Chapter 8

Outlook and Extensions for Feedback and Short Cavities

What is the next step for active feedback to the position of an atom in a cavity? A number of extensions and modifications suggest themselves for improvement of the present trapping/feedback scheme and thus realization of cooling and quantum effects discussed in previous chapters. In this chapter I conclude by briefly discussing several directions for active-feedback and short-cavity experiments – some more or less sensible, and some rather unrealistic but nevertheless quixotically appealing to me. Motivations, rough estimates, and limitations/challenges are discussed for each proposed direction of future work.

8.1 Cooling to the Axis by Breaking Cylindrical Symmetry

Feedback methods based solely on an atom interacting with the cavity TEM_{00} mode cannot in principle cool the atom to the cavity axis; because of the cylindrical symmetry of the mode, there is no mechanism for removing an atom's angular momentum. In order to remove angular momentum a symmetry-breaking force is required. Some direct measurement sensitivity to absolute angular position θ is also helpful, but not strictly required. One can imagine a feedback scheme in which the angular momentum is estimated as in the atom-cavity microscope, the symmetry-breaking force is applied to “kick” the atom, and the angular momentum is estimated again to determine if the kick was in the right direction. In this way an absolute knowledge of $\theta(t)$ can be built up and the correct phase for application of the “side force” can be determined. Repeated “kicks” to reduce angular momentum, followed by cycles of re-circularizing via feedback to $\dot{\rho}$, could cool an atom to the cavity axis.

Simple candidates for a symmetry-breaking force include externally applied transverse electric or magnetic fields, light coupled into the cavity from the side, and light in transverse modes of the cavity itself. While gravity technically breaks the symmetry in the transverse plane, its effect on this problem is very weak. To see this, we compare the effective potential ($\sim 2.5\, mK$ or $2.6 \cdot 10^{-26}$ J) with the change in gravitational potential energy over the vertical extent of the interaction region. The latter quantity can be estimated as $2w_0 a_g m_{Cs} \approx 6 \cdot 10^{-29}$ J. Thus gravity is negligible relative to the atom-field forces by more than a factor of 100 in our situation.

Light in transverse modes of the physics cavity is an appealing choice for its ability to be rapidly switched and the good prospects for incorporation into an existing experimental setup. Observation of atom transits through higher-order transverse modes has been proposed [107], though this work focused on mode symmetries technically unavailable due to birefringent splittings in actual high-finesse cavities. Here I present a few considerations for symmetry-breaking using light in the TEM_{01} mode of the physics cavity.

In considering the transverse mode as a symmetry breaker for force or for θ sensing, important quantities are the potential and AC Stark shift due to this light. In a 10.9 μm cavity with R=10 cm mirror curvature, the transverse mode spacing is 65 GHz, so light in the transverse mode is quite far detuned from the cavity QED resonance. For one photon in the TEM_{01} mode (with the TEM_{00} tuned to the atomic resonance), the AC Stark shift is 47 kHz and the scattering rate is about four per second. To noticeably affect cavity QED dynamics, Stark shifts of at least several MHz are necessary. Clearly large photon numbers would have to be used, but these would still correspond to modest driving powers in absolute terms. The TEM_{01} transverse field profile is $\frac{2\sqrt{2}y}{w_0}e^{-(y^2+z^2)/w_0^2}$, so the field maximum is at $y = w_0/\sqrt{2}$.

This is definitely close enough to kick typical trapped atoms but clearly restricts how far an atom can be driven towards the axis before this particular side force becomes ineffective.

8.2 Axial Motion: Sensing and Cooling

Cooling of radial motion, even to the cavity axis, does little to directly address axial motion or absolute lifetime for trapped atoms in the cavity. Cooling axial motion, either via active feedback or otherwise, would lead to increased lifetimes for position servo schemes or broader quantum optics protocols. Observation of axial motion is furthermore of interest because the smaller length scale ($\lambda/4$ vs. w_0) and correspondingly higher vibrational frequency make motion in this dimension a good candidate for observing effects associated with the quantized center-of-mass motion of the atom [108, 109, 110, 111, 23, 112].

Cooling radial motion does little to affect axial heating processes, since the only process mixing the dimensions is atomic spontaneous emission, the rate of which is very small compared to axial dynamics. Certainly the depth of the axial potential and the momentum diffusion rates scale with the value of ρ since $g(\vec{r}) = g(\rho, x)$, but the problem is still separable and thus cooling in the radial direction has little opportunity to extract energy from the axial motion.

The present feedback algorithm as presented and simulated in Chapter 5 can certainly be altered in the experiment to prevent unnecessary *heating* of axial motion due to radial feedback. The feedback simulated in Chapter 5 involves instantaneous switching of the drive strength (cavity input intensity), which is timed correctly with respect to radial motion but occurs at generally arbitrary times with respect to axial oscillation. One might expect this arbitrary switching between potentials to in general accelerate an atom's escape from the trap in the axial direction. A simple alternative experimentally (though computationally intensive in simulations) is to ramp the cavity drive level continuously at a speed which is roughly instantaneous for the radial motion but adiabatic with respect to axial motion. The factor of $\sim 10^2$ separation between radial and axial timescales makes this a feasible strategy to pursue.

For observation of axial motion, one avenue for increased signal-to-noise is implementation of full measurement [47] of field amplitude and phase, as mentioned already in Chapter 4. This would provide greater sensitivity for atomic motion near the field antinode where axial motion typically occurs.

