A Discussion of the AC-MOT

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1 Background and Motivation

Since the technique was first described in 1987 [1], the magneto-optical trap (MOT) has become a well-known and robust method for creating samples of cold, spatially-confined, electrically neutral alkali atoms, and is used to create and measure a variety of physical effects. As the name suggests, creating a MOT requires proper application of both light (lasers) and magnets (see Fig. 1), and the physical underpinnings of its construction will be discussed in more detail in Section 2.

One limitation of the magneto-optical trap is that the forces used to trap and cool the atoms cannot perform their function without interacting with the atoms. However, there exists a certain class of experiment which requires the use of a sample of cold, confined atoms such as may be produced by a MOT, but which also must be performed without the perturbative effects created by the MOT's magnetic field or trapping lasers.

In particular, we consider the case in which we seek to create a sample of cold, spatially confined atoms which are also highly spin-polarized. If a MOT is to be used in such a scenario, it must be used only intermittently to cool and re-confine the atoms, and then switched off for a time so that the atoms can be polarized and further data can be collected as the atom cloud expands ballistically.

While it is straightforward to rapidly eliminate the light from trapping lasers by utilizing a well-placed acousto-optic modulator (AOM), fully eliminating the magnetic field is a more challenging task. It is worth noting that although the atoms will not feel any confining or cooling forces with the trapping lasers turned off, the MOT's characteristic magnetic field gradient will still prevent the atoms from being polarized due to a non-uniform Larmor precession [3].

It is therefore necessary to develop a type of MOT in which the non-uniform magnetic field may be rapidly eliminated, such that the atoms may be polarized as rapidly and as completely as possible, before the atom cloud expands beyond the size at which it can be re-trapped. In order do this, we employ a specific type of MOT – the "AC-MOT" [4] – the details of which will be discussed in Section 3.

