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Ion trap experiments: Optical detection and addressing system

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Background

The Ion trap applies a combination of oscillating and static electric fields to confine ions to a region in space. The long storage times and ability to control the individual states of ions though laser excitation grants it many useful applications, such as precise measurements of fundamental constants and quantum computing[1]. The aim of our project is to build a system that can both image fluorescence emissions from trapped ions and manipulate their individual states. In a linear quadrupole trap, used in this experiment, several ions can be trapped along the axial potential minimum. Our trapped species are Calcium-40 ions. The $S_{1/2}$ and $D_{5/2}$ atomic states of the $^{40}Ca^{+}$ ion allow it to be used as a qubit. To achieve this, it is essential that we can both identify and manipulate the state of individual ions. As shown in figure 1, when ions excited to the $P_{1/2}$ state decay to the ground state, 397nm photons can be detected. The ions are addressed with a 729nm laser corresponding to the $S_{1/2}$ to $D_{5/2}$ transition. The $D_{5/2}$ energy level is a metastable state, and the electron is 'shelved'.

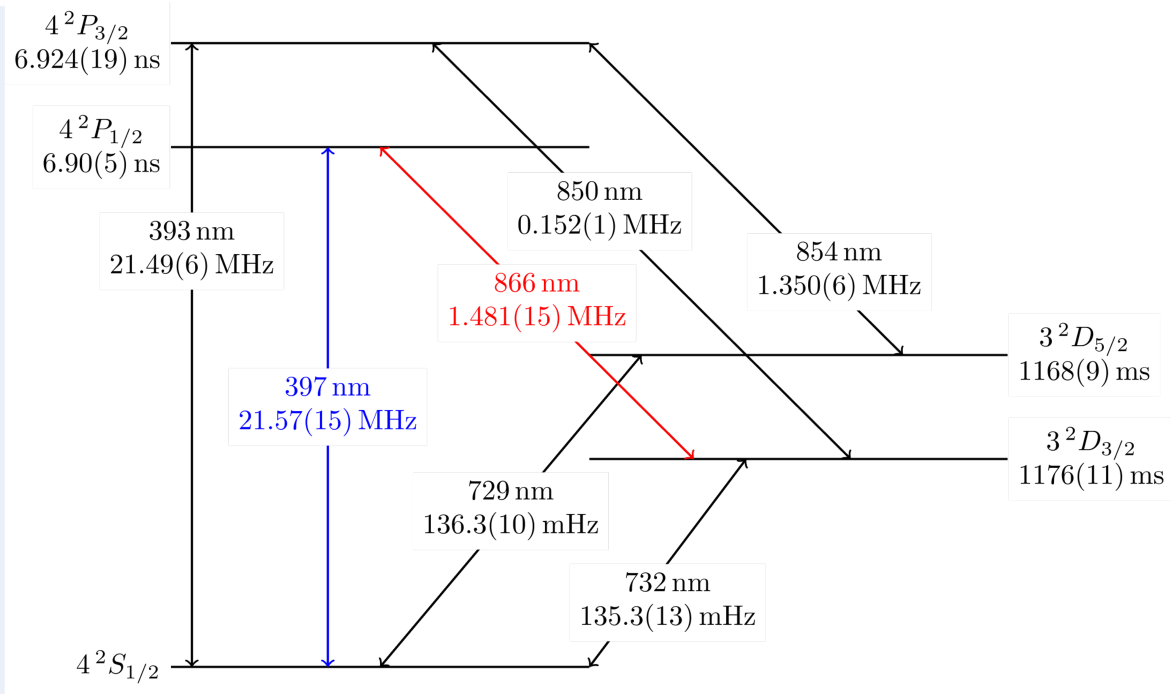

Figure 1, Energy level diagram of the $^{40}Ca^{+}$ with its transition wavelengths[2].

Method

Figure 2 shows a simplified set up. A beam splitter separates the optical paths for the 2 purposes of the system. The imaging camera EMCCD has a 16x16μm pixel size, so individual ion detection requires magnification of the separation between ions ($\sim 10\mu m$) to be resolved by the camera[3,4]. In the addressing scheme, a beam expander before the specialized lens size focuses the beam on to the ions. Focusing a larger beam results in a smaller waist, ω_0, at the image plane as $\omega_0 \theta$ is constant, where θ is the divergence angle. An acoustic optical modulator(AOM) shifts the beam on to different ions. The range of deflection of the beam at the ions is limited by the scope of the AOM. The beam waist should be offset slightly to the ion plane to allow sufficient deflection to reach different ions. When manipulating an ion's state, neighbouring ions will experience some intensity due to the laser's gaussian profile with radial distance. For sufficient single ion addressing we aim to have the ratio of excitation probabilities of the addressed ion to any neighbour to be below 1%. This constrains the necessary waist size. We will be incorporating a specialised lens which will work well for focussing the relevant wavelengths of light passing through[5].

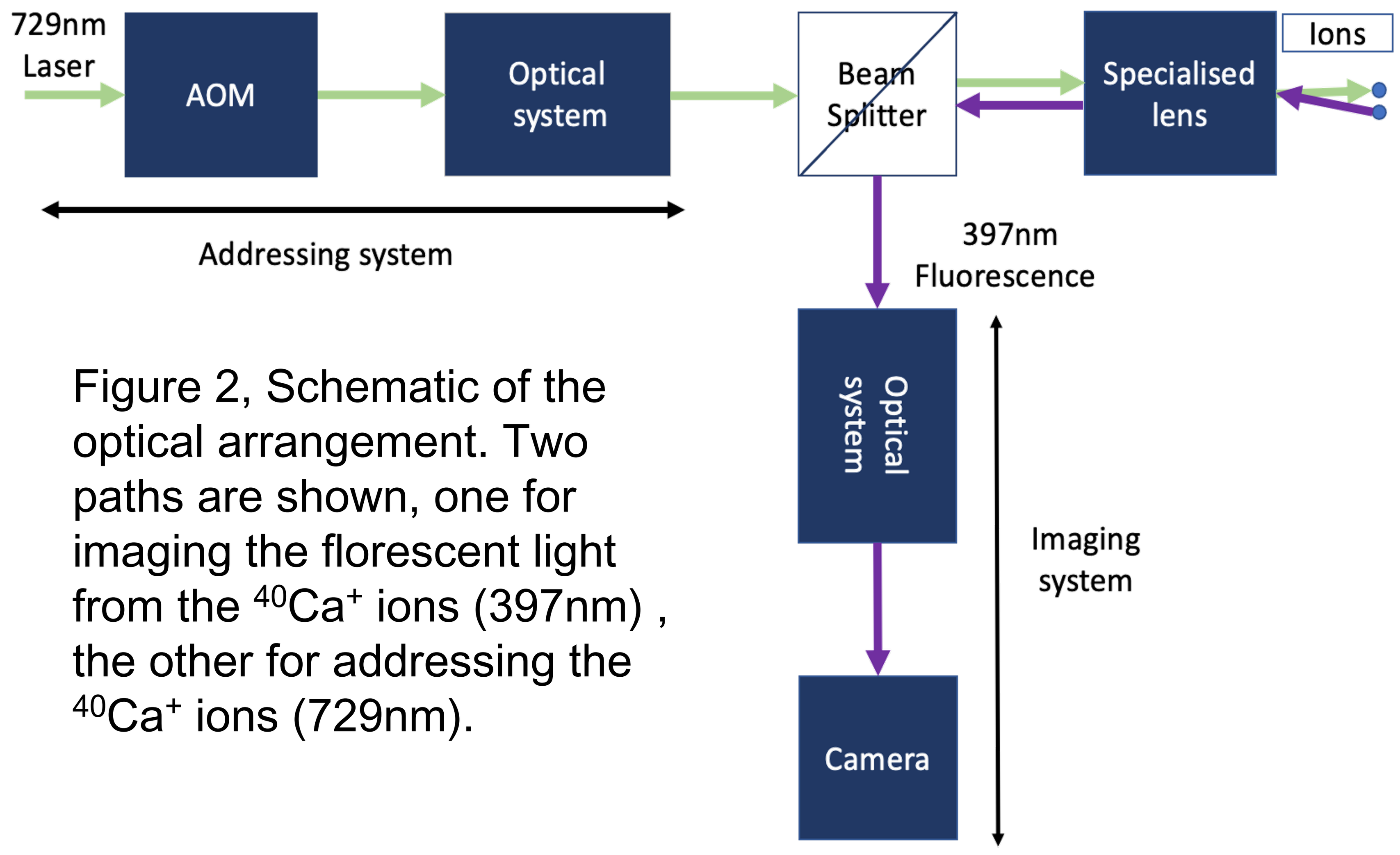

Figure 2, Schematic of the optical arrangement. Two paths are shown, one for imaging the florescent light from the $^{40}Ca^{+}$ ions (397nm) , the other for addressing the $^{40}Ca^{+}$ ions (729nm).

