A Scalable Approach to Ion Addressing in a Linear Paul Trap

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Motivation

Trapped-ion systems are a leading implementation of quantum computing. However, like all such systems, fidelity and scalability are major limiting factors.

- Fidelity: the accuracy of quantum operations
- Scalability: maintaining fidelity as complexity scales with the number of qubits

Here, we propose a new scheme with improved fidelity and scalability for individually addressing qubits in a linear Paul trap.

Optical Addressing

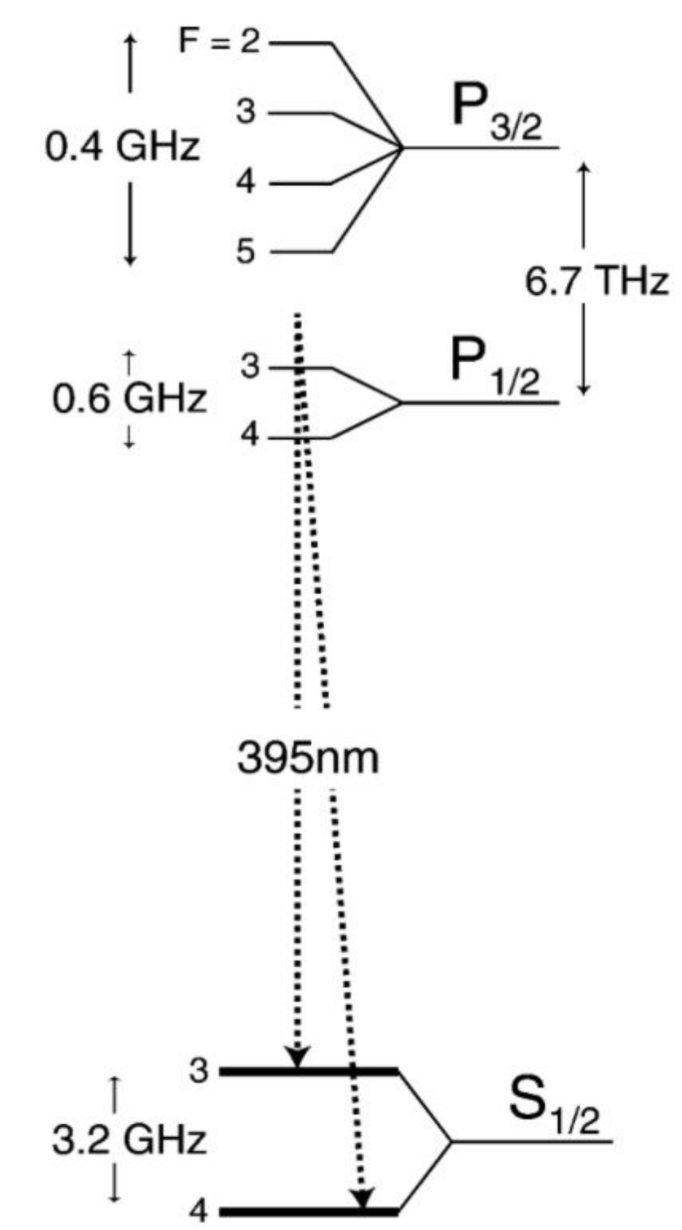

Figure 1: energy level structure of a Ca ion[1]

A qubit can be encoded in the hyperfine structure of $^{43}Ca^{+}$ isotope: $|0\rangle = |s\text{-}1/2, F = 4\rangle$ and $|1\rangle = |s\text{-}1/2, F = 3\rangle$.

In this scheme, a rotation about the Bloch sphere can be implemented by a Rabi oscillation. Multi-qubit operations leverage the shared vibrational modes of the ions.

A two-photon Raman transition driven by two beams near 395 nm with a difference frequency of 3.2 GHz moves population between the $|0\rangle$ and $|1\rangle$.

Current Disadvantages

The current scheme requires dedicated fiber-optic connection for each ion. Every beam path contains a dedicated set of optics to image the light onto the ion. The complexity of this system is proportional to the number of ions. This is not practically scalable.

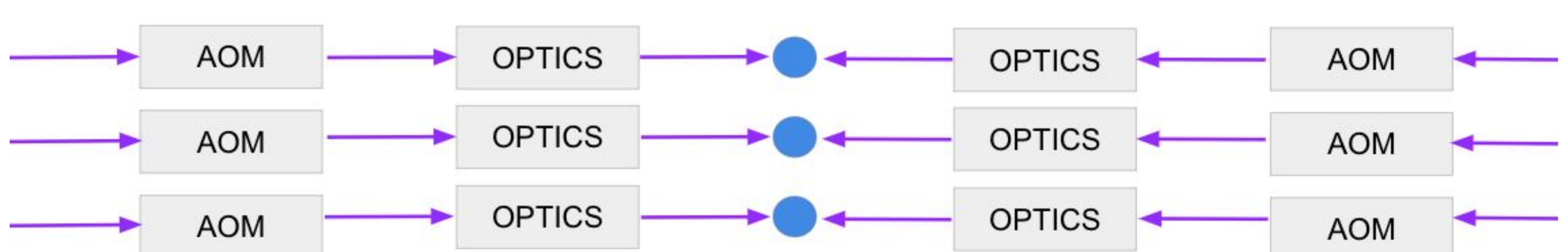

Figure 2: diagram of the current optical addressing system.

A Scalable Approach

A beam incident on an acoustic optical modulator (AOM) at the Bragg angle will diffract into multiple orders. From N distinct RF frequencies, a set of N, +1 order outputs separated in angle can be generated.

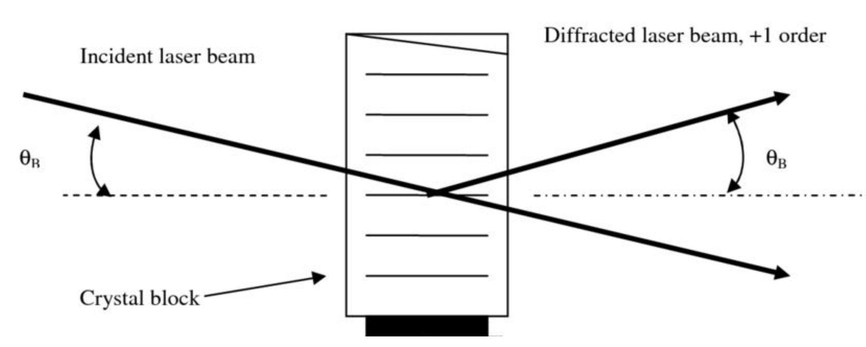

Figure 3: an RF signal maintains a sound wave in the crystal, generating a diffraction pattern[2]

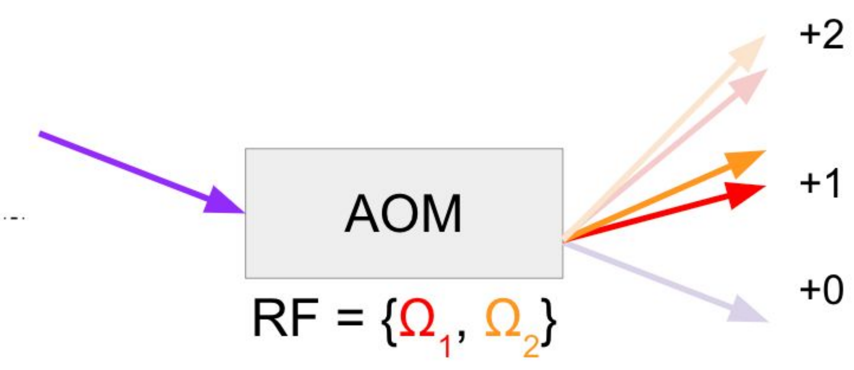

Figure 4: multiple angular deflections of an input beam

However, we lose frequency control in the process of spatial addressing. The spatial and frequency degrees of freedom can be decoupled at the ions by performing operations with a Raman transition.

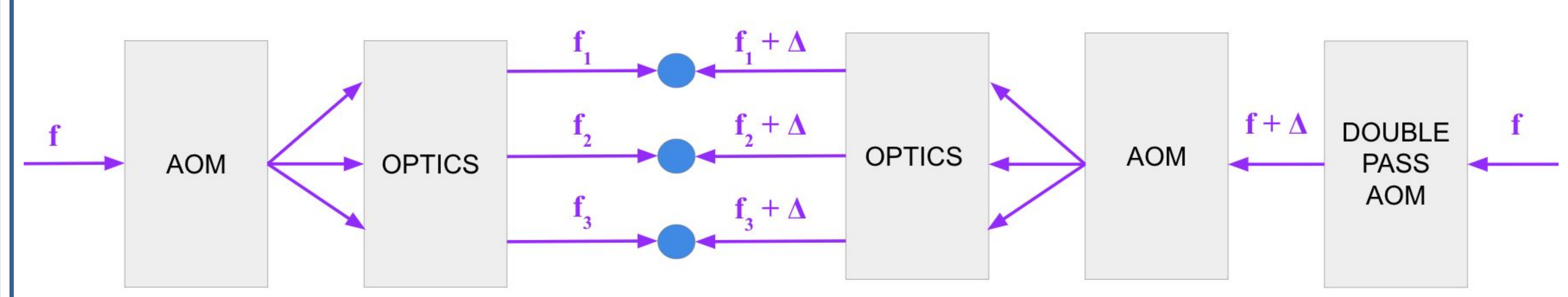

Figure 5: The updated ion addressing scheme only requires a single set of optics. Ions can be added without changing the setup.

