Chapter 1

Introduction

Chapter 2

Ion Trap Apparatus

A vast effort is spent on the initial build-up of the an ion trap system, but throughout the life of the experiment, a greater effort is spent on its daily maintenance. I hope that this chapter will serve as a resource for future members of the FastGates team, as well as provide a useful recipe for anyone building a similar system.

Due to the size and complexity of the system, we introduce an inital overview of the design, motivated by the desired functions. As the name suggests, an ion trap experiment aims to confine arrays of single ions, this is achieved by static and dynamic electric fields which, due to the ions possesing non-zero electric charge, can provide trapping potentials, section 2.2. Due to the fragility of the internal states of the ion (these are state of the art sensors after all), we must take great care in isolating the ion from any noisy environment. This neccesitates the use of ultra-high vacuum (UHV) systems, section 2.3, vibration isolation, and magnetic shielding, section 2.4. To manipulate the internal electronic states of the ion, we create local electric and magnetic fields using RF antennae and, in this work, lasers, sections 2.5 and 2.5.3. Finally, to interface with the apparatus we have built, at the time scales set by our interaction strengths, we require a sophisticated and custom control system which is discussed in section 2.6.

2.1 System Design

2.2 The Ion Trap

2.2.1 Trap RF Chain

2.2.2 Trap DC Voltages

2.3 Beam Geometries and Vacuum System

2.3.1 Vacuum System

2.3.2 Atomic Source Oven

2.3.3 Optical Access

Beam Paths

In Vacuum Prisms

Dual High NA Objectives

2.3.4 Imaging System

2.4 Magnetic Field

2.5 Laser systems

2.5.1 Photoionisation

2.5.2 Ca^+ Laser Systems

2.5.3 Narrow Line Width 729 Laser

2.5.4 Single Addressing System

2.6 Sinara Hardware and Artiq

Chapter 3

Experiment Characterisation

Before we can dive into running novel experiments involving the motion and spin of the atoms, we need to characterise our apparatus. This allows us to both benchmark our system against state of the art results, and to reveal any current limitations of the apparatus which we may need to address.

3.1 Available Transitions

3.1.1 Extracting Laser Offset and Magnetic Field

3.2 Spin

3.2.1 Rabi and Ramsey Scans

3.2.2 Spin Coherence Times

3.2.3 State Preparation and Measurement

3.2.4 Single Qubit Gates

3.3 Motion

3.3.1 Finding Motional Mode Frequencies

3.3.2 Motional Mode Stability

3.3.3 Cooling

For any interaction involving the motion of the ion, we require both the ability to prepare the motional state with high fidelity, and to subsequently measure this motional state to verify correct preparation. For entangling gates, and the creation of squeezed states which we are considering in this chapter, we assume that we begin in the motional ground state, or in other words, Fock state zero. Our initially trapped ions will be in some high temperature thermal state, (*given by the oven temperature and the PI laser momenta kicks*). We first doppler cool our ions, and then subsequently sideband cool them. We give a brief description of these two cooling processes here.
Doppler cooling exploits the fact that incident light onto a moving ion will appear frequency shifted in the rest frame of the ion. For Doppler cooling of $^{4}0\mathrm{Ca}^{+}$, we apply both the 397 nm and 866 nm lasers. We initially red detune the 397 nm laser by around 100 MHz. This results in the preferential absorption of a quanta of 397 nm light by ions with a velocity vector antiparallel photon k-vector. After this absorption, the ion will be in the excited $4P_{3/2}$ state and spontaneously decay to either the $4S_{1/2}$, or the $3D_{3/2}$ emitting a photon of either 397 nm or of 866 nm respectively into a random direction.

These two decay paths have a branching ratio of XX. As we desire many photon kicks to cool our ions, we repump the electron out of this metastable $3D_{3/2}$ level by applying an on resonant 866 nm beam. The absorption and sequential emission of this 397 nm photon will lead to a net reduction in the motional energy of the ion if the photon is emitted at a higher energy than when absorbed. The equilibrium temperature is given by the condition where the doppler cooling rate is equal to photon recoil heating of the ion. Assuming a Lorentzian absorption profile, the minimum temperature is given by,

$$T_{Doppler} \approx \frac{\hbar\gamma}{2k_B} \tag{3.1}$$

where $\hbar$ is the reduced Planck constant, γ is the natural linewidth of the transition, and k_B is Boltzmann's constant.
For $^{40}Ca^{+}$, the natural linewidth of the 397—nm transition is $\gamma = 2\pi 21$ MHz, leading to a Doppler temperature of approximately 0.5 mK.

3.3.4 Heating Rates

3.3.5 Motional Coherence Times

3.4 Experimental Control

3.5 Spin-Dependent Forces

3.5.1 Calibrating the SDF

3.6 Two-Qubit Entangling Gates

3.6.1 Collective Motion of Two Ions

3.6.2 Mølmer-Sørensen Gate

Theoretical Background to the MS Gate

Experimental Implementation of the MS Gate

3.7 Creating Squeezed States

3.7.1 Calibrations

Chapter 4

Outlook

4.1 Appendix