Chapter 10

Discussion and conclusions

"Begin at the beginning and go on till you come to the end; then stop."
Lewis Carroll

This chapter draws together the findings of the preceding chapters and outlines areas for future research.

10.1 Pulsed magnetic focusing

The limiting size of a focused launched cold cloud of atoms for various pulsed magnetic focusing strategies has been investigated using experimentally realistic parameters. The $\mathcal{ABCD}$ matrix formalism is convenient for giving an estimate as to the parameters needed for magnetic focusing, but does not contain the departure of the potential experienced by atoms from a perfect parabolic dependence for fields produced by real coils (and bars). In this thesis it has been shown how important it is to consider these aberrations as they drastically alter the results. The origin of these aberrations have been identified and techniques for minimising them have been described.

Single-coil lenses (Strategy I) have been discussed in Chapter 4, as well as five novel magnetic lenses (Strategies II-VI). Their performance and aberrations have been tested both analytically and numerically. For all of the strategies it was found that analytic results for aberrations (Section 4.5) tied in well with the numerical simulations of Chapter 6. It was demonstrated with Strategy II

(Strategy III) that a radially (axially) focusing lens formed from two coils with relative separation $S = 0.58$ (2.63) provided much tighter focusing than the single-coil lens (Strategy I). Amongst the isotropic 3D lenses it was found that the baseball lens (Strategy VI) was superior to the two coil lens of Strategy IV, which was in turn considerably better than the axially offset single coil lens of Strategy V. Of the single-impulse lenses, the baseball lens offers the best possibilities for isotropically focusing a cloud of weak-field-seeking atoms in 3D. Initial experiments to demonstrate the baseball lens have been conducted at Durham University [159, 158].

The loading and guiding of atoms by a far detuned laser beam has been analysed. A guided fountain is realised when atoms are launched vertically, the optical dipole force providing strong radial confinement. The axial width of the cloud grows by more than a order of magnitude. A hybrid approach using the optical dipole force for radial confinement and the Stern-Gerlach force for pulsed axial focusing was studied, and shows promise as a technique to refocus a cloud remotely into a second chamber with a smaller size than the initial sample.

Given comparable lens dimensions and strengths, double-impulse magnetic focusing is far superior to single-impulse magnetic focusing in terms of the relative density increases that can be achieved by a fraction of the atoms. This result is in stark contrast to the relative rms density increase of the entire cloud, which would lead to the opposite conclusion. If one wishes to minimise the rms image volume of a launched cloud then a single-impulse lens is preferable. If, however, one can selectively capture the central core of the bi-modal image, a double-impulse (alternate-gradient) lens can lead to orders of magnitude relative density increases for both pancake- and sausage-shaped image clouds. This spatial focusing would find applications in lithography or sending the atomic cloud through micro-sized apertures. The main application of interest for the magnetically imaged atoms will be loading a magnetic microtrap or optical dipole trap, for which alternate-gradient imaging is well-suited. Although only cold thermal atomic clouds have been considered in this thesis, the effects of aberrations will also be important for tight focusing of coherent matter waves [40, 41, 42, 189].

When loading a remote conservative trap there are three different approaches, see Figure 10.1. In the first method the atoms are launched vertically with enough kinetic energy (KE) that they overcome the potential energy barrier.

The problem with this is that when they fall down into the trap they are left with the unwanted KE. The second method avoids this by only switching the trap on once the atom cloud has come to rest at the apex of its flight. This loading can be repeated with subsequent clouds, if the trap is switched off briefly before the cloud arrives. A small fraction of the initial cloud is lost however, so a limit on the number of trapped atoms is eventually reached [76]. The third method utilises a magnetic anti-trap. When the atomic cloud reaches the centre of the anti-trap, the atomic state is switched so the atoms become trapped. The switching could be achieved by optically pumping to the opposite stretched state. Again, in this loading scheme, the problem of excess KE is avoided. If the atom's state is irreversibly flipped, the trap can accumulate atoms from subsequent clouds without suffering loss.

