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DEVELOPMENT OF A COMPACT SYSTEM FOR ULTRACOLD ATOM INTERFEROMETRY

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We describe a compact vacuum cell and optics platform suitable for the production of Bose-Einstein condensates and applications in atom interferometry. The cell is designed to work with an externally mounted atom chip. We present a novel atom chip design that can support implementation of a time-orbiting potential (TOP) trap useful for an atomic Sagnac interferometer.

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Development of a compact system for ultracold atom interferometry

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(Dated: October 6, 2023)

We describe a compact vacuum cell and optics platform suitable for the production of Bose-Einstein condensates and applications in atom interferometry. The cell is designed to work with an externally mounted atom chip. We present a novel atom chip design that can support implementation of a time-orbiting potential (TOP) trap useful for an atomic Sagnac interferometer.

I. EXPERIMENTAL APPARATUS

A. Overview

Using a Bose-Einstein condensate (BEC) trapped in a cylindrically symmetric time-orbiting potential (TOP) trap is a promising platform for matter-wave interferometry. Our laboratory has recently demonstrated a dual Sagnac atom interferometer using this approach, where we have achieved effective Sagnac areas exceeding 8 mm^2, and with rotation sensitivity of order 10 µrad/s. However, the demonstration apparatus is too large and complex to be a viable solution for field applications such as inertial navigation, and is poorly suited even for laboratory-based environmental testing. Additionally, the system operates at a relatively low duty cycle, which limits the achievable sensitivity at short integration times.

We describe here a new compact apparatus that aims to address these shortcomings. The apparatus was developed as part of the Atomic-Photonic Integration (A-PhI) program at DARPA. Under this program, UVA subcontracted with Northrop Grumman Missile Systems (NGMS), ColdQuanta, Inc. (CQ) (now doing business as Infleqtion), Air Force Research Laboratory (AFRL), and Space Dynamics Laboratory (SDL). CQ developed the compact system and relevant vacuum technology; NGMS developed the trap coil system and drive electronics; AFRL produced microfabricated atom chips; and SDL provided theory and numerical modeling support.

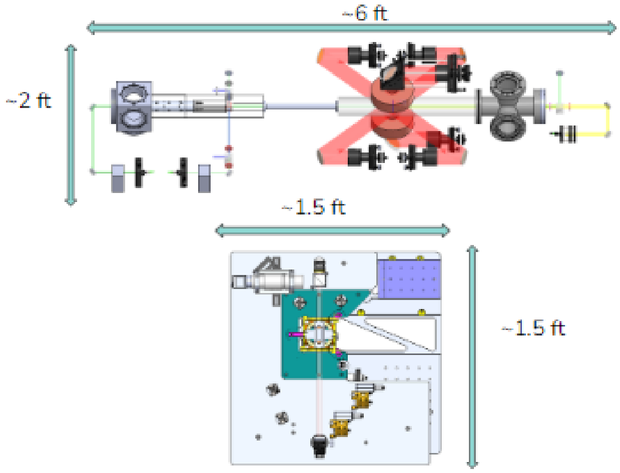

FIG. 1. A size comparison between the proof of concept experiment and the CQ apparatus

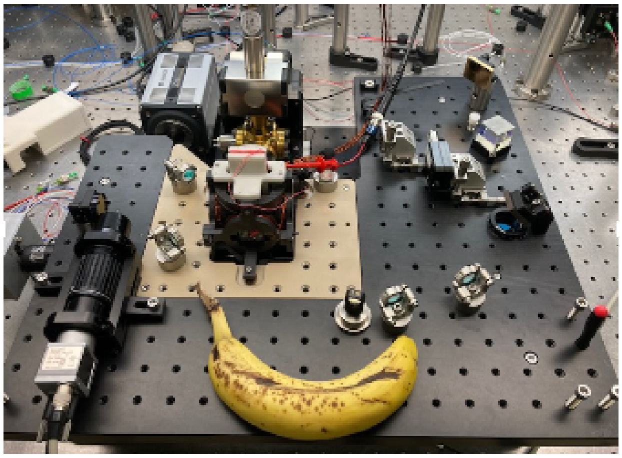

FIG. 2. A top view of the compact system with a banana for scale (chip tower not pictured; surrogate MOT wire tower in its place)

The apparatus is designed to produced the same magnetic fields and to provide the same optical access as the operational laboratory-scale system, but miniaturized to a total volume of about 30 L, not including laser sources and electronics. All of the free space optics are mounted on the assembly, with light entering through optical fiber port. The platform is moderately portable to support environmental testing, and is designed to be robust to mechanical vibrations and arbitrary orientation changes. The system is also designed to use an atom chip, which can speed up the production rate for BEC and provides finer control over the TOP trap potential. The magnet coils and atom chip are all in air, facilitating modifications to the magnetic elements in order to fix problems or test new designs.

B. Vacuum System

A key element for the compact apparatus is miniaturization of the vacuum system. In the lab-scale experiments, the vacuum system has two main chambers:

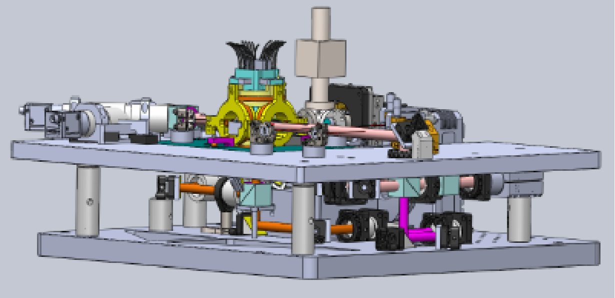

FIG. 3. CAD drawing of the compact system showing the atom chip tower and coil assembly.

the MOT chamber and the science chamber. The MOT chamber contains a Rb getter source and laser beams to collect to collect about 10^9 atoms in a magneto-optical trap (MOT). These atoms are loaded into a quadrupole magnetic trap produced by a high-current coil pair, and the coil pair is then mechanically translated to carry the atoms through a thin differential pumping tube into the science chamber. The science chamber contains trapping coils and provides optical access to produce a BEC and implement the Sagnac interferometer. The entire chamber is about 2.5 m long and about 0.5 m wide and high, at maximum extents.

The new compact system is a customized version of the CQ RuBECi product. It also consists of two chambers, where the first now contains Rb dispensers and a two-dimensional MOT. This MOT generates a slow atomic beam which is directed through a pinhole aperture into a science chamber. In this case, both chambers are small glass cells, about 10 cm long and 2 cm square. The entire assembly is about 40 cm long and 20 cm wide and high at maximum extents. The 2D MOT cell is the standard CQ Photonically Integrated Cold Atom Source (PICAS) system. It consists of three optical fiber inputs and two permanent magnets that produce the 2D MOT and launch the cold beam through the pinhole.

In the science chamber, a 3D mirror MOT collects atoms from the PICAS beam, which can then be loaded into a magnetic trap. One of the cell walls is a 1-mm thick silicon membrane. The vacuum side of the membrane is reflection coated and it serves as the mirror for the mirror MOT. The atom chip is position adjacent to the air side of the membrane. The science cell is also surrounded by a set of six bias coils that produce fields needed for both the surface MOT and the magnetic trap.

Similar technology has been previously deployed by CQ in both off-the-shelf and custom products. However, their standard products yield a vacuum-limited cold atom lifetime of 5 to 10 s, while our interferometer would require a lifetime of 10 to 20 s. To accommodate this requirement, CQ implemented two novel techniques. First, all interior steel surfaces were coated with a passivating material to reduce hydrogen outgassing. Second, a cleaner rubidium source was installed, consisting of a chemically inactive material which could physisorb large quantities of alkali metal. The sorber is loaded by running a conventional rubidium dispenser, which produces significant quantities of hydrogen and other contaminants. The conventional dispenser is then shut off, and for science operation the sorber is heated, which releases the rubidium with few contaminants. Using these methods, CQ observed a factor-of-two increase in the lifetime of atoms in an optical trap, although as discussed below we were not able to confirm this in the delivered compact system.

