

TRAPPING ULTRACOLD GASES NEAR
CRYOGENIC MATERIALS WITH RAPID
RECONFIGURABILITY

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We demonstrate an atom chip trapping system that allows the placement and high-resolution imaging of ultracold atoms within microns of any 100 μm -thin, UHV-compatible material, while also allowing sample exchange with minimal experimental downtime. The sample is not connected to the atom chip, allowing rapid exchange without perturbing the atom chip or laser cooling apparatus. Exchange of the sample and retrapping of atoms has been performed within a week turnaround, limited only by chamber baking. Moreover, the decoupling of sample and atom chip provides the ability to independently tune the sample temperature and its position with respect to the trapped ultracold gas, which itself may remain in the focus of a high-resolution imaging system. As a first demonstration of this system, we have confined a 200-nK cloud of 1×10^4 ^{87}Rb atoms within 100 μm of a gold-mirrored 100- μm -thick silicon substrate. The substrate was cooled to 35 K without use of a heat shield, while the atom chip, 100 μm away, remained at room temperature. Atoms may be imaged and retrapped every 16 s, allowing rapid data collection.

To my family

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TABLE OF CONTENTS

Dedication	v
Acknowledgements	vi
Table of Contents	vii
List of Tables	ix
List of Figures	x
1 Introduction	1
1.1 Other Probes	2
1.2 Why Atom Chip Magnetometry	3
1.3 Atom Chip Trapping	6
1.3.1 H-Trap and Z-Trap	8
1.4 Magnetic Field Imaging	9
1.5 Electric Field Imaging	13
1.6 Reconstructing a Current Image	13
2 Laser System	15
2.1 780-nm Lasers	15
2.1.1 First Generation	15
2.1.2 Second Generation	17
2.1.3 Lasers and Optics	18
2.1.4 Saturated Absorption Spectroscopy	22
2.1.5 Beat Note Lock	23
2.2 1064-nm Lasers	26
3 Experimental Control and Data Acquisition	29
3.1 Control Hardware	29
3.2 Control Software	30
3.2.1 Overview	30
3.2.2 SubBlocks	31
3.2.3 Representing Hardware	33
3.2.4 Block Object	34
3.2.5 Experiment Object	35
3.2.6 Defining an Experiment	35
3.3 Imaging	37
3.3.1 Absorption Imaging	37
3.3.2 Cameras	39
3.3.3 PIXISAdaptor	41
3.3.4 Imaging Optics	42
3.4 Translation Stages	44
3.4.1 ODTT Stage	44
3.4.2 Sample Stage	46

4	Production Chamber	47
4.1	Cleaning Procedure	47
4.2	Oven Section	49
4.3	Zeeman Slower	52
4.4	Octagon	55
4.5	Pump Section	59
5	Science Chamber	60
5.1	Cryogenics	64
5.2	Macrowire Assembly	65
5.3	Atom Chip	68
5.4	Sample	72
5.5	Bucket Window and Imaging	77
6	System Characterization	80
6.1	Cold ^{87}Rb Gas Production	80
6.1.1	MOT	80
6.1.2	Sub-Doppler Cooling	81
6.1.3	Optical Pumping	82
6.1.4	Hybrid Optical-Magnetic Trap	82
6.1.5	RF Evaporation and Loading the ODTT	83
6.2	Loading the Atom Chip Trap	84
6.2.1	Transfer to the Science Chamber	84
6.2.2	Loading the Macrowire Trap	87
6.2.3	Loading the Microwire Trap	88
6.2.4	RF Evaporation on Chip	89
7	Conclusion and Outlook	93
A	Control Hardware Outputs	95
	Bibliography	98

LIST OF TABLES

2.1	Table giving the maximum fiber output power at the experiment.	22
3.1	The matrix representing an experiment with four hardware lines and eight times steps. Each column gives the output of a single hardware line for the entire experiment, which each row gives the state of every output at that particular time step.	31
4.1	The c_i design parameters for the positive and negative Zeeman slower coils with $R = 38.3$ mm and $I_{pos} = 72$ A and $I_{neg} = 42$ A. The parameters were found by fitting the field from Eq. 4.2 to the ideal field given by Eq. 4.3	54
6.1	The current in Amps for each of the macrowire, microwires, and external coils involved in trapping atoms in the science chamber. The n/a values indicate that the wires are not used in that configuration for the given trap.	88
A.1	The mapping between digital device 1 (NI PCIe-6536) and the hardware being controlled.	96
A.2	The mapping between analog device 2 (NI PCI-6733) and the hardware being controlled.	96
A.3	The mapping between analog device 3 (NI PCI-6723) and the hardware being controlled.	97

LIST OF FIGURES

1.1	Field sensitivity vs. spatial resolution plot of different magnetometers [1–12]. Blue lines are lines of constant flux quanta. The Rb atom chip point reflects the work in [13, 14]. The dashed line shows the theoretical sensitivity-resolution limit discussed in Section 1.4.	4
1.2	Figure showing (a) anti-Helmholtz coils for generating a quadrupole magnetic trap, and (b) coil geometry for generating an Ioffe-Pritchard trap. Arrows show direction of current flow. .	7
1.3	Diagram of wire geometries in (a) a Z-Trap and (b) a H-trap. Arrows show the direction of current flow.	8
1.4	Figure illustrating how fragmentation atom chip magnetometry works. (a) An atomic cloud in a Z-Trap. The imaging laser and CCD camera show how absorption imaging gives the density distribution of the cloud. As the cloud is brought closer to the trapping wire (b) the cloud begins to fragment due to distortions in the trapping wire current path. The fragmentation appears in the absorption image of the atoms.	10
2.1	Picture of the original master cooler laser. The optical grating is mounted in a high stability optics mount. A piezo allows electronic feedback control of the grating in order to frequency stabilize the laser.	16
2.2	Picture of the original 780-nm laser system under construction at the University of Illinois at Urbana-Champaign. The three aluminum enclosures along the edge of the breadboard house the 780-nm lasers.	17
2.3	Diagram of the laser system on the laser table (a), and the experiment table (b). Master cooling light near the $ F = 2\rangle \rightarrow F' = 3\rangle$ cycling transition is shown in red and repumper light near the $ F = 1\rangle \rightarrow F' = 2\rangle$ transition is in blue. Purple indicates where the master cooling light is overlapped with the repumper light. Fibers 1, 2, and 3 on the laser table (a), connect to fibers 1, 2, and 3 on the experiment table (b).	18
2.4	(a) Picture of the laser table containing the two external cavity diode lasers and two tapered amplifiers. (b) Picture of the laser break out optics on the experiment table. (c) Picture of the 1064-nm laser system on the experiment table.	19

2.5	Diagram of 780-nm beam routing on the laser table. The MC light (A) originates at the Vortex laser. The optical isolator rejects a beam (H), which is used to provide a SAS signal. (A) is split by a PBS, sending (C) to the tapered amplifier and (B) to the beat note lock photodetector. The repumper light (D) is split by a PBS, sending (E) to a tapered amplifier and (F) to the SAS lock setup. The output of the tapered amplifier (G) is coupled into an optical fiber.	20
2.6	Picture of a beam shutter made from a hard drive. A hole is drilled in the casing to allow the beam to pass. A black metal piece is glued to the read/write head and is used to shutter the beam. The black metal was cut out of a Coca-Cola Zero can. . . .	21
2.7	(a) Trace of the SAS photodetector signal of the $F = 1 \rightarrow F'$ transitions. Arrows label the $F' = 0$, $F' = 1$, and the $F' = 2$ peaks as well as the 0,1 crossover, 0,2 crossover, and the 1,2 crossover peaks. (b) Error signal used to lock the repumper laser. The error signal (Eq. 2.5) is zero when the derivative of the SAS signal is zero. We lock the laser to the 1,2 crossover peak.	24
2.8	Diagram of the beat note lock electronics. The beat note signal from the photodiode is compared by the PLL to the reference signal from the DDS to generate an error signal. The lock box servos the master cooler laser frequency against the beat note error signal.	25
2.9	Screen capture of the PLL board settings in the Analog Devices INT-N PLL software.	26
2.10	Picture of dichroic mirror and ODTT axis imaging. Also picture is the linear air-bearing translation stage with the 750-mm focal length lens. As pictured the focus of the ODTT is at the center of the octagon. To transfer the atoms to the science chamber, the stage will move the lens 33.3 cm towards the dichroic mirror. . .	28
3.1	Schematic representation of the control software. The Experiment object contains SubBlock, LineData, and Block objects. Each SubBlock object contains the hardware instructions for a particular segment of the experiment while each LineData object contains the instructions for a single hardware output for the entire experiment. The Block object contains three pDAQDevice objects, one for each of the NI-DAQ boards, each with a $N \times M_i$ matrix representing the output for each hardware line on a specific NI-DAQ board.	32

3.2	Flow charts representing (a) the original compile sequence and (b) the second generation sequence. In (a) the array representing each hardware line is generated every time an experiment is compiled. In (b) the Block object from a previous experiment is loaded and only the hardware lines that differ between the new and the old experiment are generated. This can lead to a factor four decrease in compile time for (b) relative to (a).	37
3.3	Illustration of frame transfer kinetics mode where only the bottom two rows of pixels are used to acquire images. In (a) the first image is acquired. In (b) the second image is acquired while the first image is shifted into the two adjacent rows of pixels. In (c) the third and final image is acquired while the first and second image are shifted again. After the CCD array is full, the image is read out in the normal way.	40
3.4	Picture of the imaging optics for the ODTT-axis imaging (a) and the science chamber imaging (b).	43
4.1	Computer rendering of the vacuum chamber. The production chamber is divided into four sections, the oven section, the Zeeman slower, the octagon, and the pump section. The science chamber contains the atom chip, cryostat, and sample to be measured. The production chamber is separated from the science chamber by a pneumatic gate valve, allowing the sample in the science chamber to be replaced without disturbing the production chamber.	48
4.2	(a) Picture of the TEC covered in ice due to insufficient thermal insulation. (b) Picture of the TEC in foam insulation without ice buildup.	50
4.3	Picture of the oven chamber top flange, with attached cold cup and Uniblitz atomic shutter. The wires connecting the Uniblitz shutter to the chamber feedthru are glued to the cold cup using thermally conductive, vacuum safe epoxy (Torr Seal.)	51
4.4	Diagram of the cross section of the oven section. The window on the Rb oven is used for coarse alignment of the Zeeman slower beam. A glass thermal break isolates the temperature of the oven-tube from the rest of the oven section. A differential pumping tube (DPT) protects the octagon from background gas.	52
4.5	Shows the ideal Zeeman slower field (dashed black line) from Eq. 4.3, the designed field (solid red line) from Eq. 4.2, and the measured field (blue x).	55
4.6	Pictures of the aluminum MOT coil holder before winding the coil (a) and after the winding the coil (b).	56

4.7	(a) Diagram showing top down view of the octagon. Z-axis MOT beams, imaging beams, and optical pumping beams not shown. (b) Picture of the octagon section of the production chamber. Arrows show the direction of the MOT light, the imaging light, and the ODTT. (c) Diagram showing side view of the octagon. Connections to the rest of the chamber and the z-axis beams not shown.	58
5.1	Pictures of the science chamber. The vacuum pumps as well as imaging optics are labeled. The imaging optics are on breadboards, which can easily be removed during sample exchanges.	61
5.2	Schematic of the relative positions of the atoms, sample, sample substrate, holder, and atom chip wires from the viewpoint along the imaging axis (a) and along the ODTT axis (b). (c) Sketch in perspective of the atom chip with sample substrate underneath.	63
5.3	(a) Diagram of the cryogenic temperature test sample showing the location of the gold leads, where the blue rectangles are diode thermometers. (b) Image of the cryogenic temperature test sample attached to the sample mount.	64
5.4	(a) Shows the response of the sample temperature (red) to changes in the cold finger temperature (black.) (b) Shows the time needed for the sample temperature to reach steady state after a change in the cold finger temperature.	66
5.5	(a) Picture of the macor piece that holds the macrowires in position. This is also where the atom chip is glued. Note the metallic piece glued to the macor is a fragment from an atom chip used to test gluing the chip to the macor. (b) A copper bias macrowire. (c) The macrowire assembly mounted in the macor piece. The macor piece is connected to a water-cooled stainless steel heat exchanger, which is mounted to the top flange of the science chamber.	67
5.6	(a) Image of the first generation atom chip after wire bond failure. Bubbles can be seen in the silver near the wire edges. (b) Diagram of wire layout and current flow in the first generation atom chip shown in (a).	69
5.7	(a) Image of the second generation atom chip glued to the macrowire macor piece. (b) Drawing of the microwire layout on the second generation atom chip. There are five arm wires intersecting the central wire. We refer to the middle wire as the dimple microwire. The two arm wires closest to the dimple wire are each 1 mm from the dimple wire, and the two furthest wires are each 3 mm from the dimple wire.	71
5.8	Diagram of the currents in the second generation atom chip. The black line indicates the current direction in the Z-trap. The blue and purple lines show the currents in the H-trap	72

5.9	(a) Image of atom chip attached to macrowire-macor base and chilled-water block. View of science substrate mount from (b) ODTT viewpoint and (c) imaging beam viewpoint. (d) Science substrate 120 μm below atom chip.	74
5.10	(a) Diagram of the interferometer used to measure vibrations of the mirrored sample.	75
5.11	Vibration amplitude of the 100- μm thick, cantilevered substrate as measured using a Mach-Zehnder interferometer.	76
5.12	(a) Computer drawing of the macrowire assembly 1 mm away from the bucket window. The atom chip is attached to the bottom of the macrowire assembly. The sample mount is shown 100 μm from the atom chip. (b) A picture of the actual assembly. . . .	78
5.13	(a) Absorption image and mirror image of atoms 100 μm away from a mirror substrate. (b) Illustration of reflected imaging showing the creation of the mirror image.	79
6.1	Absorption images of the atomic cloud at various stages in the production chamber. (a) Over 1×10^9 atoms in the MOT with a 5-ms TOF. (b) 1×10^9 atoms at 20 μK after sub-Doppler cooling and a 5-ms TOF. (c) Atoms after being optically pumped to the $ F = 2, m_F - 2\rangle$ state. (d) Atoms in the hybrid magneto-optical trap after 10-ms TOF. (e) 1×10^8 atoms at 80 μK after forced RF evaporation and a 10-ms TOF. (f) 2×10^7 atoms in the ODTT after a 5-ms TOF.	81
6.2	The ODTT stage motion profile. This shows an SCURVE value of 100, giving linear changes in acceleration (c), and a corresponding velocity (b) and position (a) profile.	85
6.3	The ODTT stage motion profile. This shows an SCURVE value of 50, giving acceleration profiles that are half linear ramps, and half constant acceleration (c), and a corresponding velocity (b) and position (a) profile.	86
6.4	Plot of trap oscillation as a function of hold time after moving the center of the trap. (a) Solid line is sine fit to the transverse oscillations showing a trap frequency of $2\pi \times 830$ Hz. (b) Solid line is sine fit to longitudinal oscillations showing a trap frequency of $2\pi \times 34$ Hz.	90
6.5	Time-of-flight absorption images of: (a) 1.1×10^7 atoms 2 ms after release from the ODTT in the science chamber; (b) atoms 5 ms after release from the macrowire capture trap; (c) 8×10^6 atoms at 16 μK in the macrowire compress trap at $h = 350$ μm from the mirror sample, 1 ms after release; (d) 8×10^4 atoms evaporatively cooled to $[T_x, T_z] = [470, 810]$ nK, 1 ms after release from the H-Trap [15].	91

6.6	Figure showing the RF frequency sweep during evaporation in (a) the Z-trap, and (b) the H-trap.	92
6.7	Absorption image of 10^4 atoms at 200 nK, 9 ms after release from the Z-trap.	92
7.1	Pictures of a photomask of the calibration sample. (a) Shows grids of wires of different widths and (b) shows grids of different wire widths and spacing.	93

CHAPTER 1

INTRODUCTION

Strongly correlated and topologically nontrivial materials pose interesting unanswered questions as well as offer tremendous potential for device and material applications [16–18]. Much progress has been made in understanding these materials using techniques such as angle-resolved photoemission spectroscopy (ARPES) [19, 20], scanning tunneling microscopy (STM) [21–23], and superconducting quantum interference devices (SQUID) [24–26].

Despite this progress, outstanding questions remain, such as the origin of anomalous noise in the pseudogap of cuprate superconductors [27], the coexistence of magnetism and superconductivity in iron-based superconductors [28] and at the LAO/STO interface [29, 30], as well as the role of electronic ordering in high temperature superconductors [31, 32], and how to differentiate bulk from surface state conduction in topological insulators [24, 33]. All of these questions would benefit from further study in a sensitivity-resolution and temperature regime that is inaccessible to current probes.

In this thesis we describe the atom chip microscope (ACM)—a magnetic and electric field microscope capable of working at the 10^{-7} flux quanta level and below. The ACM uses either Bose-Einstein condensates (BECs) or thermal clouds of ^{87}Rb as a probe to measure fields as near as $1\text{ }\mu\text{m}$ away from a sample of interest. With $1\text{ }\mu\text{m}$ spatial resolution and magnetic field sensitivities as low as 1 nT, atom chip microscopy provides a unique window into mesoscopic physics in novel materials.

In addition to operating in a regime of spatial resolution and field sensitivity that few other probes can match, atom chip microscopy can image samples at temperatures ranging from cryogenic temperatures to well above room tem-

perature. The sample temperature is fundamentally limited only by the microscope's vacuum pressure at high temperatures, and the cryostat at low temperatures.

The ACM is more than an electric and magnetic field microscope, it is a powerful tool for studying hybrid quantum systems. The ACM will provide the ability to couple atoms to solid-state qubits [34], nanowires [35], and the Casimir-Polder potential [36].

1.1 Other Probes

There exists many different kinds of magnetometers with long histories of success. Figure 1.1 compares different magnetometers according to their field sensitivity and spatial resolution. Comparing magnetometers only by field sensitivity and spatial resolution ignores many of the important differences between probes that can be crucial to determining the applicability of a probe to a given measurement. In order to understand where atom chip magnetometry fits among these probes we must examine the strengths and weaknesses of other probes.

One probe that has been incredibly successful studying a range of materials has been the SQUID [6–10]. SQUIDs consist of a loop of superconductor with one or more Josephson junctions, and rely on the quantization of magnetic flux through the superconducting loop to provide very sensitive magnetic flux measurements [37]. These probes have demonstrated field sensitivities as low as $40 \text{ fT cm}^{-1/2} \text{ Hz}^{-1/2}$, for measurements at 100 Hz, but $1/f$ noise prevents them from achieving that sensitivity at DC [8].

Magnetic Resonance Force Microscopy (MRFM) has demonstrated incredi-

ble spatial resolution, measuring a single electron spin with a spatial resolution of 25 nm in a silicon dioxide sample [5]. MRFM relies on cantilevers with a ferromagnet on the tip. External fields are used to drive spin flips in the sample, which show up as forces on the cantilever tip [38,39].

Atomic vapor cell magnetometers have realized field sensitivities as low as $0.54 \text{ fT Hz}^{-1/2}$ [40]. These magnetometers consist of a cell containing a gas of alkali atoms that are spin polarized by a pump laser. A probe laser is sent through the gas perpendicular to the pump laser to measure the precession of the electron spin due to the magnetic field [41]. While these probes are very sensitive to magnetic fields, their spatial resolution is limited by the need to have a macroscopic vapor cell to probe.

Diamond Nitrogen Vacancy (NV) centers can be treated as artificial atoms embedded in either bulk diamond or diamond nanocrystals [2, 3]. Nanocrystal diamond NV centers have shown a magnetic field sensitivity of $56 \text{ nT Hz}^{-1/2}$ [42], but are only able to achieve this sensitivity for AC measurements ($\sim 33 \text{ kHz}$). At DC the same NV magnetometer has a sensitivity of $6 \text{ } \mu\text{T Hz}^{-1/2}$. Diamond NV centers also have applications beyond magnetometry, acting as nanoscale thermometers inside living cells [43].

1.2 Why Atom Chip Magnetometry

One can divide the magnetometers shown in Figure 1.1 into two groups. One group, consisting of SQUIDs, atomic vapor cells, and bulk diamond NV centers, has very high field sensitivity, but poorer spatial resolution. The other group, consisting of MRFM, scanning diamond NV nanocrystals, and scanning hall probes, has very good spatial resolution, but poorer field sensitivity.

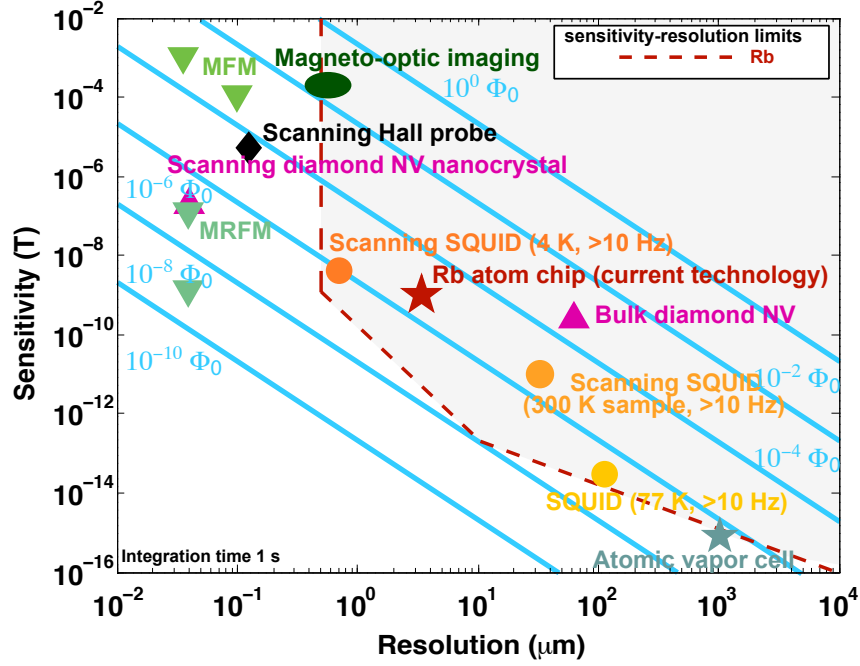


Figure 1.1: Field sensitivity vs. spatial resolution plot of different magnetometers [1–12]. Blue lines are lines of constant flux quanta. The Rb atom chip point reflects the work in [13,14]. The dashed line shows the theoretical sensitivity-resolution limit discussed in Section 1.4.

Rubidium atom chip microscopy sits in the sparsely populated space between these two groups. The proof of principle work [13], shown as the red star in Figure 1.1, demonstrates 3- μm spatial resolution and 4-nT magnetic field sensitivity [44]. As the theoretical sensitivity-resolution limit (dashed line in Figure 1.1) indicates, there is room for improvement. Single micron spatial resolution and nT field sensitivity should be possible with a 0.4 numeric aperture imaging system.

While SQUIDS have had incredible success as magnetometers, they suffer from the need to keep the superconducting probe below its critical temperature (T_c). This presents a challenge when trying to measure samples above the T_c of the SQUID, since the temperature of the SQUID and the sample are coupled by

black-body radiation. It is possible to do a room temperature SQUID measurement [9], but the requirements of shielding the probe from the sample further limits the field sensitivity and spatial resolution of the measurement.

Atom chip magnetometry avoids this problem because the temperature of the ultracold ^{87}Rb gas probe is decoupled from the temperature of the sample, allowing a 100-nK BEC to be brought a distance of $1\text{ }\mu\text{m}$ away from a room temperature sample. In order for light to interact with an atom, the frequency of the light must be near an allowed atomic transition. Black-body radiation at 300 K has a wavelength of approximately $10\text{ }\mu\text{m}$ [45], far from any atomic transitions in ^{87}Rb .

The high end of the temperature range of the probe is limited by the power of the heating element on the sample, and by the increased vacuum pressure lowering the lifetime of the atomic cloud. At the low end, the sample temperature is currently limited to 35 K by the cooling power of the cryostat and the large solid angle exposure to room temperature black-body radiation. Installation of a liquid nitrogen cooled heat shield should allow the sample to reach a temperatures below 10 K.

Another advantage of atom chip magnetometry is that it does not suffer from $1/f$ noise [37]. Instead it is shot-noise limited in the ability to image Rb atoms [13]. This allows atom chip magnetometry to make DC measurements.

The atomic cloud to be used for field measurements will have dimensions of approximately one micron in the transverse direction and one millimeter in the longitudinal direction. This will allow a single image of the cloud to provide one dimensional information about the field. By scanning the one dimensional cloud over a sample, a wide area field map can be quickly created.

Atom chip magnetometry allows simultaneous electric and magnetic field

sensing. ^{87}Rb has a scalar polarizability $\alpha = h \times 0.0794(16) \text{ Hz}/(\text{V}/\text{cm})^2$ [46], allowing an electric dipole moment to be induced via an applied electric field. When a bias electric field is applied, the atoms become sensitive to spatially varying electric fields. Electric field sensitivities as low as .4 V/cm having been demonstrated [13].

1.3 Atom Chip Trapping

Atoms in a magnetic field experience a potential $V = \mu|B|$. For ^{87}Rb , $\mu = g_F m_F \mu_B$ where g_F is the Landé g-factor. A magnetic field will split the degeneracy between different m_F sublevels. This Zeeman splitting allows certain states to be trapped at the minimum of a magnetic field. We call these weak field seeking states, and they include the $|5^2S_{1/2}, F = 1, m_F = -1\rangle$ ground state, as well as the $|5^2S_{1/2}, F = 2, m_F = 1\rangle$, and $|5^2S_{1/2}, F = 2, m_F = 2\rangle$ metastable states.

