Ion Storage Group
Time & Frequency Division

Microwave Near-Field Quantum Control of Trapped Ion Qubits

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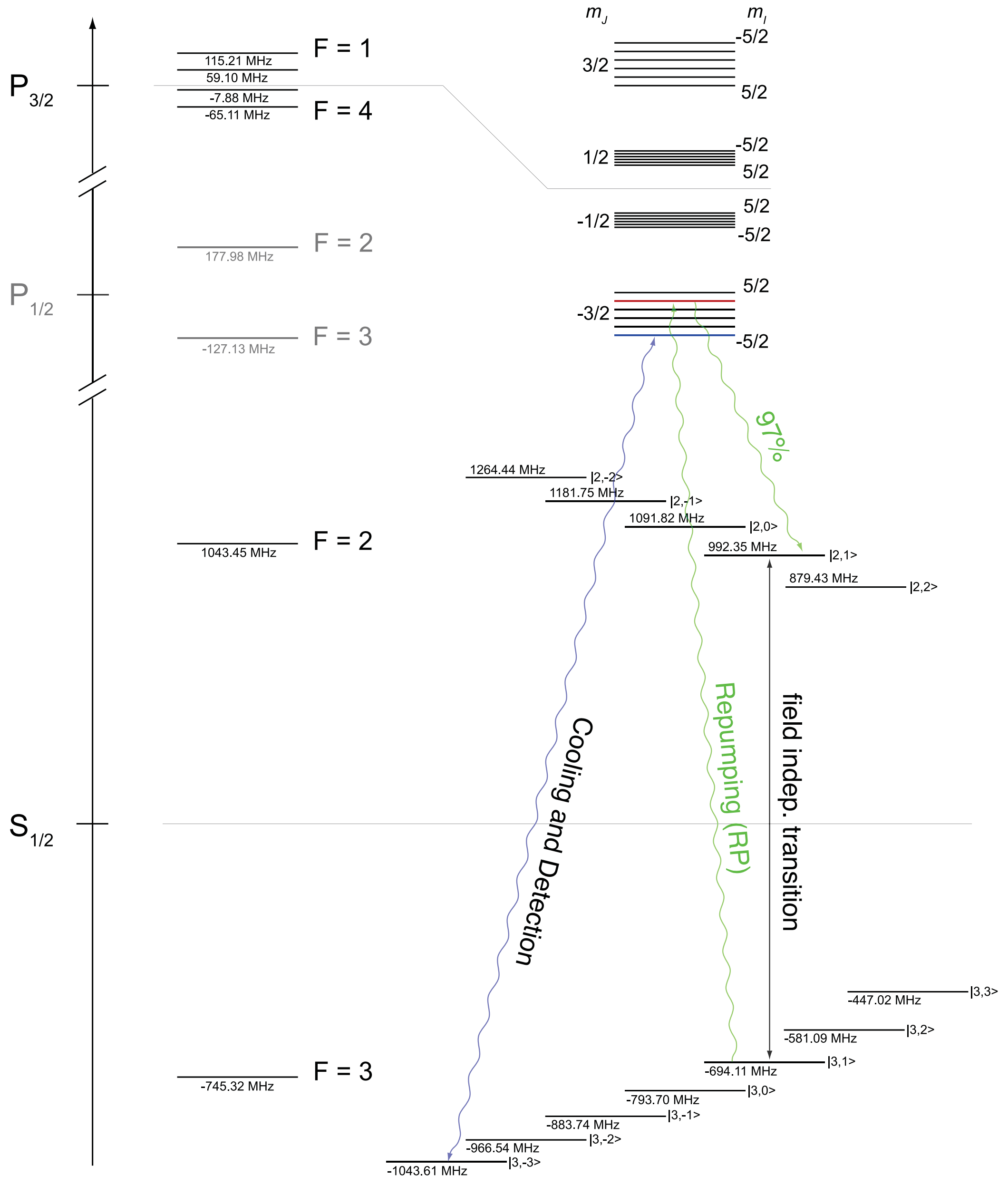
A major concern in the development of a future quantum processor is the scalability toward large numbers of qubits; its structure should enable one- and multi-qubit gates on arbitrarily selected qubits. As for a classical processor, micro fabrication leads to a promising route to build such a versatile ion-qubit quantum processor. Recent experiments with surface electrode ion traps have demonstrated the key ingredients for scalable ion loading, transporting, and trapping architecture. Here, we present an approach to incorporate ion-qubit manipulation into the surface-electrode structure which could enable its duplication along with the other infrastructure.