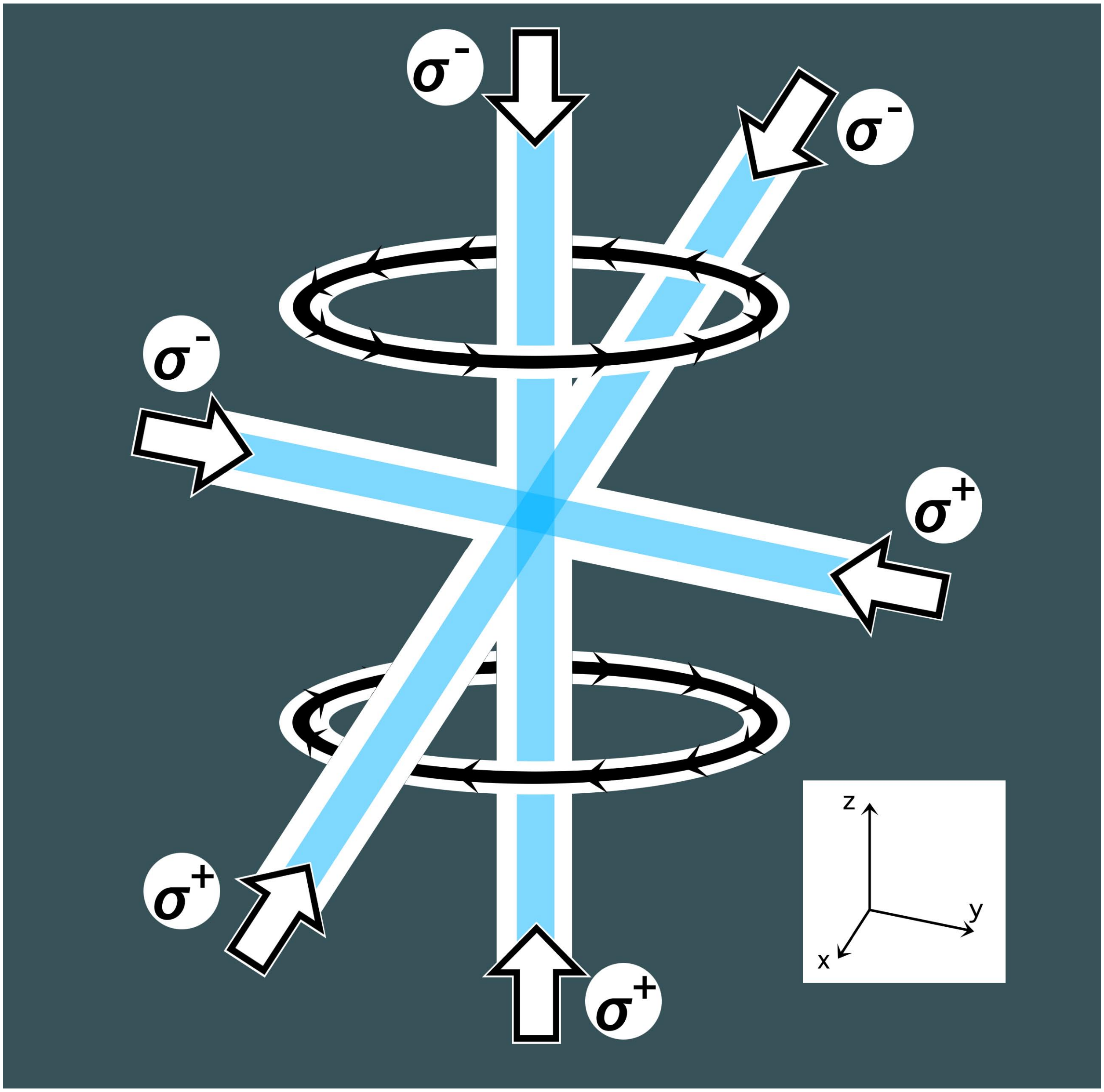

Figure 1: The necessary components of a magneto-optical trap include a pair of anti-Helmholtz coils running anti-parallel electrical currents, and six circularly polarized laser beams intersecting in the central region. The coils produce a quadrupolar magnetic field which is zero at the center [2].

The largest obstacle to rapid elimination of the MOT's magnetic field gradient is the presence of eddy currents in nearby materials, which themselves are the result of electromagnetic induction caused by changing currents in the anti-Helmholtz coils – in the case of the standard MOT, this is a direct result of switching the current off. By contrast, the AC-MOT operates by running a (sinusoidal) alternating current through its anti-Helmholtz coils. The induced eddy currents, though out of phase with the anti-Helmholtz coils, must therefore also pass through a point where they are “zero” with every cycle, and the challenge becomes shutting off the current in the anti-Helmholtz coils at this precise time, so that the eddy currents and the anti-Helmholtz current will both immediately be zero.

2 The Standard Magneto-Optical Trap

The magneto-optical trap makes use of two (primary) physical effects – Doppler cooling, and Zeeman splitting. In a MOT, both of these effects are simultaneously present, allowing atoms to be simultaneously trapped and cooled.

2.1 Doppler Cooling

Consider an atom in one dimension, interacting with a laser beam tuned slightly to the red of an atomic resonance between the ground state and an excited state. If the atom is in the ground state, an incident photon may be absorbed and its linear momentum transferred to the atom, giving it a “push” in the direction of laser propagation. If the atom's motion is against the direction of laser propagation the laser's frequency will, in the reference frame of the atom, be blueshifted, bringing it closer to the atomic resonance and therefore increasing the probability of an interaction. In this case, the atom will be slowed (with respect to the lab frame) upon absorption of the photon. Similarly, for an atom travelling in the direction of laser propagation, the laser will appear to the atom to be redshifted, making an interaction less probable. If a second, counter-propagating laser at the same frequency and intensity is added, the atom can be slowed no matter which direction it was initially travelling.