Beam Imaging

At the output of the AOM, the angular separation of the beam at the object plane must be converted to a change in position at the imaging plane. Thus, we image the angular deflection of the AOM onto each ion.

The 8 and 200 mm lenses are separated by 208 mm and serve to expand the beam waist by a factor of ~200/8. The final 150 mm lens serves to tightly focus the beam onto the ions. The beam waist is reduced from ~2 mm to ~2µm

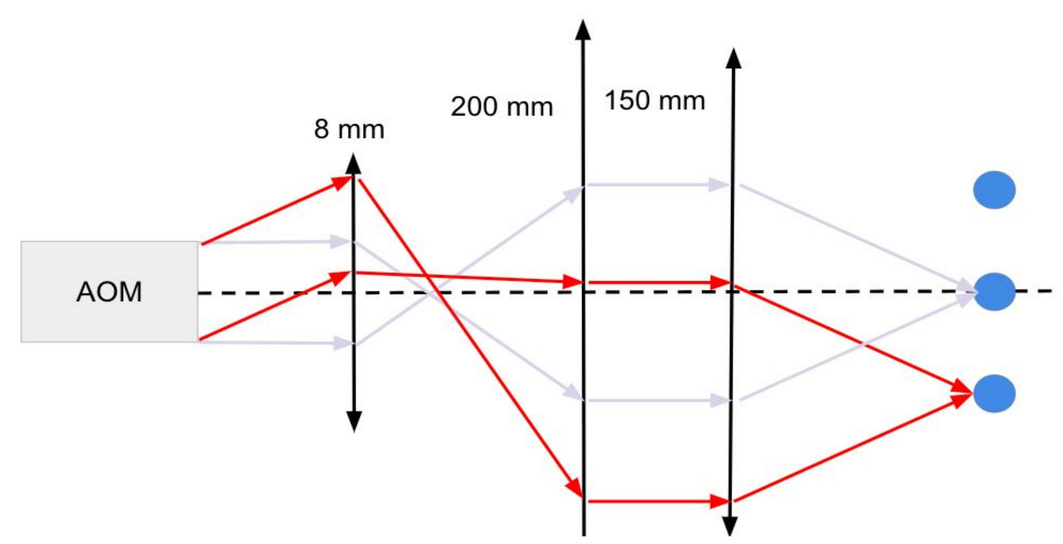

Figure 6: ray tracing of a beam waist at 2 angles (red and purple) through the imaging system

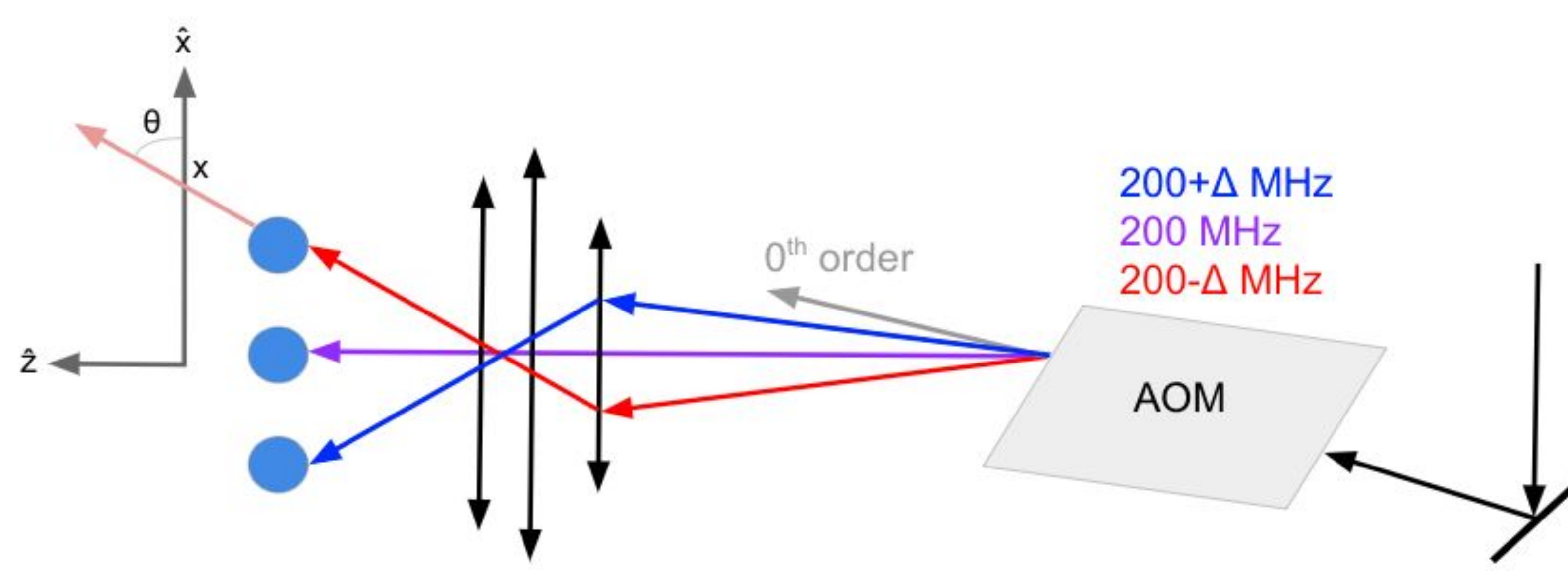

Figure 7: ray tracing of the AOM and imaging system.

Alignment

For our system, with AOM bandwidth of 150-250 MHz, the +1 order at the center frequency (200 MHz) must pass through the center of the imaging system.

In order to perform this alignment, the 4 degrees of freedom of the +1 order beam (Fig. 7) must be independent. The parameters are:

- The lateral-position and angle of the +1 order beam with 200 MHz RF (x, θ in Fig. 7)
- The lateral-position and angle incident on the AOM

The angular degrees of freedom are already independent. By placing the mirror on a translation stage and then placing both the AOM and mirror (with stage) a second translation stage, the positional degrees of freedom can also be decoupled.

There are additional degrees of freedom in positioning the 3 lenses. Alignment is particularly challenging because the beam is expanded and faint after the first lens. A counter-propagating beam is used as an alignment guide.

Aberrations

Optical aberrations in the final image of the beam are undesirable because they result in cross talk between ions.

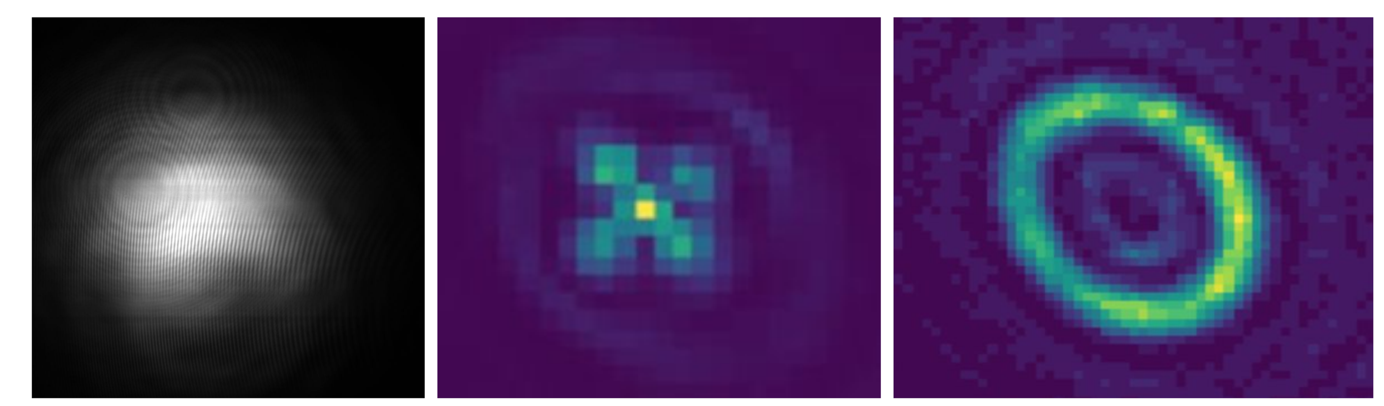

Figure 8: (a) image of the beam after the fiber collimator (object plane), (b) beam at the imaging plane, (c) beam slightly defocused from the imaging plane. The pixel size for these images is (2.2 µm)^2

Images of the final beam indicate a good focus but significant aberrations. The aberrations are asymmetric and are similar to those produced by an axicon. We predict that these aberrations can be attributed to a non-gaussian input beam. Possible solutions use a patch-fiber or a pinhole to clean the input.

Future Work

- Design robust RF control for the AOM
- Troubleshoot and reduce optical aberration and characterize beam shape
- Test optical addressing of qubit operations!

References

[1] R. Blatt, H. Häffner, C. F. Roos, C. Becher, and F. Schmidt-Kaler, "Ion Trap Quantum Computing with Ca + Ions," 2004.
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