In ongoing experiments we investigate the building block for a microwave near-field quantum control. It is based on an oscillating magnetic field generated by microwave currents in electrodes of a micro fabricated surface-electrode trap. The driving microwave frequency is tuned near resonant with a hyperfine transition in the Mg ion. The homogeneous field component is used to implement single-qubit gates, while the field gradient leads to a coupling of the ions internal and motional states. With further improvements, this coupling can be deployed to perform a multi-qubit operation.

Ion Qubit

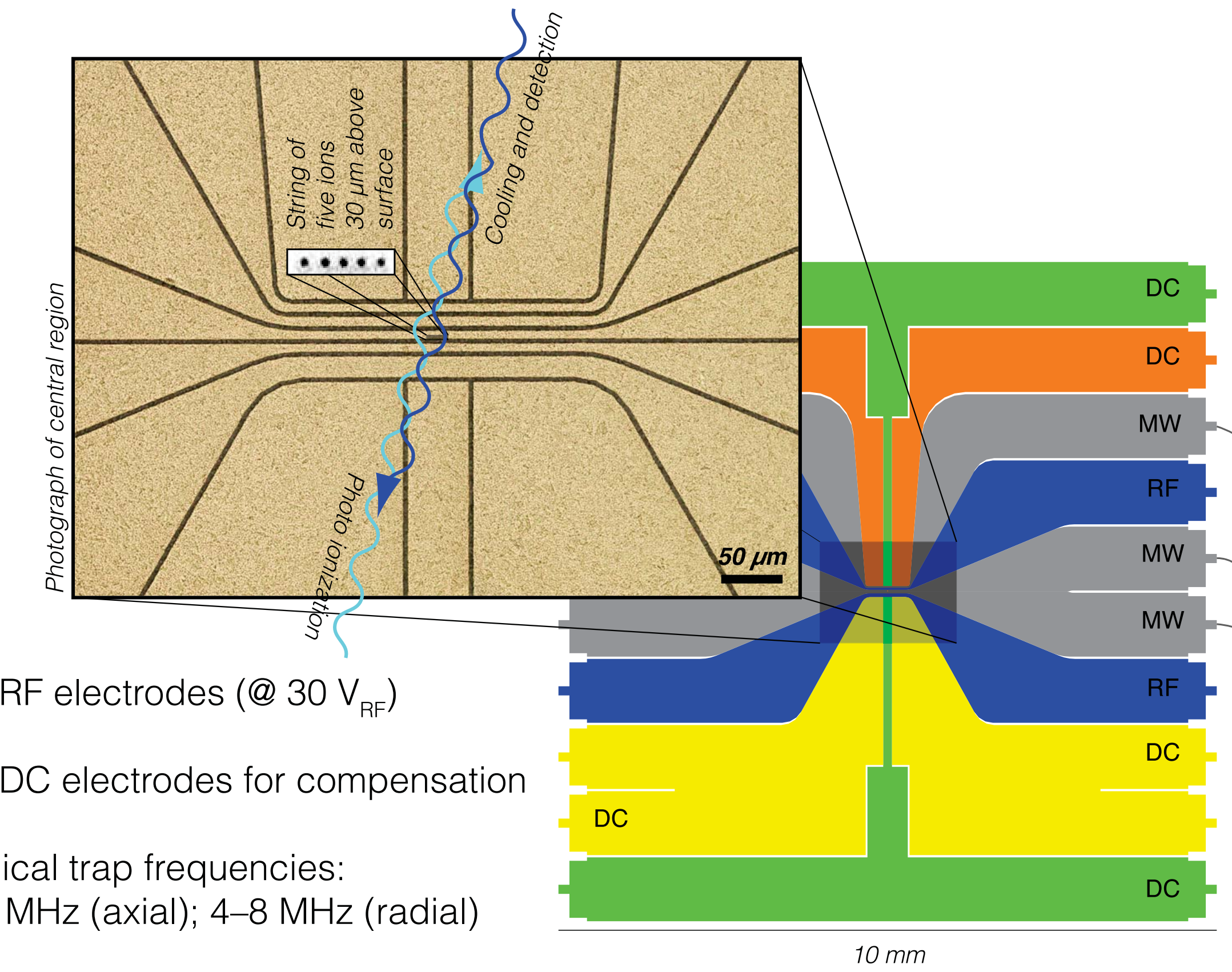
$^{25}Mg^+$ in an external quantization field of @ 213 Gauss