Magnetic traps for cold atoms have traditionally been created by macroscopic wire coils. One of the simplest coil geometries consists of two anti-Helmholtz coils creating a quadrupole magnetic potential (Figure 1.2.) Quadrupole traps produce large field gradients that lead to atomic clouds with large real space densities. Unfortunately, they are unsuitable for producing Bose-Einstein Condensates (BEC) because of the absolute magnetic field zero at the center of the trap [47].

In order for trapped atoms to stay in a weak field seeking state, the spin must be able to adiabatically follow changes in the magnetic field. This gives the requirement that field direction θ must change at a rate slower than the Larmor frequency [48]. This requirement cannot be met at the center of a quadrupole trap where the magnitude of the field is zero.

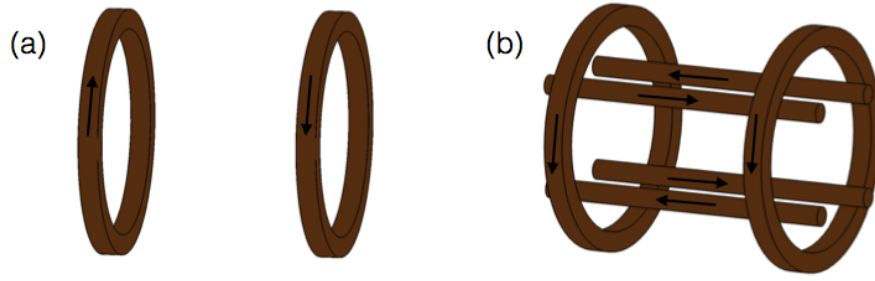


Figure 1.2: Figure showing (a) anti-Helmholtz coils for generating a quadrupole magnetic trap, and (b) coil geometry for generating an Ioffe-Pritchard trap. Arrows show direction of current flow.

An Ioffe-Pritchard trap (Figure 1.2) provides a harmonic potential with a finite magnetic field at the trap bottom. The field of an Ioffe-Pritchard trap is given by [47]

$$B = B_0 \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} + B' \begin{pmatrix} 0 \\ -y \\ z \end{pmatrix} + \frac{B''}{2} \begin{pmatrix} x^2 - \frac{1}{2}(y^2 + z^2) \\ -xy \\ -xz \end{pmatrix} \quad (1.1)$$

These coils can provide large trap geometries with ample optical access. However, in order to obtain a trap located near a surface with high trapping frequencies, a topological transformation must be made from macroscopic coils, to microfabricated wires. These microfabricated wires form an atom chip [49], and are a versatile tool for atomic physics.

Ultracold gases trapped near cryogenic surfaces using atom chips [50–52] can serve as elements of hybrid quantum systems for quantum information processing, e.g., by coupling quantum gases to superconducting qubits [53], or as sensitive, high-resolution, and wide-area probes of electronic current flow

[13, 44, 54], electric AC and patch fields [55, 56], and magnetic domain structure [57] and dynamics. Previous experiments have succeeded in trapping and imaging ultracold thermal and quantum gases of alkali atoms around carbon nanotubes [35], near superconductors [58–62] at 4 K, microns from room-temperature gold wires [14], and within a helium dilution refrigerator [63].

1.3.1 H-Trap and Z-Trap

The simplest atom chip trapping geometry consists of a microfabricated wire and a homogenous bias field provided by macroscopic coils. The field from the wire will subtract from the bias field, forming a field zero above the trapping wire

$$B(z) = B_{bias} - \frac{\mu_0 I_{wire}}{2\pi z} \quad (1.2)$$

where z is the height above the wire. This has the effect of creating a quadrupole trap in the transverse direction, with no longitudinal confinement.

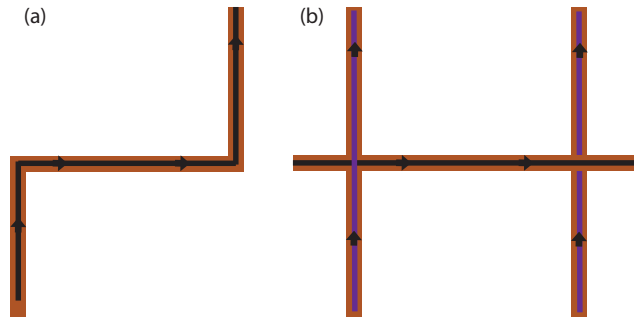


Figure 1.3: Diagram of wire geometries in (a) a Z-Trap and (b) a H-trap. Arrows show the direction of current flow.

Adding two trapping wires perpendicular to the original trapping wire creates what is called an H-trap (Figure 1.3.) The two perpendicular wires provide

longitudinal confinement of the cloud, and if the currents in these wires are anti-aligned, the trap is still a quadrupole trap. If the perpendicular arm wires are aligned, an Ioffe-Pritchard trap is realized [47, 64, 65].

A Z-trap consists of one or more wires forming a Z shape (Figure 1.3) and a homogenous bias field. The long middle section of the Z-trapping wire provides tight transverse confinement, while the ends of the Z-wire provide longitudinal confinement. Like a H-trap, a Z-trap produces an Ioffe-Pritchard trapping potential [48]. For both the H-trap and the Z-trap, a bias field pointing along the longitudinal trap axis can be applied to adjust the magnetic field at the bottom of the trap and to tune B_0 and thus the trap frequency according to [48]

$$\omega_{perp} = \sqrt{\frac{\mu_m}{m} \left(\frac{B'^2}{B_0} - \frac{B''}{2} \right)} \quad (1.3)$$

1.4 Magnetic Field Imaging

Atoms trapped in a one dimensional harmonic magnetic trap, e.g. a Z-trap, should take on a smooth, cylindrical shape tapering at the edges. Early experiments found that as the atomic cloud was brought closer to the chip ($< 100 \mu\text{m}$) [66], the cloud would begin to fragment. The fragmentation was found to be the result of angular deviations in the current path through the trapping wire [54].

More precisely, distortions of the current path lead to nonzero components of the current perpendicular to the wire. These perpendicular currents cause a magnetic field in the longitudinal trap direction, leading to a spatially varying perturbation of the magnitude of the magnetic field. The real space density of a

BEC will reflect these perturbations according to [14]

$$V_0 + V(x) = -\hbar\omega_{tr} \sqrt{1 + 4a_s n_{1D}(x)} \quad (1.4)$$

So by imaging the atomic density, n_{1D} , one can determine the spatially varying potential at the atoms, which in turn will give the magnetic field at the atoms.

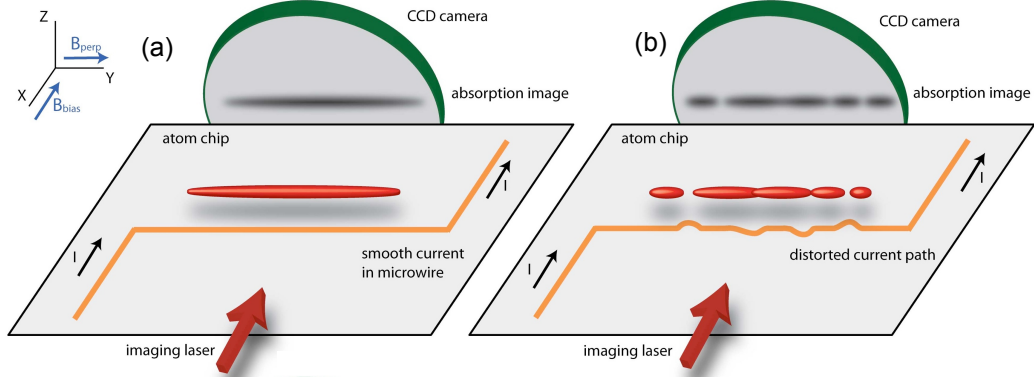


Figure 1.4: Figure illustrating how fragmentation atom chip magnetometry works. (a) An atomic cloud in a Z-Trap. The imaging laser and CCD camera show how absorption imaging gives the density distribution of the cloud. As the cloud is brought closer to the trapping wire (b) the cloud begins to fragment due to distortions in the trapping wire current path. The fragmentation appears in the absorption image of the atoms.

Since $a_s n_{1D} \ll 1$ we can rewrite equation 1.4 as

$$V_0 + V(x) = -\hbar\omega_{tr} (1 + 2a_s n_{1D}(x)) \quad (1.5)$$

Focusing on the spatial dependence, we can write

$$V(x) = -2\hbar\omega_{tr} a_s n_{1D}(x) \quad (1.6)$$

Writing equation 1.6 in terms of the magnetic field and the spatial extent of the cloud in the tight direction, $\rho_0 = \sqrt{\hbar/(\omega_{tr}m)}$, we find the relationship between the atomic density and the local magnetic field to be

$$B(x) = \frac{-2\hbar^2 a_s}{g_F m_F \mu_B m \rho_0^2} n_{1D}(x) \quad (1.7)$$

and the magnetic field sensitivity is given by

$$\Delta B = \gamma \frac{\Delta N}{\rho_0^2 \Delta x_0} \quad (1.8)$$

Where ΔN is the smallest atom number that can be resolved by the imaging system, ρ_0 is the transverse size of the cloud, Δx is the spatial resolution of the imaging system, and γ is given by

$$\gamma = \frac{2\hbar^2 a_s}{g_F m_F \mu_B m} \quad (1.9)$$

Where $a_s = 5.2$ nm is the scattering length of ^{87}Rb , g_F is the Landé-g factor, and m is the mass of ^{87}Rb . Since the field sensitivity (Eq. 1.9) scales as $1/m_F$, we choose to use the metastable state $|5^2S_{1/2}, F = 2, m_F = 2\rangle$ for magnetometry instead of the absolute ground state $|5^2S_{1/2}, F = 1, m_F = -1\rangle$.

The field sensitivity vs. spatial resolution limit can be divided into two regimes (Figure 1.1.) In the first regime, we set the transverse size of the cloud ρ_0 equal to the longitudinal imaging resolution Δx . Here the field sensitivity scales as $1/\Delta x^3$. This scaling holds for $\Delta x = 0.5 - 10 \mu\text{m}$. The regime is bounded at $\Delta x = 0.5 \mu\text{m}$ by the diffraction limit of the spatial imaging resolution. For $\lambda = 780$ nm the imaging resolution limit is about 500 nm. The right hand bound is set by $\rho_0 = 10 \mu\text{m}$. The ground state size of a BEC in a harmonic trap is given by $x_{\text{tr}} = \sqrt{\frac{\hbar}{m\omega_{\text{tr}}}}$, and a BEC with a transverse ground state size of $10 \mu\text{m}$ corresponds to a trapping potential of $\omega_{\text{tr}} = 2\pi \times 1$ Hz. It is very difficult to create and hold a BEC against gravity in a trap with a transverse frequency of less than $2\pi \times 1$ Hz [67].

The second regime is one of anisotropic spatial resolution. In this regime we set $\rho_0 = 10 \mu\text{m}$ and are free to set the imaging resolution Δx to values greater than $10 \mu\text{m}$. Now ΔB scales as $1/\Delta x$.

Looking at Eq. 1.9 one sees that the only way to improve the sensitivity-resolution limit is to replace ^{87}Rb with an atom with greater mass and larger

magnetic moment. Dysprosium is an excellent candidate because it is twice as massive as Rb, and has a magnetic moment of ten Bohr magnetons compared to rubidium's one Bohr magneton [68]. Dysprosium also has many Feshbach resonances [69] which could allow the measurer to tune the scattering length a_s and further improve the field sensitivity.

It is also possible to do magnetometry with a thermal cloud. For a thermal cloud, the density along the longitudinal direction is [70]

$$n_0(z) = Ae^{\frac{-V(z)}{k_B T}} \quad (1.10)$$

where A is a constant. Consider a cloud in a one-dimensional perturbed harmonic trap given by $V(z) = V_h(z) + \Delta V(z)$, where $V_h(z)$ is the harmonic potential and $\Delta V(z)$ is the perturbation. We can then write Eq. 1.10 as

$$n(z) = Ae^{\frac{-V_h(z) - \Delta V(z)}{k_B T}} \quad (1.11)$$

$$n(z) = Ae^{\frac{-V_h(z)}{k_B T}} \left(1 - \frac{\Delta V(z)}{k_B T} \right) \quad (1.12)$$

We can now write $\Delta n(z) = n(z) - n_0(z)$ as

$$\frac{\Delta n(z)}{n(z)} = \frac{g_F m_F \mu_B}{k_B T} \Delta B(z) \quad (1.13)$$

A thermal cloud will achieve a worse field sensitivity than a BEC, but it does offer an increased dynamic range. A thermal cloud will occupy the entire potential with a Maxwell-Boltzmann distribution, while a BEC will only occupy the potential up to the chemical potential μ .

1.5 Electric Field Imaging

Even though neutral ^{87}Rb atoms are used as the field probe, one can still measure electric fields [13]. An applied electric field will induce a potential,

$$U_e = -\alpha E^2 \quad (1.14)$$

where α is the scalar polarizability of ^{87}Rb . To measure a weak, spatially varying electric field $E(x)$ we can apply a large bias electric field E_0

$$U_e = -\alpha(E(x) + E_0)^2 \approx -\alpha E(x) \cdot E_0 \quad (1.15)$$

The bias electric field acts to amplify the signal from $E(x)$, allowing electric fields as small as 0.4 V/cm to be measured [13].

1.6 Reconstructing a Current Image

One of the strengths of atom chip microscopy is its ability to image transport in a material [54,71]. Imaging density perturbations in the atomic cloud reveals the magnetic field at a point in space above the sample. From that magnetic field map, an image of the current path through the sample can be recreated by inverting the Biot-Savart law

$$B(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{j}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r}' - \mathbf{r}|^3} d^3\mathbf{r}' \quad (1.16)$$

Where μ_0 is the permeability of free space, $\mathbf{j}$ is the current density. For the case of magnetic field sensing using a 1D BEC, the atomic cloud is sensitive to magnetic field perturbations in the longitudinal direction.

$$B_z = \frac{\mu_0}{4\pi} \int \frac{j_x(\mathbf{r}') (r_y - r'_y) - j_y(\mathbf{r}') (r_x - r'_x)}{|\mathbf{r}' - \mathbf{r}|^3} d^3\mathbf{r}' \quad (1.17)$$

If we assume a 2D current source at $y = 0$ with $j_y = 0$ then we can write Eq. 1.17 as

$$B_z = \frac{\mu_0}{4\pi} \int \frac{j_x(r'_x, 0, r'_y) r_y}{[(r_x - r'_x)^2 + r_y^2 + (r_z - r'_z)^2]^{3/2}} dr'_x dr'_z \quad (1.18)$$

Now Eq. 1.18 can be written as the convolution of two functions

$$B_z = \int f(\mathbf{r}') g(\mathbf{r} - \mathbf{r}') d^3\mathbf{r}' \quad (1.19)$$

Where

$$f(\mathbf{r}') = \frac{\mu_0}{4\pi} j_x(r'_x, 0, r'_z) \quad (1.20)$$

$$g(\mathbf{r} - \mathbf{r}') = \frac{r_y - r_x + r'_x}{[(r_x - r'_x)^2 + r_y^2 + (r_z - r'_z)^2]^{3/2}} \quad (1.21)$$

Taking the Fourier transform of both sides of Eq. 1.19 and using the convolution theorem we obtain

$$\mathcal{F}(B_z) = \mathcal{F}(f(\mathbf{r})) \mathcal{F}(g(\mathbf{r})) \quad (1.22)$$

Rearranging the equation and taking the inverse Fourier transform we find,

$$f(\mathbf{r}) = \frac{\mu_0}{4\pi} j_x(\mathbf{r}) = \mathcal{F}^{-1} \left(\frac{\mathcal{F}(B_z)}{\mathcal{F}(g(\mathbf{r}))} \right) \quad (1.23)$$

CHAPTER 2

LASER SYSTEM

Work on this project began in 2009 at the University of Illinois at Urbana-Champaign. In January of 2012 the experiment, along with the rest of the lab, moved from the University of Illinois to Stanford University. While the need to disassemble, move, and reassemble our vacuum chamber and laser system caused a severe setback in the short term, it did allow improvements to be made to the experiment. The most significant changes were made to the laser system. In this chapter we will briefly describe the original laser system as it was built at the University of Illinois at Urbana-Champaign, but will focus our discussion on the system as it currently exists at Stanford.

The laser system is divided into two separate systems, one at 780 nm and one at 1064 nm. The 780-nm laser system provides light for trapping, cooling and imaging the ^{87}Rb atoms. The 1064-nm light creates the optical dipole trap tweezers (ODTT) that is used to transport the atoms from the production chamber to the science chamber.

2.1 780-nm Lasers

2.1.1 First Generation

The original 780-nm laser system consisted entirely of homebuilt laser and tapered amplifier systems. The light was provided by two external cavity diode lasers (ECDL) (Figure 2.1) and a slave diode laser. One of the ECDLs was locked to the ^{87}Rb repumper transition. This repumper laser was used to beat note lock

(Section 2.1.5) the master cooler ECDL and to injection lock the slave laser. The repumper slave and ECDL provided all of the repumping light, while the master cooler ECDL was amplified using a homebuilt tapered amplifier.

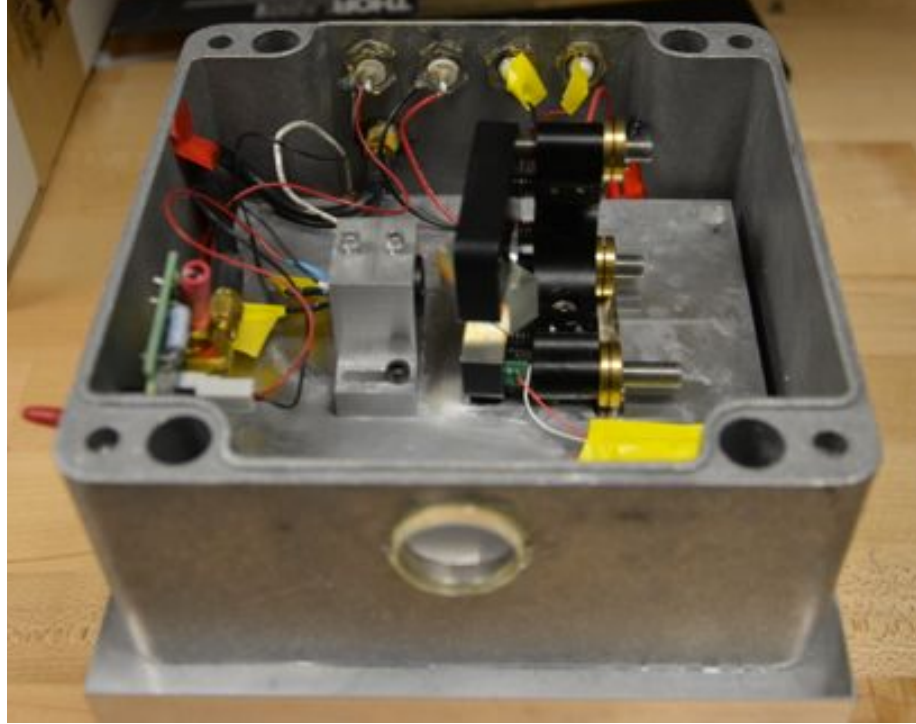


Figure 2.1: Picture of the original master cooler laser. The optical grating is mounted in a high stability optics mount. A piezo allows electronic feedback control of the grating in order to frequency stabilize the laser.

When rebuilding the laser system at Stanford, we took the opportunity to replace the homebuilt lasers with commercial lasers. This was done to increase laser power, increase stability, and to increase the mode-hop free range of the lasers. We also replaced the homebuilt tapered amplifier with a commercial amplifier, in order to achieve greater amplification and easier fiber coupling. The rest of this chapter will describe the second generation laser system currently in use.

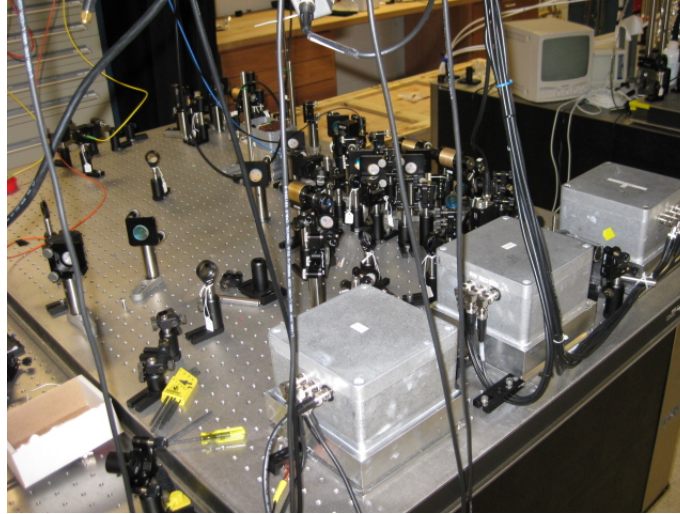


Figure 2.2: Picture of the original 780-nm laser system under construction at the University of Illinois at Urbana-Champaign. The three aluminum enclosures along the edge of the breadboard house the 780-nm lasers.

2.1.2 Second Generation

The 780-nm optics are spread across two large optical tables. The smaller table is called the laser table and only holds lasers and the most sensitive components of the optical systems. The light is generated on the laser table and transferred via optical fiber to the larger table, called the experiment table. The experiment table contains all of the physical beam shutters in order to isolate the lasers and sensitive optics from shutter vibrations. Enclosures are built around the 780-nm optics on both the laser and the experiment table to prevent stray resonant light from reaching the atoms.

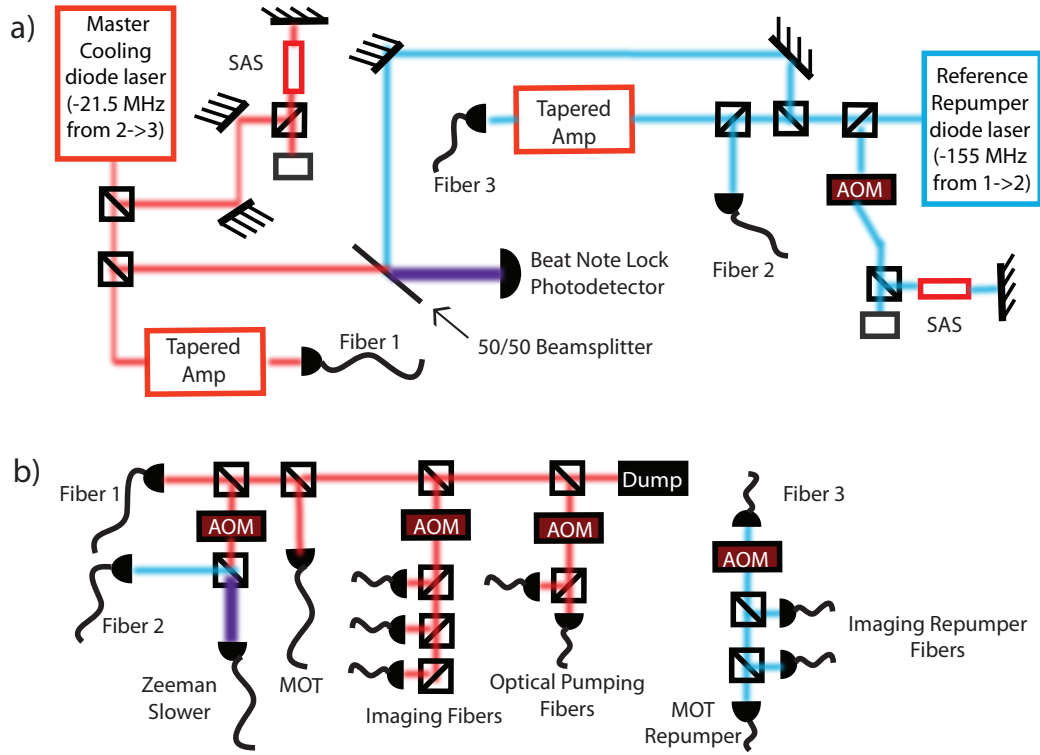


Figure 2.3: Diagram of the laser system on the laser table (a), and the experiment table (b). Master cooling light near the $|F = 2\rangle \rightarrow |F' = 3\rangle$ cycling transition is shown in red and repumper light near the $|F = 1\rangle \rightarrow |F' = 2\rangle$ transition is in blue. Purple indicates where the master cooling light is overlapped with the repumper light. Fibers 1, 2, and 3 on the laser table (a), connect to fibers 1, 2, and 3 on the experiment table (b).

2.1.3 Lasers and Optics

The 780-nm light comes from external cavity stabilized diode lasers. The master cooler (MC) light is provided by a commercial Vortex (TLB-6900 Vortex II) laser from Newport, which supplies approximately 35 mW of 780-nm light. The beam passes through two optical isolators providing roughly 70 dB of isolation. A tapered amplifier amplifies 1 mW of MC light to 1.06 W, of which 600 mW is directly coupled into a single-mode polarization maintaining fiber. The fiber

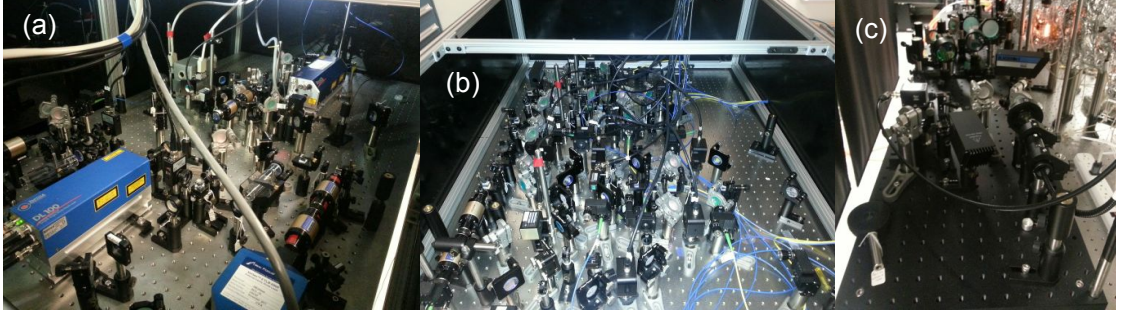


Figure 2.4: (a) Picture of the laser table containing the two external cavity diode lasers and two tapered amplifiers. (b) Picture of the laser break out optics on the experiment table. (c) Picture of the 1064-nm laser system on the experiment table.

routes the light from the laser table to the experiment table where it is broken out to provide light to the MOT, Zeeman slower, optical pumping, and imaging.

The MOT light is directly coupled into one of the fiber inputs of a $2 \rightarrow 6$ fiber splitter resulting in about 20mW power per output fiber (Table 2.1.) The Zeeman slower light is coupled into the -1 mode of an acousto-optic modulator (AOM) driven at 140.5 MHz. The AOM output passes through a polarizing beam splitter (PBS) cube and is coupled into an optical fiber that routes 45 mW of power to the production chamber. The imaging light is coupled into the $+1$ mode of an AOM driven at 80 MHz. The main purpose of the imaging AOM is to provide fast ($< 1 \mu s$) switching to the imaging light. The imaging light is then coupled into several different fibers, bringing roughly 1mW of light per fiber to the chamber. The light for optical pumping is coupled into the -1 mode of an AOM being driven at 80 MHz. The light is then coupled into optical fibers and brought to the chamber.

The repumper light is provided by a Toptica DL100 diode laser. The repump laser produces 100 mW of power that is sent through two optical isolators, pro-

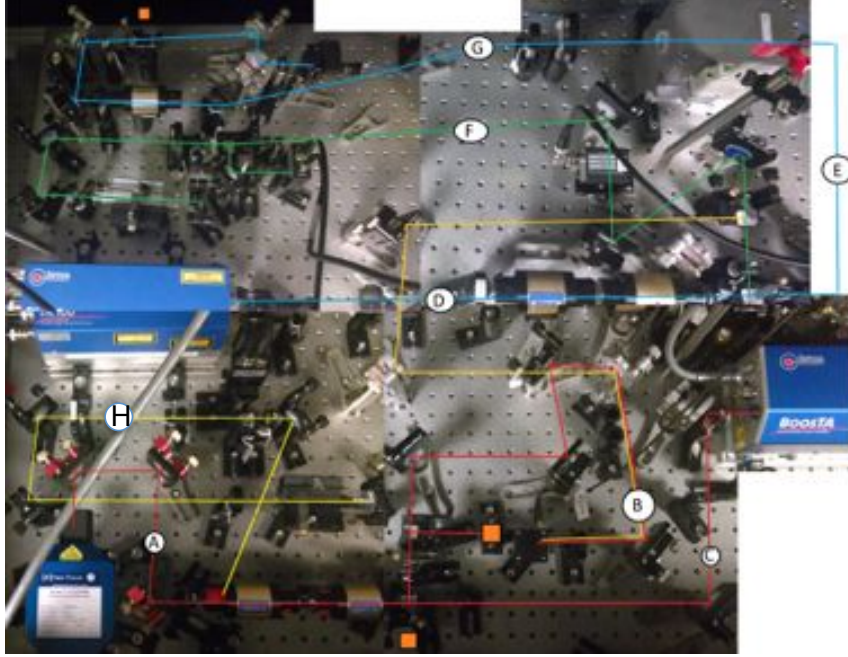


Figure 2.5: Diagram of 780-nm beam routing on the laser table. The MC light (A) originates at the Vortex laser. The optical isolator rejects a beam (H), which is used to provide a SAS signal. (A) is split by a PBS, sending (C) to the tapered amplifier and (B) to the beat note lock photodetector. The repumper light (D) is split by a PBS, sending (E) to a tapered amplifier and (F) to the SAS lock setup. The output of the tapered amplifier (G) is coupled into an optical fiber.

viding approximately 70 dB of isolation. The light is then divided into three paths. The first path sends several mW of light to the saturated absorption spectroscopy (SAS) setup. The second path goes directly into an optical fiber, which routes about 30 mW of light to the experiment table. The third path seeds a tapered amplifier with 14 mW of power, which is then amplified to 400 mW and coupled into an optical fiber. The light is then routed to the experiment table where it is coupled into the +1 mode of an AOM driven at 160 MHz. The output of the AOM is then split off for the MOT repumper, octagon imaging repumper, and science chamber repumper. The MOT repumper light is coupled into one of the input fibers of the $2 \rightarrow 6$ fiber splitter. The imaging and atom chip

repumper light is coupled into separate fibers and routed to the experiment.

In most cases an AOM is used to provide fast switching of the beams, but every fiber leading to the experiment must be preceded by a physical shutter to block stray light from reaching the atoms and CCD cameras. This includes leakage light from the AOMs that will be in the ± 1 mode even with the RF drive off.

Initially the shutters were built in lab from discarded hard drives. The magnetic memory material was removed and a hole was drilled through the case of the drive for the beam to pass through. The read/write head was used to shutter to beam.



Figure 2.6: Picture of a beam shutter made from a hard drive. A hole is drilled in the casing to allow the beam to pass. A black metal piece is glued to the read/write head and is used to shutter the beam. The black metal was cut out of a Coca-Cola Zero can.

While these shutters provided sub millisecond beam shuttering, the read-

Fiber	Output Power
MOT Fiber 1	20 mW MC, 3.3 mW repumper
MOT Fiber 2	21 mW MC, 2.8 mW repumper
MOT Fiber 3	23 mW MC, 3.3 mW repumper
MOT Fiber 4	22 mW MC, 4.4 mW repumper
MOT Fiber 5	20 mW MC, 3.0 mW repumper
MOT Fiber 6	20 mW MC, 3.7 mW repumper
Zeeman Slower	40 mW MC, 15 mW repumper
Octagon Imaging	340 μ W
Octagon Repumper	1.1 mW
σ^+ Optical Pumping	600 μ W
Science Chamber Imaging	4.2 mW
ODTT Axis Imaging	62 μ W
Science Chamber Repump	3.8 mW

Table 2.1: Table giving the maximum fiber output power at the experiment.

/write head was prone to rebounding open/close for several milliseconds. The timing delay between sending the shutter command and when the read/write head would block/unblock the beam would change by several milliseconds as the rubber material used to reduce rebounding would relax. Because of these problems, we replaced the shutters with commercial shutters (Thorlabs SH05).

2.1.4 Saturated Absorption Spectroscopy

The repumper laser is locked using frequency modulated saturated absorption spectroscopy [72]. The laser diode drive current is modulated with a frequency of 5.52 MHz by an Instek SFG-2110 function generator. The laser is locked to the ^{87}Rb $|5^2S_{1/2}, F = 1\rangle \rightarrow |5^2P_{3/2}, F' = 2\rangle$ crossover transition. An AOM shifts the repumper light by 76.5 MHz so that the repumper laser is detuned -155 MHz from the ^{87}Rb $|5^2S_{1/2}, F = 1\rangle \rightarrow |5^2P_{3/2}, F' = 2\rangle$ transition.

To see how the frequency modulation lock works consider the voltage signal from the photodetector,

$$V_{PD} \propto I(\omega_0 + \delta \cos(\omega_m t)) \quad (2.1)$$

where I is the intensity of the light on the detector which is a function of ω_0 the laser frequency and ω_m the modulation frequency. Taking a Taylor expansion of I we have,

$$V_{PD} \propto I(\omega_0) + \delta \frac{\partial I}{\partial \omega} \cos(\omega_m t) \quad (2.2)$$

The signal from the photodetector is mixed by a Minicircuits ZAD-3+ mixer with the 5.52 MHz modulation signal $V_{LO} = B \cos(\omega_m t + \phi)$ to give

$$V_{LO} V_{PD} \propto B \cos(\omega_m t + \phi) \left[I(\omega_0) + \delta \frac{\partial I}{\partial \omega} \cos(\omega_m t) \right] \quad (2.3)$$

$$\propto BI(\omega_0) \cos(\omega_m t + \phi) + \frac{1}{2} B \delta \frac{\partial I}{\partial \omega} \cos \phi + \frac{1}{2} B \delta \frac{\partial I}{\partial \omega} \cos(2\omega_m t + \phi) \quad (2.4)$$

The first and third terms in equation 2.4 are removed by a Minicircuits BLP-1.9 low pass filter to give an error signal

$$V_{err} \propto \frac{1}{2} B \delta \frac{\partial I}{\partial \omega} \cos \phi \quad (2.5)$$

that is zero when $\frac{\partial I}{\partial \omega} = 0$ which corresponds to the peaks of the SAS signal (Figure 2.7.)

The MC laser also has a SAS setup that is used for coarse adjustment of the laser frequency and for diagnosing problems with the beat note lock. The MC laser is not locked to the SAS signal itself, but is locked via its beat note signal with the repumper light.

2.1.5 Beat Note Lock

The MC laser is locked to the repumper laser by a beat note lock. Several milliwatts of MC light is split off after the initial optical isolators and is overlapped

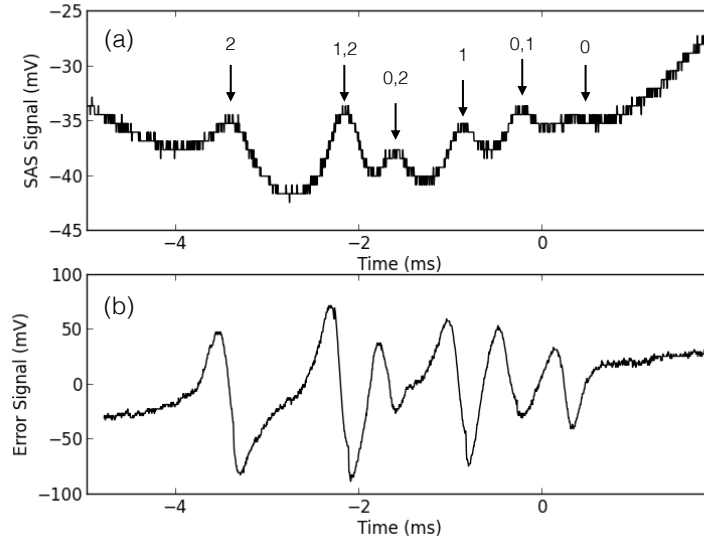


Figure 2.7: (a) Trace of the SAS photodetector signal of the $F = 1 \rightarrow F'$ transitions. Arrows label the $F' = 0$, $F' = 1$, and the $F' = 2$ peaks as well as the 0,1 crossover, 0,2 crossover, and the 1,2 crossover peaks. (b) Error signal used to lock the repumper laser. The error signal (Eq. 2.5) is zero when the derivative of the SAS signal is zero. We lock the laser to the 1,2 crossover peak.

with several milliwatts of repumper light on a 50/50 beam splitter. The overlapped beams hit a GaAs photodetector (EO Tech EOT-4000), which measures a beat signal at the frequency difference of the MC and repumper light. The EO Tech photodetector has a bandwidth of 12.5 GHz, and runs off of two batteries (3 V, 24.5 mm) that must be replaced every few months. The detector is unamplified and DC coupled. The active area of the diode is small, making alignment of the beams on the detector difficult. The DC coupling of the photodetector helps alignment by allowing us to first optimize on the DC laser intensity before optimizing the beam overlap.

The beat note signal from the detector is near 6.35 GHz and is amplified (Minicircuits ZVE-8G+ and ZVA-183+) before being sent to a phase-locked loop

(PLL) (Analog Devices AD4108 evaluation board.) A direct digital synthesizer (DDS) (Analog Devices AD9958 evaluation board) provides a reference frequency to the PLL. The PLL mixes down the beat note signal and compares the beat note and the reference signal (Figure 2.8.) From this, the PLL produces an error signal which is zero when the beat note frequency matches the reference frequency. The settings of the PLL board are controlled using Analog Devices INT-N PLL software (Figure 2.9.)

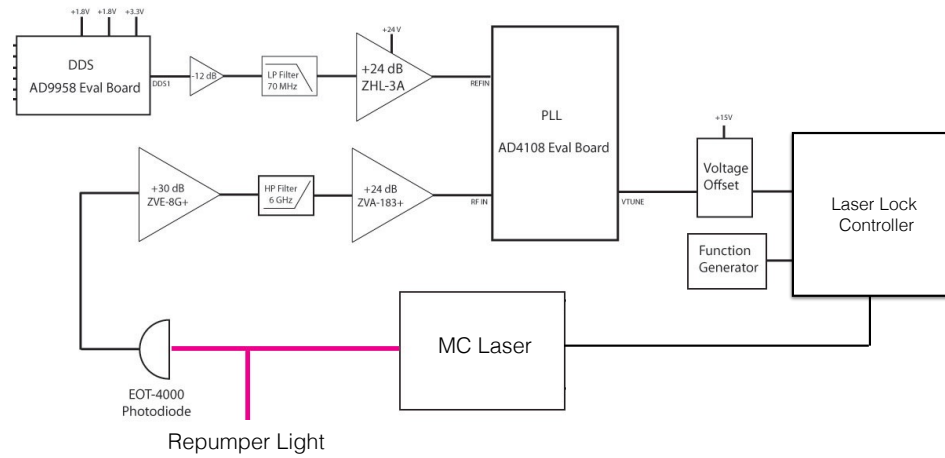


Figure 2.8: Diagram of the beat note lock electronics. The beat note signal from the photodiode is compared by the PLL to the reference signal from the DDS to generate an error signal. The lock box servos the master cooler laser frequency against the beat note error signal.

The beat note lock allows us to easily change the frequency of the MC laser during the experiment by changing the DDS generated reference signal. Over the course of a typical experiment the MC light is swept over a range of 160 MHz [15, 73] as the experiment loads the MOT, sub-Doppler cools, optically pumps, and images the atomic cloud.

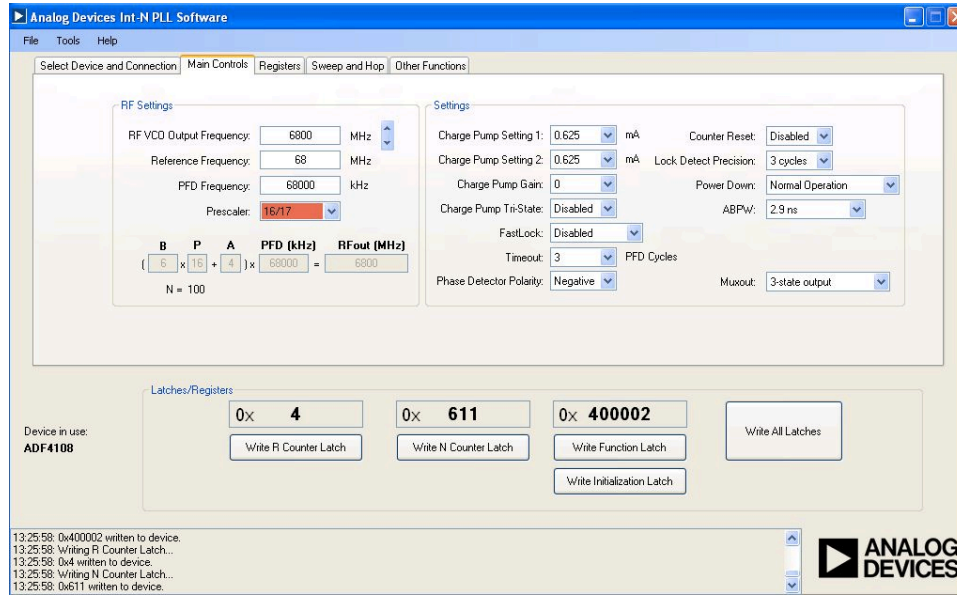


Figure 2.9: Screen capture of the PLL board settings in the Analog Devices INT-N PLL software.

2.2 1064-nm Lasers

The 1064-nm light used to generate the ODTT is generated by a Nd:YAG fiber laser (IPG Photonics YLM-30-1064-LP). The 30 W output of the fiber is collimated and sent through an optical isolator (Thorlabs IO-5-1064-VHP). After the isolator the beam passes through a half-wave plate and a polarizing beam splitter. The light reflected from the PBS is sent into a beam dump (Thorlabs BT600). During normal operation the reflected beam is minimized to allow maximum power to the ODTT, but during alignment the PBS is used to reduce the power in the transmitted beam to ease alignment. While the output power of the 1064-nm laser can be safely reduced to 30% of their maximum output, one should not align the optics in this state, since there can be slight differences in the beam profile and beam direction as the output power is increased.

The beam transmitted through the PBS passes through an AOM (Gooch and

Housego R23080-1-1.06), which is used to provide beam switching and intensity control. The AOM is driven at 80 MHz by a voltage controlled oscillator (VCO) (Minicircuits ZOS-100+). The output of the VCO passes through a voltage variable attenuator (VVA) (Minicircuits ZX73-2500-S+) before being amplified by a Minicircuits ZHL-32A-S amplifier. The VVA allows us to change the drive power of the AOM, and thus change the amount of light that is transferred to the +80-MHz beam. We use this to tune the power of the ODTT, for example, allowing us to linearly ramp down the depth of the optical trap as we transfer the cloud to the macrowire trap.

After passing through the AOM, all light that is not in the +80-MHz beam is routed into a beam dump (Thorlabs BT600). The +80-MHz beam passes through a telescope consisting of a 75-mm focal length achromatic doublet (Thorlabs AC508-075-C-ML) and a 500-mm focal length achromatic doublet (Thorlabs AC508-500-C-ML). The telescope expands the beam to a Gaussian diameter of 6.4 mm as measured with a CCD camera beam profiler.

The beam is focused on the atoms by a 750-mm focal length achromatic doublet (Thorlabs AC508-750-C-ML) mounted on a linear air-bearing translation stage. At its focus, the beam has a waist of $63\text{ }\mu\text{m}$ and a Rayleigh length of 1.2 cm [74]. The translation stage is used to move the focus of the 1064-nm ODTT beam, and the atoms trapped at the focus, from the center of the octagon to 3.2-mm below the atom chip in the science chamber, a distance of 33.3 cm in about 4 seconds.

The ODTT beam is sent into the vacuum chamber by a dichroic mirror, which reflects 1064-nm light and transmits 780-nm light. The dichroic mirror (Figure 2.10) allows a 780-nm imaging beam to be overlapped with the ODTT. This imaging beam is used to image the atoms in the science chamber in order to

overlap the focus of the ODTT with the location of the macrowire trap.

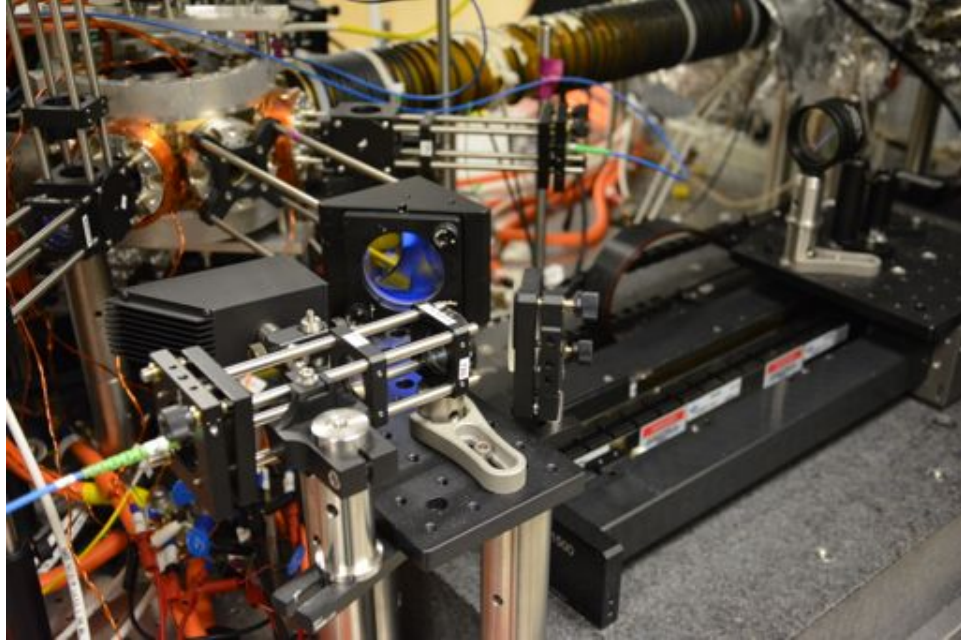


Figure 2.10: Picture of dichroic mirror and ODTT axis imaging. Also picture is the linear air-bearing translation stage with the 750-mm focal length lens. As pictured the focus of the ODTT is at the center of the octagon. To transfer the atoms to the science chamber, the stage will move the lens 33.3 cm towards the dichroic mirror.

CHAPTER 3

EXPERIMENTAL CONTROL AND DATA ACQUISITION

Virtually every piece of hardware associated with the experiment—AOMs, shutters, laser frequencies, translation stages, etc.—is controlled by a single computer. This control is accomplished by sending digital logic signals (0 or 3.3 V), analog signals (-10 V to 10 V), or through Ethernet commands. All of these signals must be precisely timed and controlled in order to run an experiment. In this chapter I will discuss how we implemented the experiment control system and how we acquire data from the experiment.

3.1 Control Hardware

The digital logic for the experiment is provided by a National Instruments (NI) data acquisition (DAQ) board (PCIe-6536) while the analog signal is provided by NI-DAQ boards PCI-6733 and PCI-6723. These boards are installed in the PCI/PCIe slots of the control computer and are connected to each other via a Real-Time System Integration (RTSI) cable. Precision experimental timing is provided by an on-board clock, with synchronization via the RTSI cable.

Radio frequency analog signals for laser locking and radio frequency evaporation are provided by an Analog Devices (AD9958) DDS. We first controlled the DDS board using the digital outputs on the NI PCI-6733 digital output board. While this provided acceptable control of the DDS board and easy integration with the control software, it suffered from severe timing and moderate functional limitations. The time it took to update the DDS board was limited by the experimental time step to about 20 ms. Also, we can only program the DDS

to output a single frequency or a linear ramp between two frequencies. To the address the update rate limitation, we use an Arduino to act as an intermediary between the control computer and the DDS. Before the start of an experiment sequence, the DDS output profile is loaded onto the Arduino which can then update the DDS during the sequence at a much faster rate of one instruction every $500\ \mu\text{s}$.

3.2 Control Software

3.2.1 Overview

The front-end control of the experiment is implemented in MATLAB to allow easy access to powerful analysis and visualization tools. Another factor in choosing MATLAB over more flexible implementations, like Python, is the widespread familiarity with MATLAB among most lab researchers. While the choice of MATLAB has allowed more researchers to easily understand and alter the control software, it has made implementing certain features more difficult, such as communicating between different computers.

Direct control of the NI boards is provided by NI through the NIDAQmx C library. Initializing the NI boards and loading the experiment sequence into their buffer is the final step up of the control process and is done by MATLABs call to the NIDAQmx library via the calllib function.

An experiment sequence can be represented by a matrix (Table 3.1) where the columns correspond to each digital or analog output and each row corresponds to an experimental time-step. The number in spot (i, j) is the value of

	Hardware Outputs			
	(Digital) Output 1	(Analog) Output 2	(Analog) Output 3	(Digital) Output 4
T_1	1	0	-2.3	0
T_2	1	0.25	-2.3	0
T_3	1	0.5	-2.0	0
T_4	0	0.75	-1.7	0
T_5	0	1.0	-1.4	0
T_6	1	1.0	-1.7	1
T_7	1	1.0	-2.0	1
T_8	0	1.5	-2.3	1

Table 3.1: The matrix representing an experiment with four hardware lines and eight times steps. Each column gives the output of a single hardware line for the entire experiment, which each row gives the state of every output at that particular time step.

output j at time-step i . The main function of the control software is to generate this $N \times M$ matrix where N is the number of time-steps in an experiment and M is the number of digital and analog outputs.

Figure 3.1 shows the overall structure of the control software. A single experiment object contains one Block object to represent the control hardware, several SubBlock objects to represent the experiment sequence, and several dozen Line-Data objects to represent individual hardware outputs.

3.2.2 SubBlocks

To generate the matrix corresponding to the experiment sequence, we divide the experiment into SubBlocks representing different parts of an experiment sequence. For example, the LoadMOT SubBlock corresponds to the part of the experiment that loads the MOT and can be represented as a $T \times M$ matrix where T is the number of time steps in LoadMOT and M is the number of digital and analog outputs.

This division allows for modular experiment design by piecing together dif-

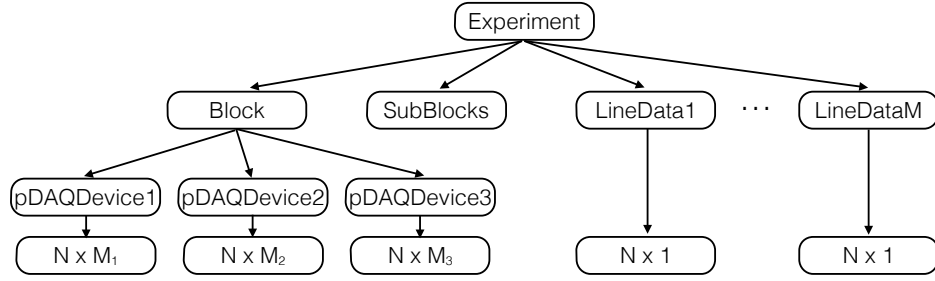


Figure 3.1: Schematic representation of the control software. The Experiment object contains SubBlock, LineData, and Block objects. Each SubBlock object contains the hardware instructions for a particular segment of the experiment while each LineData object contains the instructions for a single hardware output for the entire experiment. The Block object contains three pDAQDevice objects, one for each of the NI-DAQ boards, each with a $N \times M_i$ matrix representing the output for each hardware line on a specific NI-DAQ board.

ferent SubBlocks to form a unique experiment. While every experiment will call LoadMOT, not every experiment will optically evaporate the atomic cloud before transporting it in the optical dipole trap tweezers. By using SubBlocks, we can easily stitch together different experiment sequences without having to alter any of the SubBlock code.

The contents of each SubBlock is determined by a corresponding MATLAB script, the function of which is to fill in the values of the $T \times M$ matrix representing the SubBlock. Because the basic structure of each SubBlock rarely changes, e.g. LoadMOT will always turn on the MOT coils, open the atomic shutter, and turn on the MOT light, the SubBlock scripts rarely change. Changes to the experiment, such as the current in the MOT coil or the length of time to open the atomic shutter, are set in a separate parameters file from which the entire experiment can be controlled.

3.2.3 Representing Hardware

Digital and analog output lines are represented as `DigitalLineData` and `AnalogLineData` objects respectively. Each of these inherit from the `LineData` object and represent a $N \times 1$ vector where the i^{th} entry is the digital or analog value at i^{th} time step. Besides storing this vector, `DigitalLineData` and `AnalogLineData` contain methods for updating the vector values as well as hardware specific properties such as shutter on/off delay times.

Each $N \times 1$ vector is initialized as an $N \times 1$ vector of MATLAB's Not-a-Number (NaN). As each `SubBlock` writes to the `LineData` vector, it replaces the NaNs with an appropriate value. Before compiling the experiment sequence the control software checks each `LineData` object to make sure that none of the entries are NaN. This ensures that each piece of hardware has been given an output value for each time step in the experiment.

Since `DigitalLineData` only stores values of 0 or 1, the update methods are fairly straightforward and usually just set the value over some time interval to either 0 or 1. `AnalogLineData` values can take any value between -10 V and +10 V and the update methods reflect this increased flexibility. For example, `AnalogLineData` has methods that will create linear ramps, sine waves and error functions. Since `AnalogLineData` is written in MATLAB, it is easy to use MATLABs built in function library to create complex analog signals.

The outputs of the DDS are represented as `DDSLineData` objects. The DDS can be programed to emit a single frequency tone or to do a linear sweep between two frequencies. Unfortunately the DDS can only have one tone or linear ramp as its current state, and a single additional command in its buffer. This means that the DDS commands must be sent to the DDS throughout the experiment. Since it takes $500 \mu s$ to load a ramp into the DDS buffer, arbitrary

frequency sweeps must be approximated by a series of linear ramps where each linear segment can be no shorter than $500 \mu\text{s}$.

Like `DigitalLineData` and `AnalogLineData` objects, a `DDSLineData` object contains a $N \times 1$ array representing the output frequency of the DDS line at each experimental time-step. Since linear ramps are calculated by the DDS, the `DDSLineData` array encodes linear ramps as $[\text{startFrequency}, -1, -1, \dots, -1, \text{endFrequency}]$ where *startFrequency* is the starting frequency of the ramp and *endFrequency* is the ending frequency of the ramp. The number of -1 entries determines how long the sweep will take. When the experiment is compiled, the `Experiment` object parses the `DDSLineData` object array and sends the appropriate instructions to the Arduino.

3.2.4 Block Object

The `Block` object contains hardware specific information for the NI-DAQ boards. It is also the object that communicates with the NI-DAQ boards using the `NIDAQmx C` library. The `Block` object takes the $N \times M$ experiment matrix and breaks it into $N \times M_i$ matrices where M_i is the number of digital and analog outputs being used on the i^{th} NI-DAQ board.

Each NI-DAQ board is represented as a `pDAQDevice` object. The `pDAQDevice` object contains hardware specific information as well as the $N \times M_i$ matrix giving the output of each hardware line on the NI-DAQ board.

3.2.5 Experiment Object

The Experiment object ties everything together. Its central task is to read each of the SubBlock scripts for the given experiment and construct DigitalLineData, AnalogLineData, and DDSLineData objects for each hardware output. It does this by first creating an appropriate LineData object for each line of hardware and then going through the SubBlock scripts and collecting each call to that LineData object. The Experiment object then goes through each call and creates the $N \times 1$ vector representing the desired line output.

3.2.6 Defining an Experiment

A particular experiment may need to be repeated many times. Because of this, we designed the system so that an experiment sequence can be generated once and then reused as many times as the experiment needs to be run. We call the step where we generate the experiment sequence compiling, even though the code is not compiled in the usual sense.

Compiling an experiment results in a Block object containing the $N \times M$ matrix representing the experiment. To run the experiment, the Block object loads the $N \times M_i$ matrices onto their respective NI-DAQ board and then tells the boards to run. This running step takes a negligible amount of time.

Compiling the experiment and creating the Block object can take a significant amount of time. The time intensive step is when the Experiment object creates the $N \times M$ matrix. This step scales with the size of the matrix and can become a limiting factor as the experimental time-step decreases or the length of the experiment increases.

In early implementations of this scheme, a new Block object with a new $N \times M$ matrix was created every time an experiment was compiled. For typical experiments, N could be as large as 2.5×10^6 with $M = 50$. Creating a Block object with a matrix of that size took approximately 30 seconds, even though the experiment would only run for 25 seconds. Consider the example of measuring the response of the atoms to an applied magnetic field. The magnetic field value is set by the current through a magnetic field coil controlled by a single DigitalLineData object. For every value of magnetic field we wish to measure, we have to recreate the entire $N \times M$ matrix, even though we only change one column of the matrix.

For some experiment runs, compile time could take over 50% of the total experiment time. To alleviate this bottleneck, a second generation of the control system was implemented. Each Block object is now associated with a hash list. The hash list contains the name of every (Digital/Analog/DDS)LineData object created and associates with it a hash value. The hash value is an identifier that is uniquely determined by the $N \times 1$ LineData vector.

When a new experiment is compiled, the software first generates the hash list, without generating the $N \times M$ experiment sequence matrix. The hash list is then compared to the hash lists from the previously compiled experiments to find the hash list with the fewest number of differing LineData objects. The Block object associated with this hash list, which contains the $N \times M$ matrix from a previous experiment, is loaded into the workspace. The Experiment object then goes through and updates only the columns of the matrix that have changed for the new experiment sequence. This new compile process has led to up to a 4x decrease in compile times.

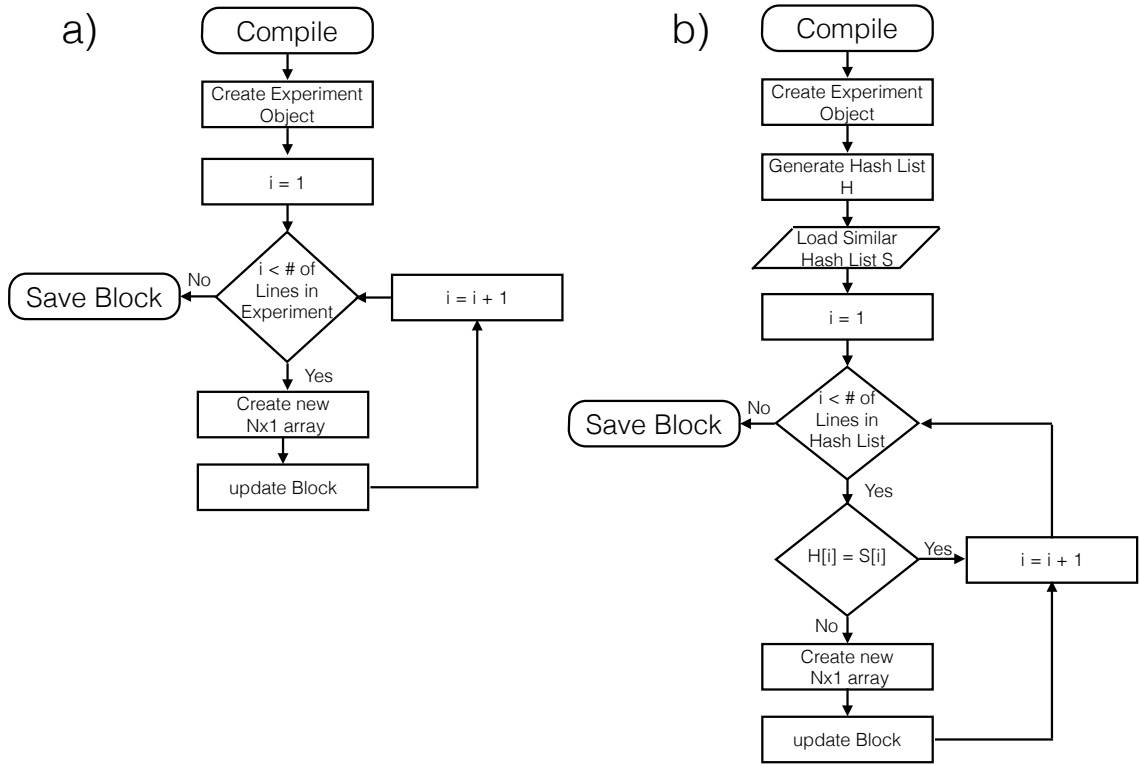


Figure 3.2: Flow charts representing (a) the original compile sequence and (b) the second generation sequence. In (a) the array representing each hardware line is generated every time an experiment is compiled. In (b) the Block object from a previous experiment is loaded and only the hardware lines that differ between the new and the old experiment are generated. This can lead to a factor four decrease in compile time for (b) relative to (a).

3.3 Imaging

3.3.1 Absorption Imaging

All of the atomic imaging is done using absorption imaging. In absorption imaging, laser light resonant with an atomic transition is sent through the atomic cloud and onto a CCD camera. The atoms absorb some fraction of the

light and cast a shadow onto the CCD. By measuring the depth and location of the shadow, we can produce an image of the atomic cloud.

We measure the depth of the shadow by the optical depth (OD).

$$OD(x, y) = \ln \left(\frac{A(x, y) - D(x, y)}{L(x, y) - D(x, y)} \right) \quad (3.1)$$

where $A(x, y)$ is the intensity image captured on the CCD with the atomic cloud present, $L(x, y)$ is the image with the imaging beam on, but no atoms present, and $D(x, y)$ is an image with no atoms or imaging light. The OD is actually a function over x , y , and z but since the imaging beam naturally integrates along its propagation direction, all we can get from a single image is $OD(x, y)$.

The OD is related to the local atomic density $n(x, y, z)$ according to

$$OD(x, y) = \sigma(\lambda) \int n(x, y, z) dz \quad (3.2)$$

where $\sigma(\lambda)$ is the scattering cross-section and is given by [75]

$$\sigma(\lambda) = \frac{\hbar\omega\Gamma}{2I_{sat}} \cdot \frac{1}{1 + 4\left(\frac{\Delta}{\Gamma}\right)^2 + \frac{I}{I_{sat}}} \quad (3.3)$$

where Γ is the natural line width of the imaging transition, ω is the imaging transition frequency, Δ is the detuning of the imaging light from the imaging transition, I is the intensity of the imaging light, and I_{sat} is the saturation intensity.

We rarely image atoms in a magnetic trap. Instead, we abruptly turn off the trapping potential and allow the atoms to free fall for a length of time called the time-of-flight (TOF.) One of the benefits of TOF imaging is that the atomic cloud will be less dense after expanding, allowing us to image clouds that are too dense to accurately image in the trap. It also allows for the application of a well defined magnetic quantization axis to ensure we image on the $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m'_F = 3\rangle$ cycling transition. Imaging in the octagon

within 3 ms of turning off the MOT coils is difficult because of persisting eddy currents that distort the magnetic quantization field.

We also use TOF imaging to measure the temperature of the atomic clouds [76]. For the atomic traps we use, a thermal cloud of atoms after some TOF will have a Gaussian density distribution. After a TOF t the density distribution will have a standard deviation of

$$\sigma_t = \sqrt{\sigma_0^2 + \sigma_v^2 t^2} \quad (3.4)$$

where σ_0 is the standard deviation of the initial distribution, and $\sigma_v = \sqrt{k_B T / m}$ for temperature T and atomic mass m . After imaging the cloud at multiple TOF's, we can fit the width of the cloud to give the temperature.

3.3.2 Cameras

The experiment utilizes two types of cameras, DragonFly cameras from Point Grey Research and PIXIS cameras from Princeton Instruments. The DragonFly cameras are cheaper than the PIXIS camera and are useful for low resolution, high signal images. They consist of a CCD on a circuit board and are thus easier to mount than the PIXIS camera, which is much larger, heavier, and has an internal fan that can introduce vibrations into the experiment.

The PIXIS camera offers many improvements over the DragonFly cameras, such as a low dark count, high efficiency CCD array. It also supports a frame transfer kinetics mode, which allows the acquisition of images at intervals as short as one microsecond.

The rate limiting step to reading out images from the PIXIS camera is the

analog to digital conversion of the CCD pixels. To read out a full image of the 1024 x 1024 CCD array takes 583 ms. In kinetics mode, most of the CCD array is masked off, leaving only a small section of the array to acquire images. An image is acquired on the exposed area of the CCD. The image is then shifted into the masked area of the CCD at a rate of 30.2 ns per line. This process can be repeated until the CCD array is full, after which it must be read out at the normal 583 ms rate (Figure 3.3.)

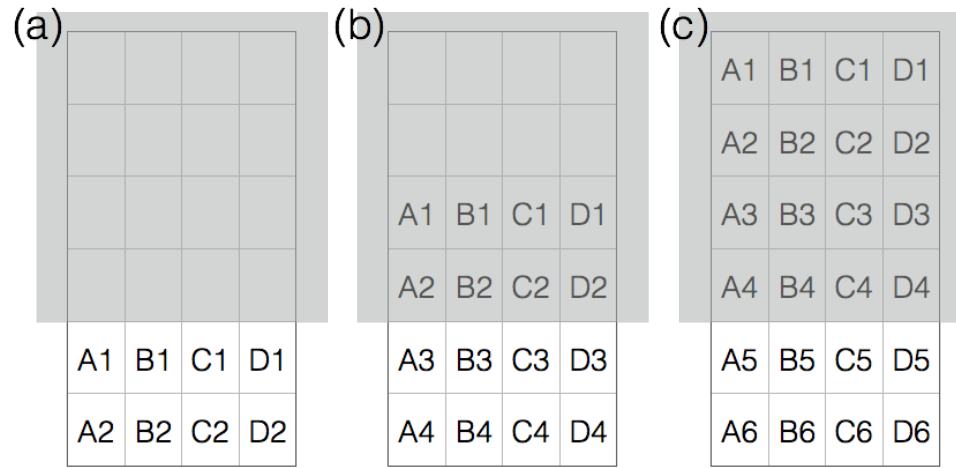


Figure 3.3: Illustration of frame transfer kinetics mode where only the bottom two rows of pixels are used to acquire images. In (a) the first image is acquired. In (b) the second image is acquired while the first image is shifted into the two adjacent rows of pixels. In (c) the third and final image is acquired while the first and second image are shifted again. After the CCD array is full, the image is read out in the normal way.

Images are acquired, viewed, and manipulated using MATLABs image acquisition toolbox. Support for the DragonFly cameras in the image acquisition toolbox is provided by Carnegie Mellon Universitys DCAM drivers [77]. Unfortunately, no similar drivers were available for the PIXIS camera on 64-bit MATLAB. In order to integrate the PIXIS camera into the existing image acquisition software, a C++ library was written to provide image acquisition toolbox

support for the PIXIS camera.

3.3.3 PIXISAdaptor

The PIXISAdaptor is the driver library written to allow the PIXIS camera to be used on 64-bit MATLAB. The library was written in C++ following the structure outlined in the MATLAB manuals [78] and utilizes the Picam library from Princeton Instruments for interfacing with the PIXIS camera.

The adaptor needs to implement five functions:

1. InitializeAdaptor: This function initializes the Picam library and returns a list of available adaptors
2. getAvailHW: Provides the image acquisition toolbox with information about the PIXIS camera
3. getDeviceAttributes: Provides the toolbox with all hardware specific properties of the PIXIS camera
4. createInstance: Instantiates an object of the PIXISAdaptorClass
5. uninitializeAdaptor: Cleans things up and uninitialized the Picam library

It must also create the PIXISAdaptorClass, which has five important methods:

1. openDevice: Prepares the camera for acquisition and creates the acquireThread
2. closeDevice: Closes the acquireThread and releases the camera
3. startCapture: Tells the acquireThread to start acquisition

4. stopCapture: Tells the acquireThread to stop acquisition
5. acquireThread: Acquires images from the camera until the stop condition is met

The PIXISAdaptor also implements the PIXISPropGetListener and the PIXISPropSetListener. The PIXISPropGetListener is called whenever MATLAB asks for a camera property. The PIXISPropGetListener retrieves the parameter value from the camera and returns the value to MATLAB. The PIXISPropSetListener acts in the same way as the PIXISPropGetListener, except that it sets the parameter value on the camera to be the value passed from MATLAB.

3.3.4 Imaging Optics

Four cameras are installed in the experiment to image atoms in the octagon and in the science chamber. The imaging system in the octagon is mounted to the chamber through the MOT cage optics. Linearly polarized imaging light resonant with the $F = 2 \rightarrow F' = 3$ transition is reflected off a PBS and sent into the octagon. Before entering the chamber the light is circularly polarized by a quarter-wave plate such that, given the appropriate bias magnetic field, it will drive σ^+ transitions. After interacting with the atoms the light leaves the chamber and passes through another quarter-wave plate, returning it to its original linear polarization. The beam reflects off of a PBS and is collected by a two lens system onto a DragonFly camera. Imaging in the octagon has a magnification of 0.23 and is used primarily for diagnostics and optimizing atomic trap.

Imaging along the ODTT axis is sometimes necessary to align the transported atomic cloud with the macrowire trap. Imaging light resonant with the

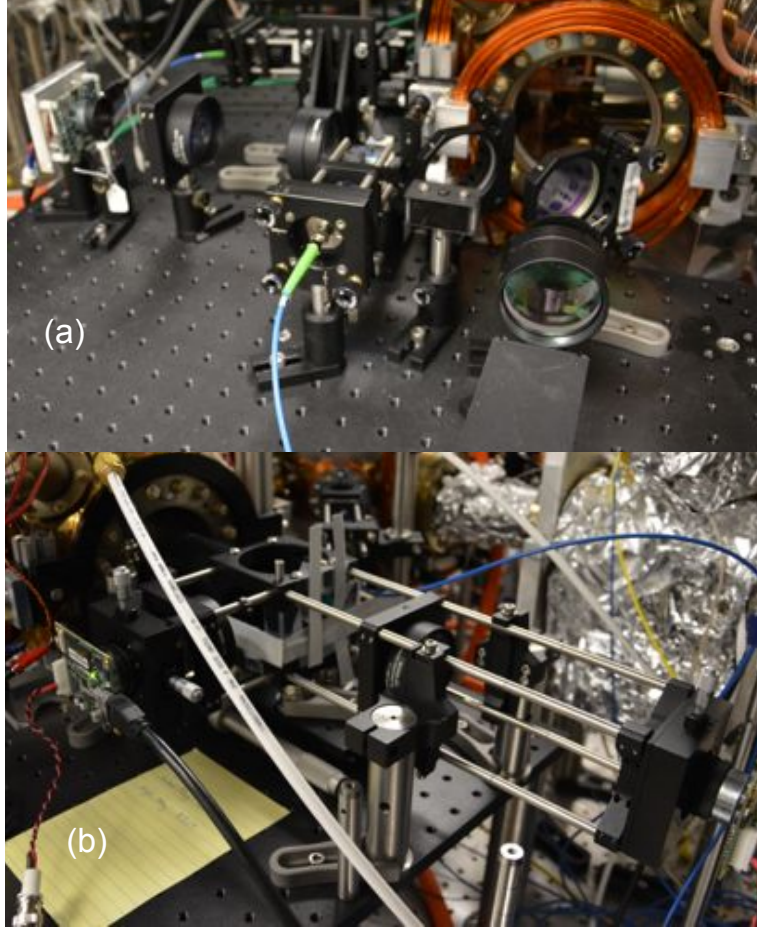


Figure 3.4: Picture of the imaging optics for the ODTT-axis imaging (a) and the science chamber imaging (b).

$F = 2 \rightarrow F' = 3$ transition is overlapped with the 1064-nm ODTT on a dichroic mirror that reflects 1064-nm light and transmits 780-nm light. The imaging light passes through the vacuum chamber and exits the science chamber, where it is split from the ODTT using another dichroic mirror. The atoms are imaged onto a DragonFly camera using a two lens system with a magnification of 0.32.

Imaging in the science chamber is complicated by the need to image atoms with high resolution near the sample surface and to image centimeter long clouds far from the sample. A dual magnification system is used, consisting of three achromatic doublet lenses and two DragonFly cameras. The imaging

light is collected by a 150 mm focal length lens and then sent to either a 200-mm lens (magnification = 1.3) or a 75 mm focal length lens (magnification = 0.5.)

To focus the imaging system on the atoms we first set the lens nearest to the camera. We set this lens by sending in a collimated imaging beam, and focusing it on to the CCD camera. Once this lens is set, we place the second lens a distance f from the atoms, where f is the focal length of the second lens. For fine adjustment we image the atoms in the ODTT. The high density of the one dimensional cloud produces fringing in the images if the cloud is not in the focal plane of the imaging system. To adjust the focus, we move the position of the second imaging lens until there are no more fringes in the atomic image.

3.4 Translation Stages

3.4.1 ODTT Stage

The location of the ODTT is controlled by a linear air-bearing translation stage (Aerotech ABL15050). We originally installed this stage with a switching power supply (Aerotech SOLOISTCP20-MXU) that introduced 40-kHz electronic noise throughout the lab. Changing to a linear supply (Aerotech SOLOISTML10) removed the 40-kHz noise.

The stage is controlled using Aerotech's proprietary software language. The first version of the Aerotech control software was generously provided by Daniel Steck with further development being done in lab. The Aerotech software runs on the SOLOISTML motion controller and listens for commands from the experiment control computer via an Ethernet port. The stage accepts com-

mands to wait for a time t , wait for an external trigger, and move to position x with speed v and acceleration a .

Before an experiment is run, all of the motion commands for the experiment are sent to the SOLOISTML by the control computer via the Ethernet port. Once the stage has gone through all of the commands in the buffer, it will return to the first command in the buffer and begin executing the commands again in the same order. For most experiments, the stage commands look like:

1. Move to $x = 133$ mm with $v = 200$ mm/s and $a = 150$ mm/s². This sets the ODTT focus to be in the octagon
2. Wait for trigger
3. Move to $x = 466$ mm with $v = 200$ mm/s and $a = 75$ mm/s². This translates the ODTT to the science chamber
4. Wait for trigger

Because the commands are sent to the stage before the experiment sequence starts, we don't have to worry about how long it takes to send commands over the Ethernet. The stage is synced to the experiment sequence through a trigger provided by one of the digital logic outputs of the NI-DAQ boards. The SOLOISTML executes an infinite loop where it keeps checking input buffer to see if it has received any new commands, and then checking to see if the trigger line is high. Because of the timing uncertainty in the SOLOISTML loop evaluation, there is an uncertainty of several milliseconds as to when the stage will execute a command. We account for this by building in extra time in the experiment sequence before and after stage motion. The uncertainty in the stage trigger leads to uncertainty in how long the atoms spend sitting in the ODTT before and after motion, which is not critical.

3.4.2 Sample Stage

The sample mount in the science chamber is controlled using a three-axis translation stage. The stage is controlled by a Newport XPS motion controller and consists of two Newport VP-25XL stages providing horizontal translation of up to 25 mm in the x and y directions, and a Newport VP-5ZA that provides 5-mm travel in the vertical direction. These stages promise 1- μm position accuracy and 140-nm bidirectional repeatability in the horizontal plane, and a 3- μm accuracy a 300-nm repeatability in the vertical direction. While the vertical accuracy is greater than the 1 μm imaging resolution goal, the atom-sample distance can always be calibrated through reflected absorption imaging of the atomic cloud.

In the current experiments, the sample stage is moved between experimental runs, not during. This allows us to send motion commands to the XPS controller via the Ethernet, and have those commands execute before the start of the experiment. The XPS controller does accept external triggers, which will allow future experiments to sync the motion of the XPS stage to the experiment sequence.

CHAPTER 4

PRODUCTION CHAMBER

The vacuum chamber is divided into two main sections, the production chamber, where cold atomic gases are prepared, and the science chamber, where the gases are brought near a sample of interest (Figure 4.1.) The two chambers are separated by a pneumatic gate valve (MDC GV-1500M-P), allowing us to isolate the vacuum in the two chambers. With the gate valve closed, we can rapidly change samples in the science chamber without disturbing the production chamber. We model the production chamber on the apparatus described in [73]

4.1 Cleaning Procedure

Grease and oil from the machining process and from human skin will outgas and limit the vacuum pressure of the chamber. All parts of the chamber must be cleaned prior to assembly and be handled carefully while wearing uncontaminated gloves.