Simulations of feedback to axial motion [113] have indicated that cooling nearly to the vibrational ground state is possible in some parameter regimes using the same basic intensity-modulation method we employ in the radial direction. Theoretical treatments of this case have considered diverse aspects of quantized atomic motion and the transition from classical to quantum servo operation [114, 115, 116]. To probe these questions experimentally, one possibility is to deliberately excite axial motion with a rapid momentum kick and then to attempt cooling of this axial excitation. To displace a trapped atom's motion from the field antinode, and to do so quickly relative to the MHz timescale of atomic motion, is not a technically trivial task, but possible avenues might include light forces from other longitudinal modes or (less likely) rapid cavity mirror displacement.

The simulations of [113] tend to operate in a regime where the cavity and probe are far detuned from atomic resonance, being as much as 4GHz to the red of the atomic transition. Moving to these far-detuned regimes involves decreased trap depth for an atom due to the cavity QED probe. Other non-active cooling mechanisms for axial motion have also been proposed [117, 118] but involve weak-driving conditions which also reduce overall trap depth. Pursuit of these conditions is limited by the need to efficiently trap atoms of our typical initial energies (dominated by fall velocity). Alternatively, the limitation arises because we rely on the same optical field – the cavity QED probe – for both sensing and trapping of the atomic motion. Getting away from these limitations is one motivation for adding a FORT to trap an atom independently of the cavity QED field. Long FORT lifetime with simultaneous high signal-to-noise cavity QED position sensing is a goal currently under pursuit in another experiment in our group [52, 76]. Introduction of the FORT also allows novel cooling schemes using the FORT and cavity QED beams simultaneously [96].

8.3 Far-Flung Applications of Very Short Cavities

The strong coupling enabled by very small mode volumes in optical cavity QED has numerous applications to protocols throughout the field of quantum information science; for a far from exhaustive set of examples and perspectives, see [119, 120, 121, 122, 59, 123, 124, 125, 60]. Proposals for observation of quantum-optical effects such as non-classical photon statistics in very short cavities are found in [19]. Here I mention instead some other potential applications of very short cavities.

Very high-finesse cavities provide sensitivity for detecting numerous intracavity processes, with detection enhanced over single-pass spectroscopy by roughly $2F/\pi$. One example is the high sensitivity for detecting birefringent phase shifts, either on the mirror surfaces or due to some more exotic physical effect (see, e.g., [105]). In this particular case the use of a very short cavity further serves to move the "signal" splitting into a frequency regime where laser locks and other resolution-broadening noise sources in the experiment do not obscure the effect. Another accidentally discovered application, as discussed by Joseph Buck in his thesis [76], is the detection (and possible deliberate excitation/cooling) of $k_B T$ thermal vibrations of the glass mirror substrates themselves. These vibrations can be detected on the amplitude of light transmitted through a cavity; the sensitivity improves as a cavity becomes shorter and κ increases, since the vibrational mode frequencies for the small substrates begin around 1GHz.

Another intriguing application of a short cavity is to the study of atom interactions with a nearby solid or surface. We may imagine, for example, a cavity of length $3\lambda/2$ in which the two field antinodes on the sides are differentiated from the central antinode by their proximity to the mirror surfaces. Atomic interactions with the mirror surfaces would produce different signals for atoms occupying the central or side antinodes. This scenario is not immediately realistic for the study of typical van der Waals forces, since an atom would naturally interact with a field antinode ~ 200 nm from the mirror surface while van der Waals distance scales are much smaller, on the order of ~ 1 nm or less. However, one might imagine a similar short cavity of just a few antinodes distinguished from one another by proximity to an auxiliary solid or surface which is being studied.

A final pipe dream involves the realization of a quantum chaos experiment, in the spirit of the delta-kicked rotor, in the standing-wave dimension of a short cavity [126]. Motion in this dimension can, as we have seen, be brought to a significantly quantized regime. With good sensing of axial motion a kicked-rotor type experiment could be envisioned with the "kick" provided by rapid displacement of the mirror surfaces, as mentioned above. Such rapid displacement presents technical challenges, but a more basic limit on the speed of a "kick" is given by κ as it gives the rate for adjustment of the intracavity field. A very short cavity is thus suitable for this scenario as it provides large κ for a given finesse.

8.4 Comment on Quantum State Estimation and Control

The work presented here on detection and control of a single atom's position in real time represents one aspect of an emerging experimental field of quantum state control. Both theoretical and experimental work in several different contexts are beginning to address the issue of practical, continuous control of a simple quantum state. These investigations aim variously towards continuous quantum error correction protocols [127], studies of quantum measurement and information-disturbance tradeoffs [98, 61, 62, 128], and realization of novel system evolutions and designer quantum states through the application of real-time feedback [63, 129].

Motivations for this line of inquiry are diverse, and range from curiosity about the quantum-classical transition to the lure of massively parallel quantum computation ("qubit-inside" technology development). I know that I, like (I believe) most other physicists in this field, am motivated primarily by the desire to get a better idea of the hazy quantum-classical transition region, obscured for much of the last century in both philosophy and computational rules of projective measurement. These questions sit at the foundations of quantum mechanics, whether or not their answers result in eventual quantum PC's (or quantum subroutines). However, I conclude with an extremely technology-oriented motive for the study of state control at the frontier of the quantum regime, and one which I rarely hear mentioned at least in the last few years. This is the ongoing miniaturization of IC components for (classical) computation, with a feature size of $\lesssim 0.1\ \mu\mathrm{m}$ today and a historical trend of an order of magnitude decrease in twenty years [130]. Looking at trends along these lines it is clear that a very finite time span will see us at the threshold of computing with – and therefore controlling – individual quantum systems, and deep in the hazy borderland of quantum measurement whether we will or no. Let us, then, at least begin to map out the territory ahead.