Surface electrode trap

Trap fabricated in NIST clean room; electroplated Gold on Aluminium nitride (AlN):

AlN for high thermal conductivity ~70–210 W/(m K)
Gold thickness 10.5 μm with a gap width (between neighboring electrodes) ≤ 4.5 μm



2× RF electrodes (@ 30 V_{RF})

6× DC electrodes for compensation

Typical trap frequencies:
1.5 MHz (axial); 4–8 MHz (radial)

3× Microwave (MW) electrodes for generating near-field oscillating magnetic field (@ 1.5-2.5 GHz)

Laser-less control

C. Ospelkaus *et al.,* Trapped-Ion Quantum Logic Gates Based on Oscillating Magnetic Fields, Phys. Rev. Lett. 101, 090502 (2008).

Manipulation of the internal (carrier transition) and motional (sideband transition) degree of freedom:

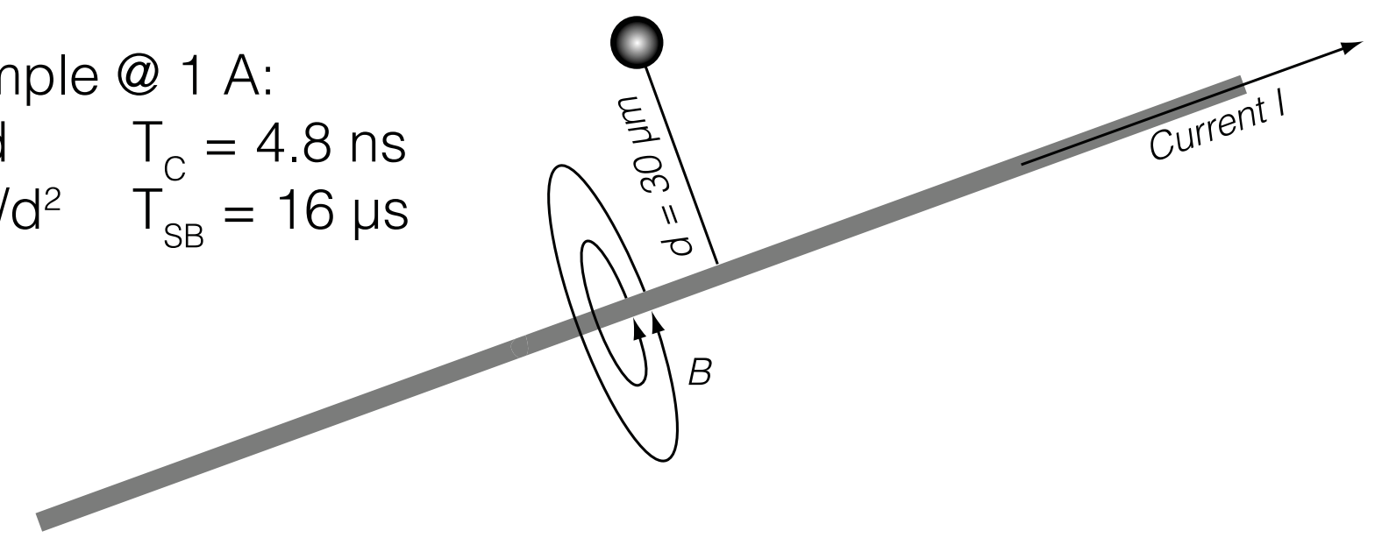
Carrier transition: $\Omega_C \propto B\left\langle \uparrow \right| \mu_m \left| \downarrow \right\rangle$

Sideband transition: $\Omega_{SB} \propto x_0 \nabla B\left\langle \uparrow \right| \mu_m \left| \downarrow \right\rangle$

Coupling of the internal and motional degree of freedom is the essence for Quantum Information and Quantum Metrology.