First the parts are sonicated in a detergent solution, we used Alconox, for fifteen minutes. One exception to the Alconox clean is bellows. The worry is that Alconox will be trapped in the ridges of the bellows. After sonicating in Alconox, the parts are sonicated in acetone for fifteen minutes. Acetone will dissolve most of the organics on the piece and it is important that acetone never be allowed to evaporate from the surface of the part. This will leave a residue that might not be removed in later cleaning steps. To avoid this, rinse the part in methanol immediately after removing it from the acetone. Do not allow the

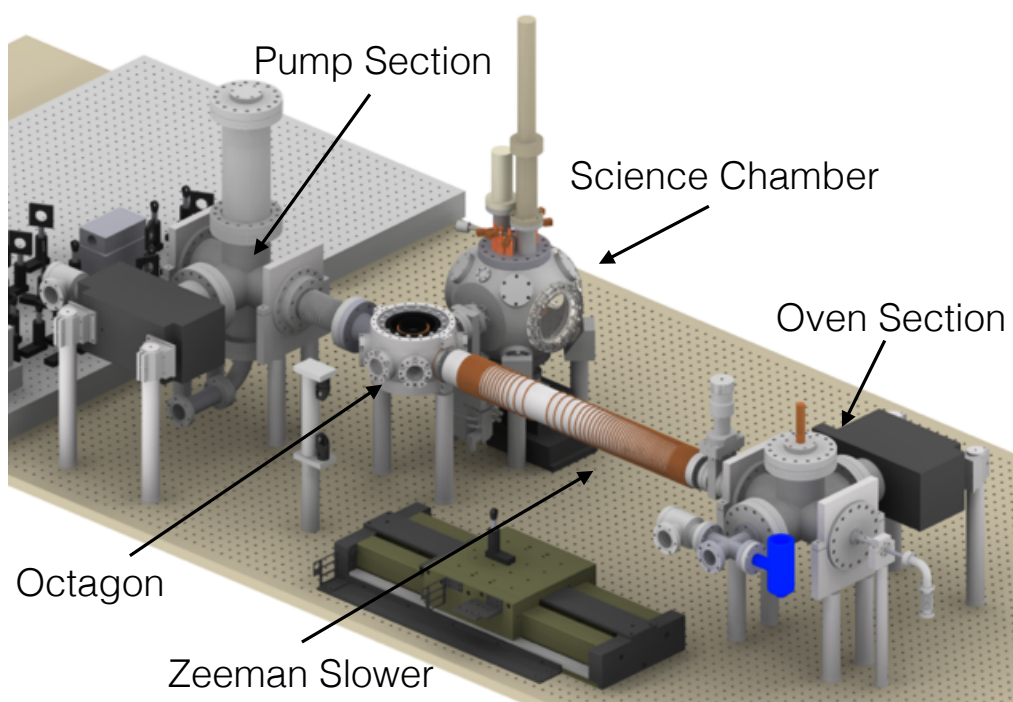


Figure 4.1: Computer rendering of the vacuum chamber. The production chamber is divided into four sections, the oven section, the Zeeman slower, the octagon, and the pump section. The science chamber contains the atom chip, cryostat, and sample to be measured. The production chamber is separated from the science chamber by a pneumatic gate valve, allowing the sample in the science chamber to be replaced without disturbing the production chamber.

part to dry in air, either submerge it directly in methanol for the next cleaning step, or use pure, high pressure air to blow off the methanol. Next, sonicate the part in methanol for fifteen minutes. Again, do not allow the part to air dry. Use pure compressed air to blow off the methanol.

Viewports with glass to metal seals are excepted from the above cleaning procedure. Since sonication can weaken the glass to metal seal, these pieces should simply be rinsed with methanol and blown dry.

After they are clean, the steel parts need to be pre-baked to 400°C to remove

excess hydrogen. Hydrogen outgassing can limit the vacuum pressure in the chamber to the 10^{-10} level. Do not pre-bake delicate parts such as windows that cannot be heated to 400°C.

To pre-bake the chamber parts, we construct an oven out of thermally insulating bricks. Each part of the vacuum chamber is first wrapped in ultra-high vacuum (UHV) foil. The wrapped parts are then wound with heater tape and covered by another layer of UHV foil. The parts are placed in the oven and heated to 400 °C for three to four days, after which the steel parts will have changed color to a golden brown. The chamber is now ready to be assembled.

4.2 Oven Section

The oven section contains the ^{87}Rb source and provides an atomic beam to the Zeeman slower. The oven section is pumped by a 75-l/s ion pump and achieves a typical pressure of 7×10^{-10} at room temperature, measured by an ion gauge (Agilent 571 ionization gauge.) The pressure in the oven section is isolated from the rest of the apparatus by a differential pumping tube.

The oven section is loaded with one gram of Rb ampuled under argon (Alfa Aesar 44214.) One gram of Rb has lasted through two years of continuous running, with no sign of diminished atomic flux. The Rb ampule is placed inside a flexible bellows. Once the chamber has been baked and is under vacuum, the Rb ampule is broken by bending the flexible bellows. The outside of the bellows and the oven-tube (Figure 4.4) is wrapped with heater tape. During operation, the tape heats the bellows to 80 °C and the oven-tube to 120 °C. These temperatures are controlled by two Omega temperature controllers (Omega CSI32K.) Heating the Rb increases the vapor pressure from 2×10^{-8} Torr

to 6×10^{-5} Torr [75] which, when combined with the oven-tube at 120 °C, creates a beam of Rb atoms.

In order to prevent Rb contamination of the ion pump, the end of the oven-tube is placed inside a copper cold cup. The cold cup is cooled by an external thermoelectric cooler (TEC) to -10 °C so that any Rb atoms that impact the cup will be stuck to the cup, and not released back into the chamber. The connection between the TEC and the copper feedthru must be well insulated or ice will build up around the interface. Initial attempts to insulate the cold side of the TEC using insulating strips were insufficient, as the irregular shape of the copper feedthru to TEC connection made wrapping difficult. The second approach using insulating foam proved sufficient to prevent ice build up (Figure 4.2.)

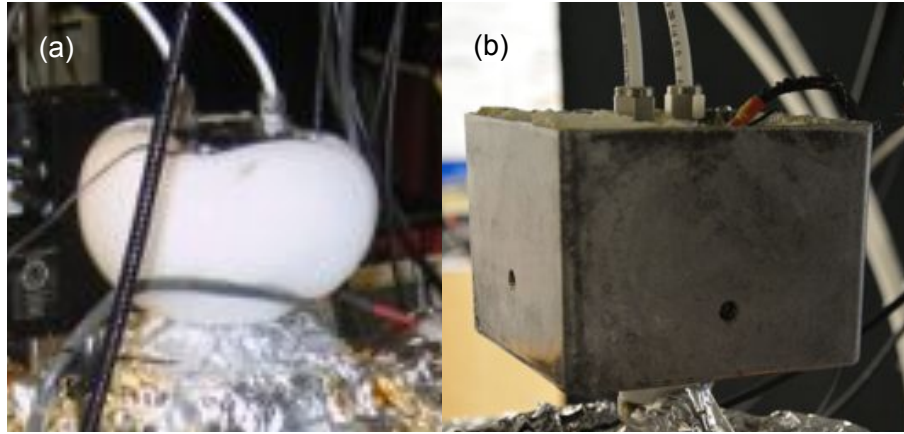


Figure 4.2: (a) Picture of the TEC covered in ice due to insufficient thermal insulation. (b) Picture of the TEC in foam insulation without ice buildup.

The cold cup has a hole through which the collimated atomic beam passes (Figure 4.4.) On the opposite side of the cold cup from the oven-tube is a shutter (Uniblitz LS6FEC). The shutter allows us to block the atomic beam after the MOT has been loaded. The atomic shutter is screwed onto the cold cup to provide mechanical and thermal connection (Figure 4.3.) The thermal connection

to cold cup is crucial, since there is no air to help dissipate the heat generated by the shutter drive solenoid.

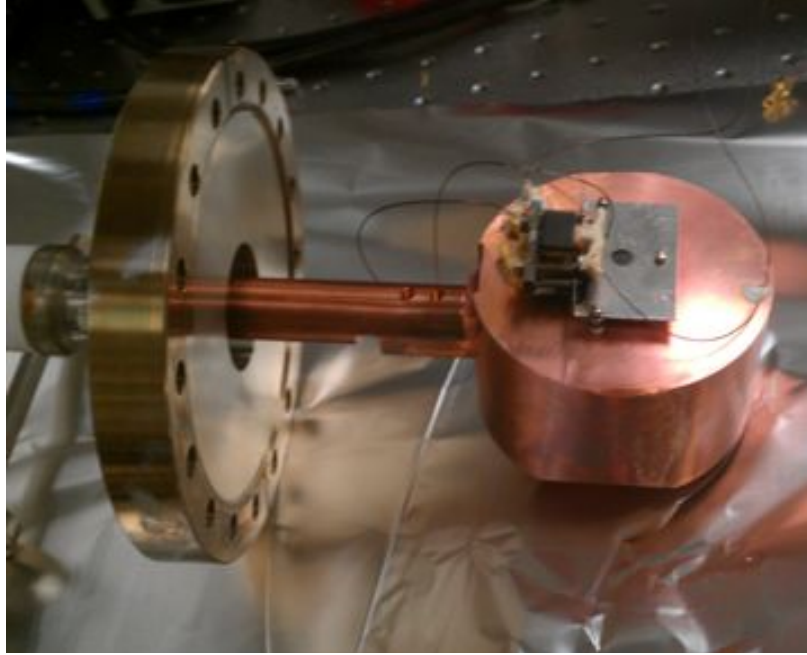


Figure 4.3: Picture of the oven chamber top flange, with attached cold cup and Uniblitz atomic shutter. The wires connecting the Uniblitz shutter to the chamber feedthru are glued to the cold cup using thermally conductive, vacuum safe epoxy (Torr Seal.)

While we have had issues with shutters failing shortly after their first use, the shutters that have survived this initial period have proven robust and reliable. Because of this, we recommend any new shutters being installed be tested prior to baking the chamber. To test the shutter, install it as normal and pump the chamber down to moderate vacuum using a turbopump. Test the shutter by cycling it open and closed with a 10-s on, 20-s off duty cycle for at least thirty minutes. We test the shutter under vacuum to account for the reduced heat dissipation compared to operating the shutter in air.

After passing through the shutter the atomic beam goes through a differential pumping tube and enters the Zeeman slower.

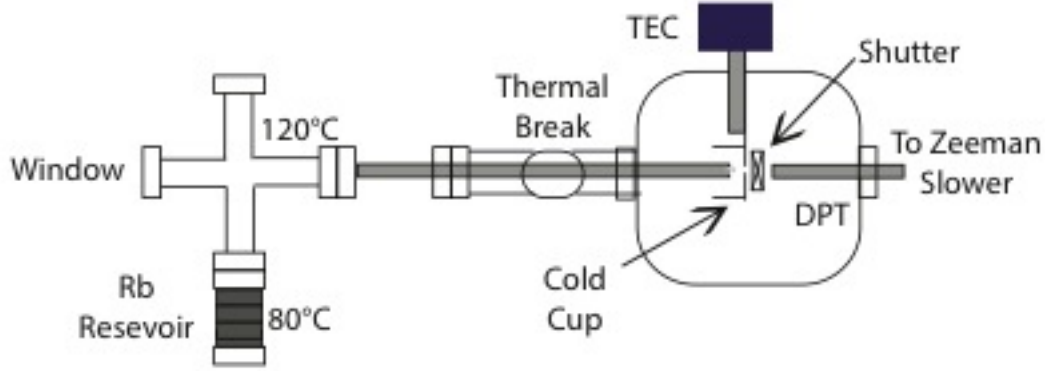


Figure 4.4: Diagram of the cross section of the oven section. The window on the Rb oven is used for coarse alignment of the Zeeman slower beam. A glass thermal break isolates the temperature of the oven-tube from the rest of the oven section. A differential pumping tube (DPT) protects the octagon from background gas.

4.3 Zeeman Slower

The atoms enter the Zeeman slower traveling with a speed described by a thermal distribution with the most likely velocity of 340 m/s [73,79]. Before they can be loaded into the MOT, the atoms must be slowed to approximately 35 m/s. To accomplish this, light resonant with the D_2 $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m'_F = 3\rangle$ transition is sent along the length of the production chamber against the direction of the atomic beam. As the photons collide with the atoms they transfer momentum to the atoms, slowing the atoms over many collisions.

As the atom are slowed by the Zeeman slower, the Doppler shift causes them to move out of resonance with the $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m'_F = 3\rangle$ transition. To compensate for the Doppler shift, we apply a spatially varying magnetic field along the length of the Zeeman slower [80]. The magnetic field changes the Zeeman shift between the $|F = 2, m_F = 2\rangle$ and $|F' = 3, m'_F = 3\rangle$ states to compensate

for the Doppler shift.

In order to reduce the magnitude of magnetic fields we need to produce, we set the frequency of the Zeeman slower beam to be -162 MHz detuned from the $|F = 2, m_F = 2\rangle \rightarrow |F' = 3, m'_F = 3\rangle$. This allows us to create a magnetic field that crosses zero inside the Zeeman slower and to keep the maximum field below 150 G.

The 40 mW Zeeman slower beam enters the chamber at the pump section with a waist of roughly one centimeter and comes to a focus at the Rb oven. The Zeeman slower beam is given a circular polarization to drive σ^+ transitions in the positive field section of the Zeeman slower. Fifteen milliwatts of repumper light is combined in fiber with the Zeeman slower beam and detuned -155 MHz from the $|F = 1\rangle \rightarrow |F' = 2\rangle$ repumper transition.

The spatially varying magnetic field is produced by two single layer coils with opposite current directions. The magnetic field is varied by changing the spacing between coil windings along the length of the Zeeman slower. Following the prescription in [79], we model the coils by

$$\begin{aligned}
r(p) &= [x(p), y(p), z(p)] \\
x(p) &= R \cos \theta(p) \\
y(p) &= R \sin \theta(p) \\
z(p) &= c_7 p + c_8 \\
\theta(p) &= \sum_{m=0 \dots 6} c_m p^m
\end{aligned} \tag{4.1}$$

where $p \in [0, 2\pi]$ is the free parameter, z is the distance along the coil, and R is the radius of the Zeeman slower. The coil design is then determined by the nine parameters c_i and the field inside the Zeeman slower can be calculated using the Biot-Savart law [81].

	Positive Coil	Negative Coil
c_0	0	π
c_1	-75.22588	4.26216
c_2	27.04621	-18.95554
c_3	-2.5647	10.52419
c_4	0	-2.9767
c_5	0.02279	0.43914
c_6	0	-0.02765
c_7	-0.10299	0.04828
c_8	0.60307	0.2972

Table 4.1: The c_i design parameters for the positive and negative Zeeman slower coils with $R = 38.3$ mm and $I_{pos} = 72$ A and $I_{neg} = 42$ A. The parameters were found by fitting the field from Eq. 4.2 to the ideal field given by Eq. 4.3

$$B(z') = \frac{\mu I}{4\pi} \int_0^{2\pi} \frac{d\mathbf{r}'/dp \times \mathbf{r}'}{r'^3} \quad (4.2)$$

where μ is the magnetic permeability, I is the current in the coil, and $\mathbf{r}' = \mathbf{r} + (0, 0, z')$. The ideal magnetic field is found by matching the Zeeman shift to the Doppler shift and is given by,

$$B_{ideal}(z) = B_a - \frac{\hbar k}{\mu'} \sqrt{v_0^2 - \frac{2\eta\hbar k \Gamma z}{2m}} \quad (4.3)$$

where B_a is a constant offset that determines the location of the field zero, v_0 is the peak velocity of the atoms to be slowed, k is the wave number of the Zeeman slower laser, and $\mu' = \mu_B(g_e m_e - g_g m_g)$. η is a free design parameter giving the ratio of atomic deceleration to the optimal deceleration. $\eta < 1$ allows for imperfections in the slowing laser and the magnetic field. Our Zeeman slower was designed for $\eta = 0.7$ [73].

We calculate the design parameters c_i by fitting the field given by Eq. 4.2 to the ideal magnetic field given by Eq. 4.3 (Table 4.1) [79]. We measure the Zeeman field using a flux magnetometer and find good agreement with the designed field (Figure 4.5)

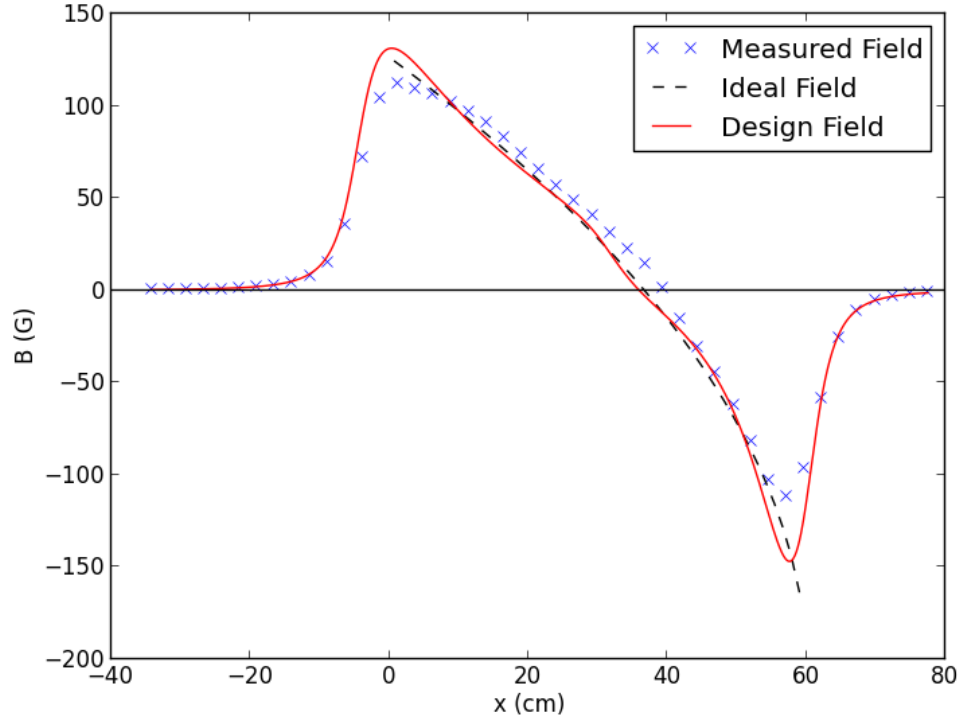


Figure 4.5: Shows the ideal Zeeman slower field (dashed black line) from Eq. 4.3, the designed field (solid red line) from Eq. 4.2, and the measured field (blue $\times$).

4.4 Octagon

The octagon is where the atoms are initially trapped and cooled before being transported to the science chamber. The top and bottom of the chamber are formed by bucket windows that are recessed into the chamber to allow for placement of magnetic field coils approximately 5 cm from the atoms. Two opposite sides of the octagon open to the Zeeman slower and the pump chamber, with one of the sides half way between them opening to the science chamber. The rest of the sides contain windows to allow optical access to the atomic cloud.

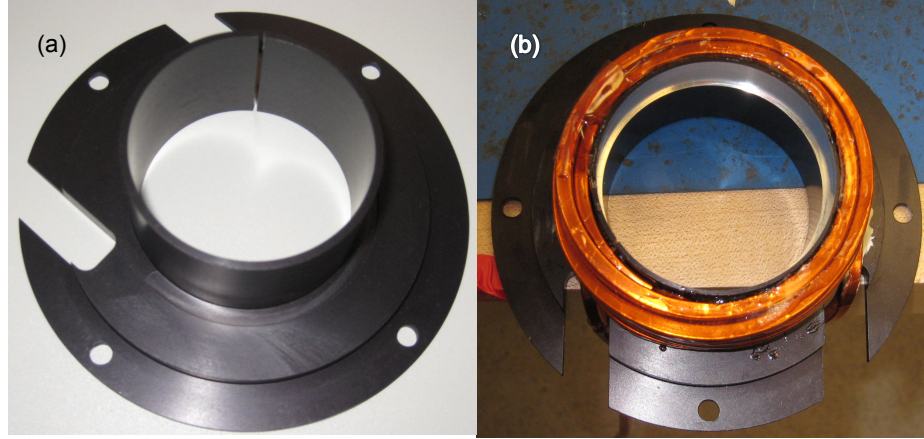


Figure 4.6: Pictures of the aluminum MOT coil holder before winding the coil (a) and after the winding the coil (b).

The MOT coils provide the quadrupole field necessary for creating the MOT and hybrid magneto-optical trap. They are each composed of eleven turns of hollow square wire and are placed inside the top and bottom bucket windows. The coils are wound around a specially designed holder. The MOT coil holder fits inside the bucket window, allowing the MOT coils to be placed as closed to the atomic cloud as possible. The coil holder also has a slit cut through it to prevent eddy currents from forming when turning on and off the field coils (Figure 4.6.) Chilled water flows through the hollow wire to allow for currents up to 850 A to be safely sent through the coils. The chilled water is kept at 59 °F while a 120-p.s.i. differential pressure is maintained across the coils.

To create a MOT we use three pairs of counter propagating laser beams. The MOT light and MOT repumper light are brought from the laser area to the octagon on a two to six port fiber splitter. It is important to provide a good heat sink for the fiber splitter. Temperature fluctuations can change the power distribution among the output fibers, leading to instabilities in the MOT. The six output fibers are mounted directly to the chamber using a cage optics system (Figure 4.7). This allows the MOT optics to be rigidly registered to the chamber

and reduces beam drift compared to free space optics. The trade off is that we have less flexibility in aligning the MOT beams, since the coarse alignment is set by the rigid cage mounting.

Each MOT beam exits its fiber and is collimated to a 2-cm diameter by a 100-mm focal length lens. The beam then passes through a PBS cube to ensure the polarization purity of the beam. Besides purifying the beam polarization, the PBS cubes allow a second beam to be overlapped on top of the MOT beam. This is done with imaging beams and optical pumping beams. Before entering the chamber, the beams pass through a quarter-wave plate to give them a circular polarization (Figure 4.7.)

Three pairs of magnetic field coils are placed around the windows corresponding to the x , y , and z -axis (Figure 4.7). The x and y -bias coils have approximately 65 turns each and the z -bias coil has approximately 15 turns. These coils are wound to provide a bias field of up to several gauss in an arbitrary direction inside the octagon. The bias coil field calibrations are as follows: x -bias = $(-400, -350, 30)$ mG/A, y -bias = $(-400, 300, 50)$ mG/A, and z -bias = $(-120, 40, -2700)$ mG/A, where $-\hat{x}$ points towards the science chamber, $\hat{y}$ points towards the pump section, and $\hat{z}$ points into the optical table.

A DragonFly camera for imaging the atomic cloud inside the octagon is mounted to the vacuum chamber by cage optics. The imaging beam is overlapped with one of the MOT beams on a PBS cube. After exiting the far side of the octagon, the imaging beam reflects off of another PBS cube and is directed onto the camera. During the loading of the MOT, some of the light from the MOT beam will be reflected by the PBS cube onto the camera. Since the camera takes approximately 150 ms to clear its CCD array, the MOT light will distort the images of the atomic cloud if the images are taken too soon after loading the

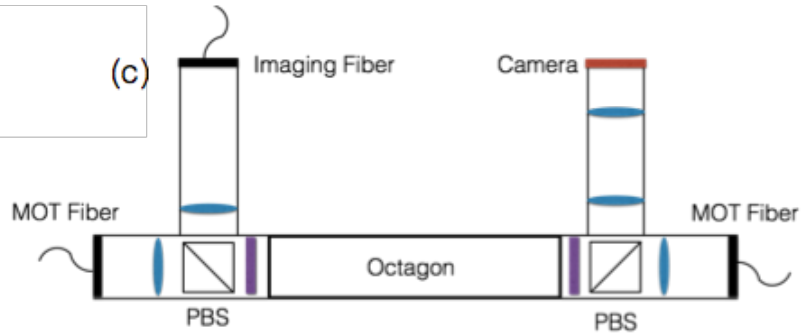
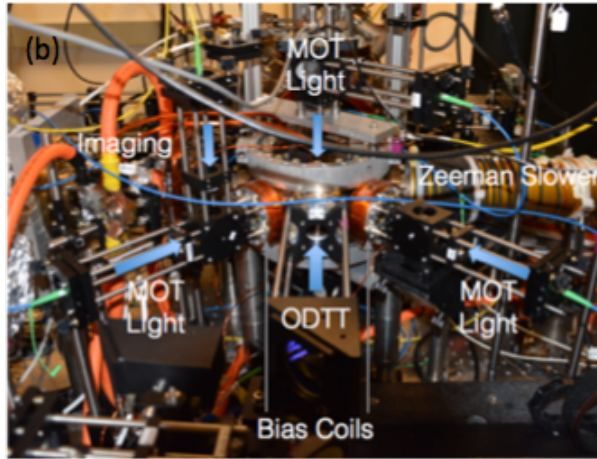
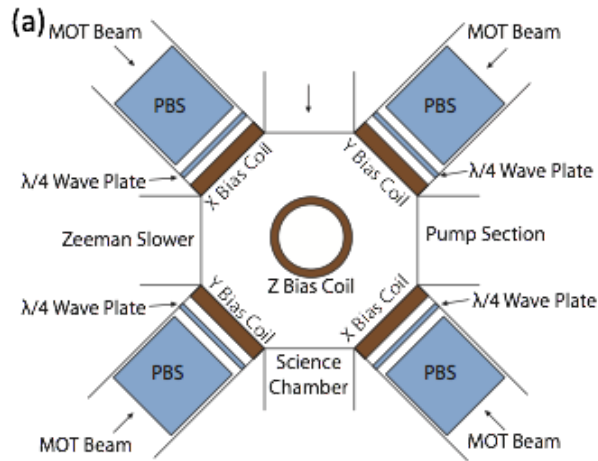


Figure 4.7: (a) Diagram showing top down view of the octagon. Z-axis MOT beams, imaging beams, and optical pumping beams not shown. (b) Picture of the octagon section of the production chamber. Arrows show the direction of the MOT light, the imaging light, and the ODTT. (c) Diagram showing side view of the octagon. Connections to the rest of the chamber and the z-axis beams not shown.

MOT. To avoid this affect, we installed a physical shutter in front of the camera to prevent any exposure of the CCD array before imaging the cloud.

Even though we image on the $|F = 2\rangle \rightarrow |F' = 3\rangle$ cycling transition, we still need to repump on the $|F = 1\rangle \rightarrow |F' = 2\rangle$ transition. Because of the imperfect extinction of the PBS cube in the cage optics, we cannot use the MOT repumper light from the 2→6 fiber splitter during imaging. Instead we use an independent optical fiber to send in repumper light orthogonal to the imaging beam.

4.5 Pump Section

The pump chamber provides a 75-l/s ion pump and a titanium sublimation pump for the production chamber, allowing the pressure in the pump section to reach 2.6×10^{-11} at room temperature, as measured with an ion gauge (Agilent UHV-24P.) The titanium sublimation pump (Agilent 9160050) consists of three Ti filaments mounted in a 3-inch diameter, 9-inch long cylinder. A fresh layer of Ti then gives a H_2 pumping speed of 1,300 l/s, although the effective pumping speed at the octagon is limited by the 100-l/s conductance between the pump section and the octagon.

The end of the pump chamber has a window through which the Zeeman slower beam enters the chamber. The Zeeman slower beam is brought to the chamber by an optical fiber, which is mounted via a cage system to the vacuum chamber. The fiber output is collected by a 150-mm focal length lens, which focuses the beam at the Rb oven in the oven section. Before entering the chamber the beam passes through a quarter-wave plate, giving it a circular polarization to drive σ^+ transitions in the positive field area of the Zeeman slower.

CHAPTER 5

SCIENCE CHAMBER

Our apparatus is rare among ultracold atom experiments in that we plan on breaking vacuum frequently to study different samples. This requirement led us to separate the vacuum chamber into a production chamber and a science chamber. The two chambers are separated by a pneumatic gate valve, allowing us to break vacuum in the science chamber without disturbing the production chamber.

The use of cage optics in the production chamber allows the science chamber to be wrapped in heater tape and vacuum baked without disturbing any of the production chamber's laser cooling and trapping optics. We have demonstrated one week sample replacement times, limited by the time required to bake the science chamber. This procedure has such a minimal affect on the production chamber that we can immediately begin transferring atoms to the science chamber, without having to tweak any production chamber steps. The optics associated with the science chamber are mounted on breadboards that can be removed from the optical table when baking the science chamber. Replacing the breadboards after a chamber bake requires minimal realignment of the optics.

Vacuum pumping in the science chamber is currently provided by a SAES NEX Torr D200-5 combination getter/ion pump and a titanium sublimation pump. The getter pump provides 200-l/s pumping of H_2 and a 5-l/s ion pump, but is limited by the conduction to the rest of the chamber to an effective pumping speed of 30 l/s. The titanium sublimation pump provides roughly 10-l/s effective pumping. With these pumps we can achieve room temperature science chamber pressures of 2×10^{-10} Torr. At this pressure the trap lifetimes in

the science chamber is limited to approximately 10 seconds.

To increase the trap lifetime, we have designed and will soon install a new pump section to the science chamber. This new pump section will replace the currently installed titanium sublimation and NEX Torr pump. The science chamber will be pumped by a titanium sublimation pump providing 300 l/s of pumping, and an ion pump giving another 70 l/s pumping.

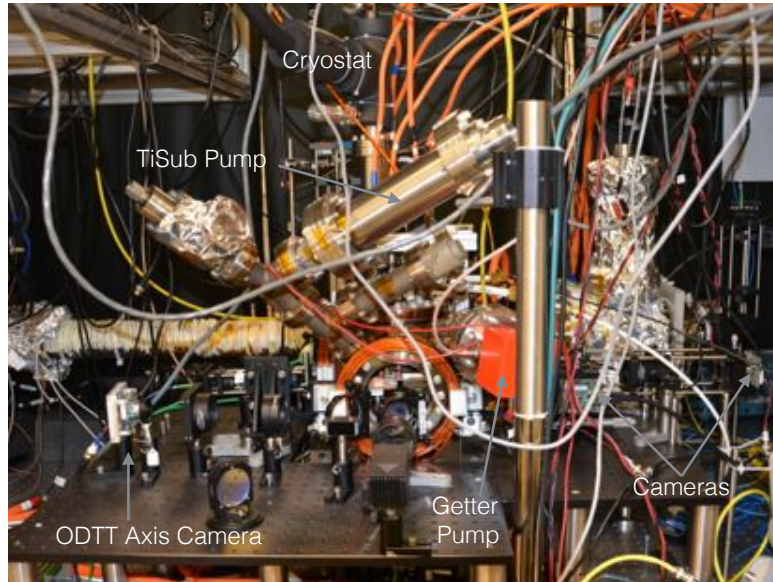


Figure 5.1: Pictures of the science chamber. The vacuum pumps as well as imaging optics are labeled. The imaging optics are on breadboards, which can easily be removed during sample exchanges.

Traditionally samples of interest are fabricated on the same atom chip that contains the atom trapping microwires [35, 54]. This design has several drawbacks, chief among them the coupling of the temperature of the trapping wire with the temperature of the sample. Placing the sample and trapping wires on the same chip poses a severe challenge to cryogenic cooling of the sample, since it must contend with the heat load from the normal-state microwires. Additionally, the temperature of the microwires can increase over 10 °C during an

experimental cycle, leading to sample temperature changes during measurement. Heating from the trapping wires can be avoided if they are superconducting [58,61], but then all sample measurements must be below the critical temperature of the superconducting trapping wires.

More problems arise if one wants to translate the atoms across the sample. One can change the location of the magnetic trap by applying a transverse bias field, but this requires adjusting the other trapping fields as well to maintain height and trap frequency. Also, one must consider the depth of focus of the imaging system. If the atoms are to be moved a distance greater than the depth of focus of the imaging system, then the imaging optics must move along with the atomic cloud.

It can also become difficult to separate the effects of the sample on the atoms, from the effects of the trapping wires. The primary field detection channel is fragmentation of the atom cloud, but this is exactly what one sees when trapping atoms within $100\text{ }\mu\text{m}$ of the trapping wires [66,70,82,83]. If the sample is on the same substrate as the trapping wires, then it can become difficult to differentiate fragmentation from the sample and fragmentation from the trapping wires.

Finally, every time the sample is changed, the atom chip would need to be changed as well. This greatly increases the fabrication time and expense, as well as the difficulty of optimizing the loading of the microtrap each time the sample is changed.

We avoid these pitfalls by physically decoupling the sample from the atom chip (Figure 5.2). The atom chip is glued to a water-cooled assembly, while the sample is attached to a physically separate mount. Because the sample is not connected to the atom chip, the only thermal contact between the sample and

the rest of the chamber is radiative. We place the $100\text{-}\mu\text{m}$ thick sample within $100\text{ }\mu\text{m}$ of the atom chip. With the atoms $300\text{ }\mu\text{m}$ from the atom chip, the trapping will not fragment the atomic cloud, meaning any density changes to the cloud we see are due entirely to the sample.

By placing the sample mount on a three-axis translation stage located out of vacuum, we can scan the field probe across the sample without ever changing the location of the atom chip trap. The horizontal translation distance is limited to 5 mm by the bellows connecting the translation stage to the sample mount. Because the atoms don't move, we can have an imaging system with a depth of focus $< 3\text{ }\mu\text{m}$ and take wide area field maps without ever moving the imaging optics.

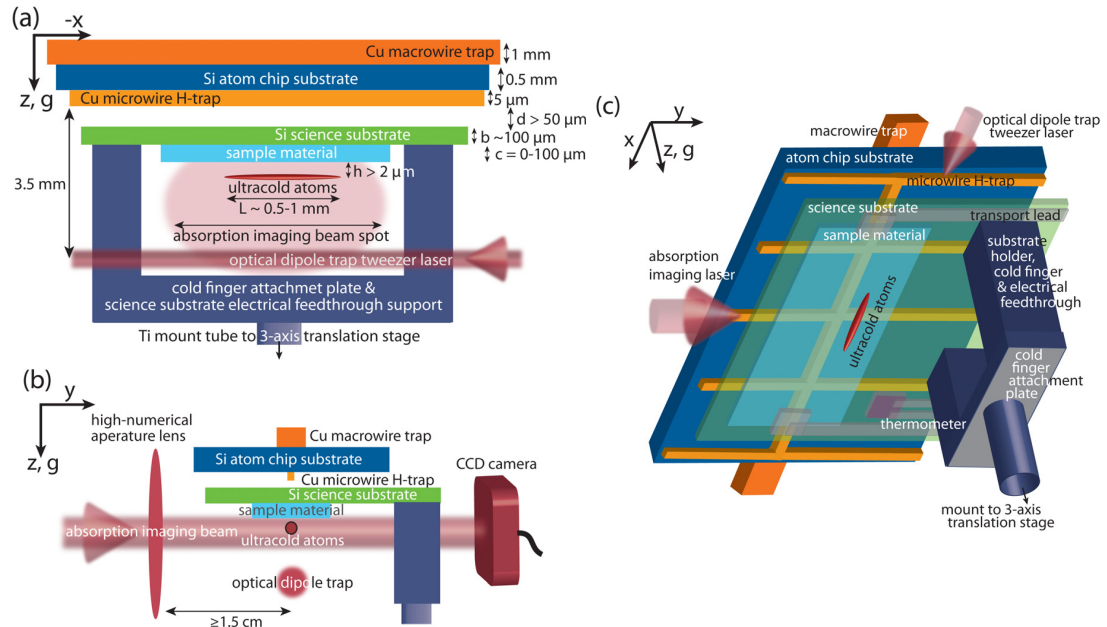


Figure 5.2: Schematic of the relative positions of the atoms, sample, sample substrate, holder, and atom chip wires from the viewpoint along the imaging axis (a) and along the ODTT axis (b). (c) Sketch in perspective of the atom chip with sample substrate underneath.

5.1 Cryogenics

We cryogenically cool the sample using a He flow through cryostat (Janis ST-400). The cold finger is mounted at the top of the science chamber and connected to the sample mount using copper braids. The sample mount is connected to the base of the science chamber and the translation stage by a hollow titanium rod to limit thermal conductance between the sample mount and the rest of the chamber. The temperature at the cold head and at the sample are measured using silicon diode thermometers.

We wished to characterize temperature gradients across the 100- μm thick silicon sample substrates as well as our ability to servo the temperature of the sample. To this end, we fabricated a 100- μm thick sample substrate with several diode thermometers spread across (Figure 5.3.)

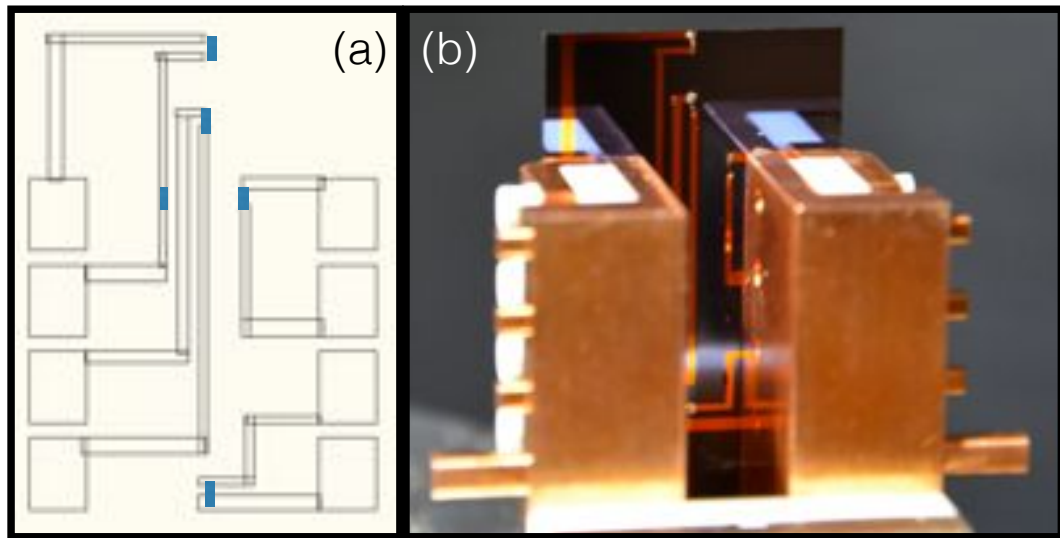


Figure 5.3: (a) Diagram of the cryogenic temperature test sample showing the location of the gold leads, where the blue rectangles are diode thermometers. (b) Image of the cryogenic temperature test sample attached to the sample mount.

We first cooled the sample using liquid nitrogen (LN_2) to 100 K, the lowest temperature we can achieve with LN_2 . Once the sample is at 100 K we replace the LN_2 flow with liquid helium (LHe) and continue to cool the sample. We reach a minimum sample temperature of 35 K when the cold finger is at 4.3 K. Through both LN_2 and LHe cooling we measure no temperature gradient across the sample to within the measurement accuracy of the diode thermometers (± 0.25 K.)

With the sample at 35 K, we tested the ability to control the sample temperature using a heater element in the cold finger. We use a commercial Lakeshore model 331 temperature controller and the heater element to servo the temperature of the cold finger to an accuracy of ± 50 mK. We found the temperature stability of the sample to be within in the measurement error of the diode thermometers. We also measured the time it takes the sample temperature to respond to changes in the cold finger temperature (Figure 5.4) to be approximately 10 minutes.

The science chamber currently has no heat shielding, despite this, we are able to cool the sample to 35 K when the cold finger is at 4.3 K (LHe), and to 100 K when the cold finger is at 77 K (LN_2). Future improvements to the experiment will include the installation of heat shielding in the science chamber to both decrease the minimum achievable temperature and to reduce the use of cryogenics.

5.2 Macrowire Assembly

The ODTT must be kept far from the sample and atom chip to avoid heating and damaging them. The ODTT is located 3.2 mm away from the sample in-

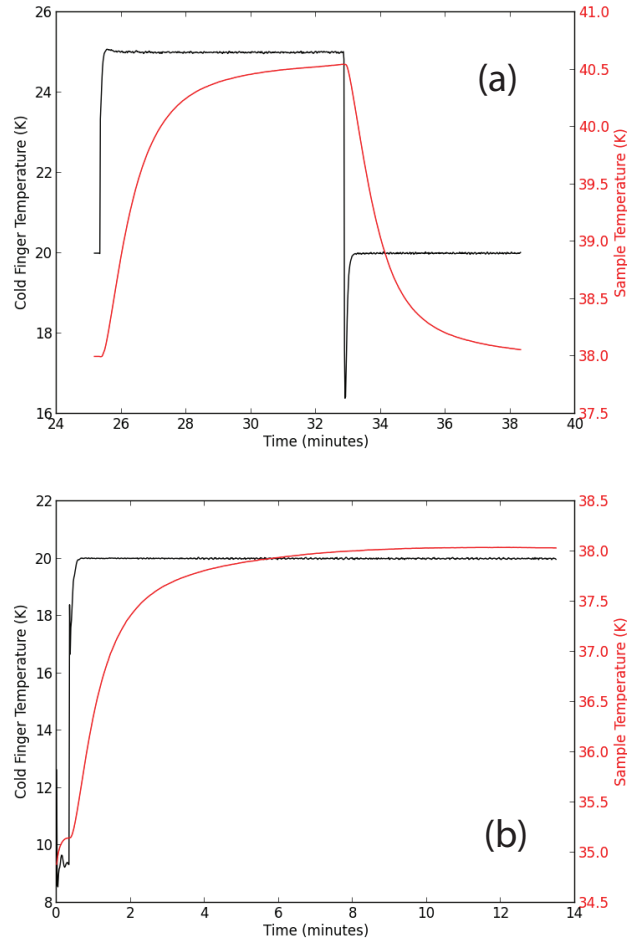


Figure 5.4: (a) Shows the response of the sample temperature (red) to changes in the cold finger temperature (black.) (b) Shows the time needed for the sample temperature to reach steady state after a change in the cold finger temperature.

side the science chamber. This poses a challenge to loading the atoms from the ODTT into the atom chip trap, since we would need to pass more current than the wires can support to trap the atoms so far from the wires.

We solve this problem by using macroscopic copper wires with characteristic dimensions of several millimeters to magnetically transfer the atoms from the ODTT to the atom chip trap. The macrowires are heat sunk via their macor support to a water-cooled stainless steel heat exchanger (Figure 5.5), allowing

the macrowires to support up to 55 amperes of current.

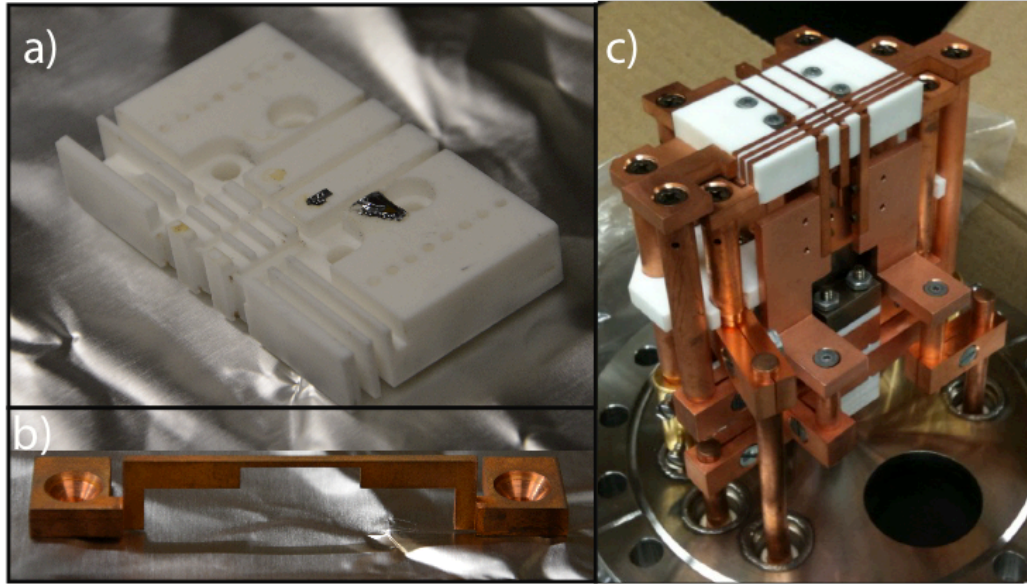


Figure 5.5: (a) Picture of the macor piece that holds the macrowires in position. This is also where the atom chip is glued. Note the metallic piece glued to the macor is a fragment from an atom chip used to test gluing the chip to the macor. (b) A copper bias macrowire. (c) The macrowire assembly mounted in the macor piece. The macor piece is connected to a water-cooled stainless steel heat exchanger, which is mounted to the top flange of the science chamber.

With approximately 30 A of current, the macrowires are able to magnetically trap the atoms 3.2 mm away from the sample. By ramping the currents in the macrowires we both transfer the atoms close to the sample and compress the atomic cloud from a length of 1 cm in the ODTT to 2 mm a distance of $350\text{ }\mu\text{m}$ from the atom chip. The atoms can then be transferred into the atom chip trap.

One design flaw that has become apparent over time is the way we connect the macrowires to the high current feedthrus in the science chamber's top flange. The macrowires connect to a complex arrangement of copper pieces that eventually connect to high current feedthrus in the science chamber's top flange. The high current feedthrus in the top flange are connected to copper rods

by barrel connectors that use set-screws to maintain electrical contact and mechanical stability. Those copper rods in turn are connected to the macrowire assembly by clamp connectors. Both of these methods of connection have proven vulnerable to coming loose during chamber baking and the thermal cycling of normal use.

When these parts loosen, the macrowires can short to each other inside the macor piece. When this happens we must break vacuum to eliminate the short. In order to prevent the macrowires from shorting if the connectors come loose, we have placed thin Kapton sheets between the bare copper macrowires inside the macor piece. The macrowires can also short to the bucket window. We prevent this by using epoxy to attach thin Kapton sheets to the macrowire assembly near the bucket window.

Since the macrowire assembly is hanging from the top flange, gravity will pull the macrowires down towards the atom chip. If the connectors come loose, the macrowires will push against the atom chip, which is held to the macor piece by epoxy. Over time the macrowires will push the atom chip off of the macor piece and will eventually require replacing the atom chip.

A second generation science chamber top flange and macrowire assembly is currently being designed that will replace these connections with ones less prone to coming loose.

5.3 Atom Chip

The first atom chip used a Z-trap configuration made of three independent wires. This design allowed the central and arm wire currents to be set independently, giving some independent control over the transverse and longitudinal

potential. The first atom chip also had a wire halfway between the Z-trap arms to create a dimple trap, as well as a separate wire running parallel to the central wire to act as an RF antenna (Figure 5.6.)

Because none of the arm, dimple, or central wires cross each other as they do in an H-trap geometry, we can drive several amperes of current through each of the wires. One drawback to this design is that we cannot add more sets of arm wires to the single layer atom chip. The rough size of the Z-trap is limited to what is allowed by the single set of Z-trap arm wires.

The first atom chip was fabricated in lab at the University of Illinois at Urbana-Champaign. The chip was fabricated on a doped silicon substrate with a resistivity of approximately $10\ \Omega\text{cm}$ and a 20-nm thick oxide layer. On top of this was deposited a 20-nm titanium adhesion layer followed by a $3\text{-}\mu\text{m}$ silver layer. The silver and titanium were ion milled to define the $100\text{-}\mu\text{m}$ wide trapping wires.

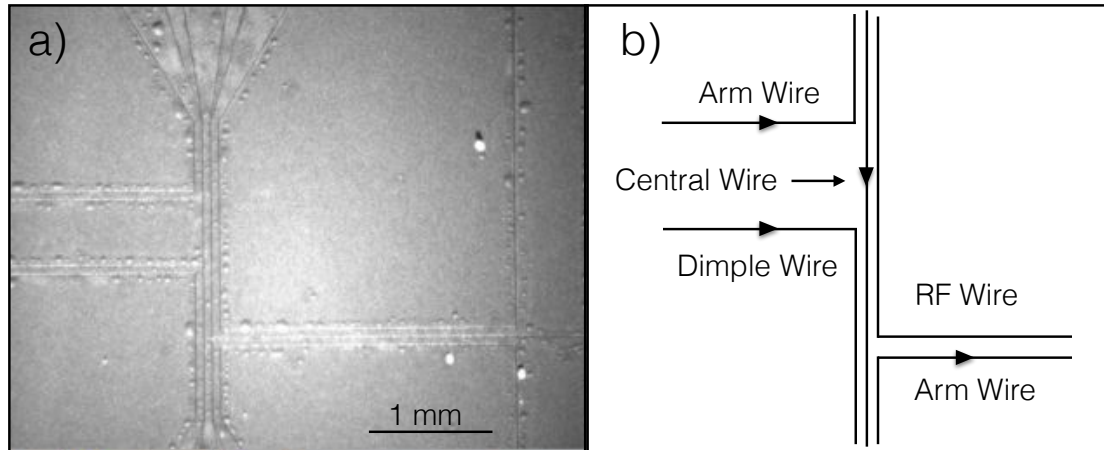


Figure 5.6: (a) Image of the first generation atom chip after wire bond failure. Bubbles can be seen in the silver near the wire edges. (b) Diagram of wire layout and current flow in the first generation atom chip shown in (a).

After fabrication, the atom chip was glued to the macrowire supporting macor block using thermally conductive epoxy (Epo-Tek H77.) Electrical contact to the micro-fabricated wires was made using gold wire bonds between the wires and pins mounted in the macor piece. Each wire was initially connected to its pin by approximately ten wire bonds. During operation these wire bonds began to fail, leading eventually to the loss electrical connection to the central Z-trap wire.

Another problem that arose during use was the loss of adhesion between the titanium adhesion layer and the silver wires (Figure 5.6.) This problem was accelerated by the thermal cycling that would occur when 2.5 A were passed through the microwires. While we could trap atoms in the Z-trap, the bubbling of the wires would have prevented us from doing magnetometry with BECs even if the wire bonds had not failed.

To replace this chip, we designed a second generation atom chip (Figure 5.7.) This atom chip used an H-trap geometry with a single central microwire and five perpendicular arm wires crossing the central microwire. Unlike the first generation atom chip, we can choose different combinations of arm wires to give us greater flexibility to determine the size of the H-trap or Z-trap.

We pay for this flexibility by having the arm wires each connect to the central microwire at a single point. In an H-trap configuration, we must be careful to ground the central microwire current supply, but to leave the two arm wire supplies floating. In a Z-trap configuration a single power supply can be used.

Another drawback of the H configuration is that the maximum current is limited by the heating of the microwires at the arm-central microwire connection. Each wire can comfortably carry 3 A of current, but the heating of the arm-central microwire intersection is determined by the sum of the currents in

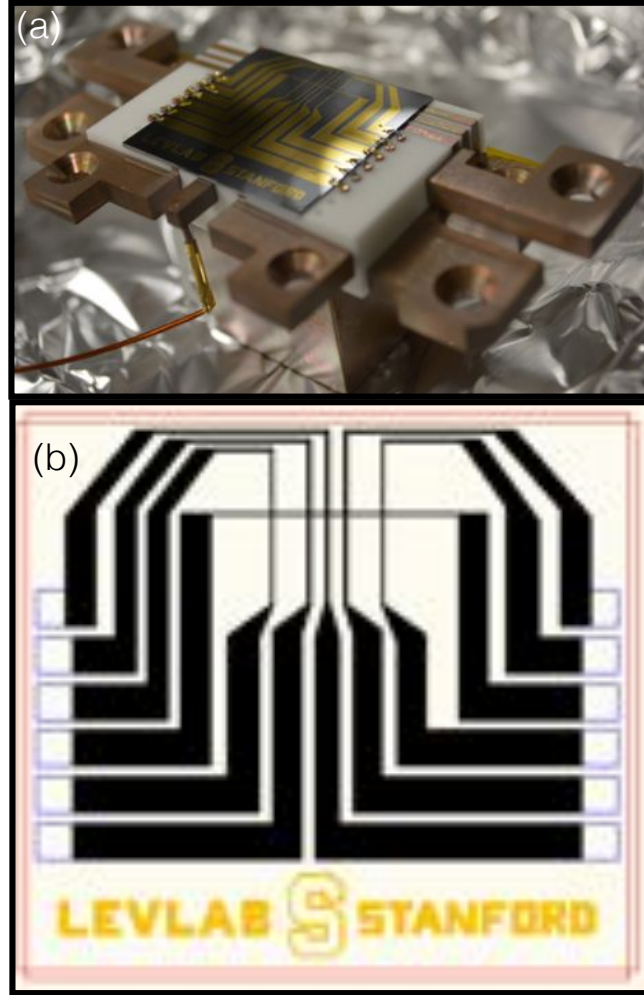


Figure 5.7: (a) Image of the second generation atom chip glued to the macrowire macor piece. (b) Drawing of the microwire layout on the second generation atom chip. There are five arm wires intersecting the central wire. We refer to the middle wire as the dimple microwire. The two arm wires closest to the dimple wire are each 1 mm from the dimple wire, and the two furthest wires are each 3 mm from the dimple wire.

the central microwire and the arm microwire. We can avoid this problem by operating in a Z-trap configuration, but then we lose the ability to independently tune the central microwire current and the arm microwire current.

The second generation atom chip was fabricated on an intrinsic silicon substrate without a grown oxide layer. An intrinsic silicon substrate gives better

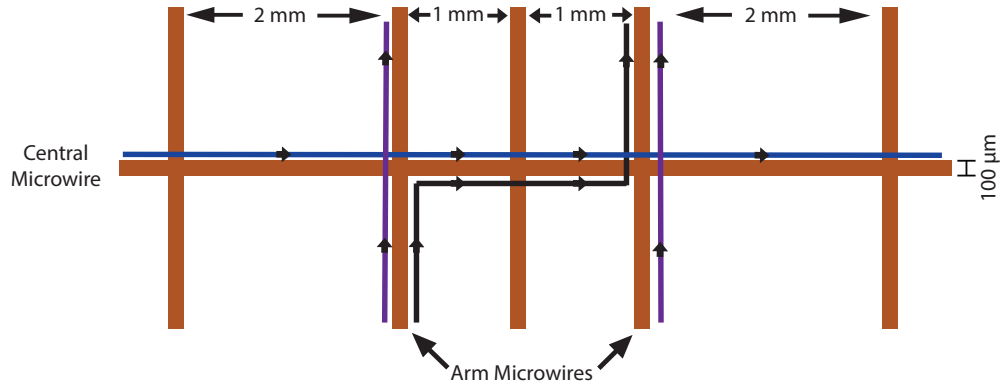


Figure 5.8: Diagram of the currents in the second generation atom chip. The black line indicates the current direction in the Z-trap. The blue and purple lines show the currents in the H-trap

thermal conductivity and has a resistivity of greater than $10,000 \, \Omega\text{cm}$. A $5\text{-}\mu\text{m}$ thick layer of copper was sputtered on top of a 20-nm titanium adhesion layer. The copper wires were covered by a 200-nm thick gold protection layer.

The second generation atom chip was epoxied to the macor block in the same way the first generation chip. Because the first generation chip's wire bonds failed, the electrical connection between the second generation atom chip and the macor mounted pins was made using gold ribbon wire bonds. The ribbon bonds have a dimension of $25.4 \, \mu\text{m} \times 254 \, \mu\text{m}$ and in aggregate offer a lower resistance connection to the microwires.

5.4 Sample

Our design relies on placing the sample on an independent substrate between the ultracold atomic cloud and the atom chip. In order to trap the atoms as close

as possible to the atom chip, and thus achieve high trap frequencies, we need the sample substrate to be as thin as possible.

We tested two different substrates, a 40- μm thick Si substrate and a 100- μm thick Si substrate. In order to achieve good thermal connection between the sample substrate and the sample mount, as well as to reduce mechanical oscillations of the sample substrate, our substrates must have a length of 5.8 cm and a width of 2.5 cm. We found that 40- μm thick Si substrates with these dimensions were too fragile to use, as they would often break during preparation. The 100- μm thick substrates require careful handling, but have proven fairly robust.

One of our design concerns was mechanical vibrations of the cantilevered sample substrate. Our 100- μm thick substrate extends one centimeter beyond the base of our sample mount. Any vibrations of the sample would imprint themselves on our measurement and reduce our field resolution. Before construction we calculated the vibrations of the sample substrate using finite element analysis. We calculated that the RMS vibration amplitude should be less than 100 nm, well below our imaging resolution.

We measured the vibrations of a mirrored 100- μm thick substrate *in-situ* using a Mach-Zehnder interferometer [84](Figure 5.10.) The interferometer optics were mounted below the science chamber and the mirrored sample was used to back reflect the interferometer probe beam.

One of the arms of the interferometer was shifted 80 MHz from the other arm using an AOM, allowing us to separately measure the vertical displacement of the sample and the angular deflection of the sample. We measured RMS amplitude oscillations below 150 nm (Figure 5.11), where some contribution to the amplitude came from the interferometer optics, and not the sample itself.

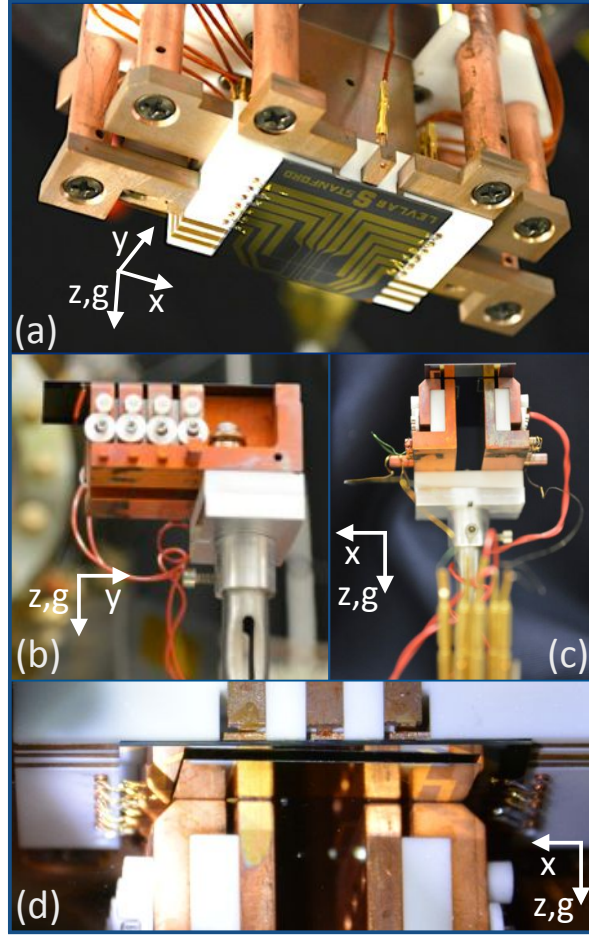


Figure 5.9: (a) Image of atom chip attached to macrowire-macor base and chilled-water block. View of science substrate mount from (b) ODTT viewpoint and (c) imaging beam viewpoint. (d) Science substrate 120 μm below atom chip.

To see why we frequency modulated one of the arms of the interferometer, consider what the detection signal would look like without modulation. Interfering two beams,

$$\mathbf{E}_1 = E_1 e^{i\omega t} \quad (5.1)$$

$$\mathbf{E}_2 = E_2 e^{i(\omega t + \delta)} \quad (5.2)$$

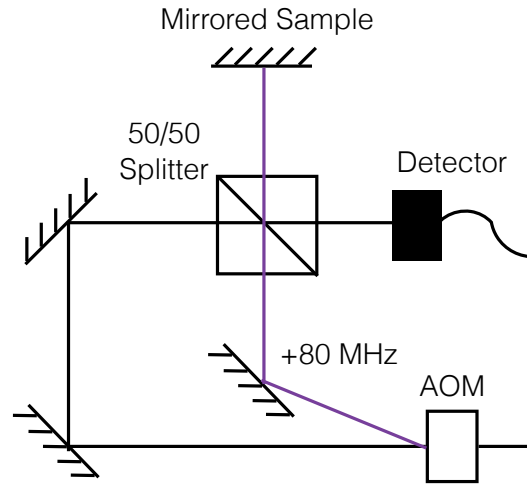


Figure 5.10: (a) Diagram of the interferometer used to measure vibrations of the mirrored sample.

Where δ is the phase difference between the two arms of the interferometer. We measure the intensity on a photodetector,

$$I = |\mathbf{E}_1 + \mathbf{E}_2|^2 \quad (5.3)$$

$$I = |E_1 e^{i\omega t} + E_2 e^{i(\omega t + \delta)}|^2 \quad (5.4)$$

$$I = E_1^2 + E_2^2 + 2E_1 E_2 \cos \delta \quad (5.5)$$

Changes in δ tell us the changes in path length between the two arms and thus the motion of the mirrored sample. In this scheme, vertical displacement of the sample mirror causes changes in the phase δ , while angular deflection of the sample mirror would change the interference intensity via E_2 . Simply by looking at the measured intensity we cannot tell the difference between these two types of motion.

Now consider the case where we modulate the frequency of one of the beams

by Δ ,

$$\mathbf{E}_1 = E_1 e^{i\omega t} \quad (5.6)$$

$$\mathbf{E}_2 = E_2 e^{i((\omega+\Delta)t+\delta)} \quad (5.7)$$

The interference signal is now,

$$I = \left| E_1 e^{i\omega t} + E_2 e^{i((\omega+\Delta)t+\delta)} \right|^2 \quad (5.8)$$

$$I = E_1^2 + E_2^2 + 2E_1 E_2 \cos(\Delta t + \delta) \quad (5.9)$$

and we can differentiate between angular deflections, which appear as amplitude modulations, and vertical displacements, which appear as a phase on the 80 MHz modulation signal.

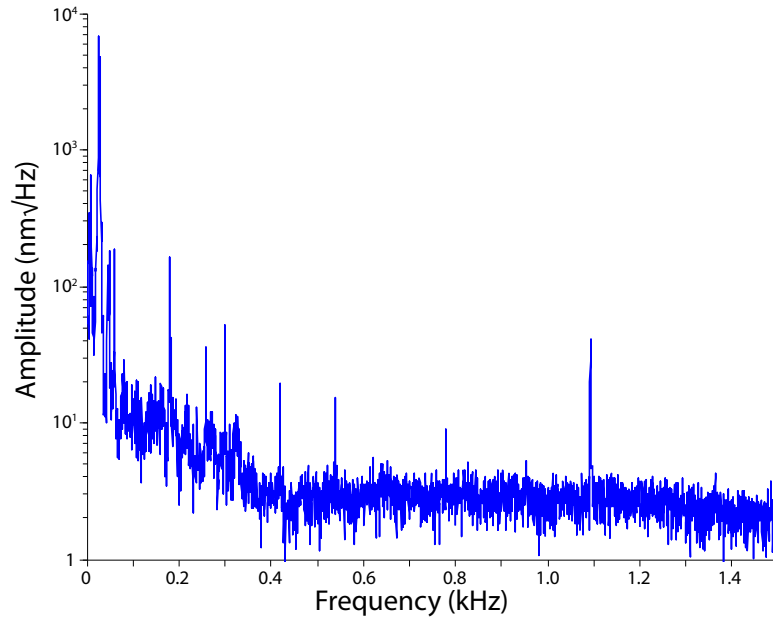


Figure 5.11: Vibration amplitude of the 100- μm thick, cantilevered substrate as measured using a Mach-Zehnder interferometer.

The sample substrate is mounted to the sample mount (Figure 5.9b,c) by electrically conductive epoxy (Epo-Tek H20E.) The sample mount is made from

copper and macor pieces and has a gap of 8 mm between the two arms to allow an imaging beam to pass. One concern with this design was the possibility of straining the thin sample substrate during thermal cycling. The sample mount was designed to minimize such strain by choosing the dimensions of the copper and macor pieces such that their thermal expansion would offset each other.

The titanium rod connecting the sample mount to the three-axis translation stage does contract by approximately $300\text{ }\mu\text{m}$, but this can easily be compensated for with the translation stage.

5.5 Bucket Window and Imaging

In order to achieve imaging resolutions less than $3\text{ }\mu\text{m}$ we need a short working distance between the atoms and the imaging lens. For flexibility and ease of alignment we opted for a bucket window with an out of vacuum imaging system. The custom bucket window (Figure 5.12) allows us to bring the first imaging lens as close as 15 mm away from the atomic cloud.

Imaging atomic clouds near surfaces can be more difficult than imaging atoms in free space. When the atoms are within $100\text{ }\mu\text{m}$ of a surface, the diffraction of the imaging beam from the surface can obscure the image of the atoms. By sending the imaging beam in at an angle to the surface, and reflecting it off the surface, one can increase the distance between the peaks of the diffraction pattern as well as move them away from the atomic cloud [85].

Reflecting the imaging beam off of a mirror surface causes the camera to image the atomic cloud and a mirror image of the cloud (Figure 5.13.) The distance d between the atom image and its mirror image provides a calibration of the distance h between the atomic cloud and the mirror ($d = 2h\cos\theta$) where θ is

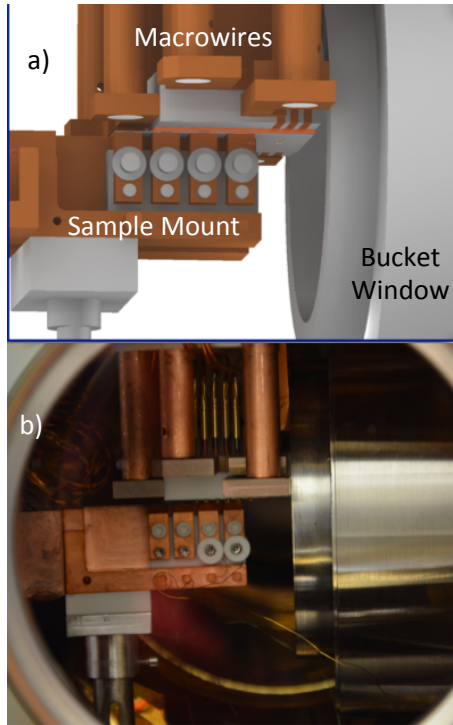


Figure 5.12: (a) Computer drawing of the macrowire assembly 1 mm away from the bucket window. The atom chip is attached to the bottom of the macrowire assembly. The sample mount is shown $100\text{ }\mu\text{m}$ from the atom chip. (b) A picture of the actual assembly.

the incident angle of the imaging beam [86].

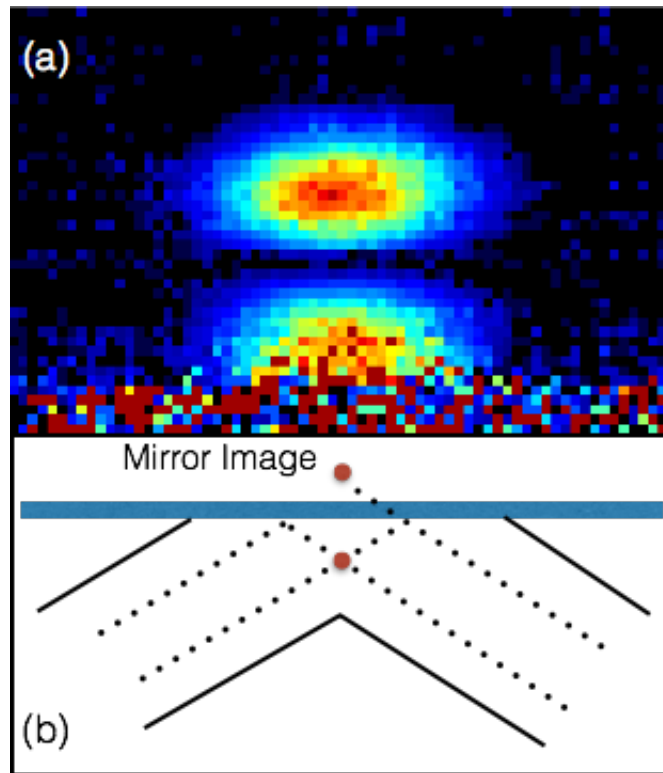


Figure 5.13: (a) Absorption image and mirror image of atoms $100\text{ }\mu\text{m}$ away from a mirror substrate. (b) Illustration of reflected imaging showing the creation of the mirror image.

CHAPTER 6

SYSTEM CHARACTERIZATION

In this chapter we describe the process of bringing a cold ^{87}Rb gas 100 μm away from a cryogenically cooled substrate. First we will discuss the process of creating a cold gas and loading it into the ODTT. Then we will show how to bring the gas close to the cryogenically cooled sample.

6.1 Cold ^{87}Rb Gas Production

Loading atoms into the ODTT follows the process described in [73] and [15]. A 3D magneto-optical trap is loaded from a thermal Rb source via a Zeeman slower. The atoms are loaded from the MOT into a hybrid quadrupole magnetic trap and a 1064-nm optical dipole trap where they are cooled by forced radio frequency evaporation. After evaporative cooling the quadrupole field is turned off and the atoms are loaded into the pure optical dipole trap. In the following sections we give further details of this process, as well as benchmarks of the system performance.

6.1.1 MOT

The MOT [87] is loaded from a thermal beam of ^{87}Rb supplied by the oven section and slowed to approximately 35 m/s by the Zeeman slower [73]. The MOT uses six beams of approximately 20 mW each, detuned -21.5 MHz from the $|F = 2\rangle \rightarrow |F' = 3\rangle$ cycling transition. The MOT beams also carry approximately

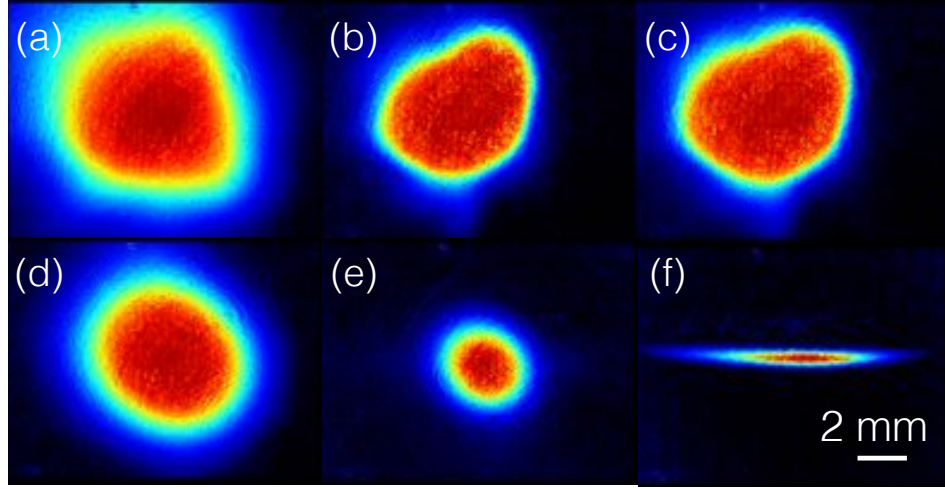


Figure 6.1: Absorption images of the atomic cloud at various stages in the production chamber. (a) Over 1×10^9 atoms in the MOT with a 5-ms TOF. (b) 1×10^9 atoms at $20 \mu\text{K}$ after sub-Doppler cooling and a 5-ms TOF. (c) Atoms after being optically pumped to the $|F = 2, m_F - 2\rangle$ state. (d) Atoms in the hybrid magneto-optical trap after 10-ms TOF. (e) 1×10^8 atoms at $80 \mu\text{K}$ after forced RF evaporation and a 10-ms TOF. (f) 2×10^7 atoms in the ODTT after a 5-ms TOF.

3 mW each of repumping light detuned -5 MHz from the $|F = 1\rangle \rightarrow |F' = 2\rangle$ repumper transition (Table 2.1.) A field gradient of 18 G/cm in the $\hat{z}$ direction is supplied by the anti-Helmholtz MOT coils. The MOT loads 1×10^9 atoms in 5 seconds (Figure 6.1a.)

6.1.2 Sub-Doppler Cooling

After loading the MOT, the atoms undergo polarization gradient cooling [88]. This is done by lowering the total repumper power to $750 \mu\text{W}$ and ramping the detuning of the MOT beams from -21.5 MHz to -136.5 MHz over 19 ms. This process cools the cloud to $20 \mu\text{K}$ with negligible atom loss (Figure 6.1b.)

6.1.3 Optical Pumping

For magnetometry we wish to prepare the atoms in the $|F = 2, m_F = 2\rangle$ state to take advantage of the increased magnetic field sensitivity (Eq. 1.9.) We optically pump [89] the atoms into the $|F = 2, m_F = 2\rangle$ by applying a bias magnetic field in the $+\hat{z}$ direction and shining circularly polarized light in from the bottom of the octagon. The light is resonant with the $|F = 2\rangle \rightarrow |F' = 2\rangle$ transition and the polarization is chosen such that the light only drives σ^+ transitions. Repumper light -5-MHz detuned from the $|F = 1\rangle \rightarrow |F' = 2\rangle$ is applied to repump any atoms falling into the $F = 1$ manifold (Figure 6.1c.)

6.1.4 Hybrid Optical-Magnetic Trap

After the atoms have been prepared in the $|F = 2, m_F = 2\rangle$ state they are magnetically trapped. The magnetic confinement is provided by the MOT coils. We load the trap by rapidly turning on a quadrupole 24 G/cm field (in the strong $\hat{z}$ direction). The field is ramped on using an error function trajectory

$$\text{erf}(x) = \frac{2}{\pi} \int_0^x e^{-t^2} dt \quad (6.1)$$

An error function is used in order to reduce overshooting and ringing by the home built current controllers.

The initial field gradient of 24 G/cm is chosen to both maximize trap loading, and to purify the atomic state population. For ^{87}Rb atoms in the $5^2S_{1/2}$ state the three magnetically trapped states are $|F = 1, m_F = -1\rangle, |F = 2, m_F = 1\rangle$, and $|F = 2, m_F = 2\rangle$. By setting the gradient below the 30.5 G/cm needed to hold the $m_F = 1$ atoms against gravity and holding the atoms for half a second, we ensure that only atoms in the $|F = 2, m_F = 2\rangle$ remain in the trap.

We then compress the trap adiabatically by linearly ramping the field gradient from 24 G/cm to 215 G/cm in 0.8 seconds. At the start of compression, we abruptly turn on the ODTT with 10 W of laser power. At the end of this compression step we are left with 8×10^8 atoms at a temperature of $300 \mu\text{K}$ and a peak real-space density of $8 \times 10^{11} \text{cm}^{-3}$ (Figure 6.1d.)

6.1.5 RF Evaporation and Loading the ODTT

Forced radio frequency (RF) evaporation [90, 91] is performed using a single turn, 1.5-inch diameter coil antenna. The RF frequency is generated by the DDS and is amplified from -8 dBm to 35 dBm (Minicircuits TIA-1000-1R8 and ZFL-500LN+). The RF frequency is linearly swept from 35 MHz to 8 MHz at a rate of 5 MHz/s. At the end of the evaporation sequence, 1×10^8 atoms remain with a temperature of $80 \mu\text{K}$ (Figure 6.1e.)

Evaporation in a quadrupole trap is made difficult by the Majorana loss of atoms from the cloud [48]. Majorana loss occurs when atoms pass through the absolute field zero at the center of the magnetic trap. At $|B| = 0$ the m_F states of the atom become degenerate and it is possible for the atom to spin flip into a strong field seeking state. Majorana loss also leads to heating as the spin-flipped atoms collide with other atoms while being ejected from the trap. This process is particularly detrimental since it is the lowest energy atoms that spend the most time near $|B| = 0$ are thus most likely to be lost.

In order to mitigate Majorana loss, we place the focus of the ODTT beam $65 \mu\text{m}$ below the center of the magnetic trap. This shifts the trap minimum away from $|B| = 0$, reducing the amount of time cold atoms spend near the field zero [73]. It also allows us to load the atoms into the ODTT once the main

RF evaporation ramp is complete.

The atoms are loaded into the ODTT (Figure 6.1f) by linearly ramping down the quadrupole field from 215 G/cm to 6 G/cm in 2.1 seconds. The bias field is ramped along with the quadrupole field to maintain the position of the cloud during the quadrupole ramp. During this process the RF frequency is ramped from 8 MHz to 7 MHz. We can then turn off the RF knife and the quadrupole magnetic fields to leave 2×10^7 atoms in the ODTT at a temperature of $15 \mu\text{K}$.

The transverse frequency of the ODTT is measured by parametric heating to be 500 Hz. With 10 W of laser power this gives a trap depth of $210 \mu\text{K}$ [74] .

6.2 Loading the Atom Chip Trap

In this section we discuss bringing the cold atomic gas from the production chamber and loading it into the atom chip trap. Once in the atom chip trap, the atoms are cooled to 200 nK by forced RF evaporation at a distance of $100 \mu\text{m}$ from the mirrored sample.

