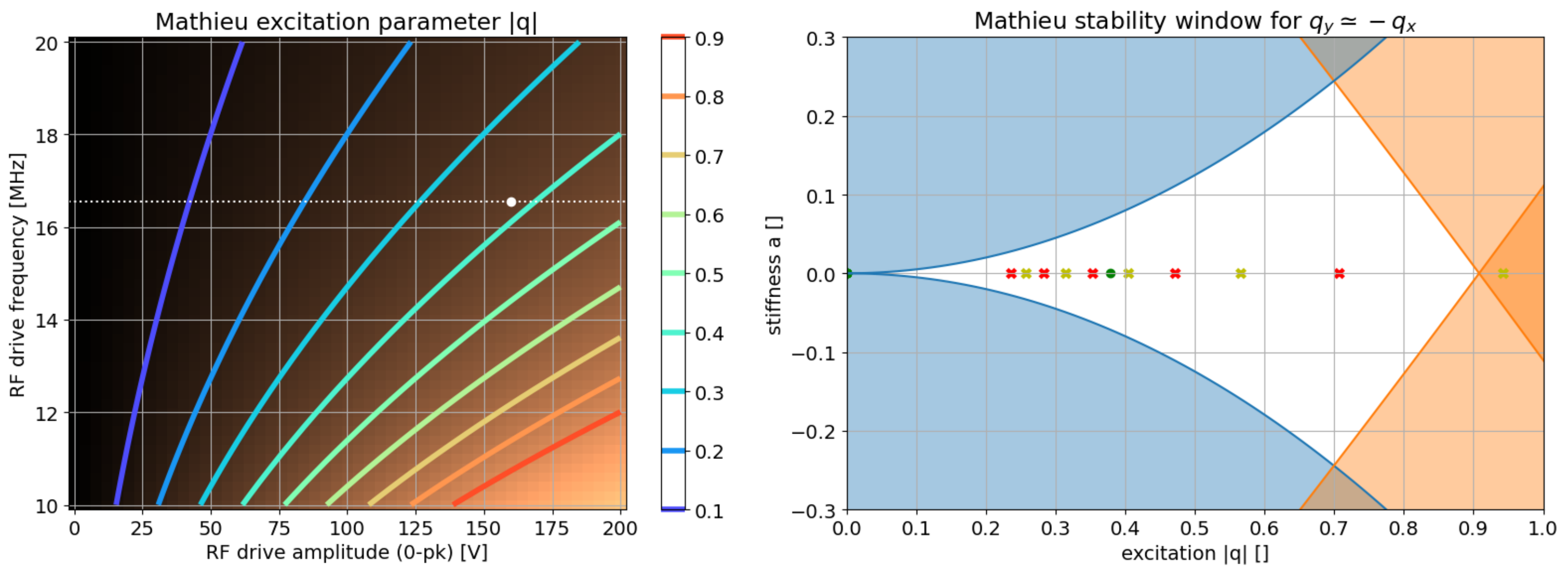


Trapping Simulations

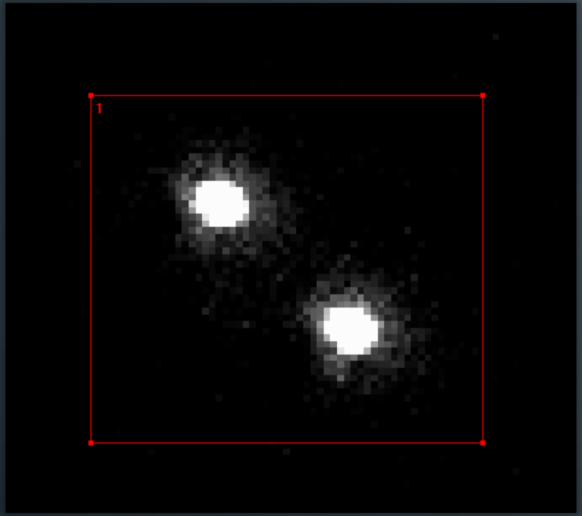
- **Top figure:** 2D contour plots & 1D line plots of the total (DC + RF) trapping potential along all three axes

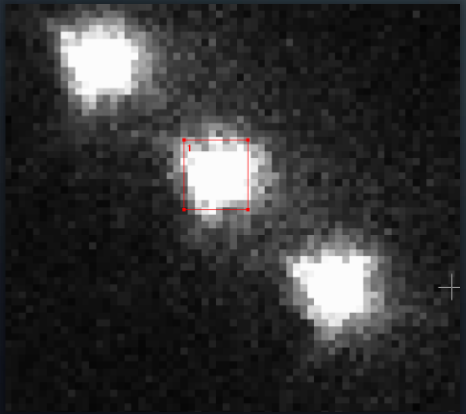
- **Bottom figure:** Q-parameter contour plot & Mathieu stability diagram

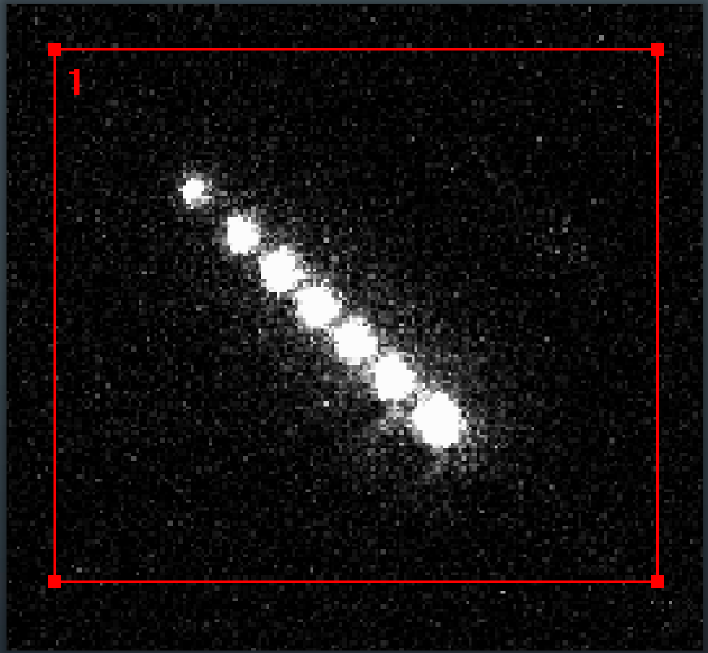




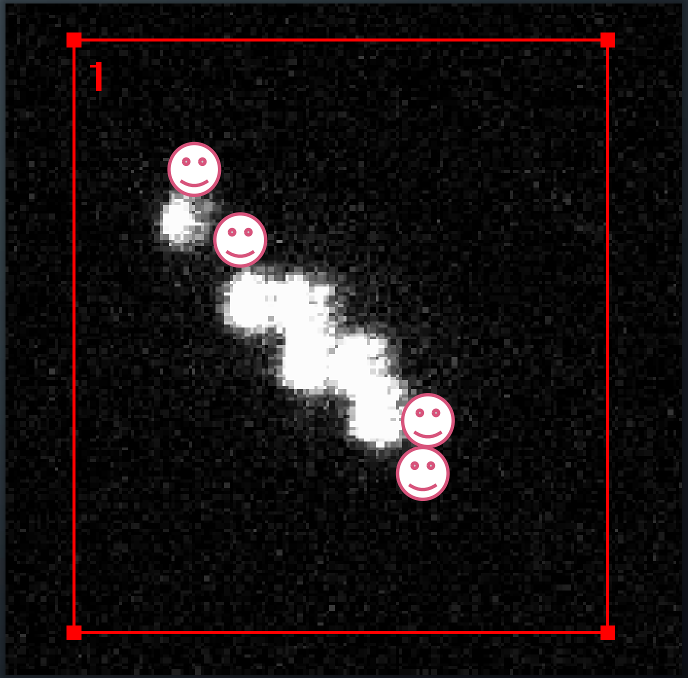
First ions on the X-junction chips!







Linear chain of 7 ions

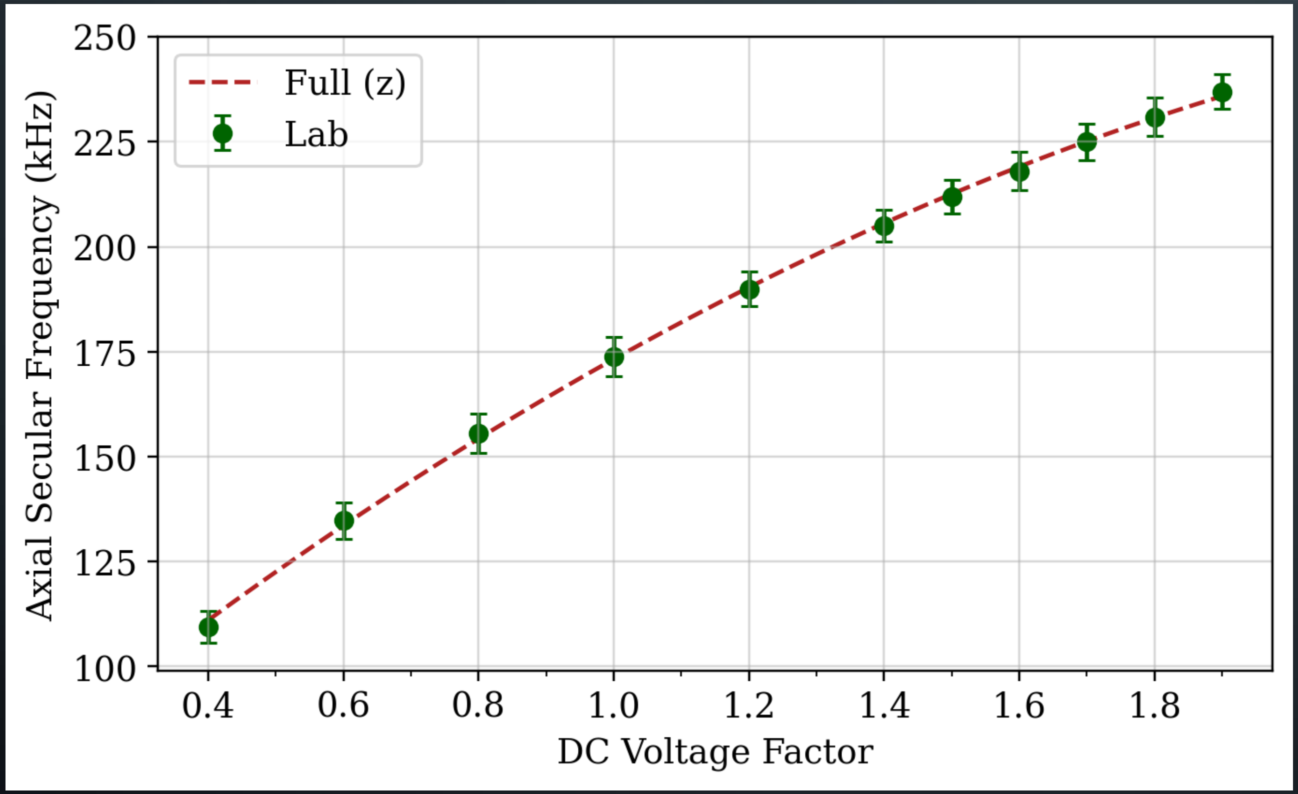


Zig-zag crystal of ~10 ions

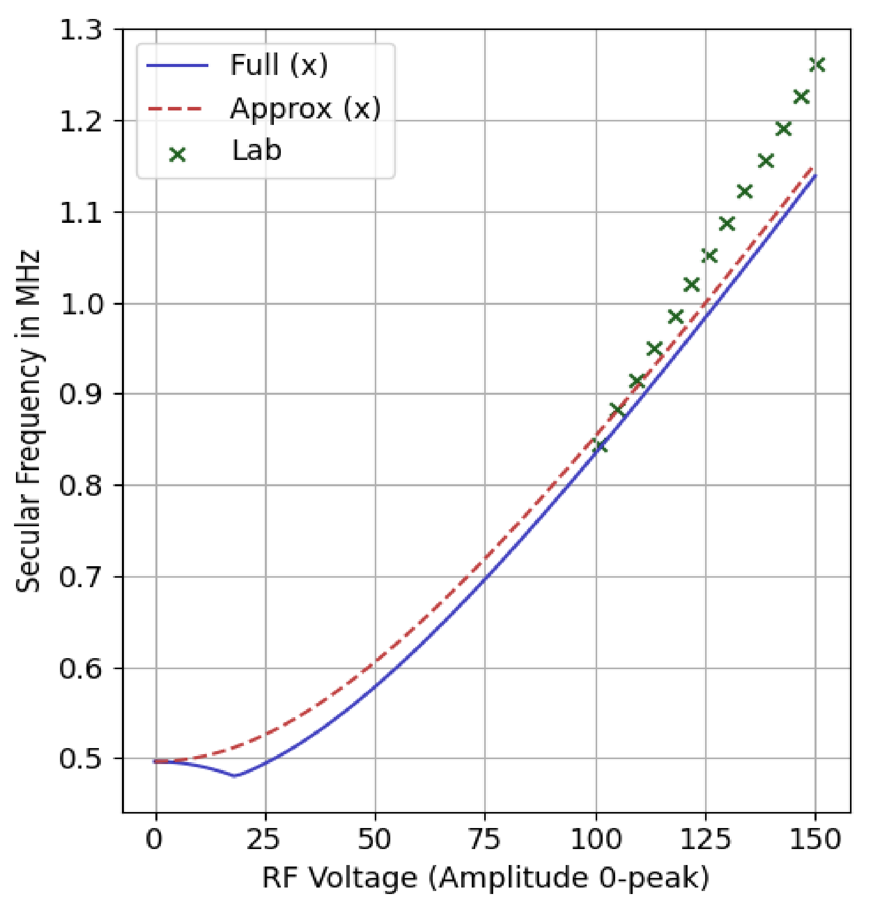
Measurements/ Characterisation

Petros Zantis, ECCTI, 12/07/2024

Secular Frequencies Measurements



Axial frequency $(\omega_z/2\pi)$ over DC voltages



Radial frequency $(\omega_x/2\pi)$ over RF voltage

Excess Micromotion Calibration

D. J. Berkeland, J. D. Miller, J. C. Bergquist, W. M. Itano, and D. J. Wineland, "Minimization of ion micromotion in a Paul trap"