For this one dimensional example, it can be shown that the net force on an atom moving at velocity $v\,\hat{z}$ in the presence of counter-propagating lasers at frequency ω_L, is

$$\vec{F}_{\text{Doppler}}(v) \;=\; \frac{\gamma\left(s_0\,\hbar\omega_L/(2c)\right)(1-v/c)}{1+s_0+\left(\frac{2}{\gamma}(\delta_0-\omega_L v/c\,)\right)^2}\,\hat{z}-\frac{\gamma\left(s_0\,\hbar\omega_L/(2c)\right)(1+v/c)}{1+s_0+\left(\frac{2}{\gamma}(\delta_0+\omega_L v/c\,)\right)^2}\,\hat{z}, \qquad (1)$$

where and γ is the linewidth of the atomic transition (and also describes the excited state's spontaneous decay rate), s_0 is the on-resonance saturation parameter for the atomic resonance at ω_A and laser intensiy I (for a single beam), given by

$$s_0 = \frac{12\pi\, c^2 I}{\hbar\,\omega_A^3\,\gamma} \qquad (2)$$

and δ_0 is the laser's detuning from the atomic resonance, given by $(\omega_L - \omega_A)$. This setup is sometimes called an “optical molasses,” and may be applied effectively in all three spatial dimensions simultaneously, causing a net cooling effect on the atoms [5].

2.2 Zeeman Splitting and the Magnetic Field

In the presence of a magnetic field, the atomic Hamiltonian picks up a term which splits degenerate energy levels according to their atomic spin state. In the weak field limit where we shall be concerned with it, this term is small, and depends on both the the magnetic field $\vec{B}$ and the magnetic moment of the atomic state μ. This Zeeman term is given by [6]

$$\hat{H}_{\text{Zeeman}} \quad = \quad -\vec{\mu} \cdot \vec{B}, \tag{3}$$

and we find that for a particular transition, the change in energy is given by

$$\Delta E_{\text{transition}} = (g_e M_e - g_g M_g)\, \mu_B B_z, \tag{4}$$

where μ_B is the Bohr magneton, the subscripts e and g refer to the excited and ground states respectively, $g_\times$ is the Landé g-factor, $M_\times$ is the $\hat{z}$ component of the atomic angular momentum, and we have implicitly chosen the axis of quantization to be along $\hat{z}$.

In such a transition, a photon is absorbed (or emitted) and the atomic angular momentum is changed by one unit, so that $M_e = M_g \pm 1$. We are able to select which transitions an incident laser couples to by using circularly polarized light of the correct handedness. We describe the two circular polarization states by σ_+ and σ_-, where the subscript denotes whether the $+\hat{z}$ component of atomic angular momentum is incremented or decremented upon absorption of a photon.

In a magneto-optical trap, a quadrupole-shaped magnetic field is created by running current through a pair of anti-Helmholtz coils, as shown in Fig. 1. The trap itself is formed in the central region, where the magnitude of the magnetic field itself is close to zero, but the field gradient is (to a good approximation) constant for a displacement from the center in any direction, as in Fig. 2.

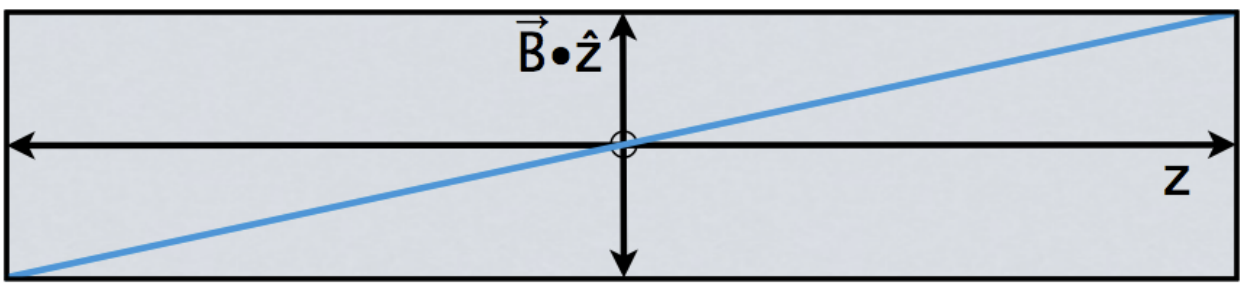

Figure 2: Magnetic field magnitude near the center of a quadrupole field, as produced by a set of anti-Helmholtz coils.

2.3 Trapping Forces in a Magneto-Optical Trap

Combining the effects from Doppler cooling and Zeeman splitting, in a system with counterpropagating lasers red-detuned and circularly polarized so as to push the atoms toward the spatial point with the lowest magnetic field, we are able to write down an expression for the average force on an atom. We find that, to an excellent approximation [5],

$$\vec{F} = -\beta\vec{v} - \kappa\vec{r}, \tag{5}$$

where

$$\beta = \frac{-8\hbar(\omega_L/c)^2\delta_0 s_0}{\gamma(1+s_0+(2\delta_0/\gamma)^2)^2} \tag{6}$$

$$\kappa = \frac{(g_e M_e - g_g M_g)\,\mu_B A}{\hbar\omega_L/c}\beta, \tag{7}$$

where A is the magnitude of the magnetic field gradient along the direction of displacement. The above expressions are valid in the regime where the following conditions apply [5]:

$$\delta_0 \gg \omega_L\, v/c \tag{8}$$

$$\delta_0 \gg (g_e M_e - g_g M_g)\,\mu_B B_z/\hbar \tag{9}$$

$$s_0 \ll 1. \tag{10}$$

Note that for a red-detuned laser, δ_0 will be negative, so that β is positive (as is κ) and therefore the first term on the right-hand side of Eq. (5) will act in opposition to the motion of the atom, creating an effective drag force. The second term acts as a restoring force on atoms located some distance $|\vec{r}|$ away from the center of the trap. With both of these forces acting together, the result to slow the atoms, at which point they are able to be confined in a cloud within the effective 'trapping potential' created by the central restoring force.

3 The AC-MOT

In an AC-MOT, the anti-Helmholtz coils which produce the trap's magnetic field gradient are run with a sinusoidal current, such that the direction of the magnetic field produced will switch back and forth at the same frequency, f_{AC}. It then becomes necessary to switch the direction of circular polarization on all of the trapping beams so as be in phase with the sign of the magnetic field – otherwise the MOT's restoring force becomes a repulsive force when the sign of the magnetic field is flipped (see Fig. 3). This can be accomplished by adding an electro-optic modulator (EOM) to the optical circuit. Given an incoming laser beam (and, of course, an external signal to drive it), the EOM is able to rapidly adjust the polarization of the output beam, allowing it to be phase matched with the changing magnetic quadrupole field [4][2]. Given a pair of anti-Helmholtz coils operated with a driving voltage of $V = V_0 \sin(\omega t + \phi)$ in the anti-Helmholtz coils, the induced eddy currents are described by the following equation:

$$I_{\mathrm{eddy}}(\phi, t) = I_0 \frac{\omega\tau\cos(\omega t+\phi) - \sin(\omega t+\phi) + (\sin\phi - \omega\tau\cos\phi)e^{-t/\tau}}{1+\omega^2\tau^2}, \tag{11}$$

which is valid for systems in which the transient response time of the AC-MOT coils is much faster than that of the surrounding materials. Here, τ is a constant which depends on the properties of the materials. We see from this expression that for $\phi = \tan^{-1}(\omega\tau)$, the eddy currents are instantaneously zero; this is therefore the optimal phase at which to shut off the current [4].

