# State of the art experimental apparatus for fast entangling gates in trapped multi-ion crystals

**Donovan Webb**

Department of Physics, University of Oxford

E-mail: donovan.webb@physics.ox.ac.uk

**Abstract.**
Scalable trapped-ion quantum computation relies on the development of high-fidelity fast entangling gates in many ion crystals. Currently the speed of geometric phase gates are limited by either large scattering errors (with Raman transitions) or off-resonant carrier excitations (with quadrupole transitions). Utilizing standing waves offers a potential pathway to achieve fast entanglement in quadrupole transitions due to suppressing undesired carrier excitations. Using a legacy apparatus we present initial results of this carrier suppression in the 674 nm quadropole transition of $^{88}Sr^{+}$. We demonstrate fast two-qubit entangling gates which exceed the entangling "speed limit" imposed by off resonant carrier excitations. To explore these "fast gates" at durations comparable to the secular trap frequency, and in multi-ion chains, a new system is been constructed. This system will use a segmented 3D Paul trap for greater control of long ion chains, and will feature single ion addressing for both selective and high power coherent operations. We present the current progress and roadmap of this next-generation platform and motivations behind design choices.

## 1. Introduction

Previously the physicist was limited to thought experiments on the nature of highly coherent quantum effects. It was even thought to be inconceivable for single atoms to be probed and entangled. However the advent of Ion traps, specifically Paul and Penning traps, have enabled the experimental exploration of Atomic and Laser physics and some of the most precise measurements of physical constants. Decoherence may be seen as measurement of a state by the environment. Ion traps allow the decoupling of single ions to the surrounding environment and thus... With the high degree of experimental control Ion trap systems coupled with low linewidth lasers provides, trapped ions are a popular platform for enabling Quantum Computation.

*Trapped Ion QC
Paul trap details
General idea of spin coupled with HO
*Entangling gates MS gate
*Non-Adiabatic interactions
*Fast Gate Schemes

Controlled light-matter interactions are essential for quantum computing [1–3], quantum simulation [4, 5], and metrology [6, 7]

****************** From paper ************************

For trapped ions, controlled light-matter interactions typically require carrier interactions that only couple the internal qubit states, as well as sideband interactions that couple these internal states to their collective motion [3]. For example, the sideband interactions, driven by the spatial gradient of the carrier coupling, are used to mediate spin-spin interactions such as entangling gates [8]. Conventionally, coherent control of laser-ion interactions is achieved using traveling waves (TWs) [3]. As the ions experience an averaged electric field and gradient over the interaction duration, the ratio between carrier coupling and sideband coupling is fixed. In contrast, the coupling strengths for ions in a standing wave (SW) vary with the spatial structure of the light field along the propagation direction. Consequently, the phase of the SW at the ions sets the ratio between the carrier and the sideband coupling. Coherent SW interactions on a single ion have been studied previously using cavities [9, 10], integrated optics [11] and free-space approaches [12]. However, coherent operations on multiple ions with a SW have so far been unexplored.

The tunability of the carrier:sideband coupling ratio is especially important for strong interactions where off-resonant terms start participating significantly and cannot be eliminated adiabatically. For example, in the conventional Mølmer Sørensen (MS) mechanism [13], the TW that generates the spin-motion coupling also gives rise to an off-resonant carrier coupling, which causes an error in the entangling operation. This error becomes significant as the carrier interaction strength approaches the motional frequency, placing a limit on the speed of the entangling operation. Using a SW instead enables high-fidelity entangling operations that can surpass this speed limit by selectively enhancing the spin-motion coupling while coherently suppressing the detrimental carrier term [14].
**********************************************************

## 2. Results and Discussion

Excerpts from carrier nulling paper kind of want to put this after the FG description... Or could I shorten this massively to reduce emphasis?

As discussed in sectionXX, the use of phase-stable standing waves (SW) is a clear route to fast entangling gates on quadrupole transition qubits. Here we report experimental results of both SW single qubit gates and SW Molmer Sorensen (MS) entangling gates performed on the Blade apparatus.

We use a free-space, phase-stabilized SW formed by two superimposed counter-propagating 674-nm beams that couple to the quadrupole qubit transition, 5S1/2  4D5/2, in 88Sr+.

**Here quadrupole so gradient couples carrier whilst XXCurlXX couples the sideband interaction
.

The single-qubit gate is created using a monochromatic SW on resonance with the qubit transition while placing the node(s) of the SW at the position of the ion(s). The two-qubit entangling gate is implemented via an MS-type scheme where we use a bichromatic SW instead of the conventional bichromatic TW. We show that the presence of the carrier coupling term, in the context of the TW-MS gate, leads to a reduction in the spin-dependent force (SDF) magnitude, which scales with the Rabi frequency of this detrimental term, posing an inherent speed limit for this mechanism. Using the SW-MS instead, with the anti-nodes placed at the ions, we strongly suppress the undesired carrier term and show that we can surpass this speed limit.

* Could shift these derivations to the intro.
First derivation of equation 1 of paper.
By setting  = 0 or  = ± z, we can bring the carrier or sidebands into resonance, respectively. With the SW has an additional degree of freedom compared to the TW: by setting 2  = 0 we can drive the first sidebands while suppressing all even terms in the Lamb-Dicke expansion [26], including the carrier term. Conversely, if we set  =  we drive the carrier coupling and suppress all odd terms in the Lamb-Dicke expansion, including the first sidebands.

The MS interaction requires two tones symmetrically detuned about the qubit resonance by ± z. To construct the Hamiltonian for a SW-MS interaction, we combine two monochromatic SWs as described by Eq. (1), resulting in the bichromatic SW interaction
Equation 2 from paper

where the phase˜ =(˜ BD +˜ RD)/2 is now the mean optical phase between the blue- (BD) and the red- (RD) detuned SWs. Further, we assume that the BD and RD SWs are in phase at the position of the ion(s), i.e. BD = RD = . The first term corresponds to a spin-dependent force (SDF) and the second term drives the carrier transition off-resonantly. Notably, these terms commute. Similar to the monochromatic SW, we can drive the motional coupling while suppressing the spurious carrier coupling by setting = 0.

It can be shown that a travelling wave MS in the interaction picture obeys equation 4 of paper, where the SDF follows a bessel like relationship as shown in fig X, featuring a global maximum achievable force amplitude. This maximum point direclty limits the speed at which gates can be achieved.

**Look at poster for description of phase feedback onto the ion - maybe exclude this to shorten section.

still to tidy Results:
We probe the position of the SW relative to a single ion by applying a monochromatic SW pulse on resonance with the qubit transition [Figs. 1(b), 2(a)]. The pulse duration corresponds to a -pulse at maximum carrier coupling, which occurs at the nodes of the SW. For an electric quadrupole transition, the maximum carrier coupling occurs at the maximum gradient of the electric field [9]. We can maximize the carrier coupling and minimize the sideband coupling, or vice versa, by selecting = or = 0 [Fig. 2(b)]. The transfer probability shown in Fig. 2(a) has a quartic dependence on near = and a quadratic dependence at = 0 [26]. When probing the suppressed motional sideband [Fig. 2(b) left], we observe only features that are due to the off-resonant (by 1.2 MHz) carrier coupling. By changing of the SW, we can realise any ratio between carrier and sideband coupling. We measure Rabi frequencies by scanning the SW pulse duration at the carrier resonance, for both = and = 0. We observe this ratio to be 18, corresponding to a suppression 01234 2Ω/ 0 20 40 60 80 Ω /2 (kHz) SDF traveling wave standing wave 024 2Ω/ 0.0 0.5 1.0 Ω /( Ω) SDF FIG. 3. Spin-dependent force magnitude ΩSDF (normalized by Ω in the inset) versus 2Ω/ , as measured for a single ion with = 0.05. We extract ΩSDF by applying a conventional bichromatic TW field (squares) or a bichromatic SW field (triangles), for variable durations. The solid lines show the analytical dependence; as predicted by the theory and shown explicitly in the inset, the TW coupling follows the Bessel functions (|J0 + J2|), while the SW coupling remains constant [34]. of 25 dB between maximal and minimal carrier coupling. This suppression is consistent with the measured interferometric stability and the residual power imbalance between b1 and b2.

Expand this section and show some data of RBM results:
Furthermore, we perform randomized benchmarking [32] to evaluate the quality of single-qubit gates implemented using the SW and TW with the same duty cycle. We obtain an error of $1.44(3) \times 10{-}3$ and $1.73(3) \times 10{-}3$ per Clifford gate, respectively. Thus, use of the SW is not detrimental to single-qubit control.

This has a lot of experimental detail. Maybe too much for the report.
Next, we experimentally investigate the saturation effect caused by the non-commuting carrier coupling [Eq. (3)] when generating an SDF with a bichromatic TW, and compare it to the SDF generated by a bichromatic SW. To create the TW bichromatic field, we apply two tones to the AOM in b1,

while for the SW we apply the same two tones in both beams, b1 and b2. These tones are symmetrically detuned by $\pm$ z from the qubit resonance. This results in an SDF on the axial mode ( z/2 1.2 MHz) of a single ion. We extract its coupling strength ΩSDF(Ω, ) by applying the SDF for variable durations [29]. We used an adiabatic ramp duration of 3.6 s for these measurements [33]. For the TW, we observe a coupling that scales with the expected Bessel function dependence |J0(2Ω/ ) + J2(2Ω/ )| [Eq. (4), Fig. 3]. Hence, when using the TW, there exists a maximum achievable interaction strength that imposes a speed limit on the interaction regardless of the available laser power. This limit is caused by the increasingly strong offresonant non-commuting carrier excitation and not by technical aspects such as pulse shaping. For the SW, we demonstrate that no such speed-limit exists. We place the ion at the maximum intensity of both the red- and the blue-detuned SWs [26] and observe that the interaction magnitude [34] increases linearly with Ω (Fig. 3).

We experimentally demonstrate two-qubit MS gates using a bichromatic TW for gate speeds in a regime where the carrier coupling induces a significant error which cannot be eliminated adiabatically. However, the bichromatic SW enables us to surpass this limit without degrading the fidelity (Fig. 4). To implement the SW-MS gate, we simultaneously suppress the carrier coupling on both ions by adjusting the ion spacing such that they are both placed at anti-nodes of the SW [Fig. 1(c)] [26]. We perform the TW and SW two-qubit entangling gates on the axial in-phase mode and optimize the experimental parameters to maximize the Bell-state fidelity for a fixed gate duration. In both cases, we use a ramp duration of 10 s to minimize coupling to the other motional modes [33]. This pulse ramping could be replaced with more sophisticated amplitude shaping techniques [16, 35]. In Fig. 4(a) we show the two-qubit fidelities achieved with the two schemes as a function of the effective gate duration (2 / g, where g = $-$ z) [37]. For slower gates, the fidelity of the SW-MS is comparable with that of the TW-MS. For faster entangling gates, the fidelity of the TW-MS degrades rapidly. This is also predicted by direct numerical integration of Eq. (3); we set all the parameters to the experimental values except for the Rabi frequency Ω, which we optimize for maximum fidelity (dashed line). We also indicate the idealized case which neglects imperfect transfer into the interaction picture w.r.t. the carrier [Eq. (3)] (dotted line). We believe that the measured fidelities degrade sooner as a result of experimental imperfections (e.g. ramp shape) not captured by the numerical integration. In contrast, the fidelity for the SW-MS is consistent with 0.95 over the entire available power range, showing that we have eliminated the limit arising from the carrier coupling. The shortest SW-MS gate was 15 s, limited by the available total power of 29 mW.

*Skip about laser power section

*Shorten conclusion and change in such a way that focusses on what to improve/adapt in FG setup

In conclusion, we implemented single- and two-qubit operations for trapped-ion qubits using a phase-stabilized SW. Two counter-propagating beams create the SW, whose relative phase at the ion position is stable to /100. This enabled us to tune the ratio of the field intensity and gradient that the ions experience, which sets the relative strengths of the sideband and carrier interactions. We use this new degree of control to suppress the unwanted off-resonant carrier coupling (by a factor of 18), while coherently enhancing the motional coupling during two-qubit gates. We show theoretically and experimentally that the non-commuting carrier term imposes a limit on the speed of conventional TW-MS gates, which were avoided using the SW-MS interaction. These optical phase control techniques could also be applied in the previous Raman-based scheme [16], where they could mitigate squeezing terms, which were the leading error source; we note that for the SW-MS those terms are inherently suppressed. Our work shows a clear path towards entangling gates with durations comparable to the motional period of the ions ( 1 s or shorter) at wavelengths that are amenable to largescale chip integration using standard integrated optics [3840] and without the technical challenges of using high-power blue Raman beams [16], pulsed lasers [41, 42] or Rydberg schemes [43].

- The ability for single addressing allows MS gate between two ions in a multi ion chain.
- Also higher intensity at ion can push quadrupole gate time down to speeds where other motional mode inclusion matters (vera).
- Hence explore Fast Optical transition gates at 729 nm in multi ion chain.

## 3. Experimental Details

### *3.1. Ion Trapping Apparatus*

The technical complexity of ion trapping experiments may be reduced to solving two problems: Controlling the state of the ion (both internal and motional); and controlling the environment the ion is within. Our Ion trap experiments consist of: an atomic source, a trap, a vacuum system encasing these, external magnetic field coils, and lasers for ionization, cooling, repumping, stateprep, coherent control and readout. As with all ventures in experimental physics, as technologies mature, so too do the capabilities and scope of our apparatus. Here we shall describe the “Old” apparatus, known in short as “Blade”, where proof of principle fast gate schemes have been tested. The limitations of “Blade” for further fast gate work will be made apparant and the new proposed system, known as “FastGates”, will be described.

### *3.2. Ion and Trap*

As mentioned, the overall system we desire is a spin coupled to a spring. Our spin in this case being a Hydrogen-like ion, and the spring being the harmonic motion of the ions within the trapping potential. The ion traps we use to creeate such a potential are linear Paul traps, a schematic of such is shown in FigureX. As explained by Earnshaw’s theorem, a stable stationary point in 3D can not be realized using static electric field. Therefore a Paul trap utilizes an oscillating electric field to create a trapping pseudopotential. There are various geometries for realizing a paul trap, shown in Figure X are: A macro 3D Blade trap; a surface trap; and a microfabricated multilayer trap. A Blade trap, as is used in the “Blade” apparatus, has axial confinement created by DC end caps and radial confinement by supplying an oscillating RF on the blades. In “Blade” the ion endcap distance is 1.15 mm, and ion-blade distance is 0.5 mm. Typical operating frequency for the RF electrodes of the “Blade” trap are 28.0133 MHz leading to an axial ion frequency of 1.860 MHz and radial frequencies of 4.077 MHz and 4.341 MHz.

For the sake of comparison, recently the surface style linear Paul trap has gained popularity due to the maturity of chip fabrication technologies and the potential route to scalability this offers. In the surface trap, the 3D blade and endcap geometry of the “macro” trap is effectively projected onto a 2D surface. The stable point of such a trap is typically on the order of 50 um from the chip surface. The ease of fabrication of surface traps has allowed the creation of complicated multizone devices with many DC electrodes. These multizone traps enable the shuttling of ions, a requirement for Quantum CCD type architectures. However these benefits come at the cost of trapping potential. Heating of an ion is XXproportionalXX to the ion electrode distance, however so too is the trapping potential. This leads to a compromise of distance... surface trap creates a poor approx of harmonic potential... Therefore weak trap and high heating rates compared to a macro 3D blade trap. Heating rates of HOA2: axial and radial frequencies...

A microfab 3D trap [See et al and Wilpers 2012], as will be used in the “FastGates” apparatus, brings together the advantages of chip fabrication as well as the low heating rates and high trapping fields of a 3D style trap. This is achieved by a multilayer chip as shown in figureX. The radial trapping is provided by RF rails on opposite diagonals of the slit whilst axial trapping may be realized by DC electrodes on both surfaces. The Ion electrode distance is now of the order 200 um, meaning lower heating, whilst the more optimal 3D geometry allows for a deep potential at this distance. The microfabrication techniques also allow a segmented design suitable for multizone operations and ion shuttling. The 3D confining potential leads to motion of the ions following the Hamiltonian

$$H = \sum_{i=1}^{N} \frac{m}{2}(w_x^2 x_i^2 + w_y^2 y_i^2 + w_z^2 z_i^2 + \frac{|p_i|^2}{m^2}) + \sum_{i=1}^{N}\sum_{j>i} \frac{e^2}{4\pi\epsilon_0 |r_i - r_j|}$$

,

where $w_v$ are the mode frequencies in the three dimensional coordinated. We define $z$ to be the axial direction of the trap and typically assume $w_z$ « $w_x$, $w_y$ to allow a 1D ion crystal to lie along the axial direction of the trap. We aim for an axial ion separation of around 5 um which, for ${}^+Ca_{40}$ ions means a trapping potential of $w_z \approx 2\pi * 1.6$ MHz. We plan for around 5 MHz for our radial frequencies as we will use one such mode for implementing two-qubit entangling gates. This higher frequency is for a few reasons: The doppler cooling limit ($\overline{n} = \Gamma/w$, where $\Gamma$ is the transition linewidth and $w$ is the frequency of the mode being cooled) goes with the reciprocal of the mode frequency and so higher mode frequencies leads to a lower temperature after cooling; a higher c.o.m. radial mode leads to better separation of radial modes in a multiion crystal => simpler implementation of fast gate schemes where multiple motional modes are all excited; can push to faster gates? Given a model of the NPL trap, we require an $\Omega_{RF} = XX20$ MHz with a driving amplitude of 180 V to find a solution with axial frequency of 1.6MHz and a radial frequency $w_x = 5$ MHz. One foreseeable issue with this arrangement becomes apparant when considering the Matthiu equation representing trapping with pseudo-potential. There are areas of stability and instability which can be quantified with the factor $q$. In Ion traps it has been shown that areas of stability exist for $q < 0.9$, however typical values of $q$ for trapping and cooling ions are considerably smaller. $q = 2 * \sqrt{2} w_{ax}/\Omega_{RF}$. For the proposed plan of 20 MHz RF and 5 MHz radial frequency we would have $q = 0.7$ which although is still stable, may not be able to practically trap from a hot source of ions. Therefore we will likely trap at a lower RF amplitude, lowering the radial frequencies to around 2 MHz where $q < 0.3$ and then ramp up to a tighter trap for efficient doppler cooling and fast gate experiments.

Some simulations to find solutions with decent axial and radial modes and figures.

Heating rates... Further, the ion being located within this slit allows for dual high NA optical access (NA = XX), which is an important factor for our proposed single addressing standing wave experiment.

### *3.3. Laser systems*

We have described the trapping of an ion, now we must look at our strategies for manipulating the internal states and collective motion of ion strings. Our key tool for this is the use of lasers as we can create highly localised, strong electric field amplitudes and gradients. Coupling to spin: carrier interaction, Rabi flopping, pi pulses. Coupling to motion: description of sidebands. Figure X shows the energy level structure of Ca40+, note the plethora of available transitions available to realize the control over our ion strings. Here we describe what transitions we have chosen for what task. Figure X shows the entry points of the laser systems into the trap chamber.

729 - Coherent control We will use the optical S->D state with the 729 quadrupole transition to define our qubit due to the D state being a metastable state: i.e. the transition from D to S is dipole forbidden as they are the same parity DelL != +-1. The lifetime of this state is X700 ms, giving a greater upper bound of the qubit coherence time than if a dipole transition is used. This long lived state means that it is a narrow linewidth transition (Heisenberg uncertainty) and so we must use a narrow linewidth laser to efficiently control. High power required as lamb dicke factor is low for 729 transition. We use a pumped Ti:Saph system coupled to a high finesse cavity to achieve this. Verdi 532 -> Solstis 729 PDH locking with Stable laser systems lock box. Below a schematic of our 729 laser system is shown. Strontium is used in Blade apparatus and has all analogous transitions. Here our quadrupole transition is at 674 nm. FNC to cavity and to laser lab. Power stabilization on the feedback AOM. High bandwidth PID feedback loop pushing the servo bump away from area of experimental interest. Acoustic isolation using foam insulated box. Trial of Verdi C unsuccesful so

far not achieving stable lasing with solstis. Improvements over Blade: - 729 more convenient Ti:Saph freq -> Higher power, low noise - access parallel to radial mode, Blade is 45 deg -> High Lamb Dicke factor - 729 more convenient for putting in fibre -> low charging

393 and 432 - PI Two step photoionization for isotope selectivity.

397 - Doppler Cooling, Fluorescent readout Dipole transition for Doppler cooling as want fast scattering. Also want higher freq light for more momentum transfer. Fluor read out so that |0> bright and |1> dark.

854 and 866 - Repumping as branching ratio from P to S and D. So during cooling and readout we lose population to these levels.

All of the above systems are Toptica Diode lasers coupled to a cavity for PDH locking.

### *3.4. The vacuum system*

Here we shall describe the instrumentation required, and being constructed, for decouping the ion from any unwanted external environments. Our primary tools for this are working under Ultra High Vacuum (UHV) $< 10^{-11}$ mbar, and using electro magenetic shielding. The UHV system consists of a main experimental chamber comprised of a CF100 Octagon and pumps. For UHV, we use protocols described in XXX and must use appropriate materials within the chamber. Note, as mentioned the NPL trap is a microfab 3D trap, our ion therefore is located between the two planes within a slit. the 729 system requires High optical access for single addressing (see below) and this limits the available entry points of the remaining beams. We therefore are using in vacuum prisms to bounce the light into the slit. We must use vacuum compatible glues and coatings of the prisms. Figure X shows an image in the cleanroom of the prisms in our system. Also in the system: Oven with thermocouple. Trap PCB with filter capacitors. Cabling to both. Interposer between trap and PCB, using fuzz buttons. Now pump system: attached ion pump, Ti:Sublimation pump, Ion Gauge Valve to connect to external pump system

design considerations and

MuMetal shielding to suppress external magnetic fields. Using XX3mm thick two layer system with a quoted magnetic field reduction of 100.

### *3.5. Single Addressing*

729 High NA (0.6) lens we can achieve waist radius of $< 1$ um. With our axial trap freq of XXX we get ion spacing of 5um. Using AOD system we can traverse this ion chain. Description of lens system from AOD to ions. Description on the mechanism on how AOD works (this is the same as an AOM). Comparison between this and a fixed waveguide array. What equations we need to find number of resolvable spots of the AOD system. AOD have extra programmable control than waveguides which is excellent as we are in an exploratory regime where we may want to alter ion spacing/Dont want to use quartic potentials to make ions evenly spaced. We will use a crossed AOD design so that we have no overall frequency shift as we scan along the ion chain. Compact design to fit beam path within MuMetal box. We want to create single addressing standing wave so must consider stabilization technique from AOD. There is minimal path length differece compared to waveguide which is ideal as we can stabilise at some central frequency and should be stable at all ion locations. Quick calculation to look at path length diff in wavlengths between two extrema points on the ion chain. Note that this will give some fixed relationship between the two beams if we assume that the small seperation of beams paths is negligible (air density and current in close proximity should be related). Using two RF freq so that we can address two ions at the same time. Initially looking at this we see that supplying two freqs and amplifying we dont have crazy cross term amplitudes. However addressing multiple ions at the same time comes at the cost of photon freq cross terms i.e. spots that we dont want that are off plane to our ions. This has two bad effects: Can get crosstalk to other ions on the chain and lose power in our 729 system. First effect we can mitigate by putting AOD at a $> 45$ deg angle (60 deg?) this pushes the unwanted spots further from the chain. (sep to ion is sqrt2/2 when at 45 deg). There is no easy way to mitigate the power loss as two freq photons are barely

distinguishable (maybe look again at the two wavelength design aods). So this may limit us to only addressing 2 or three ions at a time and using a global addressing system through the prisms if all ions need to be addressed. Quick power calculation though means we still have XXmW at each ion with an intensity of XX which could drive CNulled gates at a speed of X.

In a reductionist viewpoint, Description of Blade and limitations Proof of principle experiments have been completed on Blade, a blade-style ion trap. Blade has a few limitations for the exploration of fast gates by the above described Cnulled method, motivating the design of a new system. Blade has dual optical access of the ions however, only as 45 degrees to the chain axial direction. Only global laser addressing of the chain is possible limiting the intensity seen at the ion. The simpler blade style trap, has limited control over creation of electric potentials meaning shuttling of ions is not practical.

subtitle FastGates Apparatus
*This has been (to be) incorportated into the above section.

Here we describe the design of the new “FastGates” system which is tailored for the exploration of fast, non-adiabatic entangling gates. Figure X shows a schematic of the vacuum can of “FastGates” with the addressing directions and magnetic field highlighted. Ca40 was chosen for initial experiments due to its simple energy level structure, figure X, without hyperfine levels and with the option for a quadrupole qubit between the S and D levels. An external magnetic field of 5G is applied to define our Zeeman sublevels, this low field will not allow state selective addressing by frequency, however allows for polarization selective addressing. *** Check if 729 will actually have linewidth for frequency addressing? *** The isotope having 0 nuclear spin and hence no hyperfine levels greatly simplifies control schemes however precludes the option of using magnetically insensitive “clock” qubits. To ensure we do not greatly limit coherence time of our quadrupole transition we use a MuMetal enclosure to suppress stray environmental magnetic fields.

## 4. Outlook

Current state of building up apparatus. Immediate next steps. Proposed first experiments? GANNT diagram?