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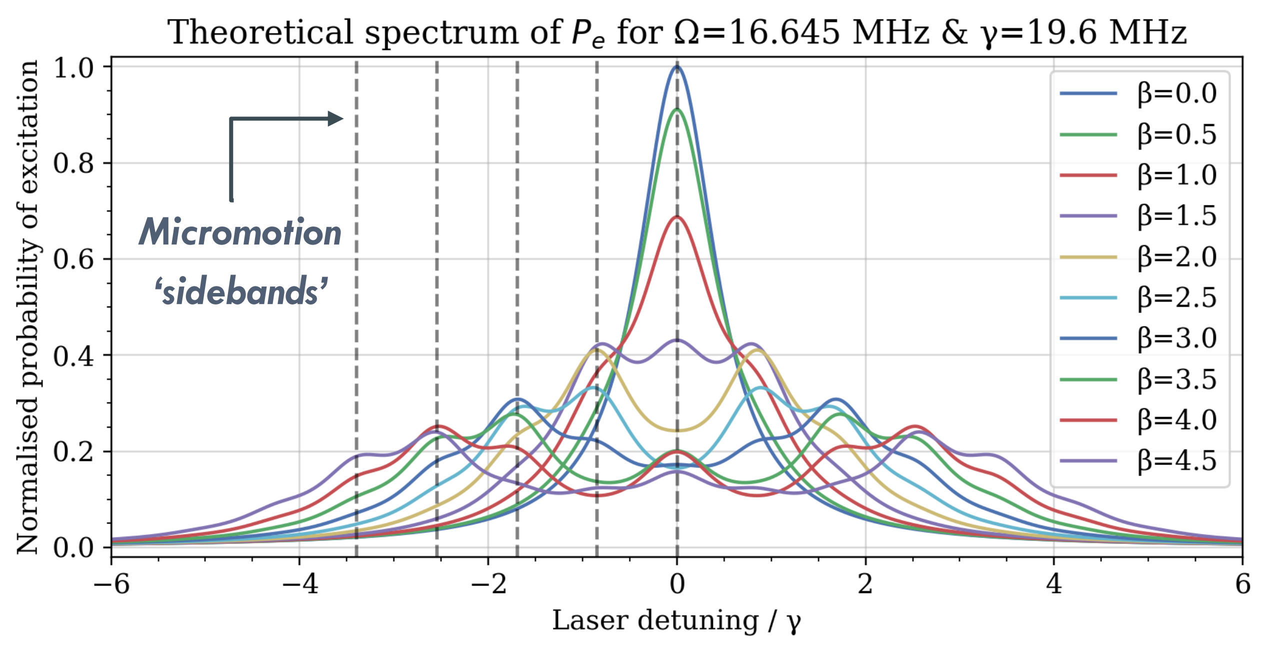
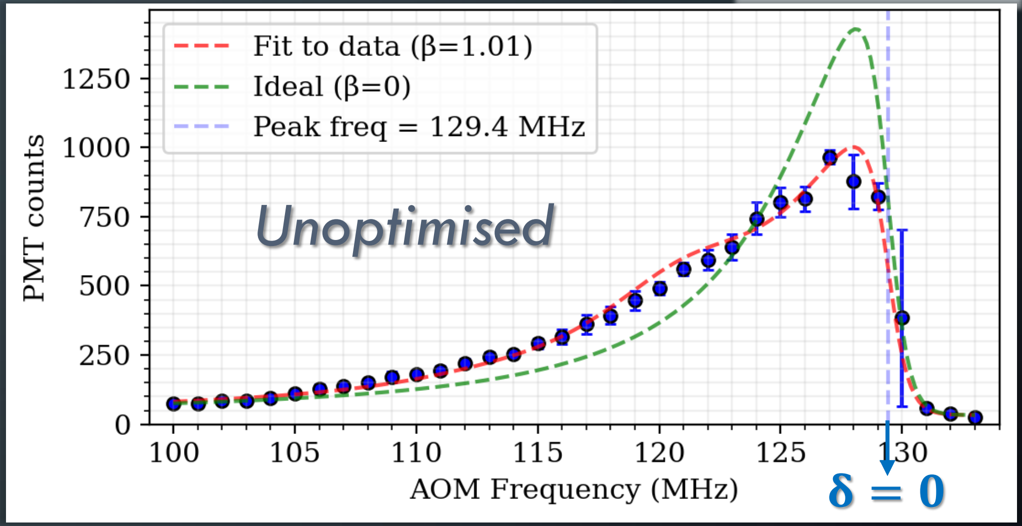
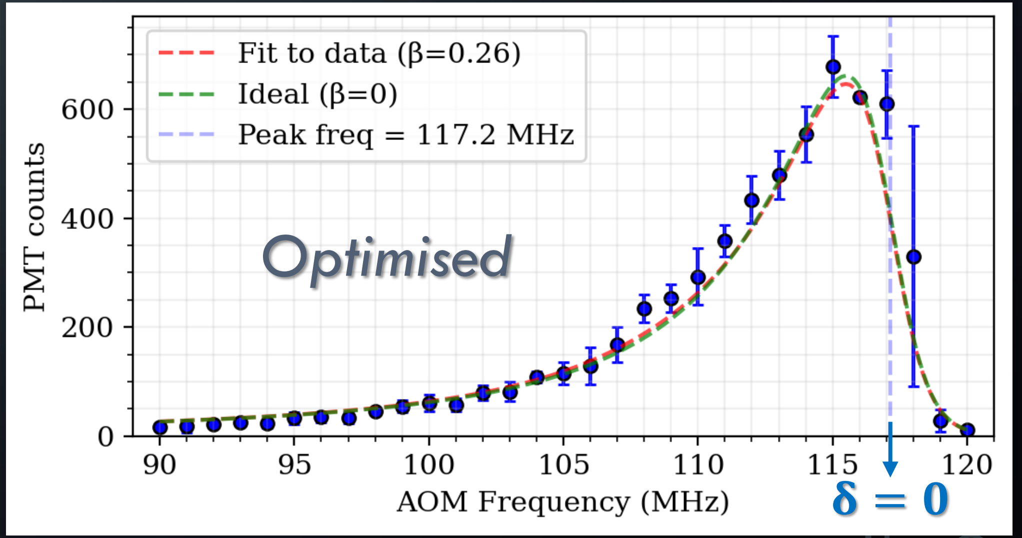
$$P_e \propto \sum_{n=-\infty}^{\infty} \frac{J_n^2(\beta)}{(\delta + n\Omega)^2 + (\gamma/2)^2}$$