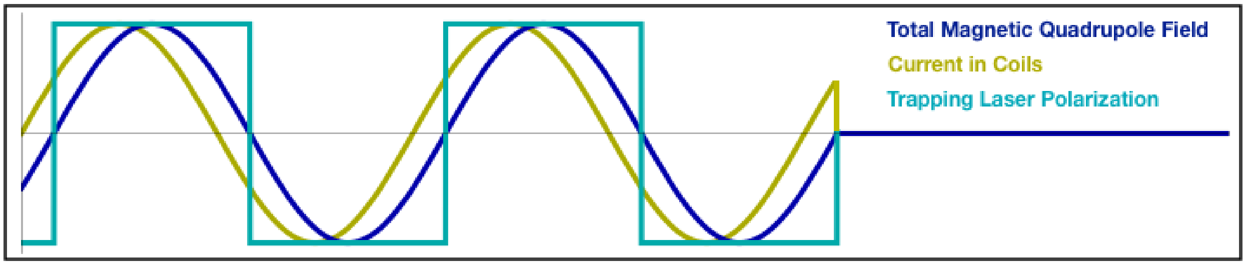

Figure 3: The relative phases of elements within an AC-MOT. The laser polarization is kept in phase with the overall magnetic quadrupole field in the central trapping region. Induced eddy currents in the surrounding materials cause the magnetic field phase to lag behind that of the current in the anti-Helmholtz coils.

4 Results

Although one might imagine that the trap position in an AC-MOT may not be stable, this turns out to largely not be the case provided that the trapping lasers and anti-Helmholtz coils are both reasonably well-balanced and aligned, as can be seen in Fig. 4.

The greatest problem with the AC-MOT is its tendency to heat up the rest of the system. Because the AC-MOT intentionally employs sinusoidally changing changing currents to produce its magnetic field, utilizing and optimizing for induced currents in the surrounding materials, inductive heating is an expected side-effect.

Inductive heating may result in two distinct deleterious effects on the system: detector problems, and vacuum outgassing. Any problems involving the collection of data, of course, will be dependent on the specifications of the detectors in question, as well as their position relative to the current-carrying coils. The greatest change in magnetic flux in the anti-Helmholtz geometry occurs directly along the coils' axis, therefore detectors located in this position will be the most vulnerable to effects from inductive heating. If the experiment necessitates placing detectors on-axis, care must be taken to either use a type of detector which is not vulnerable to being overheated, or to set these detectors up with a system for keeping them cool. In TRINAT's case, the Silicon strip detectors mounted on-axis have been seen to pick up a significantly increased background when heated, however these problems have been mitigated to some extent by forcing a flow of air around the strip detectors (which were mounted outside of the vacuum).

Vacuum outgassing as a result of inductive heating is a problem likely to affect a broader class of experiments. A magneto-optical trap can only be created within a vacuum chamber, as the presence of other gasses in sufficient quantity can destroy the trap. This is because any untrapped atoms will not be cooled, and these 'room temperature' atoms tend to have far