Microwaves are commonly used for carrier transitions. However, using microwave fields for sideband transitions is more difficult. We use a near-field approach to impose a significant magnetic field gradient on the spatial extent of the ions wave function.

A simple example @ 1 A:
$B \propto 1/d$ $T_C = 4.8$ ns
$\nabla B \propto 1/d^2$ $T_{SB} = 16$ μs

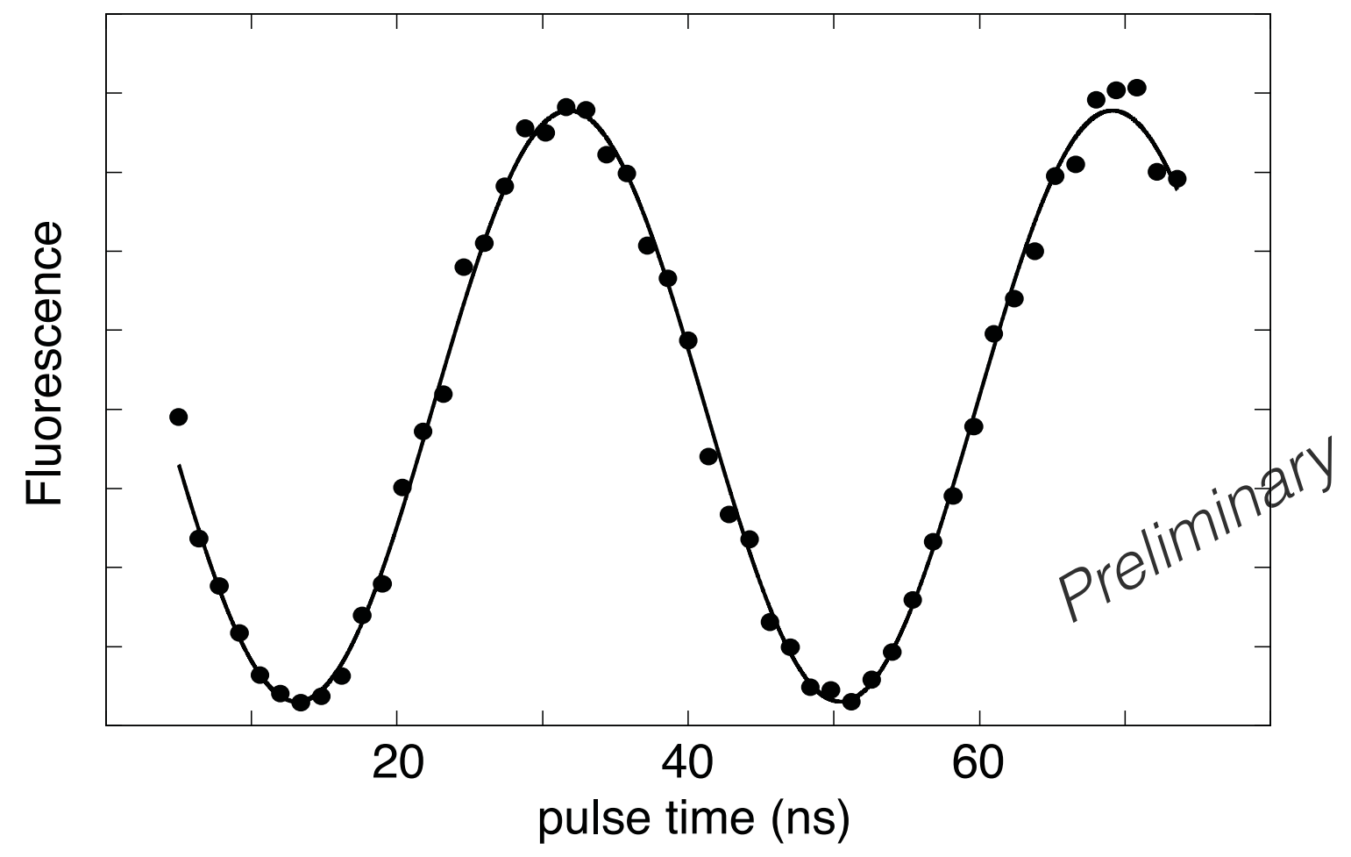


Fast single qubit flopping

Microwave current running in one electrode. We get fast Rabi flopping on the field independent transition

π-time of 18.66(7) ns

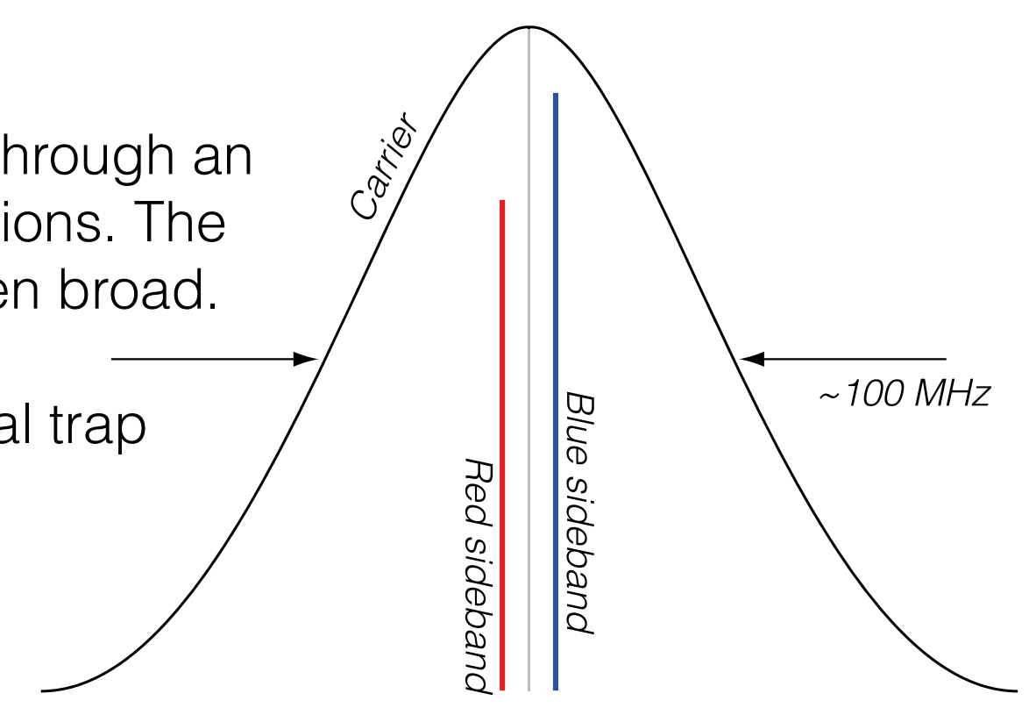
Coherence times observed to be much longer than gate time (>10 ms).



Large gradient, but no field—please...

Put as much current you can get through an electrode to get fast carrier transitions. The frequency spectrum, in turn, is then broad.

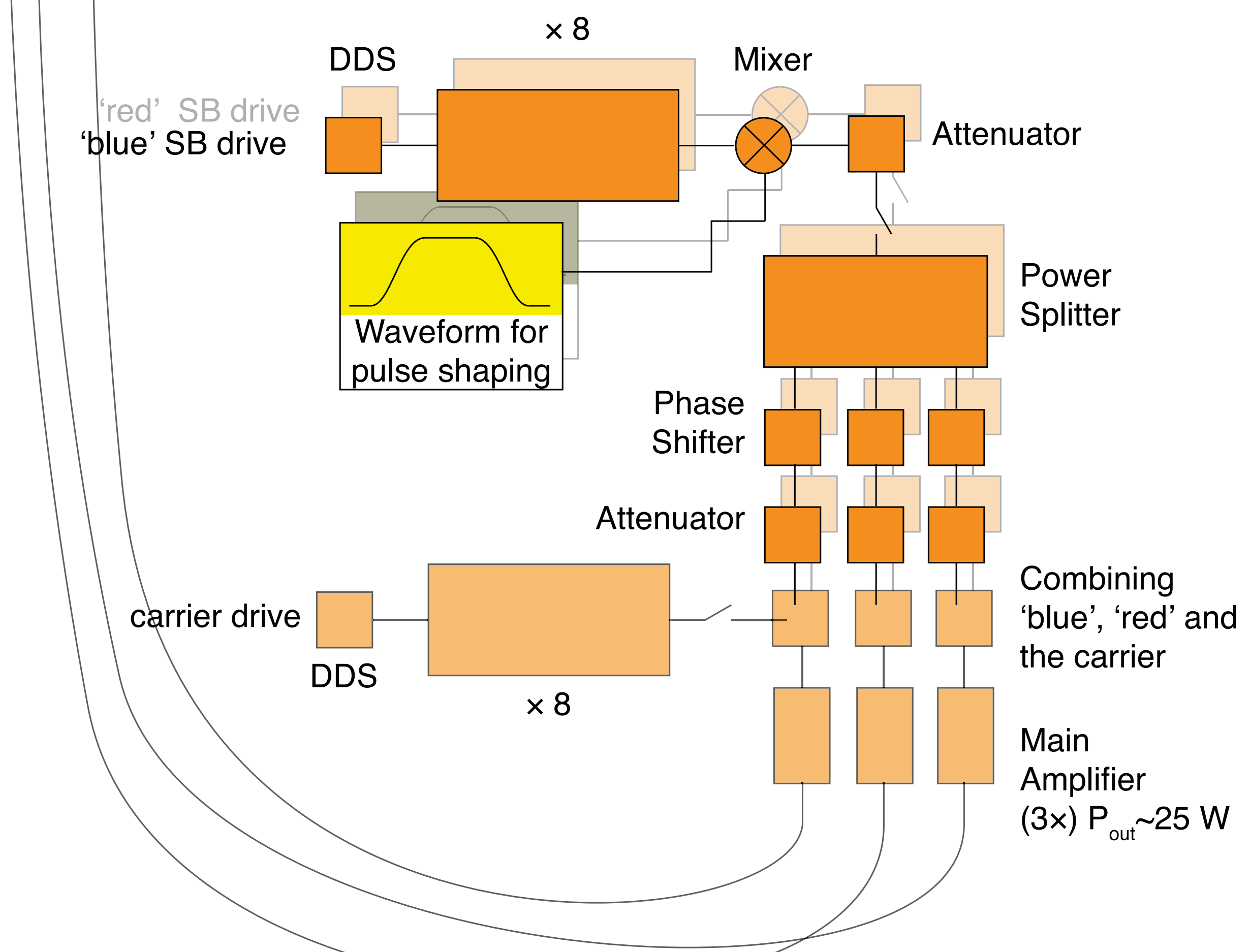
Any sideband transitions (@ typical trap frequencies of ~10 MHz) would be swamped by the carrier.



Find a way to suppress the oscillating magnetic field, but keep it’s gradient!

Microwave setup

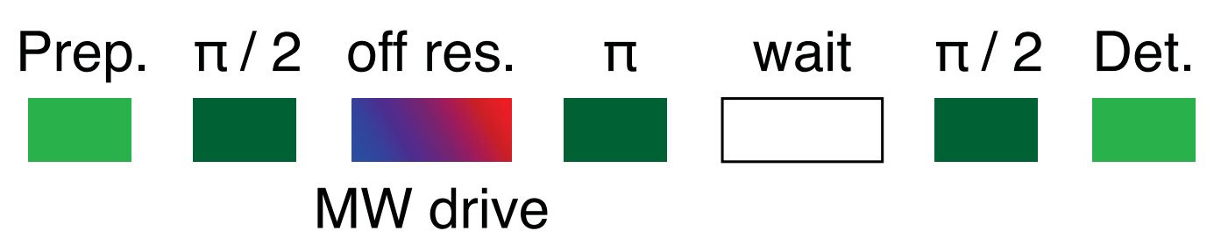
A octupling setup fed by the DDS (~210 MHz) is providing the microwave signal at around 1.7 GHz.



Phase shifter and attenuator are voltage controlled to enable the balancing (phase and amplitude) of the current running through all three microwave electrodes individually.