$$\delta = \omega_{laser} - \omega_{atom}$$

$(= 0$ *at resonance*$)$

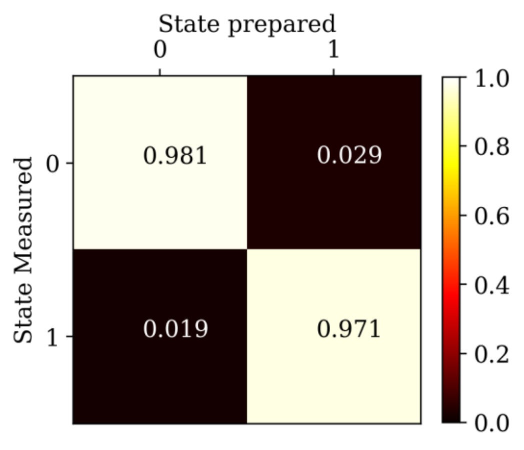




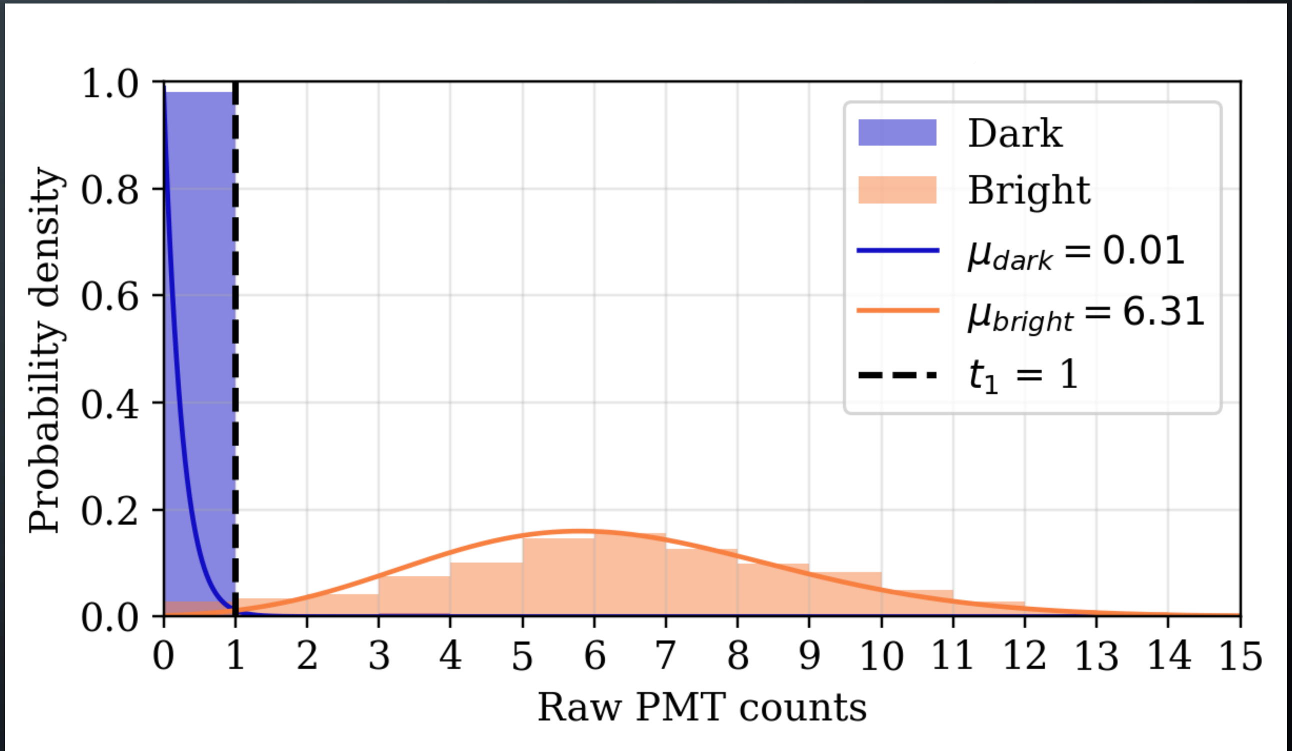


State Preparation and Measurement

State Detection Error Matrix $\boldsymbol{M}$:

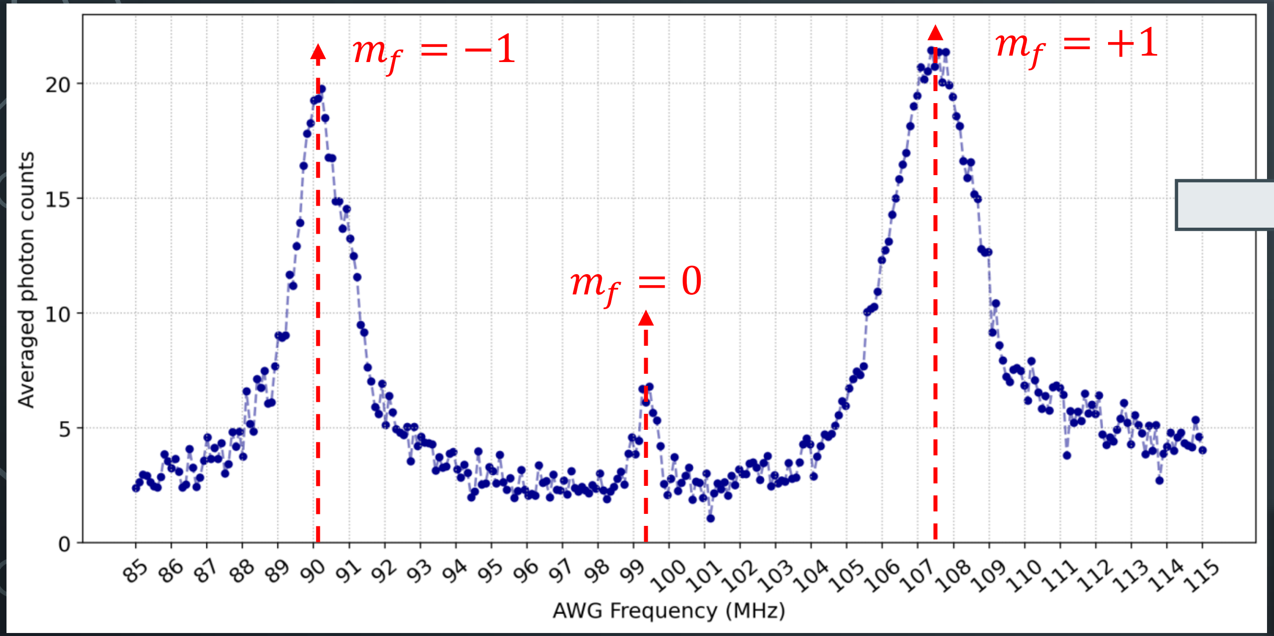


- Poisson Statistics (photon counting via PMT)
- Maximum likelihood estimation (MLE)
- **Threshold** to determine bright or dark



$$\textbf{Dark} = |0\rangle \; or \; |\downarrow\rangle$$
$$\textbf{Bright} = |1\rangle \; or \; |\uparrow\rangle$$