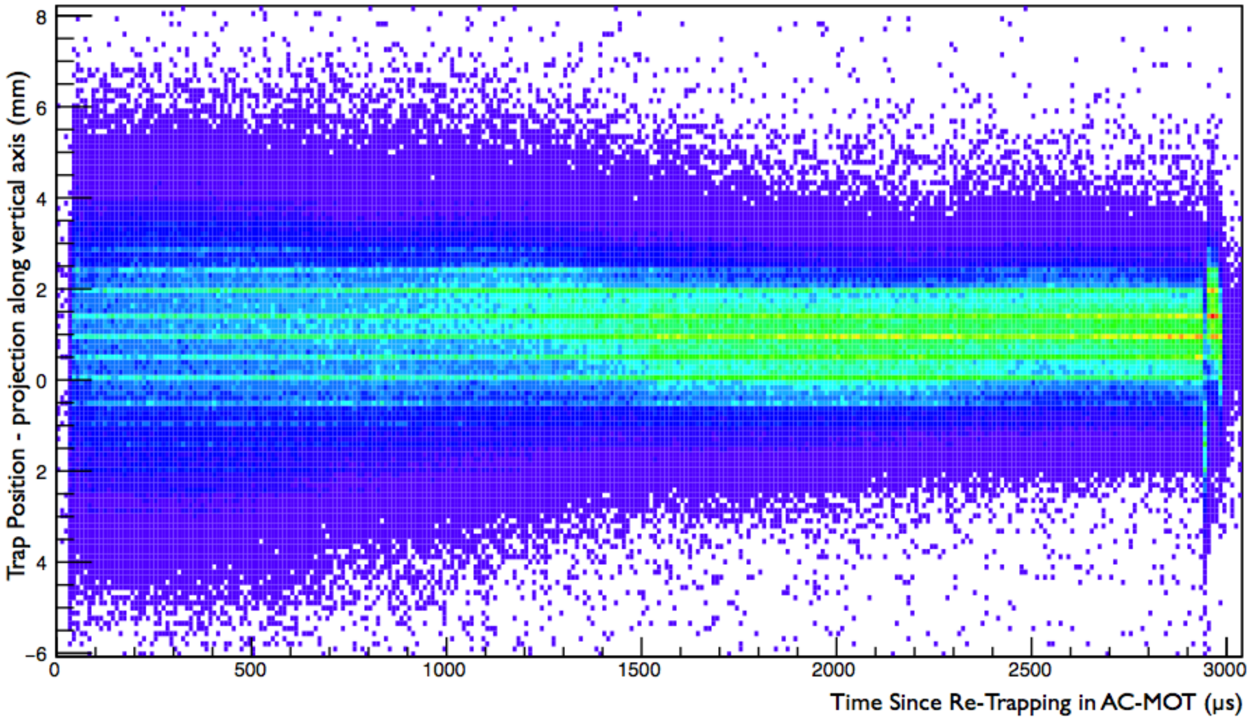

Figure 4: Cloud position as a function of time for an AC-MOT with $f_{\mathrm{AC}} = 700$Hz. At the left edge of the plot, the AC-MOT is turned back on after being having been shut off for ∼2 ms, during which time the atom cloud has expanded. Over the next ∼3 ms, the AC-MOT's restoring force causes the cloud to become more compact again, until the trapping forces are again shut off. Two full AC cycles are shown here, and then the MOT is shut off. Note the slight 'wobble' in cloud position, matching up with the AC cycle. Data collected with the online TRINAT trap, June 2014, using trapped ^{37}K.

more kinetic energy than atoms in the trap (at ∼1 mK). Therefore an interaction involving both a trapped and untrapped atom is likely to transfer enough energy to knock the formerly-trapped atom out of the trap's potential well.

When the walls of a vacuum chamber are heated, hydrogen and other gasses tend to be released more rapidly. This creates an additional loss mechanism from the trap that must be taken into consideration, particularly if the system's vacuum pumps are unable to keep up with the outgassing, or otherwise cannot be used during the experiment. This problem can be partially mitigated by 'baking' the vacuum chamber (heating it up while the vacuum pumps run) before using the AC-MOT. It should also be noted that it may take several hours or days for the system to arrive at a stable (increased) temperature after heating with the AC-MOT begins, therefore any preliminary tests to determine how problematic the effect is must be performed over a long enough timescale that the system will have time to arrive at a new thermal equilibrium.

Because the power dissipation due to inductive heating increases with the driving frequency [7], it is therefore advisable to run an AC-MOT at a relatively low AC frequency if inductive heating becomes problematic [2]. This can be accomplished without greatly affecting the quality of the trap (see Fig. 5).