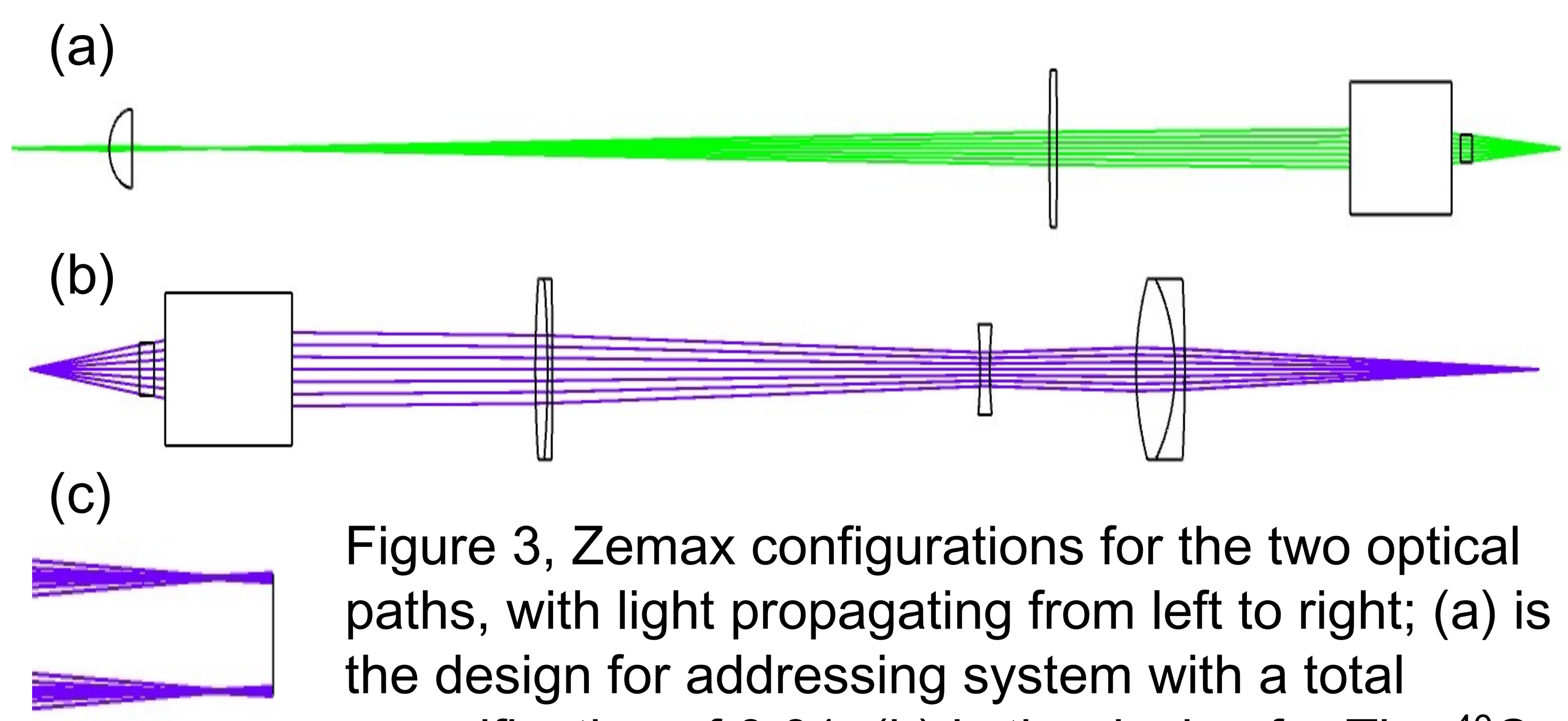

Figure 3, Zemax configurations for the two optical paths, with light propagating from left to right; (a) is the design for addressing system with a total magnification of 0.01, (b) is the design for The $^{40}Ca^{+}$ florescence detection system with a total magnification of 3.84, (c) is the enlarged image plane of 3(b) illustrating magnified ion separation.

Results

We used the optics software Zemax to simulate our design, shown in Fig.3. The total axial length of system 3(a) is 793 mm with a beam magnification of 0.01, giving a 2.5μm beam size in the image plane, which is within our aim of a 1% probability ratio. The total axial length of system 3(b) is 620mm, with a total magnification of 3.84. This gives and ion separation of 0.048mm in the image, as required for sufficient resolution.

Figure 4 shows how the beam size changes as the separation between the two simple lenses in 3(a) is varied. A beam size close to the waist is necessary for minimal crosstalk between ions, but not equal to it, as beam movement becomes restricted.