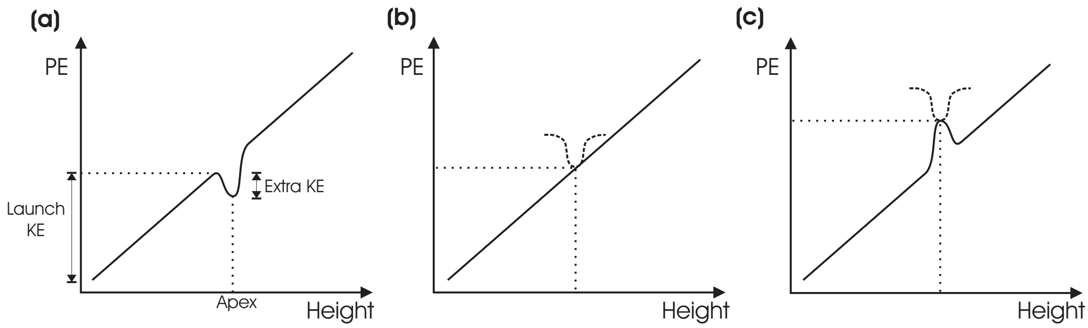

Figure 10.1: The figure depicts three different approaches to loading a trap from a guided fountain. Potential energy is plotted against height. Image (a): The trap is left on during the loading process. The atoms need sufficient energy to overcome the potential barrier, but are then left with excess kinetic energy. Image (b): The trap is switched on when the atoms have reached the flight apex. The atoms avoid having excess kinetic energy. However, the process cannot be repeated indefinitely as a maximum load is reached. Image (c): An anti-trap is created and when the atoms have reached the centre of the trap, their spins are flipped so they become trapped. The different strategies require different launch velocities.

10.1.1 Future work

The next step is to experimentally test the calculations made in this thesis. It would be good to compare the focusing properties of single-coil lenses and the optimised double-coil lenses. The lenses can then be used to construct an alternate-gradient lens system. Theory predicts a dense core at the focus, therefore an experimental cross-section through the focused cloud would reveal the atomic distribution. Finally, proof of the effectiveness of the hybrid approach of laser guiding and magnetic lensing would be good. Magnetic lenses could also be used to help improve the atom loading efficiency of the laser guides.

10.2 3D quasi-electrostatic lattices

A quasi-electrostatic trap (QUEST) is an ideal way to store cold atoms due to the very low heating experienced (Chapter 2). The multiple states and species that can be trapped is a further benefit. A CO_2 laser acts as a QUEST for Rb atoms. The long wavelength allows optically resolvable lattices to be formed when multiple beams are overlapped (Chapter 7). In such 3D lattices there are high trap frequencies which are needed to stop motional decoherence. The above features makes a 3D lattice an ideal system to implement quantum information processing. The design of a face-centred cubic lattice experiment is given in Chapter 7. The progress in constructing and optimising the experiment have been outlined in Chapters 8 and 9. Currently cold atoms are produced in a Pyramid MOT before being moved down and recaptured in the Science MOT.

10.2.1 Future work

The short term work on the experiment involves obtaining measurements for the cold atom cloud size and temperature. This can be achieved when the Andor EMCCD camera has been installed and calibrated. Timing issues with the JAI cameras made it difficult to trigger and capture an image. The other short term aim is to trap atoms in the CO_2 laser dipole trap. A measurement of the trap lifetime can then be made. In the medium term, the priority will be the imaging and manipulation of individual sites within a 1D optical lattice. It is hoped to demonstrate enhanced loading of lattice sites with a near resonant diode laser beam superimposed on the lattice site. Two-photon Raman transitions can also be made to change the hyperfine ground state level of a site. The longer term work will involve extending the lattice to 3D and implementing two-qubit gates. There is also the option to Bose condense the atoms in individual sites. Regardless of which route is taken, there is certainly interesting physics to be discovered. The unique features of the experiment make it an ideal vehicle to travel with.