6.2.1 Transfer to the Science Chamber

Once the atoms are loaded into the ODTT they are ready to be transported to the science chamber. The focus of the ODTT is moved from the octagon to the science chamber by moving the ODTT focusing lens, which is mounted on the Aerotech translation stage. The translation stage travels 33.3 cm, causing the focus of the ODTT to move the same distance.

The stage accelerates at an average rate of 75 cm/s^2 to a maximum speed of

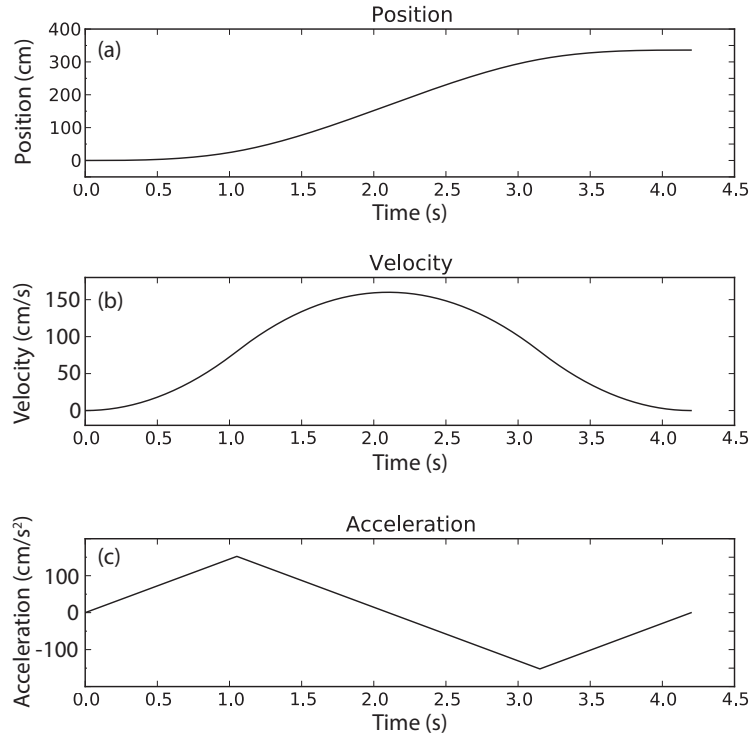


Figure 6.2: The ODTT stage motion profile. This shows an SCURVE value of 100, giving linear changes in acceleration (c), and a corresponding velocity (b) and position (a) profile.

160 cm/s. The stage acceleration profile is linear (Figure 6.2.) The acceleration profile is set by the SCURVE parameter in the Soloist control code. SCURVE accepts values between 0 and 100, and sets the percentage of the stage acceleration profile that is linear. For example, a SCURVE value of 0 corresponds to constant acceleration, while an SCURVE value of 50 (Figure 6.3) gives an acceleration that is constant for half of the acceleration time, and linear in the other half.

During the course of running the experiment we noticed that the atom number transfer efficiency fell from 50% to 10%. By transferring the atoms to an intermediate point between the octagon and the science chamber, and back to the octagon, we found a sharp drop in the number of atoms transported when

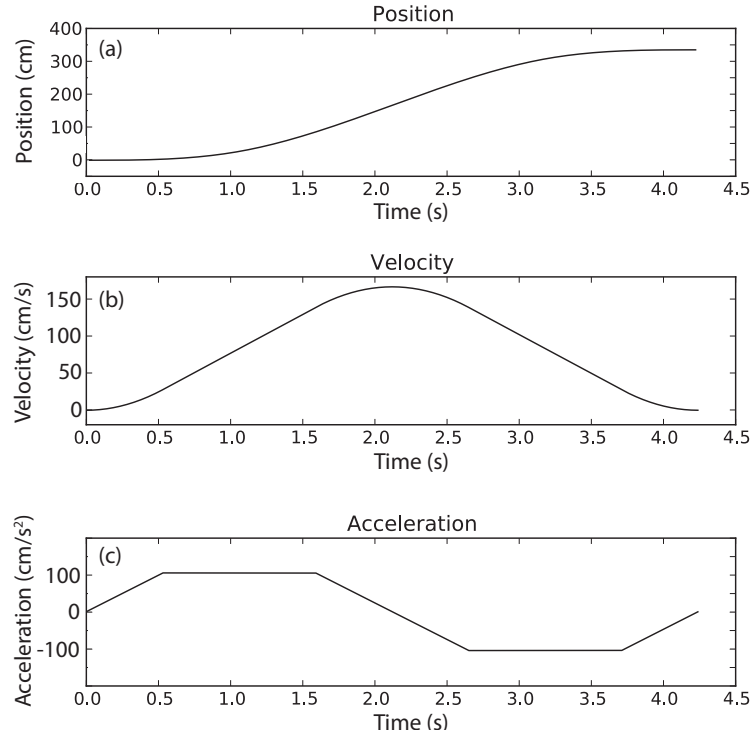


Figure 6.3: The ODTT stage motion profile. This shows an SCURVE value of 50, giving acceleration profiles that are half linear ramps, and half constant acceleration (c), and a corresponding velocity (b) and position (a) profile.

the ODTT passed through the gate valve. Measuring the magnetic field around the exterior of the gate valve with a flux magnetometer confirmed that the gate valve was producing a magnetic field of several gauss. The magnetic field gradient produced by the gate valve was causing atoms to be removed from the ODTT as they passed through the gate valve.

Removing the current from the gate valve drive solenoid had no effect on the magnetic field. The gate valve had been magnetized by the operation of some of the large field coils installed nearby. Fortunately we found that the field coils that had caused the magnetization were not needed to operate the experiment.

We degaussed the gate valve by winding a field coil around the gate valve. We drove the coil with a variac variable transformer which was connected in

series with a high power 1- Ω resistor. To degauss the gate valve, the variac was very quickly ramped up to 40 A and then ramped back down to zero current over the course of approximately 15 seconds.

This process was repeated several times, until the flux magnetometer measured no field from the gate valve. After degaussing, the atom number transfer efficiency returned to 50%.

6.2.2 Loading the Macrowire Trap

The ODTT brings the atoms to a point 3.3 mm below the atom chip. Once there, they are loaded into the macrowire magnetic trap. The macrowire trap is formed by the central macrowire, the y-bias coil, the axial macrowires, and the bias macrowire. The macrowires are the mm scale copper wires mounted above the atom chip. The currents are linearly ramped over 35 ms from zero to 25.2 A in the central macrowire, 42 A in the y-bias coil, 4 A in the axial macrowires, and 4 A in the bias macrowire (Table 6.1.) After ramping up the magnetic field, the ODTT power is linearly ramped off over 40 ms. Through this process we are able to transfer 1.1×10^7 atoms into the macrowire trap at a temperature of 1 μ K.

The atoms are then brought from 3.3 mm to 350 μ m away from the atom chip. In the process they are compressed into a trap with transverse trap frequencies of $2\pi \times 95$ Hz and $2\pi \times 160$ Hz, called the macrowire compress trap. This compression is done by linearly increasing the bias macrowire and axial macrowire current while decreasing the central macrowire current (Table 6.1) over 800 ms. We are able to load 8×10^6 atoms into the macrocompress trap with a temperature of 16 μ K.

	Trap			
	Macrowire Capture	Macrowire Compress	H-Trap	Z-Trap
Central Macrowire	25.2	14	0	0
Bias Macrowire	4	23	27	33
Axial Macrowire	4	8	0	0
Y Bias	42	0	0	0
X Bias	0.3	2.2	3	0
Central Microwire	0	0	2.5	n/a
Arm Microwire	0	0	0.5	n/a
Z Wire	0	0	n/a	2.8

Table 6.1: The current in Amps for each of the macrowire, microwires, and external coils involved in trapping atoms in the science chamber. The n/a values indicate that the wires are not used in that configuration for the given trap.

6.2.3 Loading the Microwire Trap

The atoms are then loaded into the microwire trap formed by the on chip micro-fabricated wires. We have trapped atoms using two different kinds of traps, an H-trap and a Z-trap (Figure 1.3.) In the H-trap the transversely confining central microwire and the axially confining arm microwires are controlled separately. In the Z-trap the central confinement and the axial confinement are provided by the same length of wire. The H-trap gives us greater flexibility in controlling the transverse trap frequency relative to the axial trap frequency. The drawback of the H-trap is the limited amount of current we can safely pass through the central and arm wires. The current is limited by the heating at the point where the central and arm wires cross, making us limited by the sum of the currents in the central and arm wires. In the Z-trap we lose the ability to independently tune the transverse and axial confinement, but the current is now limited by the current in a single wire. We are thus able to achieve much higher trap frequencies in the Z-trap than the H-trap.

The currents for the H-trap are supplied by three HighFinesse BCS 4/12 low noise 4-A bipolar power supplies. One of the power supplies is grounded and

connected across the central trapping wire (Figure 5.8.) The two remaining supplies are kept floating, and each supply is connected across one of the inner arm microwires.

To load the H-trap we linearly ramp up the central microwire current to 2.5 A and the arm microwire current to 0.5 A over 100 ms. At the same time, we linearly ramp the central and axial macrowire currents to zero and the bias macrowire current to 27 A. We also apply a 9.5 G bias field via the X-bias externally sound Helmholtz coil (Table 6.1.) Through this process we can transfer 3×10^6 atoms at 14 μ K into the H-trap. The H-trap has a transverse trap frequency of $2\pi \times 200$ Hz and a longitudinal frequency of $2\pi \times 20$ Hz.

We also can load the atoms into a Z-trap. The Z-trap is created by connecting a grounded HighFinesse BCS 4/12 supply to opposite ends of the two inner arm microwires (Figure 5.8). The Z-trap is loaded by ramping the current in the wire up to 2.8 A over 100 ms (Table 6.1.) This process loads 1.25×10^6 atoms at 50 μ K.

The Z-trap has a transverse trap frequency of $2\pi \times 830$ Hz and a longitudinal frequency of $2\pi \times 34$ Hz. The trap frequencies were measured by abruptly changing the location of the trap and observing the oscillations in the cloud position (Figure 6.4.)

6.2.4 RF Evaporation on Chip

Once the atoms have been transferred to the microwire trap and brought within 400 μ m of the atom chip we evaporatively cool the atoms using forced RF evaporation. The RF signal is generated by the DDS, and is amplified to approximately 3 W by a Minicircuits TIA-1000-R8 amplifier. The RF antenna is a wire

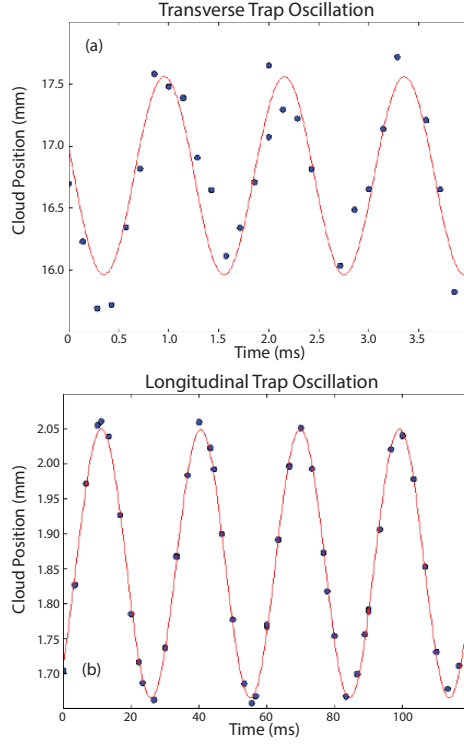


Figure 6.4: Plot of trap oscillation as a function of hold time after moving the center of the trap. (a) Solid line is sine fit to the transverse oscillations showing a trap frequency of $2\pi \times 830$ Hz. (b) Solid line is sine fit to longitudinal oscillations showing a trap frequency of $2\pi \times 34$ Hz.

coil with a 3.8 cm diameter and 2 turns. The antenna is matched to 50Ω using a π -network. The coil is mounted inside the science chamber bucket window approximately 4 cm away from the atoms.

Atoms loaded into the H-trap start at a phase space density of 5×10^{-6} . We divide the RF evaporation into two linear frequency ramps. First, the RF frequency is ramped from 15 MHz to 4 MHz at a rate of 5 MHz/s. It is then ramped from 4 MHz to 2.75 MHz at 0.5 MHz/s. At the end of this sequence we have 8×10^4 atoms at a temperature of 700 nK corresponding to a phase space density of 2×10^{-2} .

Atoms loaded into the Z-trap start with a phase space density of 1.4×10^{-5} .

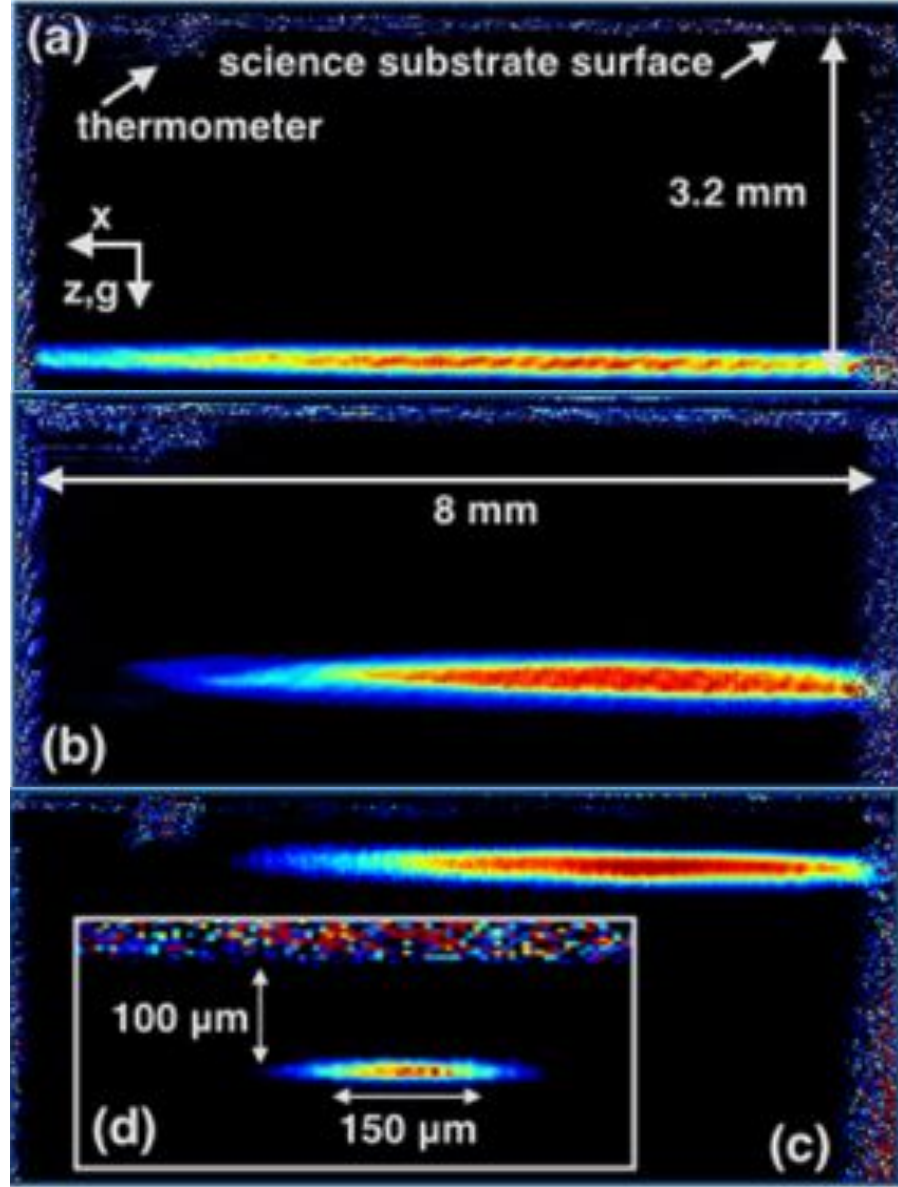


Figure 6.5: Time-of-flight absorption images of: (a) 1.1×10^7 atoms 2 ms after release from the ODTT in the science chamber; (b) atoms 5 ms after release from the macrowire capture trap; (c) 8×10^6 atoms at $16 \mu\text{K}$ in the macrowire compress trap at $h = 350 \mu\text{m}$ from the mirror sample, 1 ms after release; (d) 8×10^4 atoms evaporatively cooled to $[T_x, T_z] = [470, 810] \text{ nK}$, 1 ms after release from the H-Trap [15].

The RF evaporation frequency sweep in the Z-trap is divided into six linear segments (Figure 6.6.) The RF frequency ramp was chosen according to the process

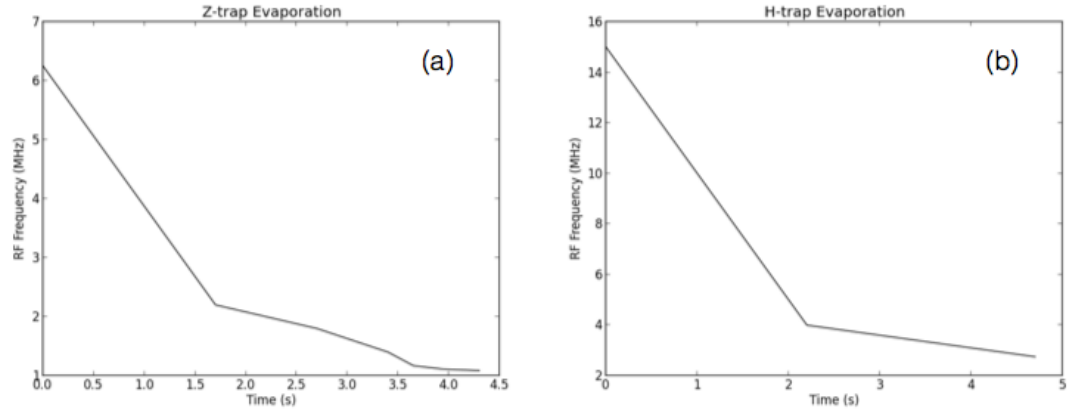


Figure 6.6: Figure showing the RF frequency sweep during evaporation in (a) the Z-trap, and (b) the H-trap.

described in [92]. At the end of the RF evaporation 1×10^4 atoms remain with a temperature of 200 nK, corresponding to a phase space density of 4 (Figure 6.7.)

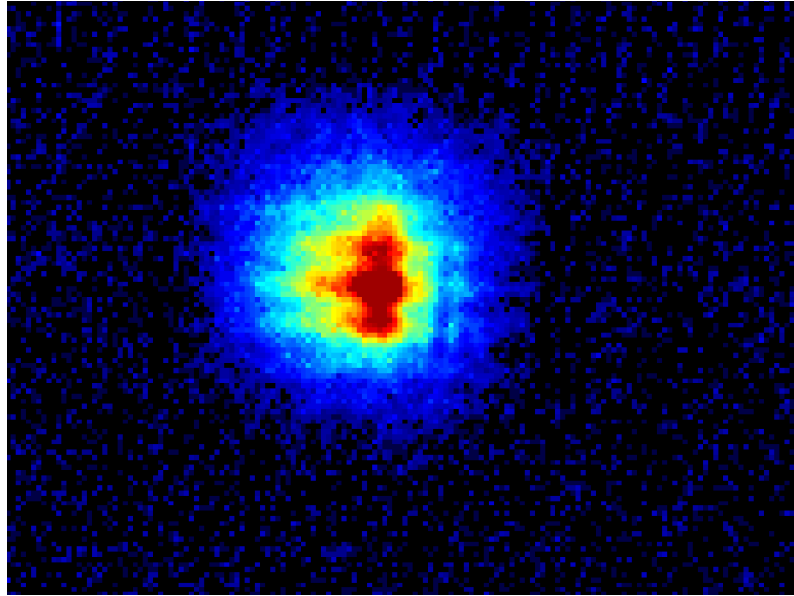


Figure 6.7: Absorption image of 10^4 atoms at 200 nK, 9 ms after release from the Z-trap.

CHAPTER 7

CONCLUSION AND OUTLOOK

We have demonstrated an instrument capable of bringing ultracold ^{87}Rb gases microns away from arbitrary materials at temperatures ranging from 35 K to room temperature. The modular design of the apparatus allows the rapid replacement of samples with minimal disturbance of the atom cooling and trapping equipment. The flexibility of the sample mounting scheme allows compatibility with a wide range of samples. The only sample requirements are that it be vacuum safe at the 10^{-10} level and that be relatively thin ($< 100\ \mu\text{m}$.)

Our near term work will focus on optimizing the procedure to produce large BECs in the atom chip trap. Once that is accomplished, we will calibrate the magnetic field sensitivity and spatial resolution of the microscope using a calibration sample (Figure 7.1.) The calibration sample is a $100\text{-}\mu\text{m}$ thick silicon substrate with 200-nm thick gold wires deposited in two types of arrangement.

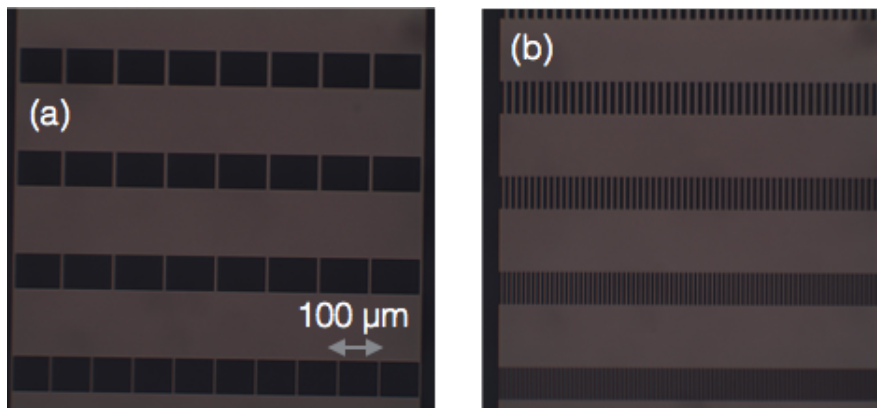


Figure 7.1: Pictures of a photomask of the calibration sample. (a) Shows grids of wires of different widths and (b) shows grids of different wire widths and spacing.

One arrangement consists of rows of uniform wires with a set spacing between the wires. Each row is an array of wires with different widths and spac-

ing, ranging from $0.6\text{ }\mu\text{m}$ to $15\text{ }\mu\text{m}$ such that the width of the wire is equal to the spacing between the wires. The second arrangement consists of wires of varying widths, ranging from $0.6\text{ }\mu\text{m}$ to $15\text{ }\mu\text{m}$. By placing the atomic cloud above increasingly small features, we will be able to directly measure the smallest features the microscope can detect, and by varying the current in the wires, we will be able to determine the true field sensitivity.

Once the atom chip microscope is fully calibrated, we will be able to study a wide range of strongly correlated and topologically nontrivial [33] materials. Besides these materials, the apparatus will be well suited to studying the Casimir-Polder potential [36,93] as well as hybrid quantum systems [35,53].

APPENDIX A

CONTROL HARDWARE OUTPUTS

The digital control output is provided by a National Instruments PCIe-6536 board. Table A.1 gives the mapping between the board output and the hardware being controlled. Analog output is provided by a National Instruments PCI-6733 board (Table A.2) and a PCI-6723 board (Table A.3)

Port, Line	Output	Digital High Equals
0,0	Zeeman Beam Shutter	Open
0,1	Repumper AOM	On
0,2	MOT Beam Shutter	Open
0,3	Zeeman Beam AOM	Off
0,4	Octagon Camera Trigger	Capture
0,5	Atomic Beam Shutter	Open
0,6	Science Chamber Imaging Beam Shutter	Capture
0,7	Imaging Beam AOM	On
1,2	DDS Profile Pin	1
1,3	DDS IO Update	1
1,4	DDS Reset	1
1,7	ODTT AOM	On
2,0	Octagon Imaging Beam Shutter	Closed
2,1	MOT Repumper Beam Shutter	Open
2,2	RF Switch	Science Chamber
2,3	DDS RF Profile Pin	1
2,4	Optical Pumping σ^+ Shutter	Open
2,5	Octagon Imaging Repumper Shutter	Open
2,6	Octagon Camera Shutter	Open
2,7	ODTT Axis Imaging Shutter	Open
3,0	Beat Note Lock	Lock
3,1	Optical Pumping σ^- Shutter	Open
3,2	Optical Pumping AOM	On
3,3	Diagnostics and Testing Line	1
3,4	Science Chamber Camera Trigger	Capture
3,5	ODTT Axis Imaging Beam Shutter	Open
3,6	Aerotech Stage Trigger	Trigger
3,7	Science Chamber Imaging Repumper Shutter	Open

Table A.1: The mapping between digital device 1 (NI PCIe-6536) and the hardware being controlled.

Line	Output
AO 0	Octagon X Bias Coils
AO 1	Octagon Y Bias Coils
AO 2	Octagon Quadrupole Coils
AO 3	Octagon Z Bias Coils
AO 4	MOT Repumper AOM Power
AO 5	RF Evaporation Power
AO 6	Imaging Beam AOM Power
AO 7	ODTT AOM Power

Table A.2: The mapping between analog device 2 (NI PCI-6733) and the hardware being controlled.

Line	Output
AO 8	Science Chamber Y Bias Coil
AO 9	Dimple Macrowire Current
AO 10	Science Chamber X Bias Coil
AO 11	Science Chamber Compression Coil
AO 12	Science Chamber Z Bias Coil
AO 13	Zeeman Slower Section 1
AO 14	Bias Macrowire Current
AO 15	Central Macrowire Current
AO 16	Axial Macrowire Current
AO 17	Arms Microwire Current
AO 18	Central Microwire Current

Table A.3: The mapping between analog device 3 (NI PCI-6723) and the hardware being controlled.

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