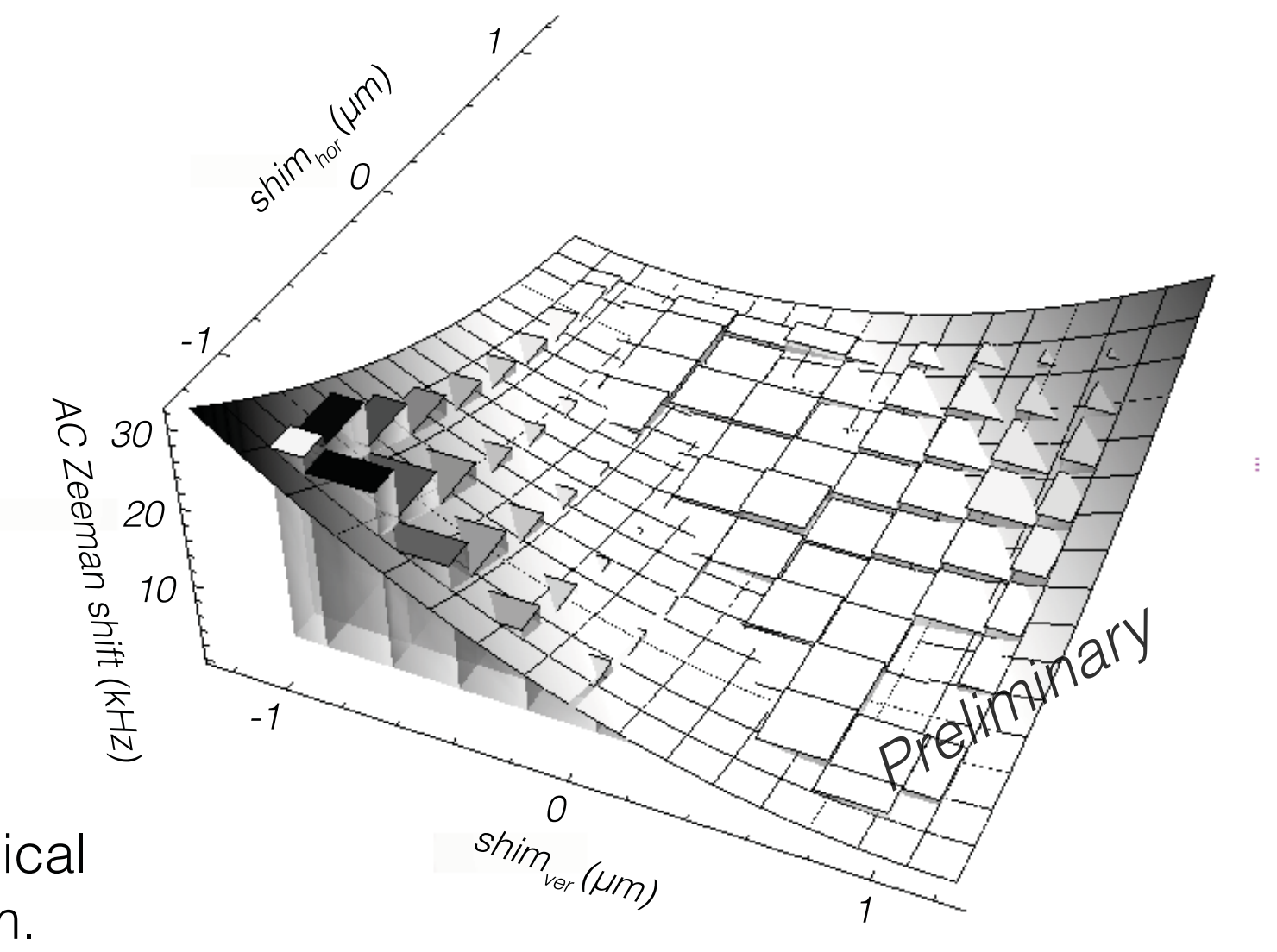
Magnetic field map

Experimental sequence for ‘nulling’ the magnetc field:



Minimizing the phase pickup in the first ‘arm’ by adjusting the phases and amplitudes running in the MW electrodes—meaning minimizing the magnetic field

Mapping the magnetic field by moving the ion in the radial plane; the results are described by a model fit yielding for example the magnitude of the magnetic field gradient.



Here we found a typical gradient of 35(1) T/m.

MW sideband cooling

Sideband cooling on a two-ion rocking mode with microwaves and a repumping laser beam

Experimental sequences: