UNIVERSITY OF OXFORD

T P Harty D T C Allcock C J Ballance H A Janacek N M Linke D N Stacey A M Steane D M Lucas

Two-Qubit Microwave Gates

Ion Trap Quantum Computing Group - Department of Physics - University of Oxford

Using Microwaves

- Microwaves are not normally used for multi-qubit gates because low wavelength leads to a low Lamb-Dicke parameter and hence gives weak coupling to motional states

- Recent proposal [1] to use microwave frequency oscillating magnetic field gradients in the near-field regime of a current carrying conductor. Here, strong field gradients lead to much higher effective Lamb-Dicke parameters than for free-space photons

Disadvantages of Laser Driven Gates

- Gate fidelity is limited by laser stability and photon scattering

- Laser systems tend to be large and complex to run, making it hard to scale this approach to a useful number of qubits

- For the ions to see a constant field gradient, they must be confined to a region which is small compared to the wavelength of light. This requires ground-state cooling for most traps.

Advantages of Microwaves

- Microwave electronics are better developed than lasers. They are inherently simpler, stabler and more scalable.

- No photon scattering

- Linear gradients can be created over large regions (~10μm), removing the need for sub-Doppler cooling

Disadvantages of Microwaves

- Current densities approach limits imposed by heat dissipation in non super-conducting traps

- Gate speed will be fairly slow (~500μs) in this trap but scales very favorably with size

- Cross talk will be an issue in traps with multiple near-by trapping zones

[1] C. Ospelkaus et al. PRL, 090502 (2008)

Trap Design

- We plan to perform a two-qubit Mølmer-Sørensen gate using microwave frequency magnetic field gradients produced above microfabricated conductors in a surface electrode trap.

-The trap we will use (right) was fabricated in-house by electroplating gold electrodes on a sapphire substrate. Sapphire was chosen for its high thermal conductivity since heat dissipation is likely to be a concern.

- Microwave simulations were done using Ansoft HFSS 12 finite-element analysis software (see image at bottom right of this panel).

- Three wires are required to produce the magnetic field gradient at the ion, which drives the gate, whilst also maintaining a magnetic field null (any magnetic field would lead to single-qubit rotations). RF and DC voltages are also required to trap and control the ions.

- Thus, [1] presents geometry with separate electrodes for RF and DC voltages and microwave currents.

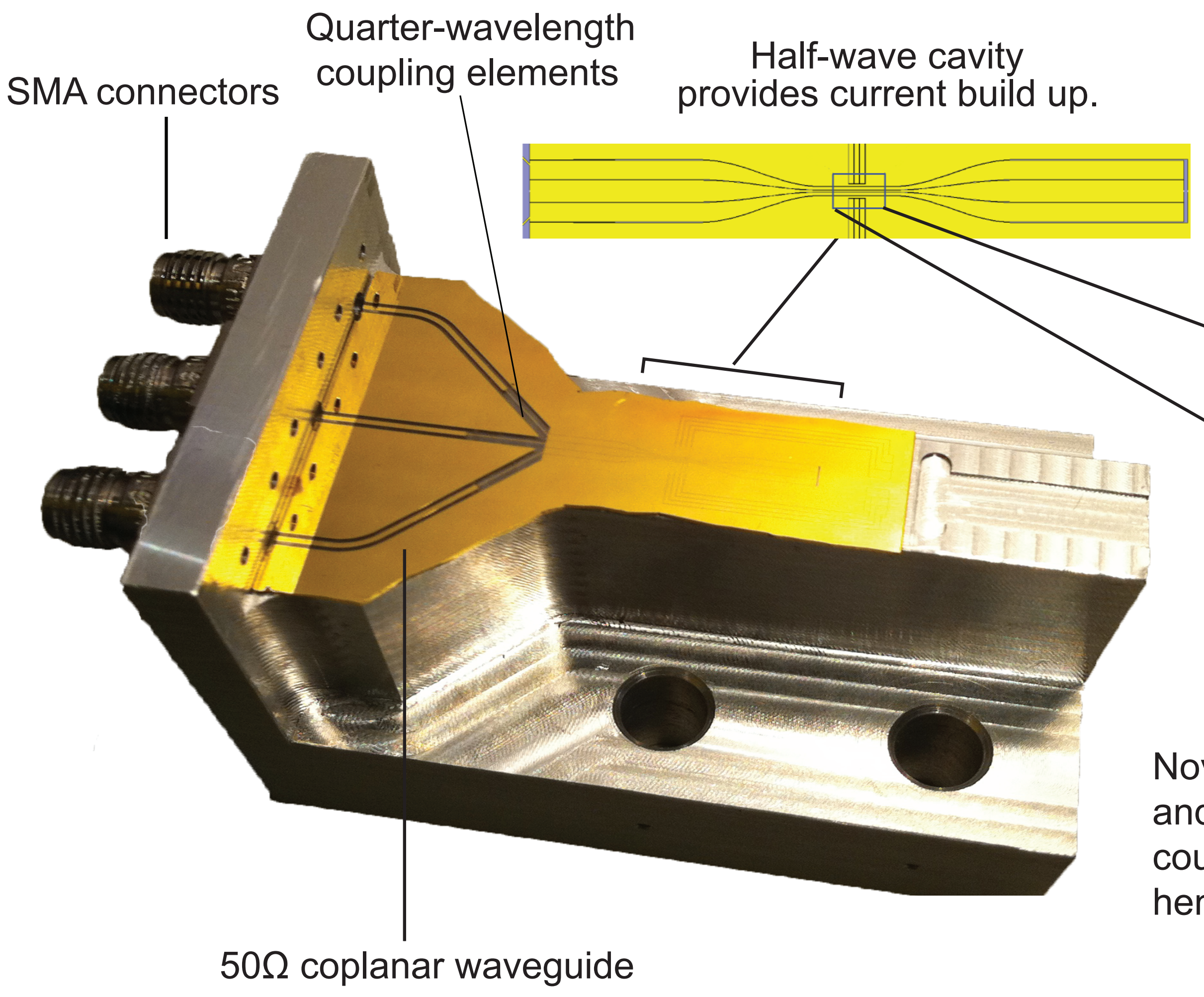
- In contrast, we use a novel geometry, with three central conductors carrying microwave currents used to drive gates, RF voltages used to trap ions and DC control voltages.

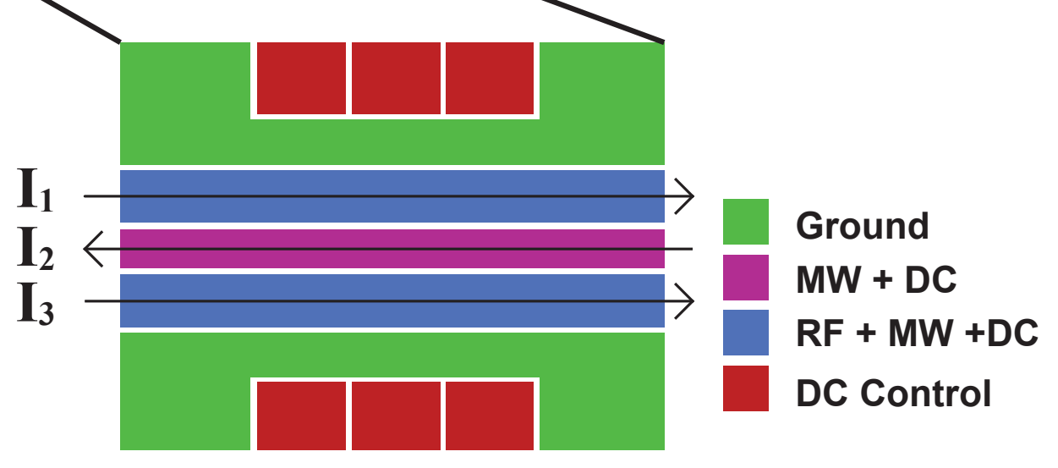
- By combining the RF, microwave currents and DC control voltages on the same electrodes, achieve larger field gradients at the ion. This is due both to the microwave conductors being closer to the ion and due to minimisation of the cancelling effects of return currents.

- Input power is further reduced by the use of three low-Q half-wave build-up cavities. These are anticipated to give a current gain of ~5. The ion is trapped above the anti-node at the centre of the cavities (see figure right).

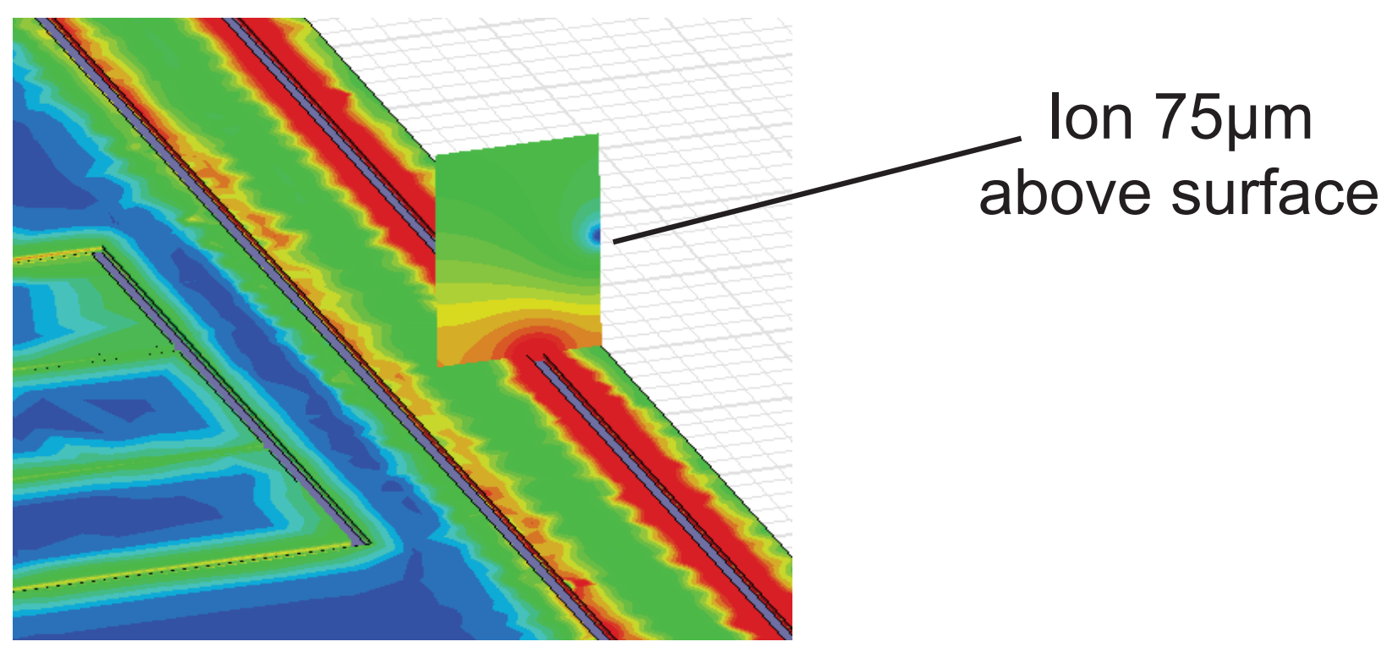
- Microwave power is coupled into the trap using SMA connectors, which have been made UHV compatible by replacing Ultem dielectric with PEEK.

- The power is then coupled from the SMA connectors to the cavities using 50Ω coplanar waveguides and quarter-wavelength transmission line sections.





Novel geometry combines RF, microwaves and DC on same electrodes, allowing tight coupling of microwave conductors and hence decreasing required input power.



Simulation of microwave currents and magnetic field gradients in and above cavities. The ion sits 75μm above the current anti-node and experiences a magnetic field null with a strong field gradient (~12$Tm^{-1}A^{-1}$).

Qubit

- We plan to use an intermediate field (146G) “clock state” qubit between two states in the ground level of $^{43}Ca^+$ (see right figure), where $\frac{\partial^2 f}{\partial B^2} = 150HzG^{-2}$ ω = 3.2GHz x 2π

- Previously, we have used a low-field (~1G) clock state qubit with M_F=0 and obtained T_2~1min. This qubit should perform significantly better.

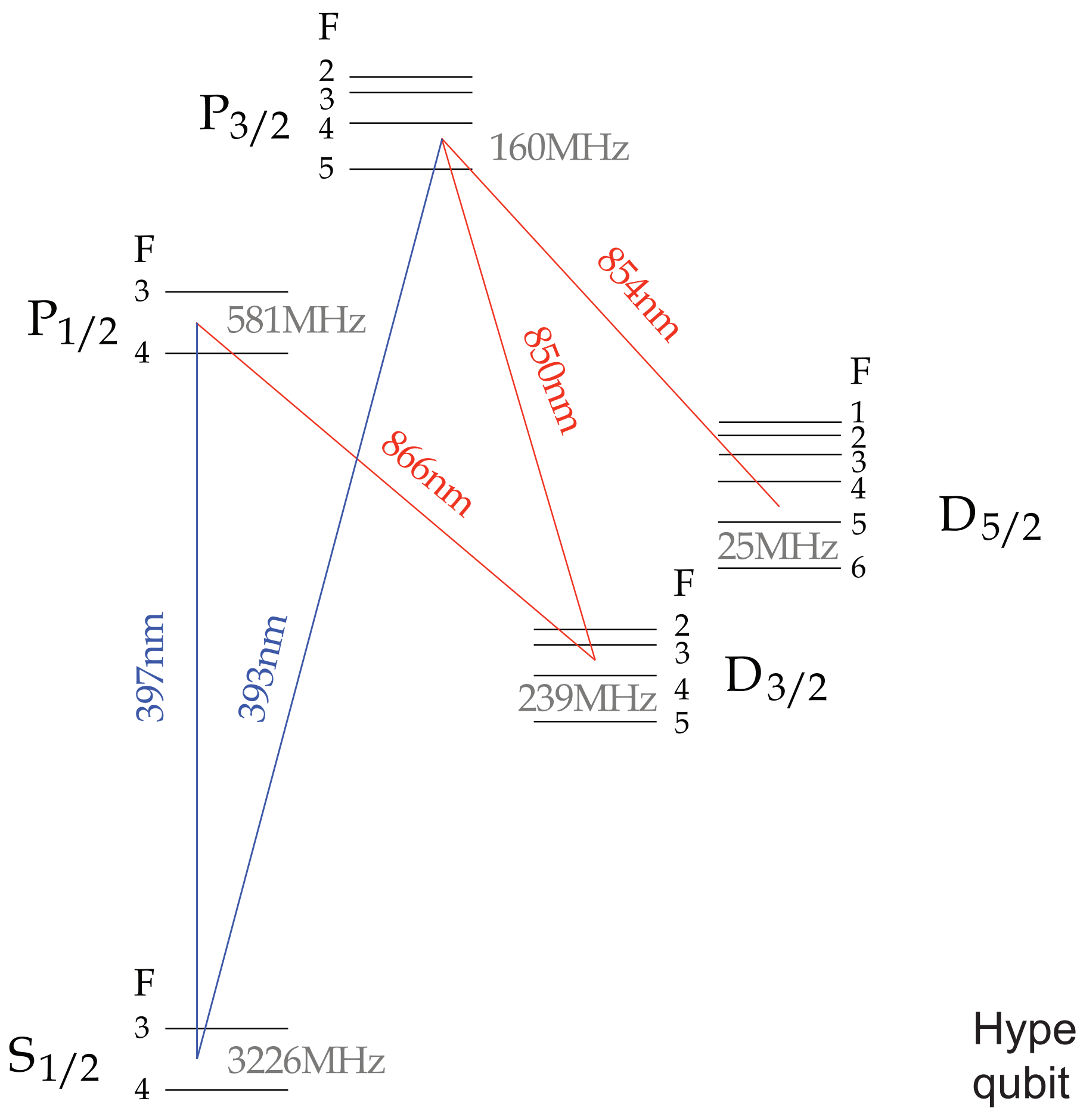
Cooling: We will cool the qubit using a 397nm laser with a 3.2GHz sideband and an 866nm laser, which has been broadened to supress dark resonances.

Initialisation: The qubit is first pumped into the M=4 stretch state using 397σ^+ light. Next, four microwave π-pulses or two 397nm Raman pulses are used to initialise to |0>.

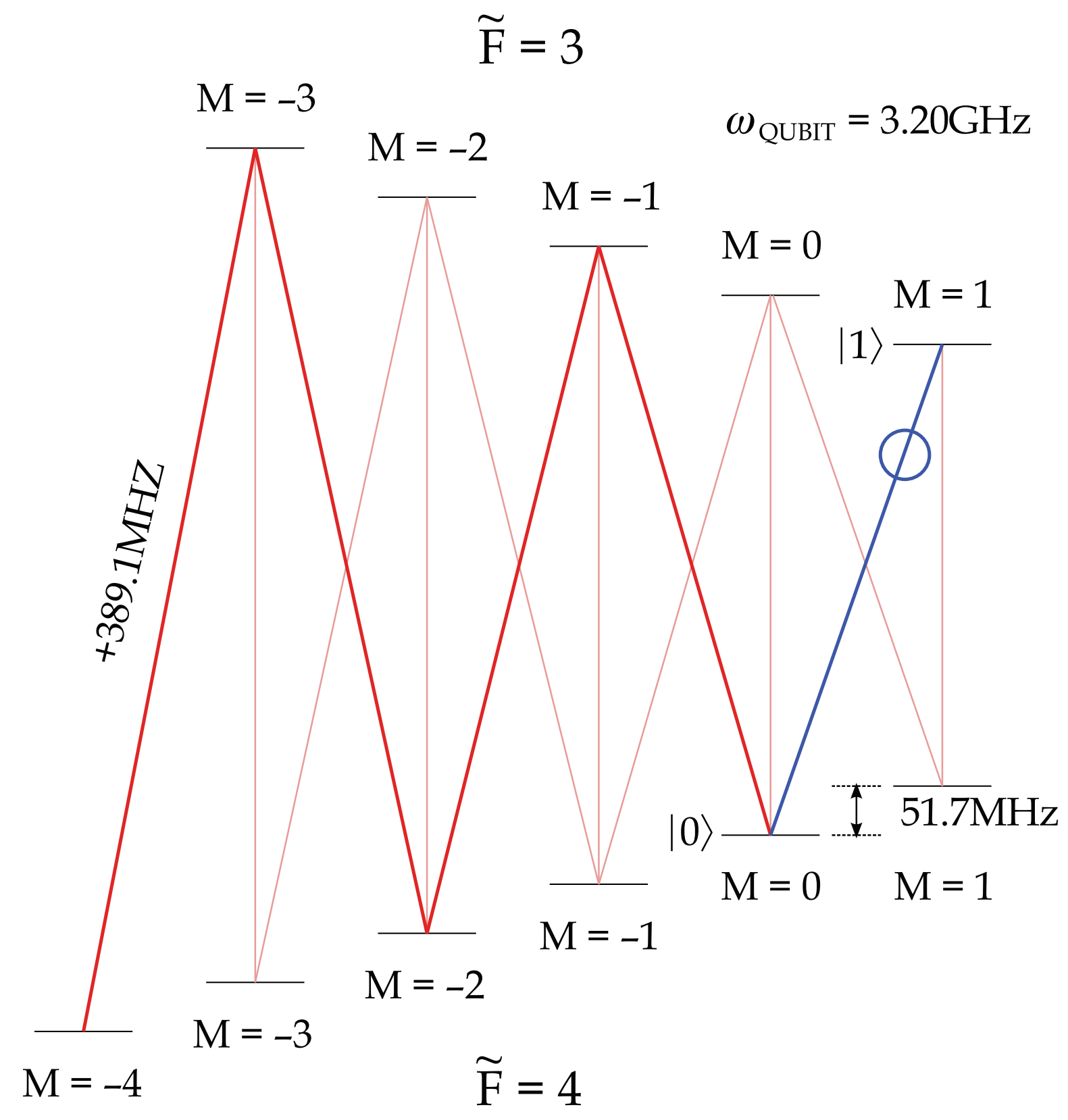
Manipulation: Single qubit operations can be done with Raman lasers or using microwaves. Two-qubit operations are done with microwaves.

Read-Out: The |0> state is first transferred back to the stretch state. Next the following sequence of pulses, repeated ~3 times, is used to shelve the ion to the $D_{3/2}$ state: 393σ^+, 850σ^+, 850π. Finally, the qubit is illuminated with 397nm and 866nm lasers and fluorescence is collected. Fidelities greater than 99% are expected. See [2] for more details.

[2] A. H. Myerson et al. PRL, 200502 (2008)



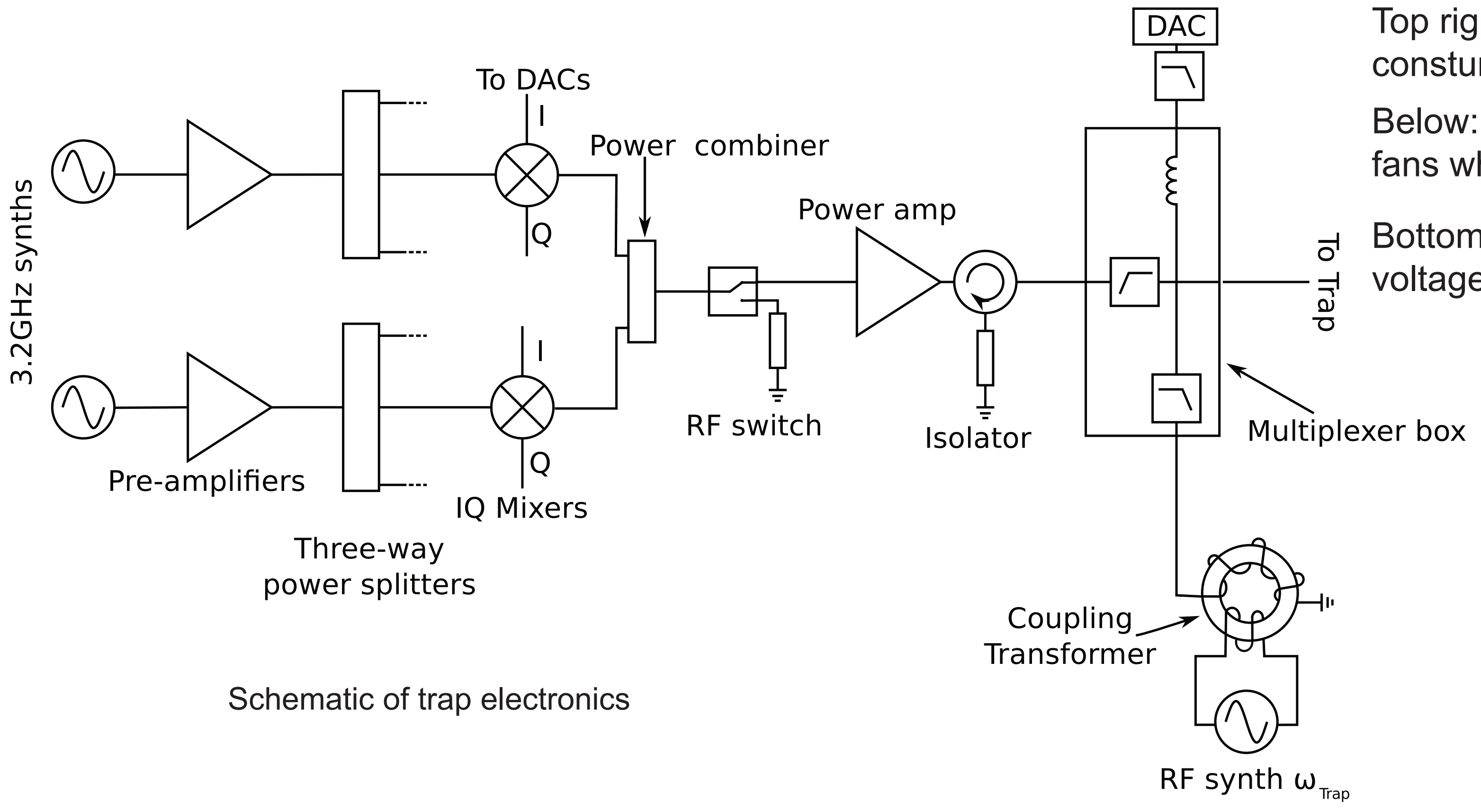
Level structure of $^{43}Ca^+$ (low field)



Hyperfine transitions in the ground level of $^{43}Ca^+$ at 146G. The qubit transition is shown in blue and the transition from the stretch state to the qubit is shown in red.

Microwave Drive System

- To fully control the magnetic field seen by the ion, we need to be able to independently control the phase and amplitude of the currents in each of the three conductors. Since the Mølmer-Sørensen gate requires radiation at two different frequencies, we require a total of six independently controllable currents. We achieve this using IQ mixers (see figure below).



Schematic of trap electronics

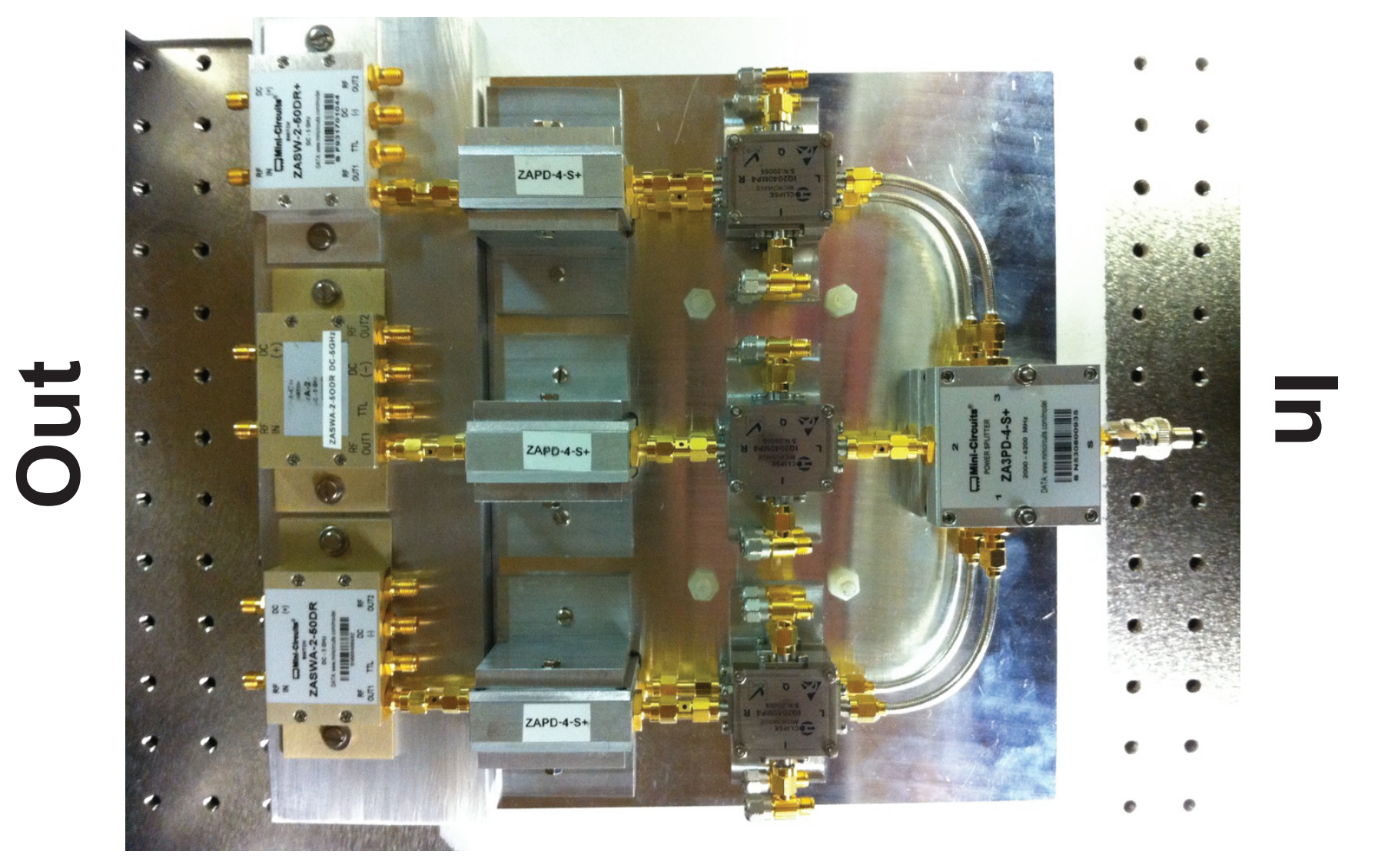
- Stability of microwave system was tested using an interferometer. Phase stability of IQ mixers better than 0.1°, amplitude stability better than 0.2% over 24 hours.