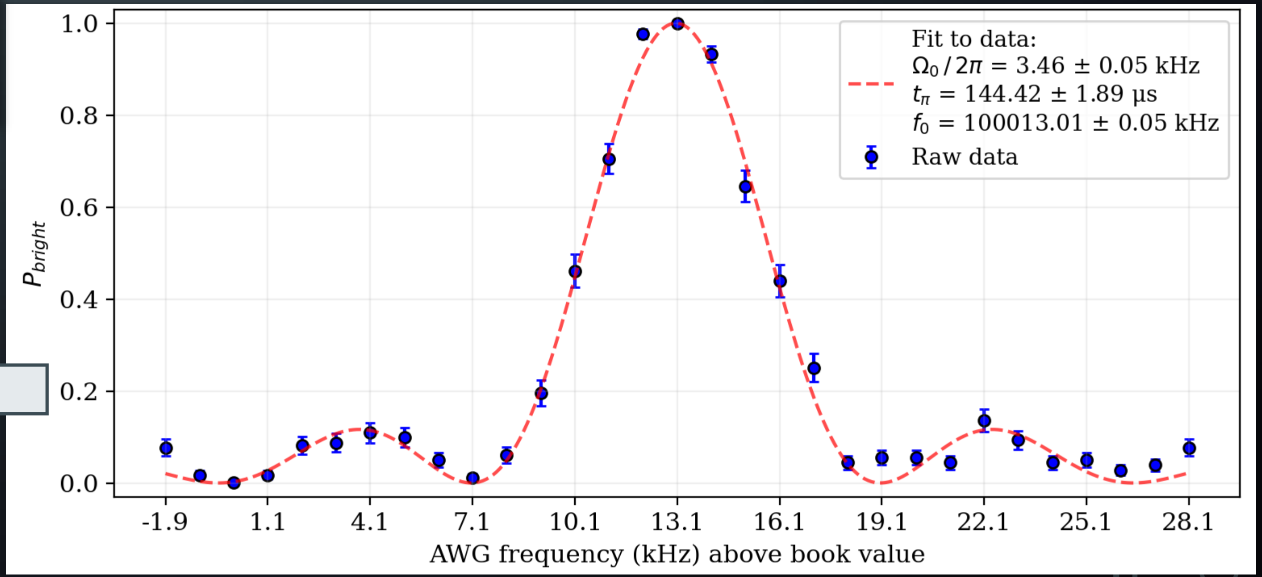
Single Qubit Characterisation



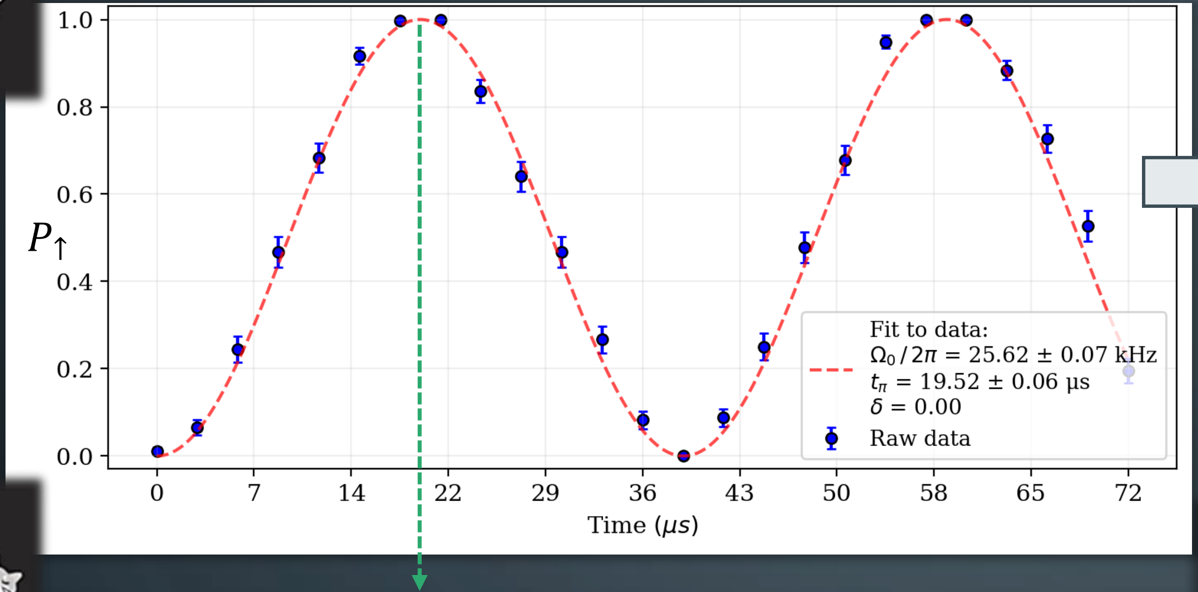
Incoherent frequency scan to locate the resonant frequencies of the Zeeman states (m_f = -1, 0, +1)

Coherent frequency scan for an accurate measurement of the transition frequency:

$$\left({}^2S_{1/2}\right)|F=0\rangle \leftrightarrow |F=1, mf=0\rangle$$



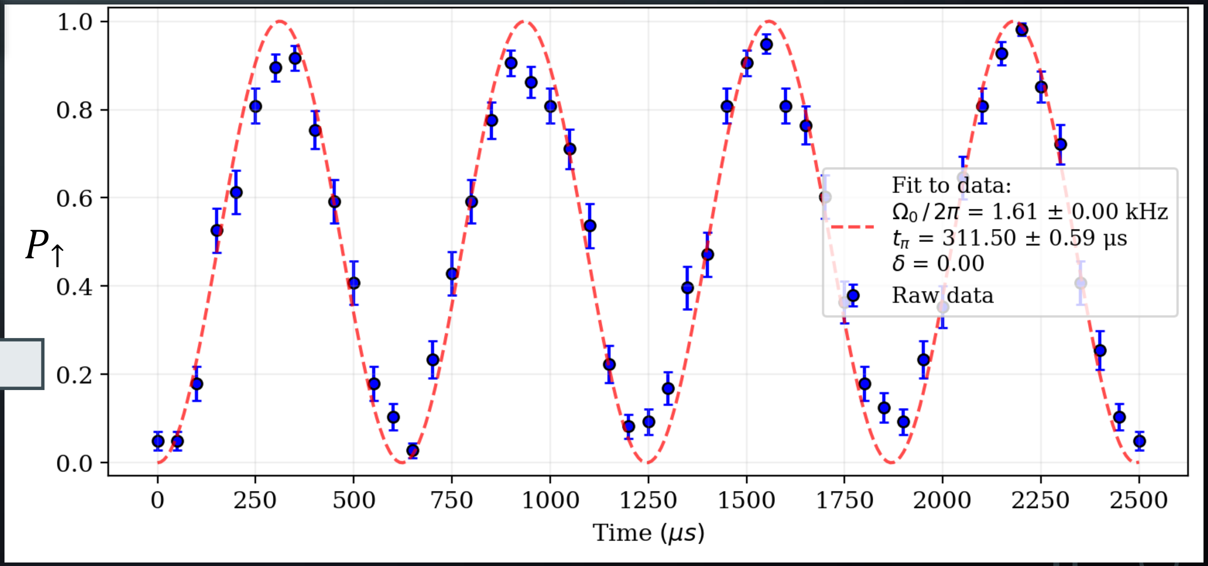
Rabi Oscillations



π-pulse

Rabi flopping on:

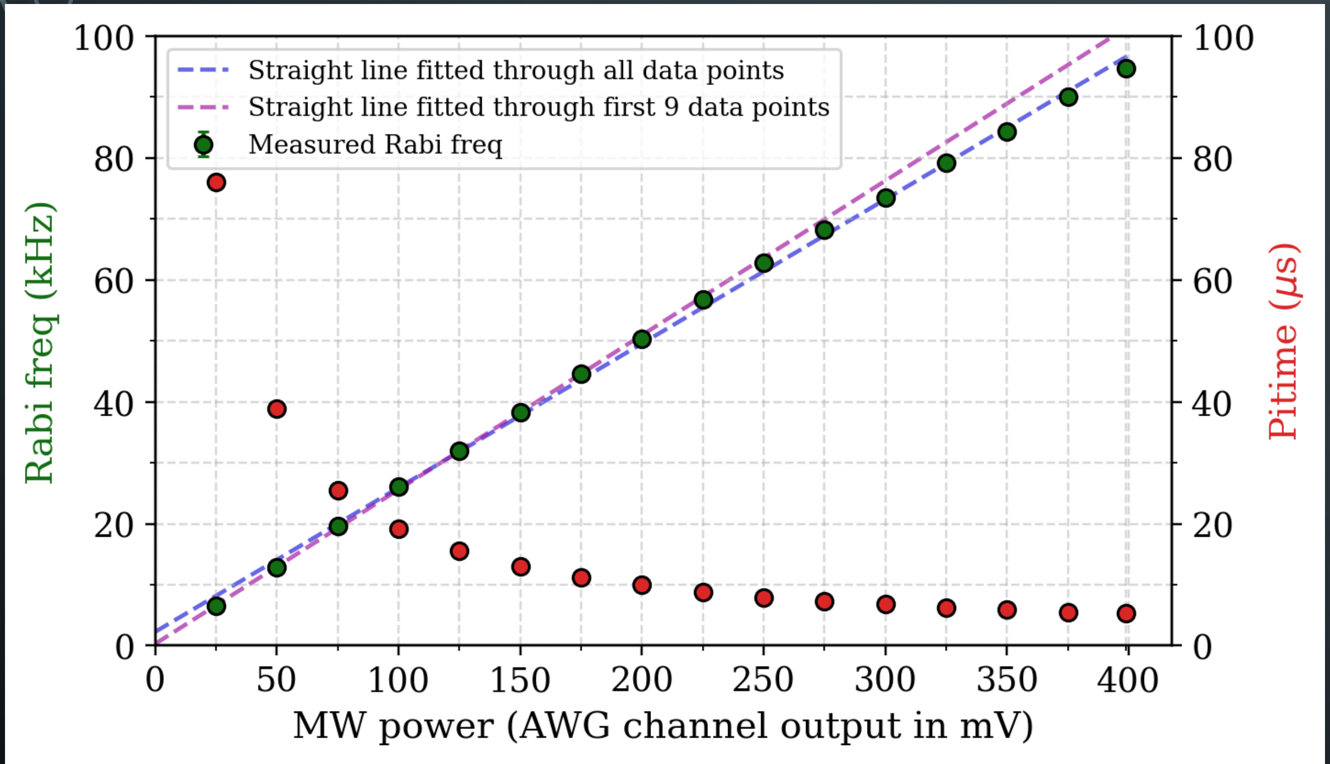
$$\left({}^2S_{1/2}\right)|F=0\rangle \leftrightarrow |F=1, mf=+1\rangle$$



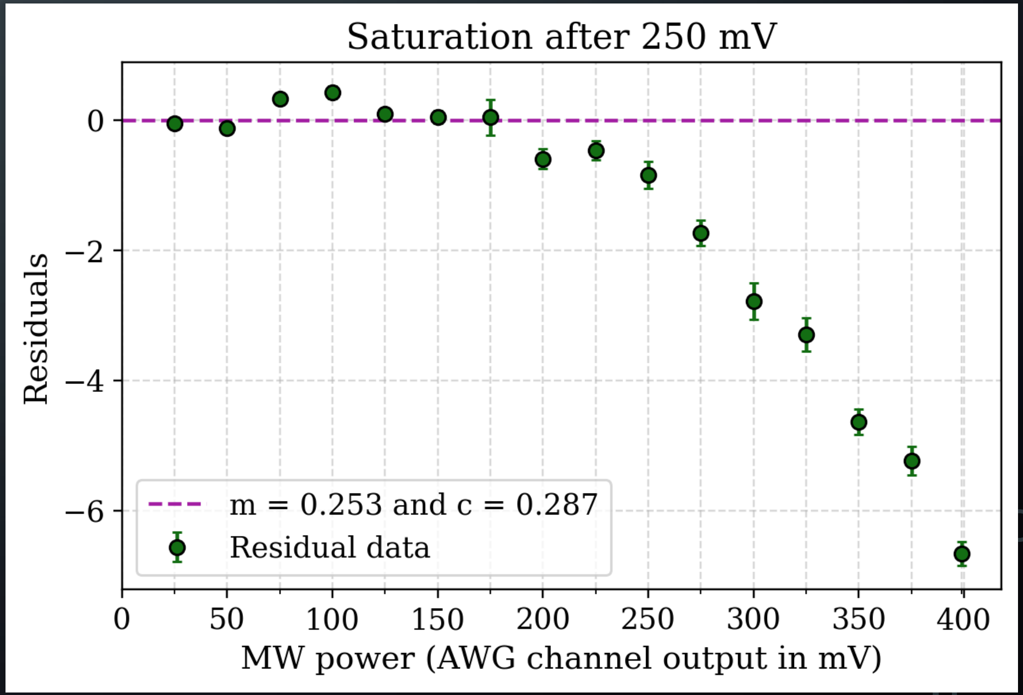
Rabi flopping on:

$$\left({}^2S_{1/2}\right)|F=0\rangle \leftrightarrow |F=1, mf=0\rangle$$

Rabi "powers"

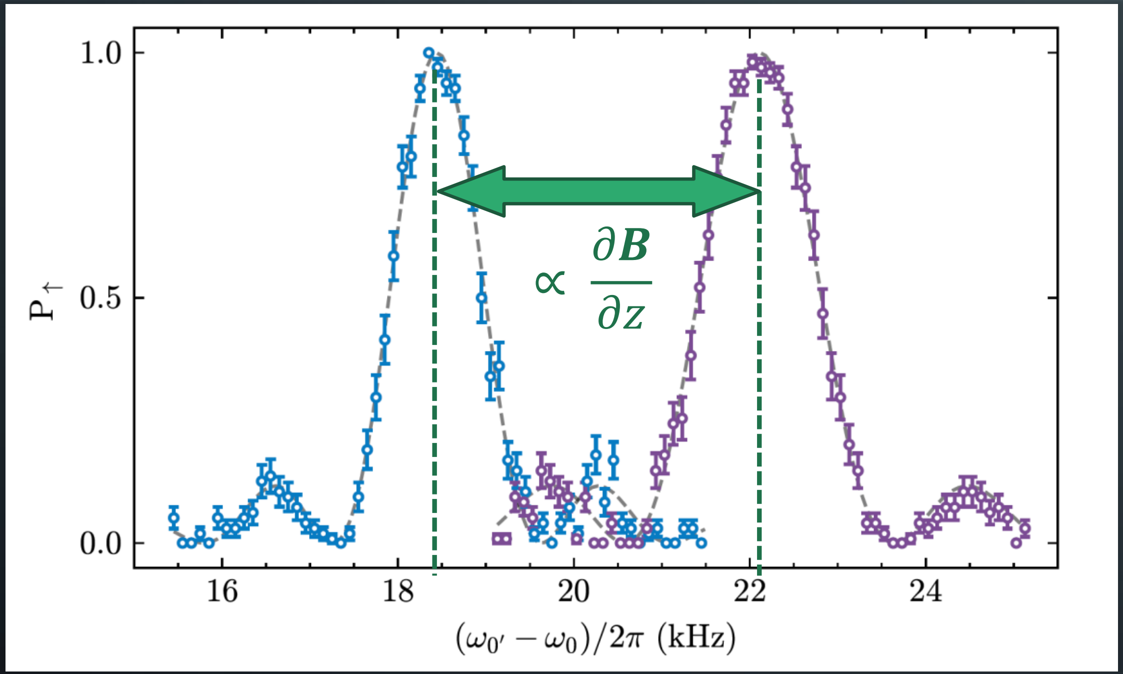


- Characterising the microwave chain by measuring the achievable Rabi frequencies *(on the Zeeman + state)*

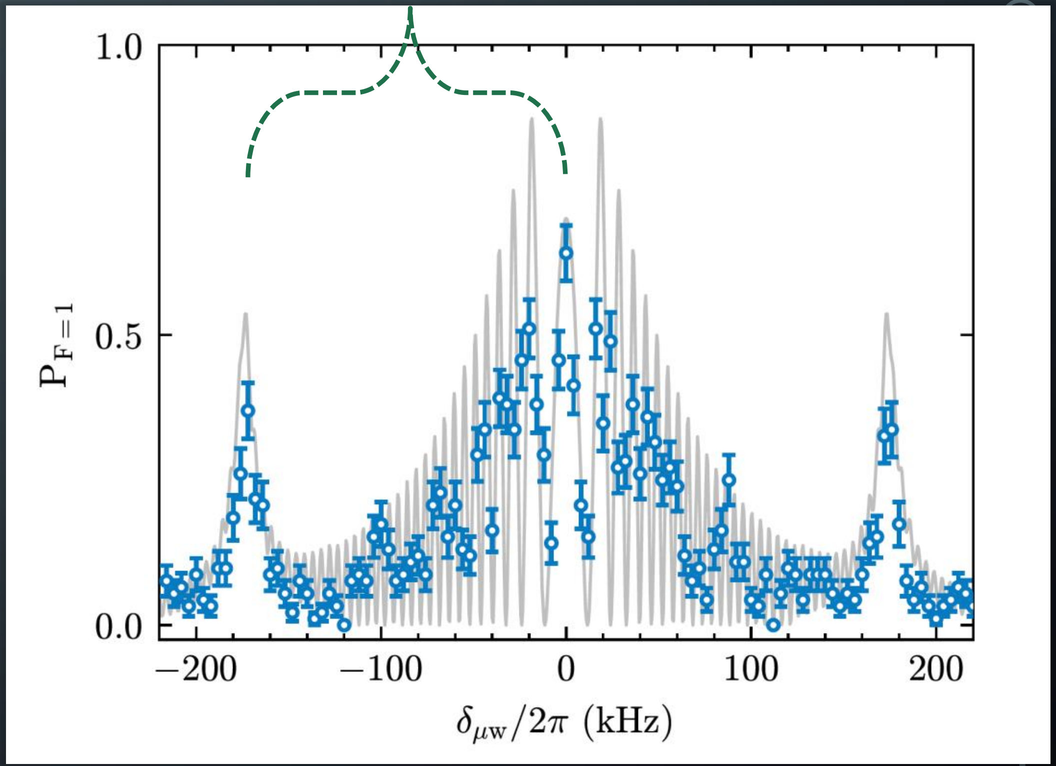


- π-times as low as 5 μs can be achieved!

Towards Entangling Gates



$\nu_z = 174\ kHz$



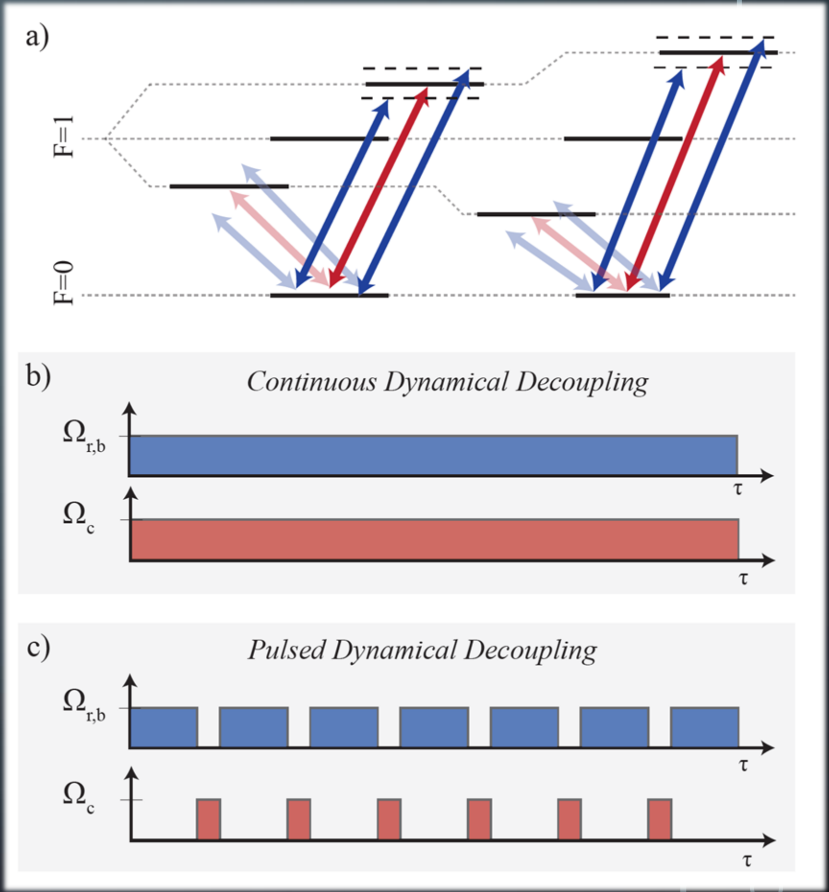
- Two-ion 'chain' (12 μm spacing)
- CCW generated gradient = 6.11(3) T/m
- Spin-motion coupling demonstration
- Motional sidebands visible at $\pm\, \nu_z$

Future

Gate Schemes

- Explore different combinations of techniques:
  - Mølmer-Sørensen gate [1]

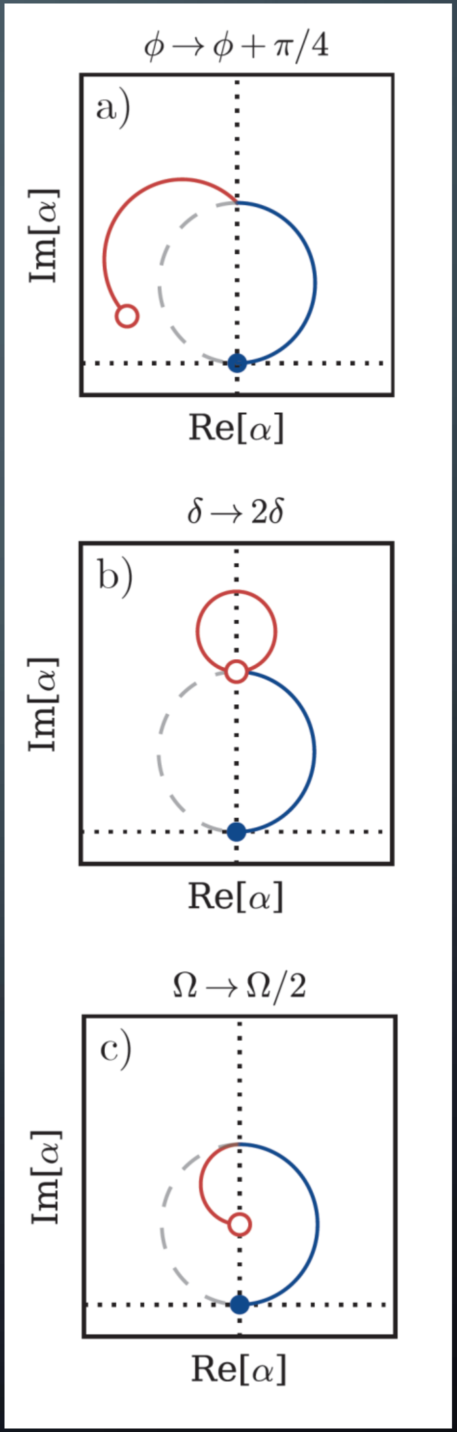
    (Primitive, PDD, CDD, Dressed States etc.)
  - Phase gate (with PDD) [2]
  - Spin-spin gate (CDD + J-coupling) [3]
- PDD or CDD :
  - Pulsed or Continuous Dynamical Decoupling [4]



[1] A. Sørensen and K. Mølmer, "Entanglement and quantum computation with ions in thermal motion"
[2] I. Arrazola et al., "Pulsed dynamical decoupling for fast and robust two-qubit gates on trapped ions"
[3] C. H. Valahu et al., "Robust entanglement by continuous dynamical decoupling of the J-coupling interaction"
[4] C. H. Valahu et al., "Quantum control methods for robust entanglement of trapped ions"

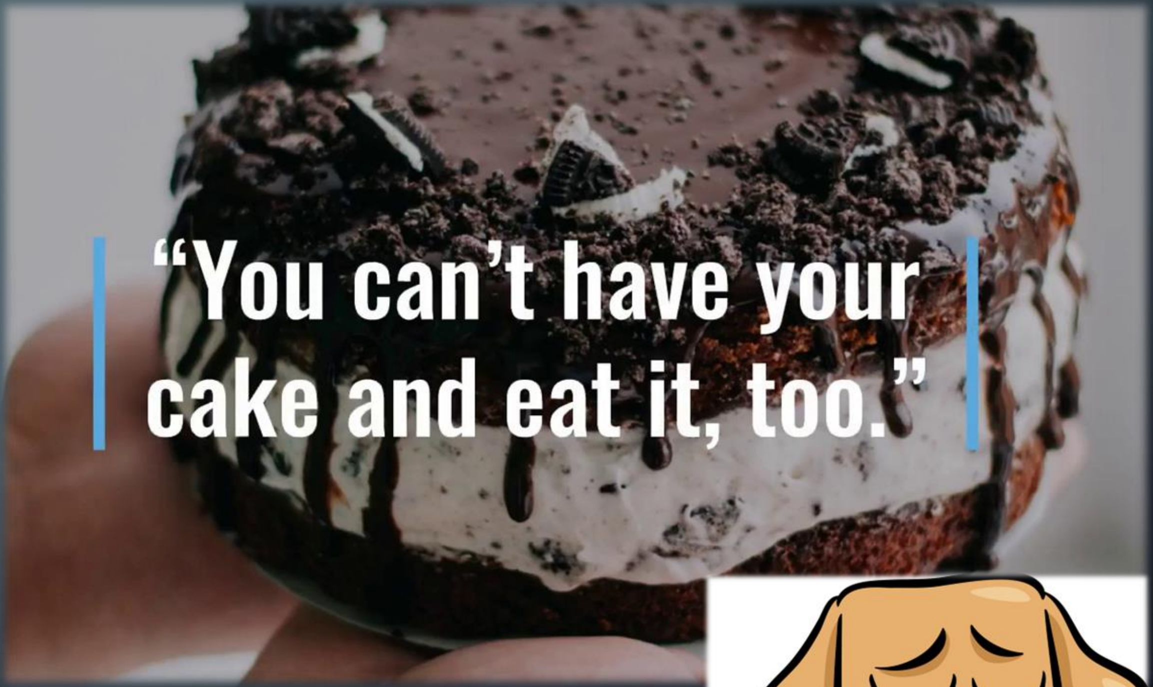
Robustness to Motional Decoherence

- Engineering phase space trajectories
- Sideband modulation
- **Phase, Frequency, Amplitude Modulation (PM, FM, AM)**
- Multi-tone MS
- Multi-loop MS



Comparison Metrics & Trade-offs

- Fidelity
- Gate duration
- Robustness
- Calibration requirements
- Experimental overhead



"Θέλει και την πίτα ολόκληρη και το σκύλο χορτάτο"

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Acknowledgments

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Quantum Computing & Simulation Hub

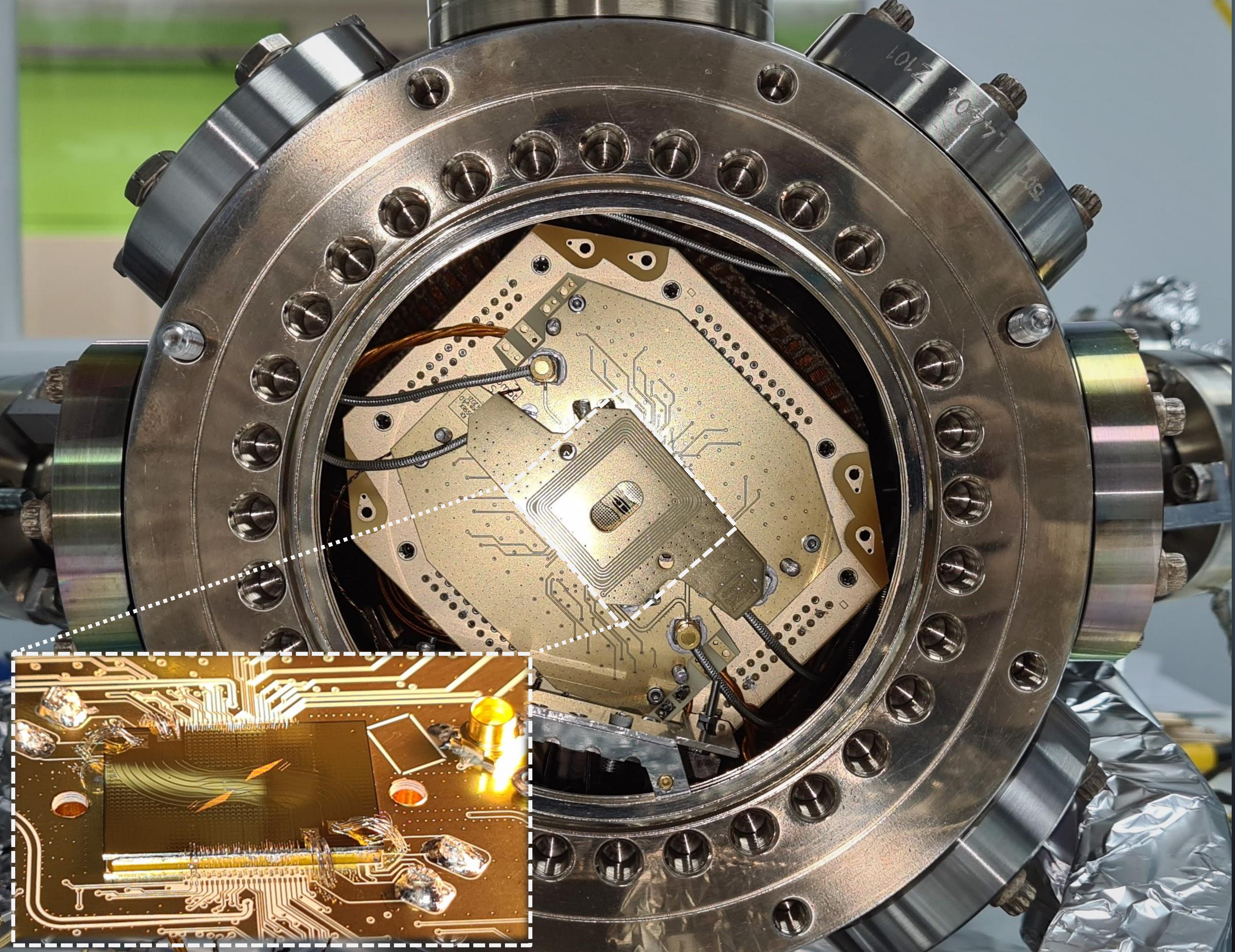
Office of Naval Research Science & Technology

QUANTUM FLAGSHIP

Controlled Quantum Dynamics

Innovate UK

UKRI Engineering and Physical Sciences Research Council



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Thank you! Questions?

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