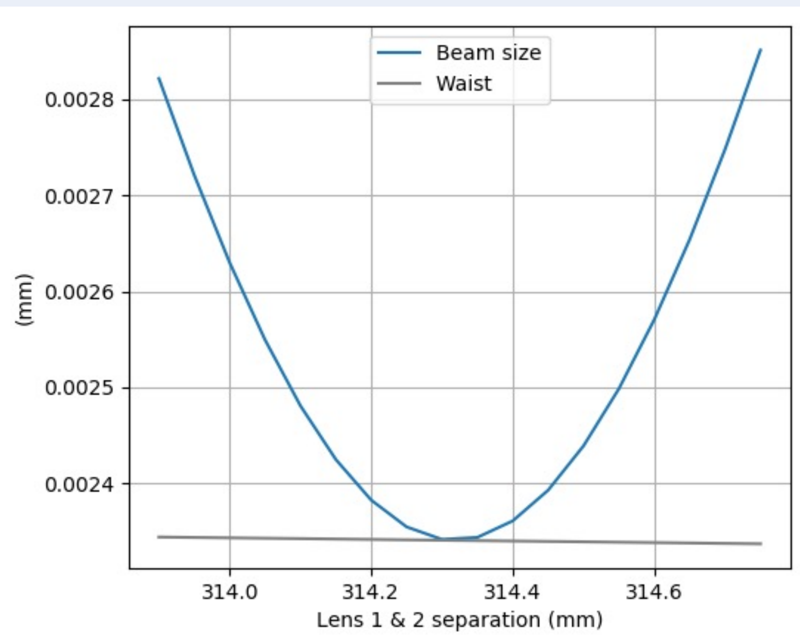

Figure 4. Beam size in the ion plane as a function of the lens separation in 3(a). Beam size is equal to the waist at a separation of 314.31mm.

Conclusion

We have created a successful model to image adjacent ions in a trap and manipulate their state. An addressing beam of 2.5μm at the ions was formed, sufficient for minimal crosstalk. An imaging system with a resolution of 3 pixels was constructed for state detection. The next stage is to build this set up in the lab and verify our simulation. We will then be able to use this setup for a variety of trap experiments. This setup could be further improved by achieving a smaller addressing beam through further optimization of parameters, as well as adjusting the AOM method to increase the range of distance which can be addressed.

References

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