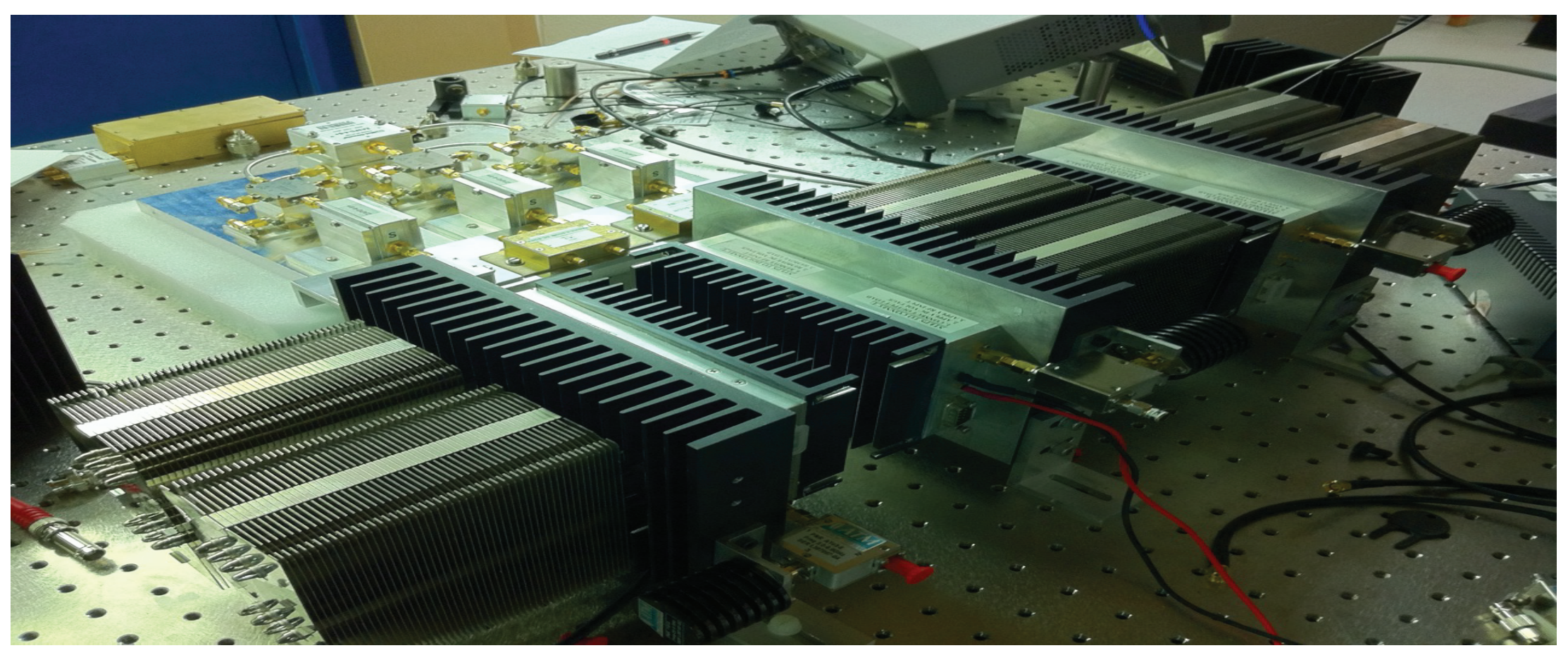
Figures:

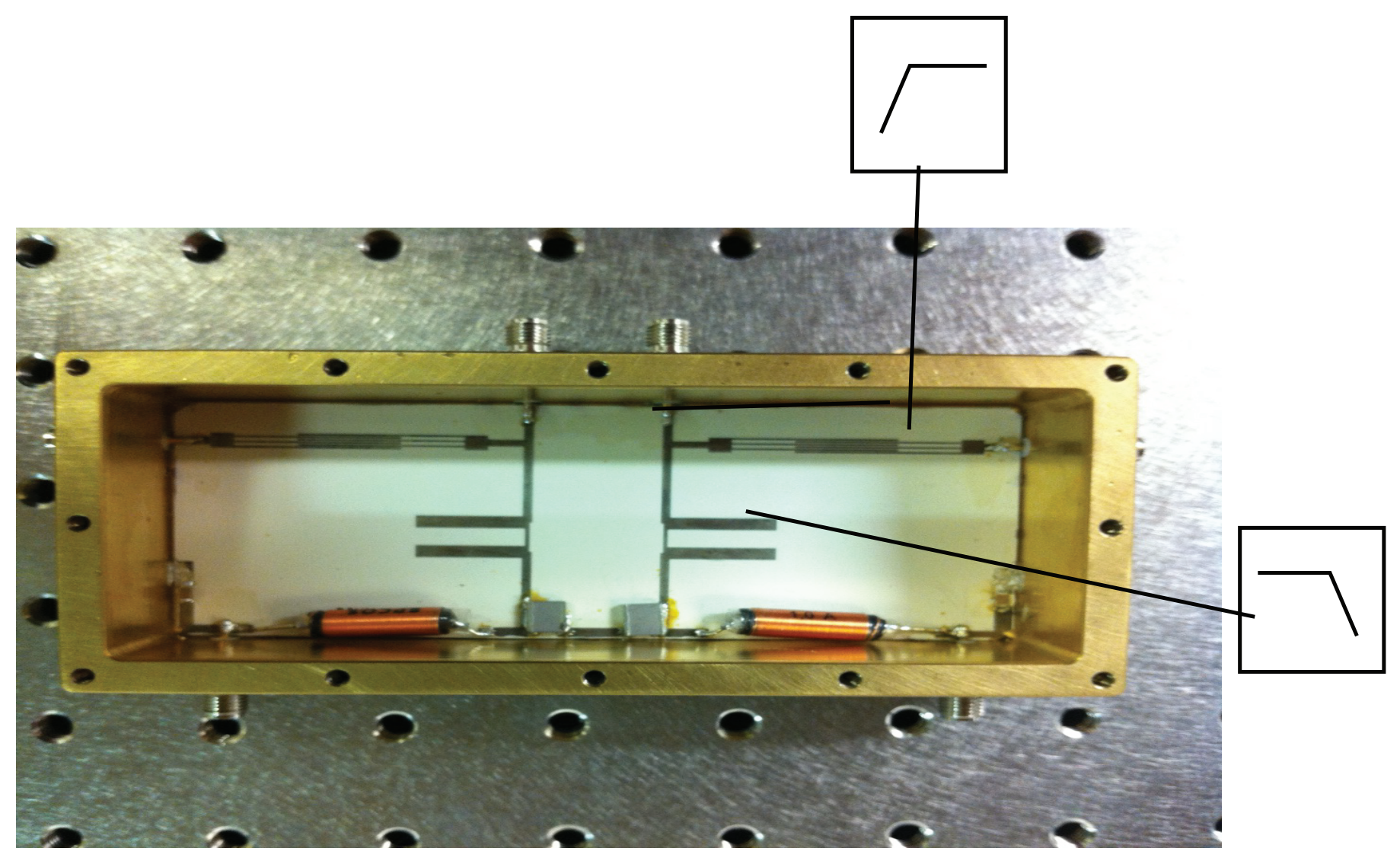
Top right: board containing IQ mixers, power splitters and switches. Rigid consturction to improve thermal and mechanical stability.

Below: Microwave power amplifiers. Heat-sinks allow efficient cooling without fans which would couple vibrations into trap.

Bottom right: multiplexer box used to combine microwaves with RF and DC voltages







http://www.physics.ox.ac.uk/users/iontrap/ Department of Physics, Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom thomas.harty@physics.ox.ac.uk

EPSRC QIPIRC