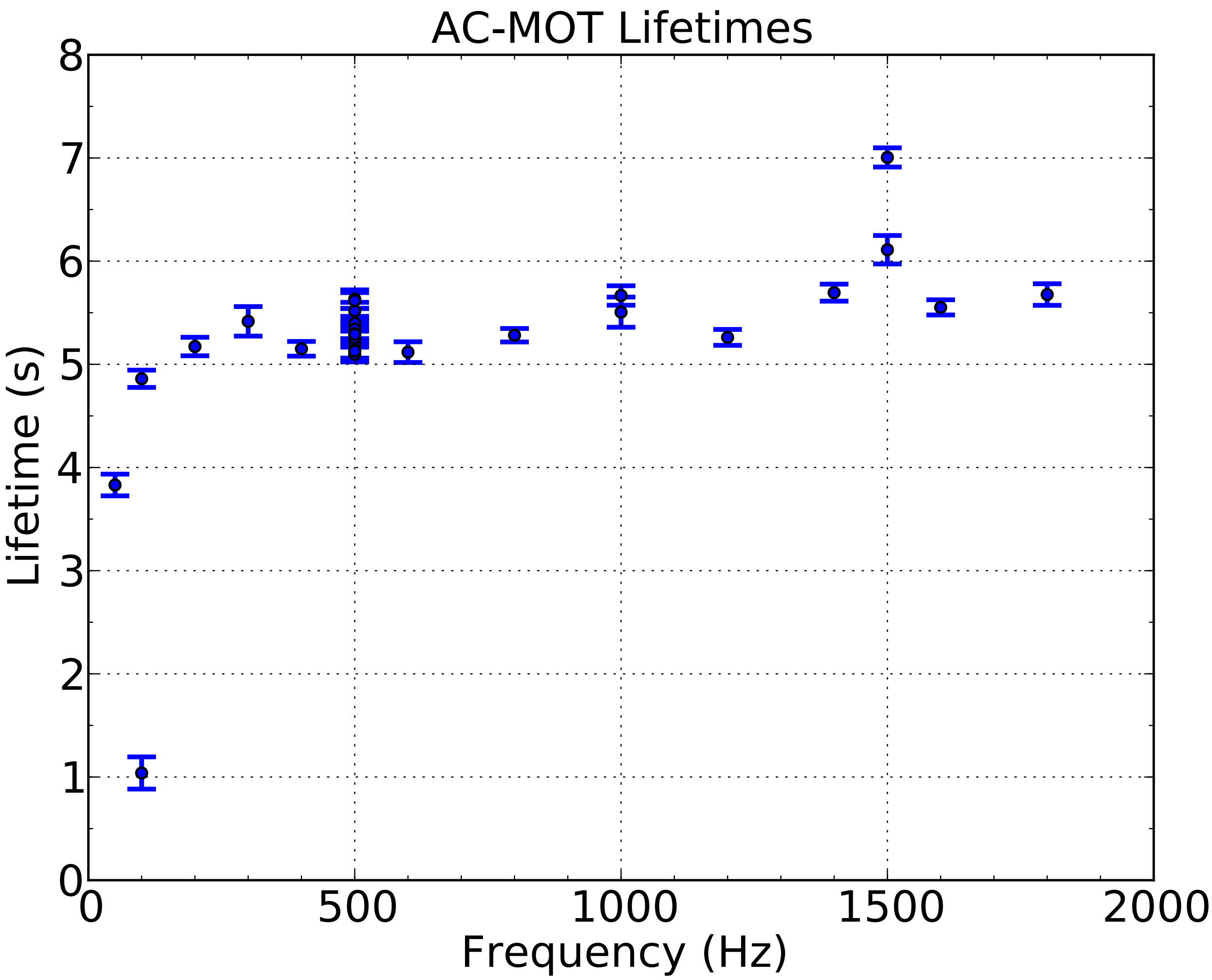

Figure 5: Trap lifetime (the $1/e$ timescale for losing atoms from the cloud after shutting off the trap) for an AC-MOT is shown as a function of AC frequency (f_{AC}). For sufficiently high frequencies, the trap lifetime does not depend strongly on f_{AC}. There is, however, a lower frequency 'cutoff' at which the trap becomes unstable. Data collected in the TRINAT offline MOT [2].

References

[1] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987), URL http://link.aps.org/doi/10.1103/PhysRevLett.59.2631.

[2] M. Anholm, Master's thesis, University of British Columbia (2014), URL https://open.library.ubc.ca/cIRcle/collections/24/items/1.0165992.

[3] D. G. Melconian, Ph.D. thesis, Simon Fraser University (2005).

[4] M. Harvey and A. J. Murray, Phys. Rev. Lett. **101**, 173201 (2008), URL http://link.aps.org/doi/10.1103/PhysRevLett.101.173201.

[5] H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping* (Springer-Verlag New York Inc., 1999).

[6] A. Corney, *Atomic and Laser Spectroscopy* (Oxford University Press, New York, 1977).

[7] J. D. Jackson, *Classical Electrodynamics* (Wiley, New York, NY, 1999), 3rd ed., ISBN 9780471309321.