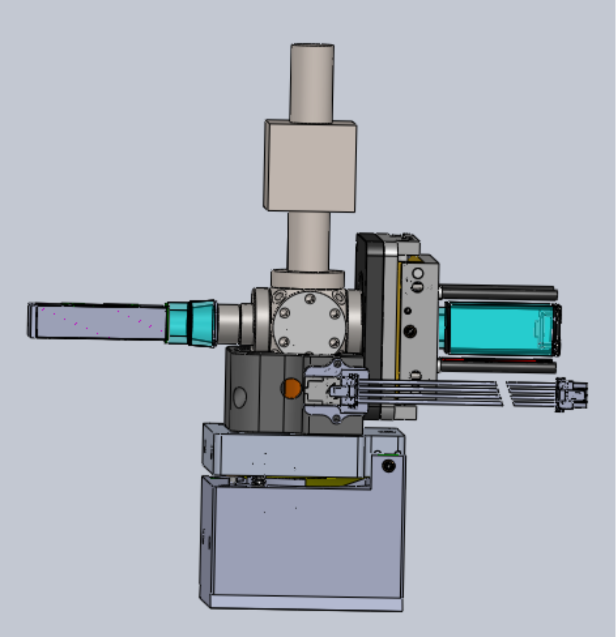

FIG. 4. A CAD drawing of the vacuum system and mounting stage. The cell on the left is the science cell and the cell on the right is the 2D MOT cell. The miniature ion pump is on top of the steel vacuum part connecting the chambers.

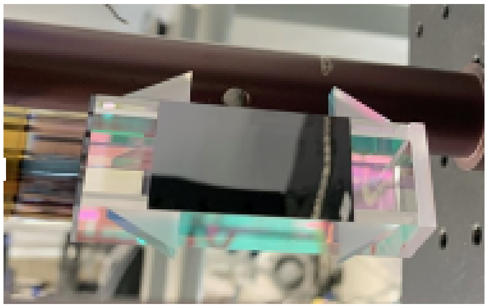

FIG. 5. A picture of the 3D MOT vacuum cell with the Bragg mirrors attached and silicon membrane

C. Optics

The light required for the experiment is produced by two 780 nm diode lasers. One of the lasers provides the Bragg laser beams required for atom interferometry, and

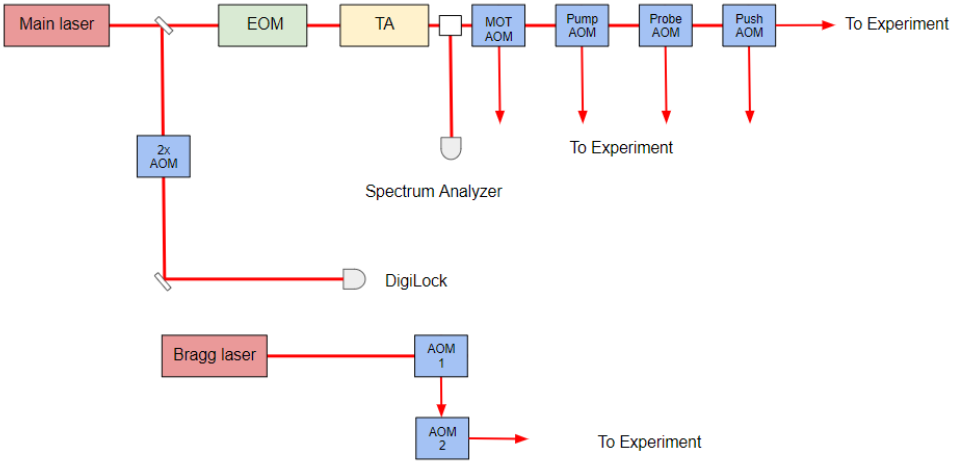

FIG. 6. Block diagram of laser pathways for the compact system

is tuned typically 10 GHz off of the $5S_{1/2}$ to $5P_{3/2}$ atomic resonance. The other laser is locked near resonance, and generates the 2D MOT beams, the 3D MOT beams, the push beam, optical pumping beams, and absorption probe beams. