THE UNIVERSITY OF CHICAGO

# THE DESIGN AND CONSTRUCTION OF A QUANTUM MATTER SYNTHESIZER

# A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS

ΒY

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CHICAGO, ILLINOIS AUGUST 2023

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# ACKNOWLEDGMENTS

First, I must extend my deepest thanks to my advisor, Prof. Cheng Chin for making this work possible and for being my teacher in the lab. No matter the subject area, Cheng has the ability to ask exactly the right questions to quickly distill problems to their essentials, then immediately begin probing beyond their scope. At the same time, he is always open to multiple perspectives on a given topic, which makes our discussions very engaging and enjoyable. Being around him and seeing him at work over the years has greatly influenced the way I think and he will always remain a model scientist I work towards becoming. Beyond his skills as a physicist, what always impressed me about Cheng is how much attention he gives back to every single one of the group members. It is clear he wants to see us grow in the lab and in our careers, and he spends ample time to foster this. Lastly, Cheng creates a very warm environment. Group dinners and outings are a frequent year-round occurrence, and they go a long way to create a friendly atmosphere in lab. I think everyone appreciates these.

I also want to sincerely thank the many amazing people that I shared time with on the QMS experiment. This experiment would not be what it is today without their contributions. In the early days of construction, Gustaf Downs set the lab's standard for attention to detail and relentless work ethic. Dr. Chen-Yu Xu showed me how to think clearly and slowly through unfamiliar and complicated situations, and gave me lots of encouraging words when I had a hard time. Later, I had the pleasure to work with Dr. Mickey McDonald, who brought a huge amount of energy and creativity to our group. His determined attitude to exhaust all possible avenues when troubleshooting our superresolution mysteries impacted me greatly. Mickey is also a great friend to have and he hosted the best parties for the group, punctuated by his ukelele playing. I also want to shout out the slew of undergrads that have passed through QMS and left their mark: Paloma Ocola, Yungpeng Ji, Mikhail Usatyuk, Jacob Pierce, Cameron Mehling, Connor Fieweger, Lucas Baralt, Huiting Liu, Samir Rajani,

Callum Welsh, and Nick Li. The QMS experiment will be carried forward by the wonderful trio of Mingjiamei Zhang, Lauren Weiss, and Evan Yamaguchi. Jiamei joined in 2018 and immediately showed virtuosity when it came to optical design and ultracold atomic physics. Her unique lattice beam setup was very elegant and compact, and we still rely on it to this day. Everyone in QMS seeks her opinion on things, because they usually make a great deal of sense. Lauren is a go-getter who brings infectious energy to the lab. She approaches tasks in the lab very proactively and meticulously — it's been fantastic to work alongside her. Evan is the newest member, but has already quickly impressed me with the minimal design present in his optical setups. I have no doubt the QMS is in excellent hands with these three at the helm.

I must also thank the Chin Lab at large for their company throughout the years. Especially those that came before me, as every one of them helped me learn important lessons about physics and experimental techniques when I was still new to the lab. They are: Li-Chung "Harry" Ha, Logan Clark, Lei Feng, Anita Gaj, Jiazhong Hu, Jacob Johansen, Colin Parker, and Brian DeSalvo. I especially got to spend time with Logan, Lei, and Brian they are three of the sharpest scientists and human beings I know. I try to emulate them when I can. I am also massively appreciative towards my "generation" of Chin Lab: Krutik Patel, Kai-Xuan "Kevin" Yao, Zhendong Zhang, and Geyue "Frank" Cai. When it came to extremely fine technical details, there was no one better to talk to than Krutik. He also has a bright personality that uplifted our lab. Kevin is one of the most intelligent people I've ever encountered; he's also very open-minded and easy to talk to. Zhendong's dedication to his work always inspired me to work harder — no matter what odd hour I went into the lab, there was a good chance I'd catch Zhendong there too. Frank is very sharp, but also very humble. I never get tired of him telling me, "long time, no see" regardless of how much time has elapsed since I last saw him. I am very excited for the future of the Chin Lab. The younger members have breathed fresh life into our space and have set a high standard

for their quality of work. Thanks to Shu Nagata, Henry Ando, Jay Jachinowski, and Sarah McCusker.

I want to also share my gratitude for the staff at the Department of Physics and the James Franck Institute. Thank you to Maria Jimenez, who plays an instrumental role in our group to keep things running smoothly — we would be in total disarray without her. Thanks to John Phillips and his successor Bentley Wall, who work tirelessly at seemingly all hours to keep our Gordon Center lab space well-regulated and secure. Thanks to Luigi Mazzenga for introducing me to and guiding me in the art of machining. Thanks to Autym Henderson, Putri Kusumo, and Zosia Krusberg for keeping me on track and informed when it came to departmental affairs.

I am deeply grateful to my family and friends. Mom, dad, and my sister Nath give me all the love and support I need, even when I don't visit them as often as I should. I am blessed to have them. Thank you to my friends in Chicago, especially Zoheyr, Andrew, Akash, Ryan, and the rest of the lunch crew. When I needed to escape the basement, they were the best people to be around. Special thanks to J. K. and to my friends from San Diego and Cupertino for continuously refilling my energy.

# ABSTRACT

Quantum simulation using ultracold atoms is a rapidly-advancing field that has made significant contributions toward our understanding of quantum many-body phenomena. The frontier of quantum simulation is tied to our ability to prepare and measure the quantum state with high fidelity.

This thesis describes the quantum matter synthesizer (QMS), a new experimental platform in which individual particles in a lattice can be resolved and re-arranged into arbitrary patterns. The ability to spatially manipulate ultracold atoms and control their tunneling and interactions at the single-particle level allows full control of a many-body quantum system.

The envisioned experimental sequence is as follows. Cold cesium atoms are first stochastically loaded into an 2D triangular lattice. Subsequently, degenerate Raman sideband cooling is applied to the atoms and their fluorescence is collected on a low-noise CCD to image the atomic distribution in the lattice. A re-arrangement algorithm computes tweezer trajectories to bring the atoms to a desired configuration. The computed moves are then streamed to a digital micromirror device, which is capable of moving an array of tweezers in small discrete steps at a speed of 2.5 kHz. After re-arrangement, the atoms are again cooled and their final distribution imaged, at which point the quantum matter is ready for quantum simulation.

We present the design and characterization of the QMS, and highlight several initial results, which include a new superresolution imaging method for cold atoms, site-resolved imaging of the atoms, and an efficient loading scheme capable of producing lattices with 74% filling. Once completed, the QMS will enable detailed studies in quantum transport and quantum phase transitions where the initial state is deterministically prepared and the final state is measured with single-site resolution.

# CHAPTER 1 INTRODUCTION

#### 1.1 Quantum simulation with ultracold atoms

The rapid rise of quantum technologies in the  $21^{st}$  century has been nothing short of remarkable. While humankind was previously an observer to the quantum world, nowadays we have the requisite tools to routinely create relatively complex quantum systems and deploy them for useful applications using tabletop laboratory setups. Some of the most exciting directions for this new era of quantum machines are in quantum computation, quantum simulation, quantum communication, and quantum sensing [1, 2].

Quantum computing and simulation are very intense research fronts, as growth in these areas promises access to a world largely unexplored in the realm of scientific understanding [3–11]. The goal is to solve a class of problems that are intractable via classical computation. Such problems arise in all areas of science, including condensed matter physics, high-energy physics, cosmology, quantum chemistry, life sciences, cryptography, search algorithms, finance, and logistics, to name a few.

As a slightly more concrete example, consider the prototypical case of a quantum system  $|\psi(t)\rangle$  evolving with time t in accordance to Schrödinger's equation under a time-independent Hamiltonian H

$$i\hbar \frac{d}{dt}|\psi\rangle = H|\psi\rangle. \tag{1.1}$$

The solution can be written as

$$|\psi(t)\rangle = \exp(-i\hbar Ht)|\psi_0\rangle. \tag{1.2}$$

In the case of a system of N qubits (i.e., spin- $\frac{1}{2}$  particles), the quantum state requires storage of  $2^N$  numbers. A system of  $N \approx 40$  already exceeds the storage capabilities of modern computers, while a system of N = 100 requires more bits in computer memory than the estimated number of atoms in the observable universe. The situation is worsened when we additionally consider storing H (a  $2^N \times 2^N$  matrix) and performing calculations.

The quantum computing approach mimics the structure of classical digital computing in that information is algorithmically processed via consecutive application of logical gates. However, instead of storing information in bits, quantum computing uses quantum bits (qubits), the source of the performance boost. This architecture represents the most general approach of quantum solvers since the algorithms can be programmed to solve any problem. Indeed, there already exist several quantum computing platforms available for Internetconnected end-users to implement rudimentary codes. While quantum computation may be considered the holy grail, it is unclear when the technology will be mature enough to *deliver the goods*. Due to the qubit's fragile nature and limitations in modern quantum computing architectures, two fundamental challenges are quantum error correction and scalability – obstacles without clear resolutions. In the meantime, we can get at many interesting problems via analog quantum simulators.

Rather than solving these hard problems computationally, the goal of quantum simulation is to re-create Eq. 1.2's  $|\psi_0\rangle$  and H in the lab, observe the evolution directly, and build up statistics over many experimental realizations. This paradigm, instituted by Richard Feynman in 1982 [3], has resulted in breakthroughs in our understanding of quantum phase transitions, quantum transport, quantum chemistry, topological phases of matter, and more.

Ultracold atoms have emerged as very attractive building blocks for a quantum simulator [6, 10, 12]. They come as both bosons and fermions. Their physical, optical, and collisional properties have been precisely measured. They can be cooled and trapped in an isolated vacuum chamber, away from the environment. We can perform coherent manipulations by controlling the electromagnetic fields we subject them to, for example by using any combination of lasers, microwave pulses, and electromagnets. Their interactions can be easily tuned with the magnetic field via a Feshbach resonance [13].

The frontier of quantum simulation is fundamentally tied to our ability to prepare, control, scale, and measure the quantum system. Within the experimental toolbox, several key technological developments in the past decades have pushed atom systems to the forefront of quantum simulation.

One of these tools is the optical lattice, a regular potential landscape formed by the interference of laser beams [9, 5, 8, 14]. These impose a crystalline structure on the quantum matter, modifying the kinetic energy to take on the familiar band structure from condensed matter systems. At far detunings, the lattices are essentially conservative potentials. Their high degree of uniformity across 100s to 1000s of lattice sites make them highly attractive testbeds for few-body and many-body systems. Ultracold atoms placed in such a pristine landscape take on quantized energies given by the lattice wells, and their dynamics are governed by easily accessible tuning of the tunneling and on-site interaction strengths. This is known as the Hubbard model. The dimensionality and geometry can easily be tailored via the beam geometry and polarization. Additional complexity can be introduced via tilting, shaking, and deforming the lattice [15–22]. Ubiquity of optical lattices in the cold atom lab has been reached due to readily accessible and affordable commercial lasers. Milestone experimental results are in quantum phase transitions [23–25], artificial gauge potentials [26], frustrated systems [27–34], non-equilibrium systems [35, 18], quantum transport [36, 37], thermalization [38–41], and more.

Another enabling tool is the optical tweezer, and specifically the optical tweezer array. An optical tweezer is a very tightly focused dipole trap with a small trapping volume compatible for single or few atom loading. These are typically made using powerful microscope objectives to create the small spot size, and the single tweezer can be extended to arrays of hundreds of tweezers. By adding movement, atoms can be re-arranged and initialized in unique spatial configurations that are amenable for Rydberg physics, long-distance entanglement, quantum algorithms, and more [42, 7, 43, 44, 11, 45–49, 37].

Lastly, the advent of the quantum gas microscope in 2010 by the groups of Immanuel Bloch and Markus Greiner have granted access to the atomic density distribution at the single atom level [50, 51]. By seeing the full density distribution, exotic matter phases can be observed directly [52, 53, 25, 54, 36, 55–63, 37, 64, 65]. Moreover, correlations and dynamics at the microscopic level can be measured.

## 1.2 Engineering quantum many-body states atom-by-atom

The topic of this thesis is about our approach to quantum simulation using ultracold atoms, an archetype which combines the optical lattice with the optical tweezer array in a microscope experiment. In this way, we get the benefits of the clean Hubbard-regime optical lattice potential for an atom distribution that is initialized by the tweezer array. Site-resolved imaging then allows readout of the density distribution over time. A sketch of a typical experimental sequence is described below and shown in Fig. 1.1.

- 1. Initial loading and imaging. We prepare atoms in the ground state of an optical lattice using degenerate Raman sideband cooling. Photons emitted from the cooling process are captured on a CCD to image the atom distribution at the single site level.
- 2. **Tweezer array re-arrangement.** The image is processed and individual site occupations are determined. A set of moves for an optical tweezer array is computed and executed to bring the atoms to a prescribed spatial configuration.
- 3. Quantum matter. A second round of cooling and imaging reduces any heat acquired during the re-arrangement and confirms the final atom distribution on the CCD. At this point the sample is ready for a quantum simulation experiment. The Hamiltonian of interest can be tuned via the interactions (using a Feshbach resonance) and the tunneling parameter (by adjusting the lattice strength).



Figure 1.1: Illustration of a quantum matter synthesizer. a) A randomly loaded lattice of atoms is imaged to determine the initial distribution. Using the site occupancies, a dynamic tweezer array rearranges the atoms to a user-specified initial configuration. Subsequent cooling produces a many-body quantum sample. b) Essential features of the quantum matter synthesizer are illustrated. Notably, the dual objective design is used to project the trapping potentials and image the atomic fluorescence.

# **1.3** Problems of interest

# 1.3.1 Quantum walks

Quantum walks, the quantum mechanical version of a classical random walk, play an important role in quantum simulation experiments as well as in quantum algorithm development. From the quantum simulation perspective, single-particle quantum walks can test the "quantumness" of the system, while many-body quantum walks have simulated nontrivial physical models such as Hanbury Brown-Twiss interference, bosonic bunching, fermionization, and polariton propagation. In the context of computer science, it has been realized that the quantum walk can be used as a general computing object, particularly suited for search algorithms.

Quantum walks behave very differently from their classical counterparts. The classical random walk was formulated in the late 19th and early 20th century in multiple contexts by Lord Rayleigh (sound propagating in an inhomogeneous medium), Louis Bachelier (finance), and Albert Einstein (Brownian motion). A key result from these studies is that a random walker will spread a distance  $\langle R \rangle$  from the origin in N steps as  $\langle R^2 \rangle \sim N$ , the essential feature of diffusive processes.

The quantum version with continuous time steps replaces the randomness from the classical version with unitary operators and wave function collapse upon measurement. For a single particle restricted to a lattice, the probability distribution develops oscillations arising from self-interference by the walker, and on-site probability amplitudes can fall and revive over time, in stark contrast to the monotonic nature of classical walkers (see Fig. 1.2). Due to the underlying principle of superposition, quantum walkers can take many paths simultaneously, leading to linear diffusion of the particle.

There have been a variety of physical systems adapted to explore quantum walks, most notably classical optics, quantum optics, quantum dots, and ultracold atoms. Since the introduction of the quantum gas microscope, a microscopic view of ultracold atom quantum walkers on an optical lattice have been demonstrated in single-particle 1D and 2D systems as well as few-body 1D systems.



Figure 1.2: Single-particle quantum walk on a triangular lattice. a) Probability distribution for a single quantum walker at time t = 2 tunneling times. b) Plots of the probability density trajectories for the initial site (blue), nearest neighbors (yellow), and next-nearest neighbors (green).

### 1.3.2 Environment-assisted quantum transport (ENAQT)

ENAQT is the phenomena whereby a finite level of noise in a quantum system can enhance the energy transport between the nodes, relative to the low-noise and large-noise limits. The low-noise case corresponds to a completely localized system (e.g., Mott insulator or Anderson localized). On the other hand, very strong noise also produces localization via the quantum Zeno effect. At an intermediate noise level, the environment can produce a state-changing kick and induce transport. This enhanced transport has garnered interest in both the life sciences and the quantum gases communities.

Just as in the case of quantum walks, the QMS is well-suited for studies of ENAQT, which is essentially a few- to many-body quantum walk connected to a noise bath. By combining an acousto-optic modulator with a DMD, it is straightforward to induce spatiotemporal noise on a walking system by projecting a random intensity on a single site. In doing so, the resulting Stark shift creates an effectively disordered lattice potential. Greyscale control of the laser intensity with a DMD can be realized via dithering.

### 1.3.3 Frustration on the triangular lattice

When a many-body system is constrained to lie on the sites of a 2D triangular lattice, situations involving frustrated behavior arise as a result of the sixfold rotational symmetry. Frustrated systems are a foundational research area in condensed matter physics, magnetism, and even the life sciences in the form of protein self-assembly. A paradigmatic example of spin frustration is given by antiferromagnetic interactions on a triangular lattice. Unlike the square lattice, where the spins can comfortably align in a checkerboard fashion, the triangular lattice prohibits a similarly clean ground state, and the spins must instead fissure into one of a multitude of available ground states with no apparent long-range order. At sufficiently low temperatures, such a system can form a quantum spin liquid, which describes a many-body spin superposition state of antiferromagnetic pairs. Excitations on the spin liquid known as spinons can travel through the lattice, disrupting the spatial spin correlations as it moves from site to site.

Due to the rich behavior of frustrated systems, they are a very active direction for quantum simulators. Several proposals exist to realize a system of frustrated bosons on a triangular lattice. To induce the appropriate antiferromagnetic interactions, the tunneling between nearest-neighbor sites must be made anisotropic. Furthermore, it is necessary to create positive tunneling matrix elements, which can theoretically be achieved by rotating the entire lattice along an elliptic orbit.

The QMS with its triangular lattice potential is well-suited to studying such problems. In particular, our lattice is formed via three off-axis beams that share multiple common optics (see Chapter. 4 for more details on the lattice). Rotating its phase along elliptical orbits is possible by simply steering one of its mirrors with electronically-controlled actuators. Quantum gas microscopy of the atoms then allows us to look at frustrated correlations at the site-resolved level.

#### **1.4** Properties of cesium

<sup>133</sup>Cs has many properties that make it amenable for quantum simulation experiments from a preparation, interrogation, and measurement perspective.

<sup>133</sup>Cs is bosonic, and is the only stable isotope of cesium. It is the heaviest alkali (hydrogenic) atom at  $2.207 \times 10^{-25}$  kg, which makes it well-suited for optical trapping. At room temperature, cesium is a solid, and at moderate temperatures of  $\geq 60^{\circ}$ C becomes gaseous. These temperatures are easy to reach without the need for a highly specialized oven.

The cesium D lines are located at 852 nm (D<sub>2</sub>, the  $6^2S_{1/2} \rightarrow 6^2P_{3/2}$  transition) and 894 nm (D<sub>1</sub>, the  $6^2S_{1/2} \rightarrow 6^2P_{1/2}$  transition). These two lines comprise a fine-structure doublet, and they can be split further via the hyperfine structure in the presence of a magnetic field. The D<sub>2</sub> line is most important for our application. It has a natural linewidth of 5.22 MHz and hosts a cycling transition for laser cooling and absorption imaging ( $F = 4 \rightarrow$ F' = 5). Laser diodes at 852 nm are readily available in the marketplace. In particular, distributed Bragg reflector (DBR) lasers, useful for their wide 10 GHz tuning range, are available at this wavelength.

Cesium has magic wavelengths at 683 nm and 935 nm, which can be used to produce traps in which the ground state and excited states experience identical potentials (light shifts). This is important for experiments involving the excited  $6^2P_{3/2}$  state, so that there are not additional unwanted complications arising from anti-trapping potentials.

One of the defining features of ultracold atomic platforms is the controlled tunability of the interactions between particles. At low temperatures, the interaction strength is typically parameterized by the s-wave scattering length a, which sets the scattering cross section  $\sigma = 8\pi a^2$ . Furthermore, the sign of the interactions also follows the sign of the scattering length a (i.e., attractive for a < 0 and repulsive for a > 0).

In the lab, the scattering length can be tuned magnetically via a *Feshbach resonance*. A Feshbach resonance occurs when the unbound energy of one molecular potential (the entrance channel) matches the bound state energy of another molecular potential (the closed channel). The two potentials arise from differences in the internal state of the atom pairs, for example their magnetic moments. For a magnetic field  $B_0$  where this condition is satisfied, the scattering length diverges to  $\pm \infty$ ,

$$a(B) = a_{\rm bg} \left( 1 - \frac{\Delta}{B - B_0} \right) \tag{1.3}$$

with B the magnetic field,  $a_{\rm bg}$  the background scattering length, and  $\Delta$  the width of the resonance.

For our experiment using cesium, the most relevant Feshbach resonance occurs at  $B_0 = -11.7$  G and has a broad width of  $\Delta = 28.7$  G that leads to a zero crossing (a = 0) at B = 17 G. This resonance allows convenient tuning of a across several hundred Bohr radii at relatively low absolute fields. At  $B \approx 0$ , the background scattering length  $a_{bg} = 1720a_0$  leads to a scattering length  $a \approx -2500a_0$ , where  $a_0$  is the Bohr radius. Tuning of the atomic interactions is an important tool in our envisioned Hubbard-model quantum simulation experiments, where the on-site interactions and the tunneling constant are fundamental parameters.

#### 1.5 Thesis outline

This thesis is organized as follows.

• Chapter 2 details the construction of the MOT chamber and the cooling performance.

Descriptions about the vacuum chamber, the frequency-locked lasers, and the electronic control are provided.

- Chapter 3 describes a new superresolution measurement technique we developed for cold atoms in an optical lattice. Based on the nonlinear atomic response to a spatially-varying light field, we demonstrate a sub-diffraction limit resolution of 30 nm and apply our imaging scheme to a dynamic system of atoms. We also observe a byproduct of our scheme: a colossal magnification of the atomic density distribution to the millimeter scale due to the moiré effect.
- Chapter 4 goes over the design and construction for the microscope portion of our experiment. I detail the alignment procedure used to achieve diffraction-limited resolution. Additionally, information about the vacuum science cell is presented. Lastly, I describe our all-optical long distance transport scheme to move atoms from the MOT location to the microscope field of view.
- Chapter 5 details the degenerate Raman sideband cooling in the science cell, our method to simultaneously cool atoms near the lattice vibrational ground state and image the single-site occupation by collecting their fluorescence. The image process-ing procedure is presented, and statistics about the loading, hopping, and loss are presented. Lastly, preliminary work on high efficiency loading is presented, where we demonstrate 74% filling of the lattice sites by controlling the light-assisted collisions.
- Chapter 6 describes our method for creating a dynamic tweezer array using a digital micromirror device (DMD). An introductory description of a DMD is given, followed by our operation of the DMD in a video-streaming mode, important for realizing a tweezer array capable of fast feedback for rearrangement. Resolution characterization and tweezer shapes are also discussed.
- Chapter 7 looks toward near-term projects for the QMS.

## CHAPTER 2

# MOT CHAMBER DESIGN AND CONSTRUCTION

#### 2.1 Vacuum system

Cold atomic samples must be prepared and probed within a low-pressure vacuum chamber so that detrimental collisions with the relatively hot background particles are limited. Such background gas collisions lead to atom loss and heating, thereby setting the ultimate achievable atom lifetime in an apparatus. Cold (i.e., non-degenerate) samples typically require  $\leq 1 \times 10^{-9}$  Torr while ultracold gases are typically prepared in  $\sim 1 \times 10^{-11}$  Torr UHV environments.

Our vacuum system can be separated into four distinct regions: the oven, the Zeeman slower, the MOT chamber, and the glass science cell. The oven and Zeeman slower maintain an elevated vacuum pressure due to large background of cesium atoms, and are isolated from the MOT chamber and glass cell regions via a long, thin pipe. Each experimental cycle begins with cesium vapor production at the oven, after which an atomic beam is formed and slowed in the Zeeman slower, and finally captured in the MOT chamber. The work on a new superresolution microscopy technique for cold atoms (Chapter 3) was done entirely in the MOT chamber before the glass cell was installed. All subsequent work was performed in the glass cell, located at the focus of the microscopes. Using a combination of an ion pump and two non evaporable getter (NEG) pumps, we achieve vacuum pressures of  $\approx 1 \times 10^{-9}$  Torr in the oven region,  $\approx 1 \times 10^{-10}$  Torr in the MOT chamber and  $< 1 \times 10^{-10}$  Torr in the glass cell, limited by the floor of our measuring apparatus.

This section will characterize the first three vacuum regions, while the description about the glass cell with unique nanotextured windows will be delayed to Chapter 4.



Figure 2.1: Overview of the vacuum system.

# 2.1.1 Oven

The oven section is where we form an atomic beam, and will be described in the order that atoms traverse the system. A Cs ingot in a glass vial is heated to  $60^{\circ}$ C with heating tape to produce an atomic vapor which, after passing through two 2 mm-diameter irises spaced 2.5" apart, forms our atomic beam. The metal vacuum parts around the glass vial are held at an elevated temperature of about  $65^{\circ}$ C to prevent accumulation of Cs on the walls. A water-cooled cold finger (TE cooler) held at  $0^{\circ}$ C is thermally contacted to the pipe section in between the two irises so that atoms diverging from the Zeeman slower axis get stuck to the walls. This helps reduce the flux of atoms entering the tube at sub-optimal angles and extend the lifetime of the oven and ion pump (less volume pumped and less buildup of cesium on the apertures). After the second aperture, a cube provides the necessary CF connector to an ion pump to maintain the necessary vacuum performance on the oven side  $(10^{-9}$  Torr). Note that in previous Cs experiments, a viewport was installed on the cube to evaluate the fluorescence and alignment of the Zeeman slower laser beam. In order to minimize risk of vacuum degradation via the fragile window, we proceeded with a blank instead of a viewport. This blank can be removed to connect a turbo pump for ion pump maintenance. Over time, Cs atoms collect on the plates of the ion pump and worsen its performance. Bakeout of the ion pump with the turbo pump attached can resolve this issue. Lastly, a hand-winding gate valve (VAT Series 48.1) is installed to provide a block to the atomic beam, and to allow maintenance of the oven section without disturbing the main chamber (or vice versa).

At this point, atoms leave the oven section in a roughly collimated beam with a velocity  $v_0 \approx 250$  m/s.

### 2.1.2 Zeeman slower

After the oven, the atoms enter the Zeeman slower section. It serves the dual purpose of providing the differential pumping to isolate the chamber from the elevated background pressure in the oven, as well as to provide a sufficiently long landing strip for atoms to decelerate during the slowing stage. For most alkali atoms, the required "stopping distance"  $L_0$  to decelerate an atomic beam for MOT capture is about 1 m, where the stopping distance corresponds to deceleration of half the maximum theoretical value. For example, Cs atoms heated to 60°C, the stopping distance  $L_0 = 2v_0^2 \tau/v_r = 1.07$  m where  $v_0 = 250$  m/s is the initial atom velocity,  $\tau = 30.6$  ns is the Cs excited state lifetime, and  $v_r = 3.5$  cm/s is the recoil velocity [66]. Our Zeeman slower is slightly shorter at 0.4 m, and is a simple pipe (ID: 0.67", OD: 0.75") that runs from the oven to the MOT chamber. The shorter length may hamper the MOT loading efficiency, but our experiments typically do not require large atom numbers. A tapered solenoid wrapped around the pipe provides the required magnetic field profile and is discussed more in Section 2.6.1. The Zeeman slower is connected to the MOT chamber via a 1.33" CF flange.

# 2.1.3 MOT chamber

The MOT chamber is an octagon with eight 2.75" CF flanges on the horizontal perimeter, sixteen 1.33" CF flanges at an angle, and two large custom re-entrants on the top and bottom. The re-entrants allow us to position electromagnets close to the center of the chamber, where the MOT is formed, and the large diameter allows optical access. The Zeeman slower is connected to one of the 1.33" CF flanges. A gate valve connected to one of the 1.33" CF flanges exists to provide an attachment point for future expansion of the apparatus (e.g., introducing a second atomic species). A cross connected to one of the 2.75" flanges provides paths from the chamber to (i) a viewport; (ii) a non-evaporable getter pump (NEG); and (iii) a gated tee assembly containing an ion gauge. The gated tee assembly with an ion gauge permits easy access for vacuum maintenance. For example, this section was used to attach a turbo pump and feed in argon during installation of the glass science cell. A tee to the glass science cell is connected to one of the 2.75" flanges. During the initial setup of the experiment, a blank was placed here. All the other flanges are outfitted with viewports and are reserved for optical access.

After several months of setup, leak checking, and baking, the vacuum pressure read by the NEG (SAES NEXTOR D 100-5) indicated  $< 10^{-10}$  Torr. Subsequently, an electrical event destroyed the accuracy of the NEG current. An independent measure of the vacuum pressure by an ion gauge confirmed that the event only affected the gauge display electronics, and the vacuum performance did not significantly degrade.

# 2.2 Optical setup

#### 2.2.1 Frequency-locked diode lasers

All the laser beams used for cooling and imaging in both the MOT chamber and science cell are derived from two independent laser setups, each consisting of three DBR lasers:



"Reference," "MOT," and "Repumper." We hereby label the 1st generation lasers "REF1," "MOT1," "REP1,", and the 2nd generation lasers "REF2," "MOT2," and "REP2." These lasers are housed in a separate "quiet" room with low foot traffic and its own dedicated temperature and humidity control in order to promote frequency stability. The light from the MOT and Repumper diodes are each split into multiple beam paths and are fiber-coupled to the main experimental optical table about 10 ft away beyond some drywall. The following paragraphs describe in detail each laser diode, how they are frequency locked, and how their power is divided into the multiple beam paths to serve different experimental functions.

#### 1st generation lasers

The 1st generation REF1 laser is locked to a cesium vapor cell at +320 MHz from the  $F = 4 \rightarrow F' = 5$  transition using saturated absorption spectroscopy. The Reference laser current controller, temperature controller, and lock circuit are all homemade by a previous generation of students.

The MOT1 laser (Photodigm PH852DBR) is locked to the Reference laser using a beat note lock and is responsible for producing light at the  $F = 4 \rightarrow F'$  transitions. A beam from MOT1 and REF1 are combined and shone on a photodiode, producing a periodic voltage signal whose frequency corresponds to the frequency difference between the two lasers. This signal is sent to a phase lock loop which produces the error signal for a PID feedback circuit. The laser current is modulated to lock the error signal, and the beat frequency is typically in the 300 MHz to 800 MHz range. The circuit can perform 100 MHz frequency jumps in approximately 1 ms. The linewidth of the MOT laser is  $\leq 5$  MHz, as measured separately on a Fabry-Perot cavity and via atom spectroscopy on the  $F = 4 \rightarrow F' = 5$  imaging transition.

The REP1 diode is also locked to the Reference laser with a beat note lock. Due to the large 9.192 GHz clock transition between the hyperfine ground states, the signal from the photodiode is mixed with a 9.18000 GHz signal (CTI XPDRO-9315) to bring the beat note under 1 GHz so that it is compatible with the PLL. The switching speed and linewidth of the REP1 diode is comparable to that of the MOT1 diode.

In order to get sufficient laser power for our MOT and Zeeman slower beams, we employ a tapered amplifier that outputs approximately 570 mW from a 11 mW seed (Sacher Lasertechnik). The seed is a two-frequency input beam formed by combining the MOT (10 mW) and repumper (1 mW) light using a polarizing beamsplitter.

#### 2nd generation lasers

The three 2nd generation lasers are all based on the Photodigm PH852DBR diode and each are temperature and current stabilized using Vescent D2-125 laser controllers.

The REF2 laser is locked to a cesium vapor cell at -320 MHz below the  $F = 3 \rightarrow F' = 2$  transition using polarization spectroscopy. The REP2 diode is locked to REF2 using a beat note lock based on the Analog Devices ADF4007 PLL. The MOT2 diode is also locked using a similar beat note lock, with the beat signal coming from a fast photodiode (Hamamatsu G4176) that is mixed with the same 9.18000 GHz signal used for the 1st generation lasers. The linewidths of the MOT2 and REP2 lasers as measured by their beat notes are approximately 1 MHz. 100 MHz jumps in the laser frequency can be performed in 40 µs.

#### 2.3 Magnetic field coils

#### 2.3.1 Shim coils

Fine control over the magnetic field (and thus the Zeeman splittings) is a prerequisite for ultracold atom experiments. We use three pairs of orthogonally-oriented shim coils to cancel the background magnetic field or introduce a controlled offset and gradient, depending on the experimental requirements. Due to space constraints, each pair of coils has a unique



Figure 2.3: Simplified laser diagram highlighting the frequency control for each beam path, which are coupled to the experimental apparatus using single-mode polarization-maintaining fibers. The dark gray boxes that denote fixed frequency shifts represent AOMs. A more detailed beam diagram can be found in Fig. B.1

Application	Laser diode	Transition	Detuning (MHz)
Zeeman Slower (ZS)	MOT1	$F = 4 \to F' = 5$	-100
ZS Repumper	REP1	$F = 3 \to F' = 4$	-90
MOT/Molasses	MOT1/TA	$F = 4 \to F' = 5$	-16 to $-100$
MOT/Molasses Repumper	MOT1/TA	$F = 3 \to F' = 4$	-4
dRSC Optical Pumping	REP1	$F = 3 \to F' = 2$	+6
dRSC Repumper	MOT1	$F = 4 \to F' = 4$	0
MOT Chamber Imaging	MOT1	$F = 4 \to F' = 5$	0
MOT Chamber Imaging Repumper	REP2	$F = 3 \to F' = 4$	0
GC dRSC Optical Pumping	REP1	$F = 3 \to F' = 2$	+10
GC dRSC Repumper	MOT2	$F = 4 \to F' = 4$	0
GC Imaging	MOT1	$F = 4 \to F' = 5$	0
GC Imaging Repumper	REP2	$F = 3 \to F' = 4$	0

Table 2.1: Summary of laser beams used to cool and image atoms in the experiment. "GC" stands for "glass cell."

geometry, but all pairs are designed to operate at 1 G/A. The x- and y-coils are wrapped tightly using shielded copper wire and are secured to the table on metal posts. Lodged inside of the larger Bitter electromagnets, the z-coil has a smaller diameter and is placed much closer to the center of the vacuum chamber.

The MOSFET driver circuit is capable of quenching the coil currents within 1 ms for typical values on the order of 1 A. The actual field in the chamber stabilizes within a few ms due to circulating eddy currents in the metal apparatus. The eddy currents can be suppressed using feedforward (e.g., by applying an overshoot in the control voltage waveform) or alternatively can be ignored by simply waiting 5 ms. Since our experiments typically do no revolve around fast magnetic field jumps in the MOT chamber, we use the latter approach by default.

#### 2.3.2 Field calibration using microwave spectroscopy

We use microwave spectroscopy near the Cs clock transition at 9.192 GHz to calibrate our shim coils. When subjected to a magnetic field, the fifteen non-degenerate  $m_F$  transitions between the F = 3 and F = 4 hyperfine manifolds will dilate at 350 kHz/G (linear Zeeman shift). By applying a microwave pulse to unpolarized atoms initially prepared in the F = 3 state, we can visualize all fifteen transitions and determine the field magnitude by their splittings. Minimizing their splittings allows us to simultaneously calibrate our shim coils as well as cancel the background field. The end result is a magnetic field uncertainty of 10 mG at the location of the atoms, see Fig. 2.4. In terms of control voltages to the current driver, the calibrations for the  $\{x, y, z\}$  coils are  $\{0.72, 0.81, 0.94\}$  G/V with the field zero located at  $\{0.21, 0.14, 0.70\}$  V.

# 2.3.3 MOT Bitter electromagnet

The MOT chamber quadrupole magnetic field is produced by a pair of coils arranged in the anti-Helmholtz configuration. We use a Bitter-type design, which has the advantage of low inductance and uniform temperature. More specifically, the Bitter electromagnet is formed by disk-shaped rings stacked on top of each other to form a coil geometry. Long bolts run through the electromagnet to clamp the assembly tightly together. The relatively large cross-section of each disk is amenable to large current values in the 10-100 A range, thus allowing fewer necessary turns to achieve the requisite magnetic fields. This also lowers the inductance, good for faster switching speeds. Furthermore, the geometry allows parallel water-cooling lines to run up and down the coil in six regions, thus providing a uniform temperature for all the disks. This is in contrast to conventional electromagnet designs that are constructed using many windings of copper tubing, which introduces high inductance and uneven cooling since the water passes through the coil in series, picking up heat as it traverses the coil.

Details of the Bitter electromagnet construction will now be presented and closely follow the scheme detailed in Ref. [67]. Waterjet cut copper arcs are stacked on top of each other with a smaller copper arc in between to enforce the coil geometry. Lasercut polycarbonate



Figure 2.4: Magnetic field calibration in the MOT chamber. a) The fifteen Zeeman transitions between the F = 3 and F = 4 hyperfine states. The  $g_F = -1/4$  for the F = 3 state, which corresponds to an energy shift with slope -350 kHz/G. For F = 4 it is +350 kHz/G. The leftmost and rightmost peaks are separated by 4.9 MHz/G. b) The fifteen peaks resolved at  $|B| \approx 0.25$  G. c) Calibration of the field strength as a function of the shim coil control voltage for one axis. d) All fifteen peaks overlapping at the zero-calibrated field. The FWHM of 50 kHz suggests a magnetic field uncertainty of 10 mG.
sheets are also inserted in between each winding to provide electrical insulation. Water cooling flows through the stacked layers via holes in the copper and polycarbonate that are sealed with custom polyester O-rings that were also lasercut. A terminating thick brass arc serves two purposes: (i) to be a winding in the electromagnet; and (ii) to provide a mechanical base to clamp the apparatus together tightly against a plastic base that distributes the water among the channels. The plastic base is mounted to the recessed top and bottom viewports of the MOT chamber, and its material (G10) is chosen to match the thermal expansion coefficient of the stainless steel chamber. 12 push-to-connect tubing connectors are placed along the circumference of the plastic base to pump water in and out of each of the six water-cooling sections of the coil. Two machined copper bus bars are mounted to the plastic base to provide external electrical connection to the first and last windings. The electrical connection to the last winding (the thick brass arc) is completed by a long set screw lined with conductive grease driven from one of the copper bus bars into the brass plate.

We measure the field to be in good agreement with theoretical values. The voltage drop across each winding is consistent: all measured values were within 5% of each other, indicating even resistance from top to bottom. Before being mounted onto the vacuum chamber, the electromagnets were stress-tested for several days by continuously running water and 30 A of current while ensuring no leaks were observed. After installation to the system, we measured the temperature on the upper electromagnet copper pieces to be a constant 28°C while running 30 A. The temperature can be reduced even further with additional chiller water flux, but we chose its current setting so that enough cooling water could be distributed to other devices that share the same chiller.

During the past six years, only two notable events happened with regard to the MOT Bitter coils. The first happened only a couple weeks after they were installed onto the system, where a high continuous current was accidentally run without any water-cooling. This caused the magnet to swell and start leaking, flooding the top viewport. No permanent damage was observed on the electromagnet or the viewport. The second incident occurred after five years of near daily operation, when a high resistance was intermittently observed on the lower Bitter electromagnet in 2021. Investigation revealed the failure point to be bad electrical contact between the silver bolt and the brass plate, caused by loosening of the bolt. This was fixed by tightening the bolt and installing additional nuts to prevent slippage.

#### 2.4 Computer control

In this section I will describe the hardware and software used to control the experiment and collect data. This includes the analog and digital output capabilities, the LabView sequence builder, and the CCD image acquisition software.

# 2.4.1 Hardware overview: analog and digital outputs

The experiments we conduct require a carefully sequenced chain of events to occur with microsecond precision. These events consist of laser power modulation (e.g., pulses, ramps, arbitrary waveforms), laser frequency shifts, and magnetic field generation. To control the electronics that make all of this possible, we employ a total of 96 electrical output channels, split evenly between digital (TTL) and analog ( $\pm 10$  V range) types.

The control scheme and hardware were originally developed by Todd Meyrath and Florian Schreck at the University of Texas at Austin (Fig. 2.5). More details can be found in Ref. [68]. The sequence is built using a National Instruments PCI card (NI 6533) on a control computer, which then outputs via serial cable to a homemade assembly of digital and analog output channels. The timing resolution of this system is set by the internal 20 MHz clock, yielding 0.5 µs.



Figure 2.5: Overview of the hardware control scheme. Constructed closely following Ref. [68]

## 2.4.2 Software overview: LabView sequence builder

We use a GUI programmed in LabView to communicate with the NI card and the downstream digital/analog outputs. Upon starting the GUI, the digital and analog channels switch to a specified initial state which is held indefinitely. The user can then build a sequence of blocks, wherein each block is a self-containing list of instructions for individual channels. For example, the "Start MOT" block contains a list of commands to turn on the MOT beams and the magnetic field gradient. Each block can be moved in time (with 0.5 µs resolution), and all the instructions within will shift along with it. All blocks that are turned on will play through in the programmed time sequence, after which the channels return to their initial state. The program will then loop, and begin a new experimental shot, unless the program is stopped by the user. This format is a very general and accessible way to build cold atom experiments.

Two additional functionalities are described here. The first is about arbitrary waveforms. It is possible to produce arbitrary waveform outputs by simply programming the corresponding voltage at each timestep (which the program takes care of). For example, we often use this to program linear ramps and sigmoid ramps. The second feature is the ability to scan a particular channel output value with each successive experimental shot. For example, say we want to see how atom number depends on a laser detuning. The "Scan Parameters" section provides keys which can be populated with the desired detuning values. The user can then input this key in place of the voltage value for the laser controller, and the experiment will run with a new voltage value each shot, specified by the key. Besides voltage values, the key can also be used to scan times, thus shifting when something occurs with each successive shot (very useful for e.g. lifetime measurements). The keys are programmed as global variables in LabView, thus allowing them to be easily accessed by other LabView programs such as our absorption imaging acquisition software.



Figure 2.6: LabView sequence builder program. The leftmost column defines the timing of sequence blocks. Each block consists of a list of commands to the digital and analog output channels, defined in the right-hand area.

#### 2.5 Absorption imaging

The main data we collect in the MOT chamber are images taken with a CCD camera using absorption imaging. In absorption imaging, resonant  $F = 4 \rightarrow F' = 5$  light is pulsed on the sample (along with  $F = 3 \rightarrow F' = 4$  repumping light). The large amount of light scattering in the atomic sample leads to a dark spot on the image where the cloud is located. The amount of attenuation corresponds to the atomic density. In particular, the z-integrated column density of atoms is given by

$$n_z(x,y) = \frac{1}{\sigma_0} \ln\left(\frac{I_0(x,y)}{I(x,y)}\right)$$
(2.1)

where  $\sigma_0 = 3\lambda^2/(2\pi)$  is the scattering cross section, and  $I(I_0)$  is the laser beam intensity with (without) atoms.

In the MOT chamber, we take images using 20-150 µs pulses on cameras (PCO.Pixelfly USB, 6.45 µm pixel size) located at two separate imaging paths. The first path is the "horizontal imaging" path, which is drawn in Fig. 2.7. This path is used for general MOT chamber diagnostics, such as measuring atom number, temperature, lifetime, and cloud shape. It is located perpendicular to the transport beam to the science cell, enabling convenient imaging of the motion and shape. Calibration of the imaging magnification was done by dropping the atomic cloud and tracking its center position under the constant acceleration of gravity. We measure a camera pixel to correspond to 6.41 µm, yielding a magnification of M = 0.99, consistent with our target magnification of M = 1. The second path is located perpendicular to the work in Chapter 3.

## 2.6 Cooling performance

In this section, I will summarize the cooling performance in the MOT chamber. Refer to Fig. 2.7 for all relevant beam paths and chamber geometry.



Figure 2.7: MOT chamber incident beams for cooling and imaging.

# 2.6.1 Zeeman slowing (ZS)

The first step in our laser cooling process is Zeeman slowing (ZS), which efficiently removes the kinetic energy from a hot vapor of atoms so that they are cold enough to be trapped in our vacuum chamber. Such atomic beam deceleration relies only on the Doppler cooling effect, plus a spatially varying field to keep the atom in resonance with the fixed-frequency laser as it slows the sample from hundreds of m/s to cm/s.

Cs atoms heated to a vapor at  $60^{\circ}$ C have an initial temperature of 250 m/s. The spatially varying field must follow the profile given by

$$B(z) = B_0 (1 - z/L_0)^{1/2} + B_{\text{bias}}$$
(2.2)

where  $B_0 = hv_0$ 

The beam passes down the center of a series of solenoids tuned to keep the atomic transition on resonance. The solenoids are arranged in four sections, each with their own



Figure 2.8: MOT beam diagram. Vertical MOT quarter waveplate and retro-mirror omitted.

current. The currents were initially set according to the original design parameters and tweaked to maximize the MOT loading rate (we iterate between MOT and ZS optimization to find a local optimum). After optimization, front section runs at 2.2 A, the tapered section runs at 1.5 A, and the bias and end sections are set to zero amps.

The ZS beam is comprised of light that is -103 MHz detuned from the  $F = 4 \rightarrow F' = 5$ transition as well as a weaker repumping component -90 MHz detuned from the  $F = 3 \rightarrow$ F' = 4 transition.

# 2.6.2 Magneto-optical trap (MOT)

After the initial slowing phase, atoms accumulate in a magneto-optical trap (MOT) and are cooled to a temperature of 20  $\mu$ K. The MOT configuration is given by three orthogonal pairs

of red-detuned beams directed to the center of a spatially varying quadrupole field (see. Fig). Atoms moving away from the trap center experience a damping force (as in optical molasses) and a restoring force resulting from a combination of the position-dependent Zeeman shift and the red laser detuning.

The quadrupole field is generated by the Bitter electromagnets and provide a gradient of approximately 15 G/cm when operated at 30 A. Our MOT beams originate from an optical fiber with output power 120 mW which is then evenly split among the three axes using polarizing beamsplitters. The circular polarization of each of the six beams (three incident and three retro) are set by quarter waveplates. Each incident beam passes through a telescope ( $f_1 = 25.4$  mm,  $f_2 = 200$  mm) to produce a slightly-focusing beam with a size of 2 cm ( $1/e^2$  radius), see Fig. 2.8. The slight focusing is present to compensate for the intensity loss accumulated by the retro-beam as it passes the additional optics. Each beam contains light -16 MHz detuned from the  $F = 4 \rightarrow F' = 5$  transition as well as a small repumper component -3 MHz detuned from the  $F = 3 \rightarrow F' = 4$  transition to bring atoms off-resonantly scattered to the F = 3 state back to the cycling transition. The alignment of the MOT beams was initially attained by retro-reflecting the incident beams on a mirror referenced to the chamber flanges. Final alignment as well as the detuning were optimized to ensure a high loading rate, density, and a symmetric cloud shape.

The MOT number reaches  $2 \times 10^7$  (about 50% to saturation) after 3 s of loading, which is a typical loading time used for our superresolution experiments, as well for performance diagnostics relating to the main chamber cooling and long-distance transport to the glass cell. However, when we study an atom sample under the microscope, we require only a total final atom number less than 1,000, which can be achieved with a loading time under 1 second. If we wish to image very sparse samples under the microscope (such as when we measure the PSF, see Chapter 5), a loading time of 20-200 ms is sufficient.

After the MOT phase, atoms reach a temperature of approximately 40 µK as measured

by tracking the radius on a CCD during time-of-flight.

## 2.6.3 Compressed MOT

After the MOT is loaded, we apply a "compressed MOT" step to increase the density. The magnetic field gradient is quickly ramped up to approximately 30 G/cm. The intensity of the MOT beams is decreased, and the frequency detuning is increased. After 20 ms, the cloud size is reduced by a factor of 2.

## 2.6.4 Molasses

Following the compressed MOT, we shut off the magnetic field gradient and further detune the MOT beams, thus cooling the atoms in an optical molasses. The final temperature after optical molasses is 8  $\mu$ K and we typically have  $6 \times 10^6$  atoms.

## 2.6.5 Degenerate Raman sideband cooling

After the optical molasses, atoms are cold enough to be trapped in a 3D optical lattice, where degenerate Raman sideband cooling (dRSC) can be applied. dRSC is a powerful sub-Doppler cooling technique which cools atoms one vibrational quanta per cooling cycle until the atom reaches the dark ground state, which is protected against spurious heating due to e.g., reabsorption. We follow the schemes described in Refs [69, 70]. A 3D lattice is created with a free-running laser 20 GHz blue-detuned from the  $F = 3 \rightarrow F' = 4$  transition (wavelength 852.280 nm, 50 mW power). To make an independently controllable 1D lattice amenable for superresolution measurements, two axes of the dRSC lattice are 80 MHz detuned from the superresolving axis (see Fig. 2.7) so that their interference with the main axis (x'') is effectively washed out.



Figure 2.9: Schematic for degenerate Raman sideband cooling. A magnetic field is applied to shift the Zeeman sublevels of the F = 3 by an amount equal to the lattice trap frequency. Raman transitions from the lattice light couple states  $|F = 3, m_F, \nu\rangle$  to  $|3, m_F - 1, \nu - 1\rangle$ . Atoms in high-lying vibrational states are quickly optically pumped to the  $|3, 3, \nu = 1\rangle$  state by the  $\sigma^+$  component. A weak  $\pi$ -component completes the cooling cycle to  $|3, 3, 0\rangle$ , a dark state.

Exp. stage	Atom temperature (K)	Atom number	Location	Vacuum pressure (Torr)
Cs vapor	330	-	Oven	$1 \times 10^{-9}$
Zeeman slowing	-	-	Zeeman slower	-
MOT	$40 \times 10^{-6}$	$2 \times 10^7$	MOT chamber	$1 \times 10^{-10}$
Molasses	$8 \times 10^{-6}$	$1 \times 10^7$	MOT chamber	$1 \times 10^{-10}$
dRSC	$0.9 \times 10^{-6}$	$3 \times 10^6$	MOT chamber	$1 \times 10^{-10}$

Table 2.2: MOT chamber performance summary. Atom number and temperature are measured using time-of-flight absorption imaging. The vacuum pressure near the oven is read out from the ionization gauge pump. The vacuum pressure in the MOT chamber is read out from the getter pump, and confirmed independently on an ionization gauge pump.

## CHAPTER 3

# SUPERRESOLUTION IMAGING OF COLD ATOMS IN AN OPTICAL LATTICE

Super-resolution microscopy has revolutionized the fields of chemistry and biology by resolving features at the molecular level. In atomic physics, such a scheme can be applied to reveal the atomic wavefunction and to perform quantum control. Here we demonstrate super-resolution imaging based on nonlinear response of atoms to an optical pumping pulse. With this technique the atomic density distribution can be imaged with a full-width-athalf-maximum resolution of 32(4) nm and a localization precision below 500 pm. The short optical pumping pulse of 1.4  $\mu$ s enables us to resolve fast atomic dynamics within a single lattice site. A byproduct of our scheme is the emergence of moiré patterns on the atomic cloud, which we show to be immensely magnified images of the atomic density in the lattice. This Chapter is based on Ref. [71].

#### 3.1 Introduction to superresolution microscopy

In the study of ultracold atomic gases, high resolution microscopy has played an important role in visualizing interesting quantum phenomena. Examples include phase transitions [72, 73], correlations [74–76], transport [77], tunneling [78], and quantum information processing with ions [79] and atoms [80, 81]. Optical microscopy of ultracold gases has been pushed to its limit to detect atoms in optical lattices with sub-micron spacings [82–88]. The spatial resolution in these experiments is constrained by the imaging wavelength to typically  $0.5 \sim$ 1 µm, a value set by the Abbe limit  $d = \lambda/2$ NA [89]. Here,  $\lambda$  is the wavelength of the imaging light and NA is the numerical aperture of the microscope.

Several schemes have been demonstrated which reach beyond the optical diffraction limit. Scanning electron microscopy of ultracold gases visualizes atoms with a resolution of 150 nm [90]. "Stochastic" techniques, which gain resolution through precise localization of point source emitters, have been applied to determine the mean positions of trapped ions to a few nanometers [91] and the occupancy of closely-spaced one-dimensional (1D) optical lattice sites [92]. Stochastic methods, however, derive their power from the assumption of point-source emission [93], meaning that the atomic wavefunction itself cannot be resolved.

Another class of super-resolution imaging techniques is "deterministic", achieving genuine sub-wavelength resolution by exploiting the nonlinear optical response of atoms and molecules to a spatially varying light field [94, 95]. Proposals exist which are based on spatially dependent coherent dark state transfer [96–99], which have been implemented to demonstrate sub-wavelength addressing of a thermal atomic cloud [100]. The capability to resolve atomic wavefunctions and their dynamics in the lattice would enable *in situ* detection of novel quantum states in single lattice sites, such as fractional quantum Hall states [101] and anyonic excitations [102].

# 3.2 Using a phase-controlled optical lattice as a scanning probe microscope

#### 3.2.1 Experimental setup and implementation

In this work we demonstrate 1D super-resolution microscopy of ultracold atoms at the nanometer scale. Our technique shares conceptual similarities to saturated structured illumination microscopy (SSIM) [95] and stimulated emission depletion (STED) microscopy [94], and is schematically illustrated in Fig. 1. Atoms are initially localized in the trapping lattice and polarized in the  $|F = 3\rangle$  ground state, where F is the total angular momentum. An additional optical pumping (OP) lattice is applied which pumps atoms to a different hyperfine state  $|F = 4\rangle$ . Since just a few photons are required to pump atoms to the new state, only atoms within a narrow window around the nodes of the OP lattice are likely to

remain in the initial state, while those outside of this window have near-unity probability to be pumped to the  $|F = 4\rangle$  state. By sweeping the location of this window across the atomic density distribution and measuring the fraction of atoms remaining in  $|F = 3\rangle$ , a map of the atomic density distribution can be built up with a resolution given by the width of the window. As we will discuss below, this width can be made arbitrarily small compared to the optical wavelength, which is key to attaining high resolution.

Our experimental implementation is illustrated in Fig. 1(b). A cloud of <sup>133</sup>Cs atoms is collected in a magneto optical trap, subsequently cooled by degenerate Raman-sideband cooling to  $< 1\mu$ K [69], and polarized in the  $|F = 3\rangle$  ground state. About  $2 \times 10^6$  atoms are then adiabatically loaded into a one-dimensional optical lattice with approximately 90% occupation in the motional ground state along the lattice direction. The trapping lattice with lattice constant  $\lambda_{trap}/2 \approx 426$  nm is blue-detuned from the resonance transition  $|F = 3\rangle \rightarrow |F' = 4\rangle$ by  $\delta = +10$  to 500 GHz. The OP laser is resonant with the  $|F = 3\rangle \rightarrow |F' = 4\rangle$  transition at  $\lambda_{OP} = 852.335$  nm (see Fig. 1(c)), and is retro-reflected and polarized perpendicularly to the co-propagating trapping lattice. The retro-reflection of the OP beam is carefully aligned and balanced to cancel the electric field at the nodes of the standing wave. The relative phases of the two lattices are controlled with nanometer precision using a piezoelectric transducer.

To image the atoms, we apply a 1.4  $\mu$ s pulse of the OP lattice while the atoms are still confined to the trapping lattice, which transfers atoms to  $|F = 4\rangle$ . This pulse is short compared to the timescale of atomic motion, but much longer than the  $6P_{3/2}$  excited state lifetime of  $1/\Gamma = 30$  ns. The OP pulse is followed by *in situ* imaging with a camera in the direction perpendicular to the lattice. From measuring the atomic population in  $|F = 4\rangle$ , we determine the excitation fraction  $\mathcal{F}$  across the sample.

# 3.2.2 Eliminating systematic sources of resolution broadening

#### Lattice phase control

Calibration of the piezo displacement  $\Delta x$  must be accurate to within nanometers in order to prevent systematic distortion of the signal. Here  $\Delta x$  is primarily determined by the relative positions of the two retro-reflecting mirrors of the OP and trapping lattices, which are measured interferometrically every shot. To perform this measurement, we turn on the trapping lattice and make use of leakage light from the polarizing beam splitter shown in Fig. 1(b). The two arms of the polarizing beam splitter re-combine and interfere on a photodiode. A second piezo, attached to the trapping lattice mirror, is scanned over a few lattice spacings, and the phase (in nm) of the resulting sinusoidal signal on the photodiode is measured.

Additionally, a correction term to  $\Delta x$  is applied in order to account for position drift in the trapping lattice nodes due to frequency drift of the laser. The trapping lattice originates from a Ti:sapphire laser that is stable to  $\approx 50$  MHz/hour. The nodes of the lattice will shift by  $(\Delta f_{\rm tr}/f_{\rm tr})L$  where  $\Delta f_{\rm tr}$  is the change in frequency,  $f_{\rm tr} = 351$  THz is the frequency of the trapping light, and L is the distance between the atom cloud and the retro-reflecting mirror. For our setup, L = 0.50 m so that the trapping nodes will shift at a rate of 1.4 nm/MHz. We calibrate the frequency drift of the trapping laser every shot by observing its peak position on a Fabry-Perot cavity relative to a stable reference laser to within 1 MHz.

### Lattice alignment precision

To take full advantage of the nonlinear optical response described by Eq. (1), it is critical that the OP lattice has clean zero-intensity nodes. Due to small losses accumulated in the optical path (e.g. from windows, beamsplitters, etc.), the retro-reflecting beam diameter is made to be 84% the incident beam diameter so that incident and retro intensities can be closely matched. Additional fine tuning of the retro intensity is provided by adjusting its transmission through a polarizing beam splitter using a quarter waveplate QWP2 (Fig. S1). The retro intensity is optimized by maximizing the signal-to-noise of  $\tilde{n}$  at  $I/I_{\text{sat}} \gtrsim 1$ .

Precise alignment of the OP and trapping lattices is necessary to minimize blurring due to angled moiré fringes. We do so by outputting both beams from the same optical fiber, and precisely aligning their retro-reflections via fiber back-coupling to within  $\pm 20 \ \mu$ rad of optimal. This procedure is performed within a few hours before experiments are run to correct for mirror drift.

## 3.3 Results of superresolved imaging

#### 3.3.1 Resolution characterization

To explore the resolving power of this technique, we record traces of the excitation fraction  $\mathcal{F}$  versus piezo displacement  $\Delta x$  (see Fig. 2). At sufficiently low OP beam intensities  $I \ll I_{\text{sat}}$  the excitation fraction  $\mathcal{F}(\Delta x)$  varies sinusoidally, mirroring the sinusoidal intensity profile of the OP lattice  $I(x) = 4I \sin^2(2\pi x/\lambda_{\text{op}})$ . At higher intensities, however, the response of atoms to optical pumping becomes more nonlinear because the excitation fraction quickly saturates to 1 unless atoms are located sufficiently close to the nodes of the OP lattice. In this regime the remaining fraction g(x) of atoms in the  $|F = 3\rangle$  state near a node is approximately given by

$$g(x) = \exp\left[-\frac{\beta\Gamma}{2}\frac{I(x)}{I(x) + I_{\text{sat}}}t\right],\tag{3.1}$$

where we have assumed a long exposure time  $t \gg 1/\Gamma$  and  $\beta = 7/12$  is the branching ratio of spontaneous emission into the  $|F = 4\rangle$  state. At the nodes, g(x) develops narrow peaks.

Equation 3.1 can be derived from a three-state optical pumping model in the long pulse regime. The rate equations can be written as,

$$\begin{split} \dot{p_{4'}} &= -\frac{s\Gamma}{2}(p_{4'} - p_3) - \Gamma p_{4'} \\ \dot{p_3} &= -\frac{s\Gamma}{2}(p_3 - p_{4'}) + (1 - \beta)\Gamma p_{4'} \\ \dot{p_4} &= \beta\Gamma p_{4'} \\ f &= p_4, \end{split}$$
(3.2)

where  $p_i$  denotes the F = i population,  $\beta = 7/12$  the branching ratio for excited state decay to F = 4,  $\Gamma$  the excited state linewidth, and  $s = 2\Omega^2/\Gamma^2 = I/I_{\text{sat}}$  the normalized pulse intensity. The solution for the F = 4 fraction is given by:

$$f = 1 - \frac{\gamma_{+}}{\gamma_{+} - \gamma_{-}} e^{-\gamma_{-}t} - \frac{\gamma_{-}}{\gamma_{-} - \gamma_{+}} e^{-\gamma_{+}t}$$

$$\gamma_{\pm} = \frac{\Gamma}{2} (s+1) \left( 1 \pm \sqrt{1 - 2s\beta/(s+1)^2} \right).$$
(3.3)

For the 1D optical pumping lattice intensity profile employed in the experiment,

$$\Omega(x) = \sqrt{2s_0 \Gamma^2} \sin(2\pi x/\lambda_{\rm op}), \qquad (3.4)$$

where  $s_0 = I/I_{\text{sat}}$  and  $\lambda_{\text{op}} = 852.335$  nm is the optical pumping wavelength.

In the long pulse time limit  $(t \gg 1/\Gamma)$  near the nodes  $(s \gg 1)$ , we obtain Eq. 3.1.

The narrowing of the excitation dips at higher OP intensity (see Fig. 2(b)) results from the nonlinear optical response described in Eq. (3.1). This narrowing can also be understood as revealing the atomic density distribution with increasing resolving power. Given a spatial density distribution n(x) for an atom (in either a pure or mixed quantum state) under the spatially varying OP intensity I(x), the excitation fraction  $\mathcal{F}(\Delta x)$  directly relates to the atomic density n(x) as

$$1 - \mathcal{F}(\Delta x) = \int n(x)g\left(\Delta x - x\right) dx \equiv \tilde{n}(\Delta x), \qquad (3.5)$$

where  $\tilde{n}(\Delta x)$  is the convolution of the atomic density distribution with the point spread function given by g(x). When the width of g(x) is smaller than that of the atomic density distribution,  $\tilde{n}(\Delta x)$  (and, equivalently,  $1 - \mathcal{F}$ ) reveals the atomic density distribution (see Figs. 2(c) and 2(d)). Because the excitation fraction  $\mathcal{F}$  is measured with a finite imaging resolution, the extracted density distribution  $\tilde{n}(\Delta x)$  is an average over sites contained in the resolution limited spot.

For an OP pulse of duration  $t \gg 1/\Gamma$ , the imaging resolution is defined based on the full width at half maximum (FWHM) w of the point spread function g(x), and is calculated to be [103]

$$w = \frac{\lambda_{\rm op}}{2\pi} \sqrt{\frac{2\ln 2}{st\beta\Gamma}},\tag{3.6}$$

where  $s = I/I_{\text{sat}}$  and I is the single beam intensity. In our experiment, the calculated imaging resolution above s = 0.6 is high enough to reveal the shape of our atomic density distribution (see Fig. 2(c)).

Our measured widths, reaching a minimum of 55(2) nm, are in good agreement with the expected widths from the theory prediction (see Figs. 2(c) and 2(d)). From the measurement at s = 2.1 we calculate an imaging resolution, defined by the FWHM of the extracted point spread function [94], to be 32(4) nm, which is less than 1/25 of the 852 nm imaging wavelength. Furthermore, from Gaussian fits, the center positions of the atomic density can be localized to about 0.4 nm. Notably, the imaging resolution worsens at very high OP intensity s > 2.5 because of the limited signal-to-noise ratio.

Since the extraction of the atomic density can be realized locally, we can characterize its spatial inhomogeneity across the cloud. Figure 2(f) shows the fitted widths of the measured

density distributions. Here a variation of 40% is seen, likely due to the combination of inhomogenous cooling efficiency and trap depth. We note that such spatially-resolved information about trap parameters is often inaccessible using conventional imaging techniques.

# 3.3.2 Application to a microsecond-scale dynamic system

An important feature of this imaging scheme is the short  $\mu$ s duration of the OP pulse compared to the timescale of typical atomic motion in the lattice. Our scheme is thus ideally suited for probing dynamics of atoms within a lattice site. To explore this capability, we quickly displace the trapping lattice by 79 nm and record the evolution of the atomic density distribution after different hold times (see Fig. 3).

The displacement initiates an oscillatory motion of the atoms (see Fig. 3(b)). The "jagged" features of the motion come from the anhamonicity of the lattice potential [103]. From the time evolution, we further extract the oscillation frequency and damping rate of the atomic motion, as shown in Fig. 3(c) for two bins in separate locations, and construct the complete maps of these quantities in the sample (see Figs. 3(d) and 3(e)), which clearly show the inhomogeneity of lattice parameters.

#### 3.4 Colossal magnification due to the moiré effect

Thus far all measurements have required repeating the experiment many times, each with a small increment in the piezo displacement. Here we develop an alternative method that exploits the slight difference in wavelengths of the optical pumping and trapping beams to obtain the atomic density distribution at nanometer scale in a single shot based on the moiré effect.

When two gratings of slightly different periodicity overlap, a moiré interference pattern emerges at a macroscopic length scale (see Fig. 4(a) for an example) because the relative phase of the two gratings advances slowly and linearly along the grating direction. In our experiment, the slight difference in the wavelengths of the trapping lattice  $\lambda_{\text{trap}}$ and OP lattice  $\lambda_{\text{OP}}$  causes the atoms trapped in neighboring lattice sites to be probed at slightly different positions within each site. If the atomic density profile is identical along the lattice direction, the resulting moiré pattern imprinted onto the cloud represents a greatly magnified image of the density profile (see Fig. 4(b)). The magnification M is given by [104]

$$M = \frac{\lambda_{\rm OP}}{|\lambda_{\rm OP} - \lambda_{\rm trap}|},\tag{3.7}$$

which in our experiment can expand 10 nm features to 1 mm scale in a single shot image.

Figure 4(c) shows a representative series of moiré patterns of excitation fractions observed at different detunings of the trapping lattice. The stripes, appearing with greater number at larger detuning, show the rephasing of the two lattices, and the separation between two stripes corresponds to the microscopic lattice constant.

To confirm that the moiré patterns represent a faithful magnification of the atomic density distribution in a lattice site, we compare the pattern to the density profile extracted from piezo scanning (see Fig. 4(d)). Here a weaker lattice is chosen so that the measured width is dominated by that of the atoms. The two measurements match excellently, which confirms the interpretation of a moiré pattern as a magnified image of atomic density distribution in a lattice site. We determine the magnification for each image in Fig. 4(c) and the result also shows good agreement with Eq. (4). At the smallest detuning of 10 GHz in our experiment, the magnification reaches M = 20,000.

This moiré pattern based imaging scheme is also a convenient tool to study the atomic dynamics in the lattice. After displacing the lattice by 79 nm, the moiré pattern appears straight in the beginning, but develops snaking wiggles after 20~30  $\mu$ s and finally relaxes to a wider stripe at a displaced location (see Fig. 4(f)). The snaking wiggles in each stripe indicates the inhomogeneous trap parameters across the cloud, confirming the observation in Fig. 3(c) based on piezo tuning.

# 3.5 Outlook

Our imaging method is generic and can be readily applied to other atoms and molecules. Extension of the method to two and three dimensions is straightforward. By implementing this scheme in a system with single-site imaging resolution (e.g. quantum gas microscopes), one can gain full information of the quantum system at every site, down to the nanometer scale. Our scheme also suggests a convenient alternative for realizing site-resolved microscopy when the diffraction limit of the imaging system is well above the lattice spacing.



Figure 3.1: Super-resolution imaging of ultracold atoms based on optical pumping. (a) Given an intense standing wave of optical pumping (OP) light, the excitation probability (red solid line) is nearly unity unless the atoms (blue shaded area) are within a narrow window at the nodes of the OP lattice (red dashed line) where the intensity vanishes. Red shaded area approximates the fraction of the atoms that are not excited. (b) The trapping lattice (cyan) and OP lattice (red) overlap on the atoms. The relative displacement between the two lattices is controlled by a piezo transducer behind one of the retro reflection mirrors. The atomic distribution is measured by scanning the piezo displacement  $\Delta x$ . A CCD camera from the side images atoms *in situ* on the strong  $|F = 4\rangle \rightarrow |F' = 5\rangle$  cycling transition. (c) Relevant atomic levels. Atoms initially in the  $|F = 3\rangle$  ground state are optically pumped to  $|F = 4\rangle$ , and imaged with the imaging beam. Primed and unprimed letters refer to levels within the excited state  $6^2P_{3/2}$  and ground state  $6^2S_{1/2}$  manifolds, respectively.



Figure 3.2: **Optical setup for super-resolution experiment.** The 1D OP and 1D trapping lattices emerge from the same fiber to ensure good relative alignment. A polarizing beam-splitter (PBS) is used to separate the two beams, which are linearly polarized in orthogonal directions. The photodiode PD is used to calibrate the relative positions of the two retro-reflecting mirrors, which are both 0.50 m away from the atom cloud.



Figure 3.3: Performance of super-resolution imaging. (a) Images of excitation fraction  $\mathcal{F}$  taken at different piezo displacements  $\Delta x$ . For these images, the OP intensity is  $I/I_{\rm sat} = 1.3$ , and atoms are prepared in a trapping lattice with detuning  $\delta = 10$  GHz and lattice depth  $U = 200 \mu K$ . The region outlined in green indicates the area from which the data in panels (b)-(d) are collected. (b) As the optical pumping intensity increases, the atom response becomes more nonlinear and the dips in the excitation fraction narrow. From low to high, the traces show measurements at increasing intensity with  $I/I_{\text{sat}} = 0.017$ (light blue), 0.041(green), 0.22(orange), 1.3(blue), 2.1(purple), 2.7(grey). Solid curves show fits based on a sum of Gaussians separated by  $\lambda_{OP}/2$ . Piezo displacement is interferometrically measured with nm accuracy [103]. (c) FWHMs of the fitted Gaussians at different OP intensities (orange circles) are compared with those of the ground state (40 nm. green), a thermal state with 90% ground state occupation (45 nm, purple), theoretical resolution (blue) and the expected width (orange) of the convolution of the thermal state and the point spread function q(x) [103]. Error bars show one standard error. (d) Derived single site atomic density distribution. The measurement reflects the density distribution averaged over sites contained within the green-outlined region in panel (a). From Gaussian fits, we determine FWHM=55(2) and 62(1) nm, and uncertainty in the peak positions of 0.8 and 0.4 nm, for  $I/I_{\text{sat}} = 2.1$  (purple) and 1.3 (blue), respectively. (e) A typical optical density (OD) image of all atoms. (f) Distribution of the FWHM across the cloud at  $I/I_{\text{sat}} = 2.1$ . Only area containing signal sufficient for fitting is shown.



Figure 3.4: Microscopic dynamics revealed by super-resolution microscopy. (a) A cartoon illustrating the experimental procedure. After preparing atoms in the ground state, the trapping lattice is displaced by an amplitude A = 79 nm, causing the atoms to oscillate. (b) Atomic density evolution within a single lattice site. After a hold time  $\tau$  we record the atomic density using the same procedure as Fig. 2(d). Here the trapping lattice detuning is  $\delta = 20$  GHz, lattice depth  $U = 10 \ \mu$ K and OP intensity  $I/I_{\text{sat}} = 1.3$ . Jagged motion of the atoms results from anharmonicity of the lattice potential [103]. Data are extracted from the location shown in the red box in panel (d). The data presented in (b) are smoothed using a window of  $\lambda_{\text{trap}}/20$  [103]. (c) Evolution of the atomic position determined from Gaussian fits. Blue and red circles are based on measured data from bins of the same color in panel (d). Solid curves show exponentially decaying cosine fits  $x_c = -Ae^{-\gamma\tau} \cos 2\pi f_{\text{osc}}\tau$ , where  $\gamma$  is the decay constant and  $f_{\text{osc}}$  is the oscillation frequency. Error bars show one standard error. (d) Typical absorption image of the atomic cloud. (e) Map of fitted oscillation frequency  $f_{\text{osc}}$  across the cloud. (f) Map of fitted decay constant  $\gamma$  across the cloud.



Figure 3.5: Moiré magnification of the atomic density distribution. (a) When two periodic structures of slightly different pitch are overlapped, a large-scale moiré pattern emerges. (b) Magnification of the atomic density distribution based on moiré interference. The OP lattice (red) interrogates the atomic density distribution (blue shaded) at different positions (red dots) within each confining lattice site. If the atomic density distribution in every site is identical, then the resulting excitation fraction across the cloud traces out the density distribution with large magnification. (c) In situ images of excitation fraction taken at different lattice detunings  $\delta$  with a field of view of  $(2.44 \text{ mm})^2$  with  $I/I_{\text{sat}} = 0.89$ . In each image the moiré pattern reflects the microscopic atomic density distribution. Spacing between stripes is  $\lambda_{\rm trap}/2$ . White bars show the microscopic length scale. (d) Comparison of the moiré pattern within the orange rectangle in panel (c) (orange circles) to the microscopic atomic density distribution measured in the cyan box in panel (c) by piezo scan (cyan circles). The horizontal axis of each data set is scaled to match spatial periodicity, and translated to overlap the peaks. (e) Dependence of moiré magnification M on detuning  $\delta$  [103]. The solid line is based on Eq. (3.7). The statistical errors are smaller than the marker size. (f) Evolution of the moiré pattern after a 79 nm lattice phase jump with detuning  $\delta = 200$  GHz. After hold time  $\tau$  the moiré pattern oscillates and becomes distorted, indicating that the dynamics of the atoms in the lattice are not uniform across the sample. The dashed green line serves as a reference indicating the initial position of the center stripe.

# CHAPTER 4 QUANTUM GAS MICROSCOPE DESIGN AND CONSTRUCTION

## 4.1 Introduction

In this chapter, I detail the design of the dual-objective microscope portion of the QMS. Large portions of this chapter are based on Ref. [105].

# 4.2 Optical setup

## 4.2.1 A stable dual-microscope mount

In order to image, trap, and manipulate atoms at the site-resolved level, the relative mechanical stability between the optical lattice at 935 nm, the tweezer array at 532 nm, and the atom fluorescence at 852 nm must be kept within the spatial extent of the on-site wavefunction in our system (approx. 30 nm). To this end, we prepare the imaging, lattice, and tweezer beam paths such that all pass through the microscope optics in order to reduce their relative mechanical instability (see Fig. 1.1b). The optical system is comprised of two identical microscopes placed symmetrically above and below the atom sample. The objectives (Special Optics, Inc.) are custom-designed to offer diffraction-limited performance at all the relevant wavelengths of 532 nm, 852 nm, and 935 nm. The objectives have a numerical aperture of NA = 0.8 and a working distance of 1.05 cm. This dual microscope configuration allows us to image the tweezer and lattice light using the diagnostic CCD in order to analyze the quality of the optical potentials on the atoms. This is in contrast to most experiments which use a single objective and rely on the atomic response to the light field in order to diagnose optical aberrations.

We use standard optical microscopy procedures to align the system. Initial alignment uses



Figure 4.1: Mechanical design and stability of microscope optical system. (a) A thick stainless steel cage (blue) holds the two microscope objectives (green) around the glass cell (yellow). Nearby optics and components are also shown, including  $45^{\circ}$  steering mirrors (orange), Bitter electromagnets and mounts (red), fixed mirror mounts and magnetic shim coil (cyan), the vacuum chamber (dark grey), and the 3-layer breadboard structure (light grey). (b) We analyze the mechanical stability between the tweezer light and the lattice light by imaging both simultaneously on the diagnostic CCD and observing their positions over time. We fit the lattice position (red dashed line) and the tweezer position (green dashed line) using the CCD image (inset). (c) The deviations of the tweezer position  $x_D$  and lattice position  $x_L$ are highly correlated as a result of their shared beam paths. Data is taken over 1 second at a rate of 650 Hz. (d) The difference in lattice and tweezer positions  $x_D - x_L$  (orange) shows a much tighter distribution than the mean position of the lattice and DMD (blue). The RMS noise of  $x_D - x_L$  is 9 nm, which is much smaller than their average fluctuation of 26 nm. Data is taken over a 20 second long measurement.

an independent reference beam and replica glass cell while the vacuum chamber is withdrawn. Afterwards, fine tuning is done by placing a USAF target inside the replica glass cell and simultaneously bringing both the upper and lower imaging systems to diffraction-limited resolution. Lastly, the real glass cell replaces the replica and atoms are brought into focus by tuning the position of the trapping potentials.

An ultra-stable stainless steel cage around the glass cell holds the two microscope objectives and other supporting components (Fig. 4.1a). By connecting the two objectives via a cage, the relative vibrational noise between these two sensitive optics is greatly reduced. In addition to the objectives, the stainless steel cage also supports auxiliary mirror mounts. A nearby water-cooled Bitter electromagnet is mounted on a separate structure to avoid acoustic noise caused by the water flow or large magnetic field quenches [67].

We test the relative mechanical stability of the 935 nm optical lattice and the 532 nm tweezers by imaging them on the lower diagnostic CCD at a fast frame rate of 650 Hz. By fitting the recorded images of the lattice sites and the tweezers, we track the variations of their positions  $x_L$  and  $x_D$  over time with high precision (see Fig. 4.1b). Details about the optical setup of the imaging, the lattice, and the tweezers can be found in Sections 5.2.1 and 6.2.

We observe that the two optical potentials experience highly correlated motion, indicating the common-mode behavior of the optical paths (see Fig. 4.1c). While  $x_L$  and  $x_D$  display a root-mean-square instability of 26 nm, their relative instability is only 9 nm (Fig. 4.1d), smaller than the expected on-site wavefunction extent. Thus, the small relative instability makes the QMS amenable to reliable arrangement of atoms in the lattice using tweezers.

#### Floating the optical table to remove low frequency acoustic noise

During our initial high framerate imaging of the lattice and DMD, we noticed significant oscillations in the 30-34 Hz range. An accelerometer placed on the optical table confirmed



Figure 4.2: Accelerometer measurement of acoustic noise on the optical table. Vibrations stemming from a local air handler on the building floor are completely damped when the table is floating.

the acoustic noise, but the source of the noise was a mystery. In the following days, we took measurements all around the table, lab, and surrounding rooms, but could not pinpoint an obvious source. Over the next week or so, we expanded the search to the entire building floor and the floor above our lab. It was discovered that an air handler about 50 m away from our lab was vibrating strongly at 30 Hz. With permission to modify the air handler settings, we tuned the fan speed to different frequencies and observed the noise peak on our optical table move in unison. Since changing the fan speed permanently could lead to negative consequences for the temperature and humidity stability of the serviced lab space, we opted to suppress the noise by floating our optical table. Fig. 4.2 shows the noise measurements on our optical table before and after floating. The strong 30 Hz peak disappears completely into the noise floor. No sign of oscillations were observed in subsequent measurements with the microscope.

# 4.2.2 Initial microscope alignment

### Alignment procedure

I will walk through the alignment procedure used to achieve diffraction limited resolution at both 532 nm and 852 nm. In order to get satisfactory alignment without relying on a cold atom sample, the initial alignment was completed using a test setup with a replica glass cell *before* the microscopes surrounded the real glass cell under vacuum. Once the microscopes were well-aligned in the test setup, we carefully moved the vacuum chamber into its final position at the focus and completed the final alignment using the atoms (see 4.4.3).

The central idea in our procedure is to create an absolute reference beam and align each optic in series to this reference beam. The components under consideration in this section are: DMD, M1, M2, upper tube lens, upper 45° mirror (M3), upper objective, lower objective, lower 45° mirror (M4), M5, lower tube lens, M6, M7, and the lower CCD. See Fig. 4.3.

Once this is achieved, the only degree of freedom remaining is the relative axial position of the two objectives. The reference beam used is a central patch of digital micromirror pixels of variable size. The digital micromirror device is an especially useful light source since beyond being able to generate beams of varying size, it can just as easily generate optical test patterns for resolution characterization (e.g., a 1951 USAF test chart).

1. Creation of the reference beam. We start with a 532 nm beam reflected by the central DMD mirrors propagating freely across the upper breadboard platform into the upper 45° mirror mount with no intervening optics except for planar mirrors and dichroic beamsplitters. To center the beam on the upper 45° mirror mount, we first place a 3"-diameter laser cut dummy optic with a 4 mm aperture into the mount (due to the angle and thickness of the dummy optic, the effective aperture size is reduced). Two additional mirror mounts in between the DMD and tube lens position are used to ensure



Figure 4.3: Partial beam diagrams for science cell (upper and lower breadboards). The three lattice beams originate from a single fiber that is split into three paths using polarizing beamsplitters. The 532 nm beam is a relatively large collimated beam so that the DMD area can be utilized well.

the incident beam is parallel to the surface of the table and well-centered on the iris. For convenience, we also ensure the beam approximately propagates along the holes of the breadboard, noting that this degree of freedom (yaw) has relaxed requirements. After this is done, the dummy optic (iris) is removed and replaced with the real 3"-diameter mirror. A dish of water is placed in between the upper  $45^{\circ}$  mirror and the upper objective. The petri dish we used had a relatively large 4" diameter so that the meniscus could be safely ignored. We adjust the alignment of the incident beam until its reflection from the water surface is retro-reflecting. If substantial adjustment of the 45° mirror back to the iris to make sure the beam remains centered and iterate the alignment process. At this point we have created the reference beam from the DMD to the upper  $45^{\circ}$  mirror, which shoots downward into the objectives along the direction of gravity.

- 2. Alignment of the upper tube lens. Next, the tube lens is placed into the reference beam path on a fixed V-mount and we align it by hand. A removable iris referenced to the case of the tube lens ensures the incident beam passes through the center of the last optic. A mirror is pressed flush against the back end of the case to retro-reflect the incident beam. At this point, the tube lens is aligned to the reference beam.
- 3. Upper microscope objective XY and tip/tilt. A removable iris is referenced to the objective case. We use the XY-translation stage so that the reference beam passes through the iris. The iris is removed and a mirror is placed flush against the case of the objective. The objective mirror mount is adjusted so that the reference beam is retro-reflecting from the inserted mirror. We iterate between the XY and tip/tilt degrees of freedom until the objective axis is aligned to the reference beam.
- 4. Lower microscope objective XY and tip/tilt. A second gravity-based reference beam is created, this time pointing upwards into the lower objective. Similar to the

upper objective, we place a mirror flush against the lower objective housing and retroreflect the upward-pointing reference beam to set the tip/tilt degrees of freedom. The mirror is removed and we switch back to the original downward reference beam. An iris placed on the lower objective and the lower XY translation stage is adjusted until the original reference beam cleanly passes through the iris. At this point, the lower objective axis is aligned to the reference beam, and we can observe the original reference beam passing through the center of both objectives. Alignment of both objectives' relative z-position still remains.

- 5. Lower tube lens. The lower tube lens is aligned with a mirror and iris following the prescription in Step 2, this time using mirrors M5 and M6 to guide the reference beam.
- 6. Lower CCD XY and tip/tilt. The reference beam passing through the lower tube lens is then aligned to the lower CCD using mirrors M7 and M8, ensuring that the spot on the CCD remains centered while translating its z-position back and forth using the 7 cm range translation stage.
- 7. Objective and lower CCD Z. Lastly we iterate between the lower objective and lower CCD z-position while imaging a test pattern to bring the image into focus at the design magnification of M = 87. The test pattern can be produced using 532 nm via the DMD or by using 852 nm light passing through a negative USAF 1951 test chart. Details of the PSF extraction and magnification calibration can be found in the following subsections.

## 4.2.3 Resolution characterization

### 852 nm PSF from 1951 USAF test chart

For 852 nm testing, we insert a glass slide USAF test chart (Edmund Optics 38-256) inside of the replica glass cell. The test chart is mounted on multiple stages to provide fine tip/tilt



Figure 4.4: Measuring the 852 nm PSF using coherent illumination. (a) A raw image showing 852 nm light from a laser transmitting through the negative 1951 USAF target located in the replica glass cell. (b) Integrated profile from an image cropped near the edge of the square. (c) Extracted  $1\sigma$  resolution as a function of the target z-position, tuned using a precision translation stage. The resolution reaches diffraction-limited performance with a depth of field of approximately 1 µm.

and XYZ control. Before inserting the slide, we ensure good tip/tilt by retro-reflecting a separate gravity-referenced beam. We typically image either the Group 1 square or the Group 7, Element 6 lines and extract a PSF from the rate of intensity falloff between a point inside the line and a point outside the line. When illumination is provided by a coherent laser, the one-dimensional PSF h(x) is given by  $h(x) = (dg/dx)^2/g$ , where g is the measured intensity. For the case of incoherent illumination using an LED, the PSF h(x) in one dimension is given simply by h(x) = dg/dx. From the 852 nm setup, in both the coherent and incoherent cases we extract a PSF corresponding to a diffraction-limited Rayleigh resolution of 650 nm  $(1\sigma = 220 \text{ nm}).$ 

# 532 nm PSF from DMD

532 nm pattern generation is straightforward: the DMD pattern is simply switched to one containing an array of point sources. Alternate test patterns include the pinwheel and repeating lines. From the 532 nm pattern of point sources, we measure a nearly diffraction-limited Rayleigh resolution of 450(25) nm (see Fig. 4.5). By imaging the size of the edge-

to-edge DMD pattern with all mirrors on, we also verified the magnification matched the design specification of M = 87.



Figure 4.5: 532 nm PSF from the DMD. The Rayleigh criterion resolution is 450(25) nm, consistent with diffraction-limited performance.

# 4.3 Magnetic field control

## 4.3.1 3D-printed Bitter electromagnet

For the glass science cell Bitter coils, we proceeded with a newer design that incorporates an internal water distribution system made possible by 3D-printing. This reduces the number of external input and output water connections from 8 to 2. Not only does this save precious space for optical access around the science cell, this reduces the number of connections at risk of leaking. The design of the electromagnet itself follows that in Chapter 2. The main change is the G10 base plate, which is replaced by a VeroWhite plastic material with internal channels.


Figure 4.6: Bitter electromagnet with 3D-printed water channels.

## 4.3.2 Shim coils

The shim coils for the glass cell, as in the MOT chamber, come as three pairs to generate small offsets and gradients. Each coil is constructed of wound magnet wire and mounted on the stainless steel cage structure. Each axis is designed to produce fields at 1 G/A (i.e., 1 G at center for 1 A running in each coil).

The driver circuit is based on a bipolar Howland current source (see Appendix for schematic). An input control voltage tunes the current level at 200 mA/V with fast switching speeds below 50 µs. The gradient for each axis is set manually using the front panel potentiometers.

As in the main chamber, we perform microwave spectroscopy near the clock transition. In terms of the input control voltages to the coil driver, we find the zero field setting at V = -0.02, 2.41, 4.42 V. The calibration for each axis is given by 73, 69, 74 kHz/V.

#### 4.4 Nanotextured glass science cell

## 4.4.1 Optical characteristics

In order to maximize the optical transmission at wide acceptance angles for imaging, projection, and lattice formation at different wavelengths, we adopt a glass science cell (Precision



Figure 4.7: Measured glass cell reflectance. Shown is the total reflectance (two reflections, one from each surface) from one window. The low reflectance at large angles of incidence is advantageous in a high numerical aperture setup.

Glassblowing Inc.) constructed with special nanotextured windows, rather than a traditional polymer-coated solution. The windows (TelAztec LLC) provide excellent broadband anti-reflection (AR) in the 532 nm to 1064 nm range for angles of incidence up to 45°. The glass cell window is textured with roughly 100 nm protuberances that have a large degree of randomness in the size and spacing, which contribute to their broadband, wide-angle AR performance (Fig. 4.7a). The nanotexturing provides a smooth transition in the index of refraction from air to glass, thus avoiding the large mismatch that causes strong reflections. These nanostructures are similar to the so-called "motheye" metamaterials that typically consist of a 2D array of pillars which are uniform in size and work well for narrowband applications [106, 107]. Note that the reflectivity increases with the wavelength, owing to the fact that the gradient in the index of refraction effectively sharpens as the ratio of wavelength to protuberance length grows.

We measure the window reflectivities (combined front- and back-reflections) at various wavelengths and verify that their reflectivity is 1% or less at angles of incidence up to  $45^{\circ}$ 

(Fig. 4.7b). No significant differences between the front and back reflections of the tested windows were observed. The measurements were consistent for the dozen or so windows we tested, including the actual windows on the cell.

## 4.4.2 Installation and vacuum performance

Significant effort was spent to ensure the glass cell could reach UHV <sup>1</sup>. A drawing of the glass cell is shown in Fig. D.2.

To prepare the cell, we carefully cleaned the inside and outside in a chemical bath as instructed by the manufacturer. The aim of the bath is to remove any deeply lodged molecules that can inhibit good vacuum performance, as well as remove any foreign residue on the windows that can hamper optical transmission. The steps of the cleaning process are copied below.

- Ammonium hydroxide (N<sub>4</sub>OH) bath at 35°C for 5 minutes. The cell is immersed in the ammonium hydroxide and simultaneously filled on the inside using a pipette. Only the glass portion should make contact with the bath; avoid getting the glass-to-metal transition or flanges wet. We gently swished the cell around the bath to knock off any possible large particulates.
- 2. Water rinsing to remove the ammonium hydroxide. We first pipette out a majority of the ammonium hydroxide and then dunk the cell into a clean reservoir of room temperature water (DI or distilled are both acceptable). The inside of the cell is then flushed with water. We repeat the rinsing process 8-10 times to remove as much ammonium hydroxide as possible. Proceed to the next step as quickly as possible to avoid water stains.

<sup>1.</sup> An earlier version of the glass cell showed leaks in the windows, a consequence of the non-traditional assembly recipe to avoid damaging the nanostructures. A second iteration proved successful.

- 3. Methanol rinse. We repeat the rinsing process, this time using room temperature methanol. Proceed to the next step as quickly as possible to avoid letting the methanol dry and leave a ring stain.
- 4. Isopropyl bath at 30-50°C for 5 minutes. Repeat the bath instructions in Step 1, this time in isopropyl alcohol, which dries quickly without staining. After the bath, we let the cell dry in a fume hood for 30 minutes.

This cleaning process was attempted multiple times after we noticed a blemish on one of the large step windows. The blemish was later determined to be a scratch after inspection using a countertop lab microscope. We decided to proceed, planning to ultimately orient the cell so that the scratched window faced upwards, so as to not disturb our primary imaging path which uses the lower window. After the cleaning, we re-measured the window reflections from the two step mirrors and found no change, thus confirming the cleaning process did not destroy the fragile protuberances.

Next, the glass cell was mounted on a test vacuum setup along with the custom tee and NEG. A handmade copper oven was outfitted to the glass cell to provide heat on the glass parts. We checked for leaks and baked this test assembly at  $250^{\circ}$ C with a turbo pump attached in order to reach a pressure of about  $10^{-10}$  Torr, after which we proceeded to installation on the MOT chamber.

The custom tee has a rotatable flange as its connection to the MOT chamber, providing adjustment on the roll degree of freedom. Our aim was to align the roll with respect to an absolute reference, which we naturally chose to be the direction of gravity. This gravity reference is also used when we align the microscope (see Chapter 5), providing a consistent way to align both setups independently. In preparation for the vacuum installation, we first set up a downward-pointing green laser reference beam aligned to gravity by retro-reflecting the beam on a dish of water. The horizontal position of the beam axis was carefully measured to be dead on the theoretical glass cell position once it was in place. We prepared the MOT chamber by closing the gate valve to the oven and flooding the interior of the chamber with argon, accessed via the ion gauge and tee assembly mentioned in Chapter 2. The argon serves to create a positive pressure environment, prohibiting the moist room air from contaminating our vacuum assembly. Once the pressure inside the chamber came to within two orders of magnitude to room pressure, we opened the blank flange and quickly increased the argon flux until we could hear and feel the gas exiting the chamber. The glass cell, custom tee, and NEG assembly was roughly positioned on the open vacuum chamber with the bolts in place but not tightened. Using the reference beam we had set up, the glass cell roll was adjusted to retro-reflect the center of mass of the four reflections upwards (two from each step window). The flange was tightened while we simultaneously decreased the argon flux to zero.

As an aside, note that the pitch degree of freedom is not correctable with the custom tee alignment. We ultimately used stainless steel shims placed under the four feet of the optical table to finely adjust the roll and pitch of the glass cell windows. This was implemented after the vacuum installation was completed.

Once the glass cell and MOT chamber were connected, we leak checked and then pumped the apparatus down with a turbo pump. We initially reached a pressure of  $10^{-6}$  Torr, at which point we activated the NEG for one hour, after which we quickly reached  $10^{-8}$  Torr. To attain lower pressures, we baked the glass cell, tee, and NEG assembly at 250°C with a turbo pump attached. After multiple rounds of baking and NEG activation spanning a week, we attained a current reading of 0-1 nA on the NEG gauge, corresponding to  $<10^{-10}$  Torr.

At this point, the vacuum situation is complete and the glass cell windows are aligned to gravity.

# 4.4.3 Positioning the science cell under the microscope

Once the vacuum chamber was completed with the glass cell aligned to gravity, and the microscope setup was completed also aligned to gravity, we merged the two together. This was a tedious process as it involved moving the massive vacuum chamber platform into a position with 1 mm precision. Specifically, the stable mounting cage of the microscope objectives only allowed a few millimeters of error, limited by the cutout reserved for the science cell NEG. Our biggest worry, however, was the science cell running into the objectives, since there is only a 1 mm air gap in between the final objective lenses and the glass cell windows on the top and bottom.

To address the latter issue, we had conducted our alignment of the microscope using a replica cell placed precisely at the same height as the real science cell. The height had been calibrated using a stainless steel pillar mounted on the table that was incrementally shimmed with sub-mm precision until it came within one shim-thickness of reaching the real science cell. After the both objectives' heights were adjusted according to the calibrated pillar, we further separated them by an additional 2 mm to leave a margin of error during the move.

In order the slide the vacuum chamber along the surface of the optical table, we used two jacks mounted on the optical table. These jacks could be re-positioned and independently controlled in order to change the angle of approach. The jacks themselves are simply right angle brackets mounted to the table, with a 1"-diameter stainless steel pillar protruding horizontally from a 1/4"-20 tapped hole via a bolt. To engage the jack, we turn the bolt to drive the pillar into the legs of the vacuum chamber.

The entire process took two days with the majority of time spent making fine adjustments with the science cell within 1" of its final position. Once satisfied, we re-positioned the objectives to each be 1 mm closer (i.e., returned them to their pre-aligned position). Then, we took a series of pictures with a mobile-device camera all around the science cell to pictorially analyze its alignment with respect to the objectives, which we determined to be within a few microradians of ideal.

Lastly, we re-imaged patterns from the DMD and obtained images identical to those with the replica cell. We also imaged the 935 nm lattice again, which also showed no significant change.

#### 4.5 Long-distance optical transport of atoms to the glass cell

Long-distance transport to a second vacuum chamber with greater optical access or other special characteristics is becoming an increasingly common feature in modern cold atom experiments. Typical ways to achieve long-distance transport are a moving dipole trap (either by linear motion or by tunable lens), moving magnetic trap, or the conveyor belt optical lattice. We choose the latter approach, which has the least amount of acoustic noise (something we guard against at all times to reach a low noise floor).

# 4.5.1 Optical setup

A 1D optical lattice ( $\lambda = 1064$  nm, a = 532 nm) with controllable phase passes through the center of the MOT chamber and glass science cell to allow transport of pre-cooled atoms to the microscope (a distance of 28 cm). Up to 40 W of power (Coherent Mephisto MOPA 55 W) is directed to the transport beam path, which creates a standard Gaussian beam that retro-reflects to form a circularly-polarized lattice. The beam double-passes a pair of AOMs to acquire a controllable frequency shift. Both the incident and retro-reflected beams are shaped to mode match with their focus located halfway in between the two chambers, with a waist of 280 µm, see Fig. 4.9 for measured beam profiles. To prevent the retro-reflection from going all the way back to the laser, we dump the retro power using a polarizing beamsplitter.

#### 4.5.2 Lattice phase control

The phase of the transport lattice is controlled with the detuning of the second AOM, see Fig. 4.8. A single frequency DDS synthesizer with two phase-controllable outputs drive each AOM. At zero detuning, the beam accumulates zero frequency shift after the four AOM passes, and we have a stationary lattice. At non-zero detuning, the frequency shift in the reflected beam will cause the lattice phase to acquire a velocity, with the direction being given by the sign of the detuning.

# 4.5.3 Performance summary

We tested a host of trajectories and optimized the final parameters empirically based on the transport efficiency. Given the total transported distance of 28 cm and a set transport time T, we craft generic piecewise functions for  $f_2(t)$  that are symmetric about T/2. We introduce a flat-top region in between the initial and final frequency ramp times ( $T_{\rm ramp}$ ) to cover the distance for fast ramps < T/2. Using a sinusoidal ramp with a total total transfer time of T = 450 ms and  $T_{\rm ramp} = 20$  ms, we end up with  $5 \times 10^5$  atoms in the glass cell (20% efficiency) at a temperature of 25 µK. Other shapes tested included quenches, linear ramps, and exponential ramps. Of the tested ramp shapes, the exponential and sinusoidal shapes were the best, and each resulted in similar performance.



Figure 4.8: Long distance transport of atoms based on a 1D optical lattice. An incident beam at  $\lambda_0 = 1064$  nm is retro-reflected, passing a pair of AOMs twice. The first AOM is driven by a fixed frequency  $f_1 = 80$  MHz while the second AOM operates at a tunable frequency  $f_2(t) = 80$ MHz +  $\delta(t)$ . We take the +1 order from the first AOM and the -1 order from the second AOM, which results in the retro-reflected beam acquiring a frequency shift of  $-2\delta(t)$ . We vary  $\delta(t)$  along a smooth trajectory to translate the lattice sites 28 cm with speed  $\delta(t)\lambda_0$ . Both the incident and retro-reflected beams have a beam waist of 300  $\mu$ m near the center of transport, resulting in a long Rayleigh range and good trap uniformity to within 5% for the entire length. The images show the initial atom cloud in the MOT chamber and the transported cloud in glass science cell.



Figure 4.9: 1064 nm transport beam measurements. The incident beam measurements are taken by diverting the beam away from the vacuum chamber and recording profiles on a CCD. The retro-reflecting beam measurements are taken on a replica setup due to space constraints in fitting a beamsplitter before the chamber.



Figure 4.10: Example transport trajectories, shown here for a sinusoidal ramp shape with total transport time set to T = 450 ms. Optimizing based on transported number, we choose the initial and final ramp times to be  $T_{\text{ramp}} = 20$  ms, with a flat-top region of constant speed occupying the trip time between the ramps.

## CHAPTER 5

## COOLING AND SITE-RESOLVED FLUORESCENCE IMAGING

## 5.1 Introduction

In this chapter I detail the cooling and site-resolved imaging of atoms using the dualmicroscope setup. I also describe our observation of high-efficiency loading of atoms into the optical lattice. Large portions of this chapter are based on Ref. [105].

#### 5.2 Optical setup

In this section I will describe the trapping and cooling beams used on the science cell. These include the 2D triangular lattice beams, the light sheet, and the RSC optical pumping and repumping beams. Refer to Fig. 5.1 for incident beam orientations.



Figure 5.1: All incident beams on the science cell.

#### 5.2.1 The 935 nm triangular lattice

Horizontal trapping of atoms in the glass cell is provided by a 2D triangular lattice formed by interfering three laser beams at wavelength  $\lambda = 935$  nm. The majority of lattice optical design was completed by Mingjiamei Zhang; further details on the lattice will be provided in her thesis. Here I will recount the basic design and the up-to-date lattice parameters.



Figure 5.2: 935 nm triangular lattice beams. (a) Three lattice beams enter the objective symmetrically 17.5 mm off-axis. The polarizations for the three right-handed lattice beams are shown, as measured directly before the upper  $45^{\circ}$  mirror. The *x*-direction corresponds to north, and *z* is up. The polarizations were chosen based on empirical optimization of the atomic imaging fidelity. (b) The lattice intensity pattern directly measured on the diagnostic CCD. The lattice constant is measured to be consistent with our prediction of 881 nm.

We use 935 nm light to generate the lattice, the so-called "magic wavelength" for the Cs  $D_2$  transition at which atoms in the ground state and  $6P_{3/2}$  excited state experience the same lattice potential landscape [108]. In the lattice setup, we split one laser beam (SolsTiS, M Squared Lasers) into three beams each with 0.25 W of power, and send them off-axis downwards through the upper objective (Fig. 5.2a). They are aligned to be symmetric around the optical axis of the objective. The polarizations for the three lattice beams are shown in Fig. 5.2a, where the ellipticity and azimuth correspond to those given by the polarization ellipse. After the glass cell window, the three beams propagate inwards with an angle of

 $\theta = 45^{\circ}$  and intersect each other at a projected angle of  $120^{\circ}$  in the horizontal plane. The interference of the three beams creates a triangular optical lattice with an expected lattice constant of  $2\lambda/3\sin\theta = 881$  nm. The  $1/e^2$  beam radius at the crossing point is approximately 40  $\mu$ m for all three beams. After passing through the atoms and the lower objective, the three lattice beams are directed to a diagnostic CCD for real-time monitoring of the lattice potential on the atom plane. The interference pattern on the CCD is a magnified image of the 2D lattice at the objective focus, so from this we can infer lattice beam parameters and potential pattern at atoms location. The polarization of the lattice beams can be individually controlled. From our simulation, we found that the lattice pattern can change from triangular to hexagonal depending on the polarization configuration of the three beams. To achieve the deepest lattice potential, we set all beams to be circularly polarized (Fig. 5.2b) to maximize the polarization overlapping between all three beams. From the lattice beam parameters, we estimate a trap depth around 150  $\mu \mathrm{K} \approx$  760  $T_R$ , where  $T_R = 0.198 \ \mu \mathrm{K}$  is the recoil temperature. The lattice trap frequency is measured to be 75 kHz in the horizontal plane, consistent with our estimate. The three beams share the same set of beam-shaping optics and propagate through almost-identical optical path lengths. This setup contributes to the phase stability of the optical lattice and the pointing stability of beams at the crossing point.

## 5.2.2 The 1064 nm light sheet

To provide strong vertical confinement, we use a light sheet; i.e., an optical dipole trap tightly focused in one direction. An 8 W beam (1064 nm, Coherent Mephisto MOPA 55 W) is output from a fiber and passes through a cylindrical lens telescope, magnifying the vertical beam size. The beam passes through a final lens placed as close as possible to the glass cell to focus the beam down to a final size of 3 µm-by-70 µm at the atom location, measured using the knife edge technique (see Fig. 5.3).

We require the atom distribution at the bottom of the trap to remain within the 1  $\mu$ m



Figure 5.3: Light sheet beam-shaping optics. All optics are mounted on a standalone solid stainless steel breadboard so that the setup can be easily removed for beam measurements. 1064 nm light from a fiber passes through a M = 16 telescope with cylindrical lenses to elongate the vertical direction. The beam then passes through an aspheric lens which focuses the beam onto the atoms. The translation stage provides axial tuning of the focus position. The mirror M1 is equipped with precision 508 TPI actuators to adjust the beam pointing. This is the main way we bring atoms into the lower objective depth of field. Inset: beam profile imaged on a CCD with the breadboard removed from the system. Knife-edge measurements yield a beam waist of 3 µm-by-70 µm.

depth of focus of the microscope. The dipole potential experienced by the atoms is given by:

$$V(\mathbf{r}) = \frac{3\pi c^2}{2} \left( \frac{1}{3} \frac{\Gamma_1}{\omega_1^3 \Delta_1} + \frac{2}{3} \frac{\Gamma_2}{\omega_2^3 \Delta_2} \right) I(\mathbf{r}) = -k_B \times 2.34 \text{nK} \cdot \text{cm}^2 \text{W}^{-1} \times I(\mathbf{r}).$$
(5.1)

In Cartesian coordinates with the beam propagating along z, the intensity  $I(\mathbf{r}) = I(x, y, z)$ from a gaussian beam can be written as:

$$I(x, y, z) = \frac{2P}{\pi w_x(z)w_y(z)} \exp\left[-\left(\frac{2x^2}{w_x(z)^2} + \frac{2y^2}{w_y(z)^2}\right)\right],$$
(5.2)

with power P and beam radii  $w_x(z)$  and  $w_y(z)$ . The density distribution along the center

in the tight axis (vertical) direction y is

$$n(0, y, 0) = n_0 \exp\left[-\frac{V(0, y, 0)}{k_B T}\right].$$
(5.3)

At 1 W, the atom distribution is already totally within a 1 µm range. We choose to operate at a higher power to relax the alignment requirements and focus the atom sample even tighter to get the best resolution possible. At 8 W, the entire atom distribution is predicted to be contained within a 0.3 µm range. The trap depth is estimated to be 5.8 mK with a vertical trap frequency of 50 kHz. The axial and horizontal (radial) trap frequencies were measured to be 1.1 kHz and 1.7 kHz, respectively, using the release-and-recapture method.

The light sheet was initially aligned by looking for an effect on the transported cloud density. The transported cloud provides a relatively large atom sample to "catch" beams incident on the glass cell. After seeing a thin line-shaped region of higher density on the side CCD (the side of a disk), we moved it to the position of the lattice-trapped atoms. This lets us align the pointing of the beam quite well, but it is not very sensitive to the focus position, which is aligned by tuning the final lens using a translation stage and feeding back on the atom signal on the lower CCD, see the next paragraph.

The final alignment was done using the atoms after getting a site-resolved signal on the lower CCD. We release atoms from the lattice into the light sheet trap only, and then recapture into the lattice. If the focus is severely misaligned, we observe large atom number loss due to the focus position attracting atoms away from the lattice potential, which is required for the fluorescence imaging. This is also subtly observable on the side CCD, as the atom density will smear along the light sheet away from the lattice position when the focus is not well-aligned. We optimized the retained atom number at the center of the lattice potential after the release and re-capture.

The vertical light sheet position is critical to obtain diffraction-limited images of our

atoms. Anecdotally, it seems to the author that high-N.A. microscope setups universally experience drifting out of focus in the axial z—position of either the objective or the sample over a timescale of hours to days. Our setup is no different, and we typically make at least one small adjustment per day to keep the atom sample in focus. During the system warm-up time, freshly turned-on lasers and electronics change the heat distribution in the environment, and the alignment is particularly unstable during this period. We usually wait until temperatures have fully stabilized before attempting site-resolved imaging. In the future, we plan to replace the hand-winded knob (Kozak Micro TSBM3-05-25/9) with a piezo actuator to make the alignment more convenient.

#### 5.3 dRSC in the science cell

#### 5.3.1 Technical considerations

Our particular lattice setup introduces extra complications not typically seen in other dRSC experiments. Namely, the limited laser power forces us to use a less-than-ideal polarization assignment for each beam. In a standard implementation of dRSC, a 3D lattice is created using counter-propagating beams of linear polarization. Then, the polarization axis of the retro-reflecting beam of one axis is tuned by a small angle in order to introduce the necessary effective field gradient for  $\nu \rightarrow \nu - 1$  transitions. Without this small adjustment, only every other vibrational state has significant wave functin overlap, restricting the cooling to occur on  $\nu \rightarrow \nu - 2$ . This severely hampers the cooling speed and ultimate achievable temperature of the atoms, which in general require a  $\nu \rightarrow \nu - 1$  transition for  $\nu = 2$  atoms to reach the dark ground state.

In our lattice geometry with a total power of  $\approx 1$  W, a purely linear configuration results in a shallow lattice in which ample hopping and loss occurs. Our first experiments involved a linear lattice, and the resulting fluorescence images showed a blurred signal with low SNR to determine the lattice sites.

Instead we opt to use three identically circularly-polarized beams for the lattice (see Sec. 5.2.1). While this produces a much deeper potential, a side effect is the effective field produced along the vertical direction that depends on the laser intensity. This must be compensated, and we do so by applying a downward magnetic field using our shim coils. While this works acceptably well, it must be noted that the total spatial extent of our cooling (and the resulting fluorescence) is limited by the Gaussian intensity profile of the lattice beams, since we cannot produce an arbitrary and radially symmetric compensation field in the vertical direction. Thus, we typically restrict our focus to the central region of atoms when it comes to cooling and imaging, and this occurs with application of a vertical compensation field of 2.5 G.

#### 5.3.2 Modulated cooling scheme to eliminate light shifts

In 2022 we revised the cooling sequence in order to eliminate the inhomogeneous light shifts brought on by the tightly focused 1064 nm dipole trap. Rather than detune the optical pumping and repumper beams to try to compensate for the light shifts, we instead modulate the 1064 nm light sheet out of phase with the same frequency modulation applied to the cooling beams. By bypassing the light shifts, the atom sample can then experience the same unshifted cooling light across the its entire spatial extent, which produces more uniform cooling and an overall higher atom number. We choose a modulation frequency of 1 MHz, which is much higher than any trap frequency in the system. Higher modulation frequencies up to 4 MHz showed similar performance. With this scheme, low-SNR time-of-flight images taken from a side CCD suggest a final temperature of 6 µK.

## 5.3.3 Experimental sequence

The entire experimental sequence after transported is described in the following.

- Lattice-only dRSC (20 ms). Directly upon arrival in the science cell, the 1064 nm transport beam is ramped off and the atoms are loaded into the 935 nm triangular lattice. The 1064 nm light sheet is off. The xy- magnetic shim coils are turned on to create a  $\approx 75$  kHz Zeeman shift to match the trap frequency and provide a quantization axis for the  $\sigma^+$  optical pumping light. The z-coil is also turned on to cancel the effective field from the lattice at the center of the trap. dRSC optical pumping and repumper beams are then applied to the atom sample, which cools quickly in the 2D horizontal plane of the lattice, and thermalizes in the vertical z-direction. The cooling in this step does not use the modulated scheme, since the lattice is made with magic wavelength 935 nm light (no light shifts present). We found that this lattice-only cooling is empirically useful to load a higher atom number into the 1064 nm light sheet, see next step.
- Ramp on 1064 nm light sheet (≈ 20 ms). The cooling beams are turned off and the 1064 nm light sheet is adiabatically ramped on in 4 ms. Due to the large trap depth of the light sheet, atoms are attracted to its center position to form a disk-like shape, which settles in a few tens of milliseconds.
- dRSC in lattice and light sheet. Modulated dRSC is applied to re-cool the atoms in both traps, reaching a final temperature of ≈ 6 µK. Lower CCD maging during this step leads to virtually zero signal, as a large fraction of atoms occupy the dark ground state.
- Fluorescence imaging. The optical pumping beam power is increased to scatter atoms out of the dark state, thus providing us with a higher photon flux to image individual atoms, see the next section for details.

## 5.4 Site-resolved fluorescence imaging

#### 5.4.1 Detection with a low-noise CCD

An important part of low-signal imaging is careful characterization of the detector. We use a low-noise CCD (Andor iKon-M 934) whose on-chip TE cooler provides low dark current noise. Using a conventional CCD instead of the frequently-used electron-multiplying CCD (EMCCD) grants us access to faster readout speeds, important for fast tweezer feedback.

#### Noise considerations

We start with a standard CCD noise model to characterize our CCD. The signal on each pixel  $n_{\text{tot}}$  is given by:

$$n_{\rm tot} = \alpha n_{\rm photons} + n_{\rm read} + n_{\rm d} + n_{\rm offset}.$$
 (5.4)

Here  $n_{\text{photons}}$  is the signal,  $\alpha = QG$  is the product of the quantum efficiency Q and the electronic gain G,  $n_{\text{read}}$  is the readout noise,  $n_{\text{d}}$  represents the dark current, and  $n_{\text{offset}}$  is the factory offset.

We can first take test images at various exposure times with a cover installed to block 100% of the incident light, eliminating the first term from the RHS of Eq. 5.4. Fig. ?? shows a sample image and plots of the mean count and variance as a function of time. The plot is essentially flat, suggesting the dark count is completely negligible and can be ignored. The remaining count is completely due to the factory offset (mean) and readout noise (variance). We find that the readout noise has a variance of 31.83, consistent with the factory test result of 30.25.

To characterize G we illuminate the CCD with a large uniform source so that  $\alpha n_{\text{photons}} \gg n_{\text{read}}$  and the dominant source of fluctuations comes from the light rather than the readout.

The wavelength is unimportant for this calibration. We additionally perform background subtraction so we are left with  $n_{\text{tot}} \approx \alpha n_{\text{photons}} = QGn_{\text{photons}}$ . The Poisson noise from the illumination is converted to CCD counts via  $G\sqrt{Qn_{\text{photons}}}$ . Then the ratio of the squared noise and the mean signal reveals G,

$$\frac{\text{noise}^2}{\text{mean}} = G. \tag{5.5}$$

From measurements taken at various exposure times, we find a photon-to-count conversion of G = 0.92. Along with the specified quantum efficiency of 90% at 852 nm, this provides us with the necessary calibration to accurately determine the scattering rate of atoms when we perform fluorescence imaging.

The author additionally notes that the CCD exhibits excellent uniformity, as evidenced by integrated profiles with the cover installed.

# 5.4.2 852 nm PSF from isolated atoms

In order to characterize our imaging resolution using the atoms, we image a sparsely-filled lattice sample created with a shortened MOT loading time (100 ms typ.). The sparse filling gives plenty of space for the atom fluorescence to spread without contamination from neighbors. We then take these images of isolated atoms and overlap them to form a supersampled mean PSF, shown in Fig. 5.5b. The Rayleigh criterion resolution implied by the PSF is 655(3) nm, consistent with the theoretical resolution of 650 nm. We will make use of the PSF during our deconvolution step in the next subsection.

## 5.4.3 Deconvolution and on-site counts

On-site counts are extracted by performing a kernel deconvolution as described in Ref. [109]. This type of deconvolution is useful when the source emitters adopt a constrained and wellknown geometry (in our case, the triangular lattice). The kernel is the matrix of weightings applied to each pixel signal, where the weightings are determined by a linear combination of PSFs arranged on the lattice. The kernel "squeezes" the signal in the tails of the PSF to the central region of pixels; i.e., a kernel located on site (l, m) is

$$\int k_{i,j}(r)h_{l,m}(r)dr = \delta_{i,j}\delta_{l,m}.$$
(5.6)

The resulting kernel for a gaussian PSF based on measured results is shown in Fig. 5.4. The key feature is that pixels very close to neighboring sites are negatively weighted, while pixels closer to the center receive an increased weighting (i.e., the kernel squeezes the leaky signal back to the center).



Figure 5.4: Deconvolution kernel used to extract on-site counts. The darkest color corresponds to negative weighting.

This type of deconvolution works very well in determining the site occupancies, as our resulting histogram of on-site counts has a very clear bimodal distribution with a fidelity in excess of 99% based on Gaussian fits.

However it should be noted that there may be imperfections in our deconvolution step, as evidenced by a non-constant 0-atom peak as a function of the filling fraction (Fig. 5.6b). Further work must be done to eliminate this noise source, which is an important step towards studying correlations in the atom emissions.

## 5.4.4 Filling statistics

We check for systemic problems in the atom distribution by studying the homogeneity of the filling and the neighbor number statistics. As seen in an averaged image, the atomic number density takes on a well-behaved Gaussian envelope with no dark patches (which often occur due to unwanted reflections).

If we look at the neighbor number, it agrees excellently with the corresponding binomial distribution, indicating the loading process into the lattice is completely stochastic, with no preference to form bunches or anti-bunches, see Fig. 5.6.

## 5.4.5 Comment on the broadened fluorescence signal

Fig. 5.5c shows a broadened 1-atom fluorescence peak that is much wider than the expected Poissonian  $\sqrt{N}$  width by an order of magnitude. A similarly broad feature has been observed in virtually every quantum gas microscope experiment. As all of these experiments utilize some form of sub-recoil dark state imaging scheme (e.g., gray molasses or Raman sideband cooling), the author speculates that the broadening could be a result of Lévy statistics in the quasi-dark state regime [110]. More specifically, all of these imaging techniques involve a quasi-dark state in which the atoms are continuously leaving the cold dark state in order to scatter more photons for detection. A true dark state cooling scheme is unlikely to produce the requisite 100s of photons necessary for high-fidelity atom detection.

Lévy statistics, which follows from stochastic processes with a fat tail, is amenable to these systems. In particular, the event of an atom leaving the dark state can be seen as a



Figure 5.5: Site-resolved imaging with the microscope. (a) Typical raw fluorescence images taken 5 ms apart on the lower CCD with markers drawn in the central region to guide the eye. Each image has an exposure time of 200 ms. Sites that were empty and became filled are marked red, and sites that were filled and became empty are marked black in the second image (right). (b) Radial profile of a point source averaged over  $180^{\circ}$  (black) and Gaussian fit (red). The width (based on the Rayleigh criterion) of 655(3) nm indicates diffraction-limited performance. Inset: Averaged image of a point source generated using a sparsely-filled atom sample. (c) Histogram of counts per site in the central region using data from 40 images shows a peak for unoccupied sites (blue, N = 0) and a peak for occupied sites (red, N = 1). The blue and red lines are Gaussian fits, and the vertical dashed line defines the threshold for the determination of site occupancy.



Figure 5.6: Neighbor statistics. a) The probability of finding a certain number of neighbors follows the expected binomial distribution, suggesting truly random loading and no unexpected clustering. b) The on-site counts increases with the filling fraction, indicating imperfect deconvolution.

fat-tailed event. A simple toy simulation can be implemented to gain some intuition. We consider the atom residing in the bright state (with Poissonian scattering rate  $\Gamma$ ) or the dark state (with zero scattering). An atom in the bright state, via the dark state cooling, has some probability P(D|B) of entering the dark state. Likewise, an atom in the dark state has some probability P(B|D) of re-entering the bright state. We let the single-particle system evolve in time steps of  $\Delta t$ .

Fig. 5.7 shows simulation results for  $\Gamma = 87.5$  kHz and  $\Delta t = 4$  ms, which correspond to a typical scattering rate and dRSC cooling time observed in the experiment. Compared to the 100% bright state peak with Poissonian noise, the Lévy flight version shows a decreased mean signal and higher fluctuations as a result of the state switching. Asymmetry in the probabilities leads to asymmetries in the distribution.

I show these plots simply to illustrate that this process can naively lead to extreme broadening by a factor of 2-10. Further work is necessary to realistically characterize the stochastic process in our setup. A direct measurement of the single-atom fluorescence at the nanosecond timescale would be ideal. Experiments exist in which a few atoms living in a



Figure 5.7: Toy-model simulation of Lévy statistics in the atomic fluorescence. a) Symmetric case with P(D|B) = P(B|D) = 0.3. b) Bright state preferred case with P(D|B) = 0.5 and P(B|D) = 0.1. c) Dark state preferred case with P(D|B) = 0.1 and P(B|D) = 0.5.

tweezer fluoresce via optical molasses and is measured on a single-photon counter, though significant 1-body loss prevents confirmation of a dark state. The idealized experiment to measure the Lévy flight may involve single-photon counting combined with single-atom detection (post-selection) on a quantum gas microscope. Plans are underway to set up such an experiment on the QMS, see Chapter 7.

## 5.4.6 Evaluation of hopping and loss

By tracking the atom occupancy in each site across multiple images of the same sample, we gain full information about the atom loss and hopping processes, which collectively form the total error rate. In the early days where we had low imaging fidelity and high error rates, the hopping and loss were comparable to each other. Once our cooling, imaging, and lattice parameters were optimized, the main source of error was only the 1-body loss, with a lifetime greater than 10 s. The total error rate was typically 3-6%, with loss being the dominant contributor to errors.

One useful visualization tool when taking more than one image is the correlations plot of the on-site counts between two images. This tool is simply an extension of the usual histogram, where the data points are split in time along each axis, which can help identify loss processes and rate of error occurrence. See Fig. 5.8. Sites that are unoccupied in the first image and remain unoccupied in the second image cluster in the bottom left peak circled in green. Sites that are occupied and stay occupied cluster in the upper right peak. Sites with counts outside of these two clusters have a changing count rate, and can be identified as errors. This definition of error is stricter than the traditional threshold method, represented in Fig. 5.8 as four quadrants.



Figure 5.8: On-site count correlations between consecutive images. The two concentrated zones represent sites that remained unoccupied (bottom left peak) or occupied (upper right peak) across both images. Sites with counts not inside the green peaks correspond to erroneous events. The upper left region corresponds to sites that became filled; i.e., hopping in. The lower right region corresponds to sites that became unoccupied; i.e. lost or hopped out. The red lines represent the thresholds for traditional single-histogram error detection, which can be considered relaxed requirements.

#### 5.5 Attaining high filling fractions via light-assisted collisions

Achieving a high phase space density through laser-cooling without evaporation is highly desirable to permit fast experimental cycle times and limit the atom number loss inherent in evaporation [?]. Historically, the number density for non-degenerate atom array experiments saturated to 50% filling at each site due to 2-body loss induced by the cooling or imaging light. In recent years, researchers routinely began to control the collisional process using blue-detuned light, allowing >80% single atom loading efficiencies in optical tweezer experiments. So far, the same effect has not been directly observed in optical lattice systems.

After we established high imaging fidelities and low error rates in 2022, we began to observe atom samples with uncharacteristically high 75% filling fractions. Our subsequent investigation suggested the cause was blue-detuned light assisted collisions. While our atoms remained thermal, a high-filling is extremely useful in reducing our anticipated number of tweezer moves, as well as providing a good starting ground to observe correlations in the system.

In this section, I will quickly review the essentials of light-assisted collisions and how they apply to our system. Then I will describe the experimental sequence used to obtain highly filled lattices. Lastly I will discuss optimization of the "collision beam" parameters.

## 5.5.1 Light-assisted collisions

At small internuclear distances, as in the case of two atoms occupying a single lattice site, atoms experience an interaction potential that depends on the states of their valence electrons. For example, two ground state atoms  $|S + S\rangle$  will form a loosely bound pair due to the  $C_6/R^6$  attractive molecular potential. In the case with laser excitation bringing one atom to the excited state, the S and P atoms then experience a molecular potential that is either repulsive or attractive, depending on the sign of the laser detuning (see Fig. 5.9a) [111]. In the case of red-detuned light, the atoms move into the attractive potential at the red-detuned Condon point  $R_C$  and gain a tremendous amount of kinetic energy, which manifests in powerful 2-body ejections from the trap during the de-excitation. This 2-body loss is the reason why it is typically expected to observe a 50% filling fraction in experiments with red-detuned cooling and/or imaging (i.e., parity imaging). If the light is blue-detuned, atoms instead interact through the repulsive  $C_3/R^3$  potential and begin to separate, during which they gain a maximal  $h\delta$  in kinetic energy, where  $\delta$  is the laser detuning. With careful choice of  $\delta$  one can control this elastic collisional process so that  $h\delta \approx U_0$ , thus expelling only one atom from a multiply-occupied site with depth  $U_0$ . The end result is a single atom remaining in the trap, regardless of the initial number. In the presence of both cooling and elastic collisions, the lost atom can hop to a neighboring site and continue the redistribution process until the dynamics terminate when every site has either 0 or 1 atom, see second panel in Fig. 5.9b.



Figure 5.9: Attaining high filling fractions through controlled collisions. (a) Schematic of light-assisted collisions. For red-detuned light, the atoms associate to the attractive  $|S + P\rangle$  potential and gain a tremendous amount of kinetic energy, leading to both atoms exiting the trap. In the blue-detuned case, the atoms move to the repulsive potential, where the maximum amount of kinetic energy gained is capped at  $\hbar\delta$ . (b) Overview of the experimental procedure used to obtain high filling. First, the atom sample is compressed so that multiple atoms can be loaded into a single site. Next, the optical pumping beam used for dRSC is tuned to the blue side, inducing collisions within multiply-occupied sites while still providing the optical pumping mechanism to cool single atoms. This process redistributes the atoms until each site is left with 0 or 1 atom. The end result is a lattice with high filling fraction.

#### 5.5.2 Experimental sequence

Our experimental sequence starts with pre-cooled atoms residing in the lattice and light sheet traps at a temperature of 6  $\mu$ K and a filling of roughly 50% (left image, Fig. 5.9c). We require multiple atoms per site if we want collisions to occur. To get a high-density sample, we compress the atoms by releasing them from the lattice into the light sheet, and then subsequently re-capturing them in the lattice after some hold time. This compression sequence can be done quickly by ramping the lattice of f and on quickly, with only a quarter period hold time. Alternatively, it can be done slowly (e.g., 1 ms ramps with 10 ms hold times), where atoms settle at the bottom of the light sheet trap. We observe similar loading performance with either method, but by default choose the latter due to its relaxed timing requirements, which is sensitive to long-term drift in the lattice trap frequency. After the compression, atoms now occupy a small volume with high density (see middle panel of Fig. 5.9c). We then pulse on the dRSC optical pumping and repumper lasers (20 ms typ.). Importantly, the optical pumping beam is tuned blue from the resonance. Just as we modulate the 1064 nm light sheet and optical pumping beam to eliminate light shifts during cooling, we also turn on the modulation during this collisional phase. The beam simultaneously provides (i) cooling; (ii) fluorescence imaging; (iii) redestribution of atoms due to blue-detuned light-assisted collisions. At this point, fluorescence imaging reveals a high filling fraction between 70-75%. The compression and collisional steps can be repeated multiple times, which can very slightly increase the filling. During each step of compression and collisions, a significant number of atoms are lost from the trap, but we are left with a high-density sample in the central region.

#### 5.5.3 Results

In order to characterize the collisions, we vary the optical pumping laser detuning during the collisional pulse and look at the final filling fraction, temperature, and overall atomic lifetime.

When looking at the final filling fraction as we scan the laser detuning, an asymmetric feature appears, with a hole on resonance and a maximum on the blue side. Applying a higher laser intensity appears to deepen the on-resonant loss feature.



Figure 5.10: High filling fraction via blue-detuned collisions. (a) Mean image of 20 shots. (b) Raw single-shot image showing high filling fraction. The colorbar is the same as in (a). (c) Histogram of 20 shots for the central 81 sites.



Figure 5.11: Filling fraction as a function of number of compression-collision cycles for red and blue detunings. Filling fraction quickly saturates to 74% after one cycle of blue-detuned collisions. On the red side, the filling decreases when we induce collisions. The initial sample with 65% filling for this dataset was prepared with blue-detuned light. The detunings were chosen to optimize the filling fraction on either side of the resonance. The errorbars represent the shot-to-shot standard deviation in filling fraction.

#### CHAPTER 6

# A DIGITAL MICROMIRROR-BASED OPTICAL TWEEZER ARRAY WITH FAST FEEDBACK

#### 6.1 Introduction

In the past decade, digital micromirror devices (DMDs) have surged to ubiquity in the cold atom community by offering precise and arbitrary spatial control of atoms. This has shown to be especially fruitful in initial state preparation for quantum gases, as demonstrated in vortex creation, interesting 1D and 2D geometries, localized interactions, and optical tweezer arrays [112–115]. Rudimentary re-arrangement protocols have also been implemented using DMD tweezers, an experimental verification of the device's viability [116]. Phase-based spatial light modulators have also demonstrated atom re-arrangement using tweezers [117].

A DMD is a chip containing roughly 1 million  $\sim 5 - 10 \ \mu m$  sized mirrors that can switch angles between an ON and OFF state. In the ON state, incident light is reflected toward the atom sample, projecting an arbitrary optical potential through a microscope objective. In the OFF state, the mirrors reflect the light into a beam dump. A typical implementation of the DMD uses either a static pattern or a triggered sequence of patterns pre-loaded onto the on-board memory of the control electronics.

In the QMS, we plan to use the DMD as the basis for our dynamic optical tweezer array to arrange atoms on a 2D lattice. Long pattern upload times ( $\sim 1-10$  s typ.) from a control computer to the on-board memory preclude the use of a DMD for optical feedback within a single experimental shot. In order to bypass the slow upload speed, we operate the DMD in a video streaming mode in which it receives a continuous stream of pattern frames at a speed of 2 kHz and a short delay time of < 100 ms.

In Section 6.2 I describe the optical characteristics of our DMD in conjunction with its design in our dual-microscope setup. Section 6.3 covers our unique streaming method which

unlocks fast feedback.



Figure 6.1: Overview of the digital micromirror device. (a) The DMD is an array of roughly 1 million mirrors of size approximately 10 µm that can flip between an ON and an OFF state. They are typically used in commercial projectors. (b) The active area of the DLP4500 chipset consists of  $912 \times 1140$  mirrors with a center-to-center spacing of 7.637 µm. The mirrors are oriented like a diamond, where the tilt axis runs up and down the diagram. Each pixel is indexed using the rows and columns as shown. (c) A cartoon of the DMD in our microscope setup used to project a tweezer array onto the atom plane. (d) An image taken with the lower CCD showing a circumcoronene (C<sub>54</sub>H<sub>18</sub>) pattern of dark tweezers. The high contrast is consistent with diffraction-limited resolution.

#### 6.2 Optical considerations

#### 6.2.1 DMD projection

We use a DMD (Texas Instruments DLP4500) that has a  $912 \times 1140$  array of mirrors spaced by 7.637 µm. The mirrors have a measured efficiency of 50% in the main diffracted order when illuminating 532 nm light at a 36° angle of incidence for ON mirrors. In order to
eliminate unnecessary diffracted orders from contaminating the optical potential, we place a rectangular iris to isolate the most powerful reflection. The DMD is placed in the image plane of our microscope setup so that we perform real-space optical manipulations. This has the advantage of performing localized operations with minimal disturbance to regions not of interest (in the case of a DMD in the Fourier plane, global changes to the mirror array are necessary to create local changes on the atom plane, and imperfections can disturb other atoms). The imaging magnification of M = 87 implies we have 10.02 mirrors per 880 nm lattice spacing, allowing gradual sliding of the tweezers from one lattice site to its neighbor.

#### 6.2.2 Tweezer power calculation

We wish to create a sufficiently deep tweezer potential with a depth exceeding 100  $\mu$ K using the smallest possible dark spot contained entirely within the hexagonal Wigner-Seitz cell of the optical lattice.

In order to reach the maximum contrast, we must choose a cluster of pixels such that the diameter is at least the size of the resolution-limited spot. For a diffraction-limited system at 532 nm, the PSF has a  $1/e^2$  radius of 280 nm. With a magnification of M = 87, this results in a minimal tweezer radius of 3.2 DMD pixels. Given a 10 pixel lattice spacing, we can expect the size of the tweezer spot pattern to be between 3 and 5 DMD pixels in radius.

To be more precise, we can assemble a set of potential tweezer mirror patterns and convolve them with the PSF to simulate the actual tweezer intensity on the atoms. Example trial patterns and the resulting convolutions with the theoretical PSF are shown in Fig. 6.2. The trial patterns denoted by pixel radius R are determined by,

$$\theta(r) = \begin{cases} 1 & , r > R \\ 0 & , r \le R \end{cases}$$
(6.1)

where r is the radial position from a tweezer's center. This turns off all the pixels inside



and on radius R. The contrast C is determined by  $C = 1 - \min(g(x, y))$  where g(x, y) is the convolved result.

Figure 6.2: Simulation of DMD tweezer patterns convolved with the PSF. a) Binary DMD pixel patterns at various radii. b) DMD pixel patterns convolved with the diffraction-limited PSF. Axes on all plots are in units of micrometers.

To calculate the required power for each tweezer, we assume uniform illumination across the Wigner-Seitz cell (hexagon with side length 508 nm), i.e.,

$$I_{\rm bg} = \frac{P}{6.7 \times 10^{-9} \,\,{\rm cm}^2}.\tag{6.2}$$

The potential experienced by the atoms is given by,

$$V(x,y) = \alpha I(x,y) \tag{6.3}$$

with  $\alpha = 101 \ \mu \text{K} \cdot \mu \text{m}^2 \cdot \text{mW}^{-1}$  for 532 nm light and  $\max(I(x, y)) = I_{\text{bg}}$ . For perfect contrast

C = 1, we require 0.67 mW per tweezer with a depth of 100 µK. For the convolved results in Fig. 6.2, we extract a fitted spot size, contrast, and required power, see Fig. 6.3.



Figure 6.3: DMD spots and resulting power requirements. a) Gaussian fitted widths for the convolved images. b) Contrast extracted from the convolved images. c) Power requirement per Wigner-Seitz cell calculated from the extracted contrast. Dashed lines denote a realistic range of DMD tweezer spots for our experiment such that the  $1/e^2$  radius does not exceed half a lattice spacing.

A preliminary measurement of the contrast shows good agreement with the predicted results for small to moderate spots, see Fig. 6.5. At larger radii, the measured contrast saturates to just above 80%. A more careful measurement when the microscope is in good alignment and proper background subtraction is applied should be carried out to see if 100% contrast can be reached.

In order to satisfy the power requirements (Fig. 6.4), we use a powerful 8 W green laser (Lighthouse Photonics, Sprout-Solo 8W). Accounting for isolator efficiency (90%), AOM transmission (75%), DMD diffraction efficiency (50%), and other transmissive loss (75%), this laser can project 2 W onto the atoms. Imposing a strict uniformity requirement where we only use the brightest region of a Gaussian beam  $(0.9I_0 \leq I \leq I_0)$ , we throw away 90% of the total power. To reach 0.67 mW per tweezer, we use a beam size with  $1/e^2$  radius 2.3 mm at the DMD. Targeting 90% uniformity, such a beam can address a circular region of interest on the atom plane with radius of 7-8 sites (i.e., approximately 200 sites). Relaxing the uniformity requirement to 80%, we can reach a region with radius 11 sites (380 sites).

By utilizing a high-efficiency beam-expander instead of a Gaussian-beam aperture, we



Figure 6.4: Required incident power on the DMD. Given 100% contrast, the plot shows the total power required to generate 100  $\mu$ K tweezers for a region of interest of radius R and intensity uniformity  $I_R/I_0$ .

can expect to gain almost an order of magnitude in power per site (or expand the number of addressable sites). This assumes the flat-top profile can be maintained over the long distance between the DMD and the atom plane.



Figure 6.5: DMD contrast measurement. Radius here corresponds to the  $1\sigma$  Gaussian width.

#### 6.3 Video streaming and fast feedback

This section describes how to set up the DMD assembly (Texas Instruments DLPLCR4500EVM) in a high-framerate streaming mode with equal exposure time for each mirror pattern.

For the most common application of the DMD as a consumer-electronic projector, a 24-bit color video is rendered. The maximum framerate is given by the "refresh rate" (typ. 60-120 Hz), and each frame is a 24-bit color image. The color image is created by sequentially exposing a red-illuminated grayscale pattern, followed by a green-illuminated grayscale pattern, and finally a blue-illuminated grayscale pattern (RGB). Each color is associated with an 8-bit grayscale pattern. To create the grayscale using a binary on-off device like the DMD,

each bit-plane (a binary pattern) is exposed for an amount of time proportional to the bit number, thus building up 0-255 levels of gray.

We modify the above projection protocol in two ways. First, since we are only interested in using the DMD for monochromatic light, we can throw away any notion of different illumination sources. This is achieved by simple removing the onboard RGB LEDs and illuminating the DMD with our green laser. Second, because our goal is to project a movie of moving tweezers, we suppress the grayscale exposure and instead let each bit-plane take on an equal weight. In doing so, we transform the 24-bit color video signal running at a refresh rate  $f_R$  to binary pattern streaming at a framerate of  $24 \times f_R$ .

In order to run the DMD with equally-weighed bit-planes, the user can specify the weightings in the "Pattern Sequence" mode accessible through the Texas Instruments software. It is important that the computer also treats the DMD as a display device with the appropriate settings that are compatible with the specified Pattern Sequence timings. Table 6.1 gives a set of tested display parameters for the DMD that specify how the computer-outputted signal is formatted. These settings can be conveniently changed using a third-party software such as the Custom Resolution Utility [118]. Ultimately, we are able to reach a binary pattern framerate of  $24 \times 105 = 2520$  Hz where the refresh rate  $f_R = 105$  Hz is limited by the 146 MHz processor on the DMD evaluation board.

	Horizontal (pixels)	Vertical (lines)
Active	912	1140
Front porch	8	3
Sync width	64	10
Back porch	208	17
Total	1192	1170
Pixel clock Refresh rate		146.00 MHz 104.686 Hz

Table 6.1: DMD signal format and timing parameters.

We confirm the 2.52 kHz framerate by measuring the reflected light on a photodiode

while sending a video stream that alternates between all mirrors ON and all mirrors OFF for each frame. The resulting photodiode signal is shown in Fig. 6.6. The small oscillations originate from the test light source used and does not represent mechanical noise in the mirrors. Besides the speed matching expectations, we note that this signal can be produced with zero errors and no signs of mirror "flickering" [119].



Figure 6.6: Measured photodiode signal for the DMD running at a 2.52 kHz framerate.

# CHAPTER 7 CONCLUSION & OUTLOOK

In this thesis I have discussed the design and construction of our new apparatus, the quantum matter synthesizer (QMS). A novel superresolution imaging scheme for atoms was presented in Chapter 3. The dual-objective microscope system was described, and our first results with high-fidelity single-site imaging along with high-efficiency atom loading were presented in Chapters 4 and 5. A new approach for fast-feedback enabled optical tweezers using a DMD was described in Chapter 6. In the following sections, I outline several short-term experimental efforts in the lab.

#### 7.1 Tweezer integration

At the time of writing, the video-streaming-capable DMD (Texas Instruments DLP4500) is being installed and aligned onto the QMS. In the previous chapter, images of the DMD optical potential taken by the lower CCD were generated by an older model (Texas Instruments LightCrafter 3000), while the streaming characterization was based on bench testing the newer model. The reason we switched models is because we found that the older version was not capable of streaming equal-weight binary patterns. Instead, each bit-plane in the old model is always exposed in proportion to their bit number; i.e., grayscale is always enabled. Since we wish to project a tweezer movie with uniform time steps, it became necessary to find an upgrade. Note that the diamond-geometry and pixel size are identical for both DMDs, thus making imaged patterns in Chapter 6 representative of the newer model.

Further details of the new DMD beam path will be available in Lauren Weiss' thesis. Besides the replacement of the DMD, another major change in the beam path is the switch from fiber-coupled 532 nm to a free-space 532 nm source. This decision was made after we were unable to attain good fiber coupling efficiency (limited by strimulated Brillouin scattering).

Once the tweezers and atoms are simultaneously well-aligned, we will want to calibrate their relative positions such that a mapping  $f : \mathbb{R}^2_{\text{atom}} \to \mathbb{R}^2_{\text{DMD}}$  can used to update the DMD settings as we receive atom position information during each experimental shot. Since the 532 nm DMD and the 852 nm atom fluorescence have significantly different wavelengths, we cannot naively assume exact correspondence given an image of both on the lower CCD.

The initial calibration is envisioned to involve disrupting the atomic density distribution with DMD-projected patterns in order to visualize its imprint on the atoms. This can be done in both the positive manner (bright patterns to blow away atoms) or the negative manner (dark patterns to trap atoms).

An example calibration procedure is presented. First, the atomic density distribution is imaged as usual to extract the lattice parameters. Specifically, the lattice vectors  $\{\mathbf{v}_1, \mathbf{v}_2\}$ and the offset  $\mathbf{r}_0$  are determined. A DMD lattice pattern is projected with a random scaling factor  $\alpha\{\mathbf{v}_1, \mathbf{v}_2\}$ , and a random positional shift  $\mathbf{r} = (x, y)$  where  $|\mathbf{r}| \leq a$  the lattice spacing. The 935 nm lattice is then ramped down, held off, and ramped back up. The resulting retention from this release-and-recapture procedure is then determined by a second image of the atomic distribution. A 3-parameter optimization can then be performed to find the  $\alpha$ , x, and y that yields the highest retention.

Following the faithful reproduction of DMD patterns on the atoms, a following goal will be to characterize the movement of tweezers. Specifically, we would want to try various movement types and speeds and measure the resulting heating and retention.

Once these two tests are satisfactorily completed, the door to atom rearrangement is opened.

#### 7.2 Adiabatic ramp to degeneracy

When atoms in a deep optical lattice potential reach a sufficiently high phase space density, it is predicted that an adiabatic ramp down of the lattice can lead to the creation of a Bose-Einstein condensate. This would be a much faster route to degeneracy than the  $\sim 10$  s long evaporative cooling. Given that our current dRSC implementation results in a 0.75 filling fraction at low temperatures (first few vibrational levels), and that the addition of tweezers can increase the filling fraction even further, we are extremely close to the predicted regime necessary to initiate an adiabatic ramp to degeneracy. A more careful determination of the atom temperature after dRSC as well as improvements to the cooling performance would help to move in this direction.

#### 7.3 Single photon counting with a quantum gas microscope

Another direction for the QMS is to enable single-photon detection from a single atom. By isolating the atomic fluorescence from a single atom and measuring it on a single-photon counter, we can obtain an unprecedented level of precision in terms of the scattering process. First of all, this would enable the study of dark-bright state switching in the context of Lévy flights. Secondly, this provides an entanglement readout signal for an ongoing quantum networking effort in our lab that is just getting off the ground. With the QMS's ability to prepare and record the retention of an atom at a single site, it is an ideal platform for experiments involving one atom.

#### APPENDIX A

### LIST OF PUBLICATIONS

- M. McDonald, J. Trisnadi, K.-X. Yao, and C. Chin. Superresolution Microscopy of Cold Atoms in an Optical Lattice. *Phys. Rev. X* 9, 021001 (2019).
- J. Trisnadi, M. Zhang, L. Weiss, and C. Chin. Design and construction of a quantum matter synthesizer. *Rev Sci Instrum* 93, 083203 (2022)

### APPENDIX B

### BEAM DIAGRAMS



JT 2023

Figure B.1: Generation 1 laser box beam diagram. This box provides resonant 852 nm light to the MOT chamber and glass cell. It is based on three DBR lasers: a Cs-locked reference laser; a  $F = 4 \rightarrow F'$  (MOT) laser; and a  $F = 3 \rightarrow F'$  (REP) laser.



Figure B.2: Generation 2 laser box beam diagram. This box provides resonant 852 nm light to the MOT chamber and glass cell. It is based on three DBR lasers: a Cs-locked reference laser; a  $F = 4 \rightarrow F'$  (MOT) laser; and a  $F = 3 \rightarrow F'$  (REP) laser.



Figure B.3: MOT chamber beam diagram.



Figure B.4: Science cell beam diagram (middle layer).

### APPENDIX C

# ELECTRONIC CIRCUIT DIAGRAMS



Figure C.1: Bitter coil current driver circuit.



Figure C.2: Science cell compensation coil circuit by Lucas Baralt.



Figure C.3: Zeeman slower current driver circuit (for single ZS segment).

### APPENDIX D

# MECHANICAL DRAWINGS



Opposing small windows are 8" apart.

Figure D.1: Drawing of the MOT chamber.



Figure D.2: Drawing of the glass science cell.



Total transport distance

Figure D.3: Drawing of the custom tee that connects the MOT chamber to the science cell, relevant for atom transport.

### APPENDIX E

# PHOTOS OF THE EXPERIMENT



Figure E.1: The science cell and the microscope objectives.



Figure E.2: The science cell after its installation onto the vacuum chamber.



Figure E.3: The microscope mounting structure during its initial setup.



Figure E.4: Science cell middle layer optics.



Figure E.5: MOT chamber optics (North side).



Figure E.6: 1st generation 852 nm laser box.



Figure E.7: 2nd generation 852 nm laser box.

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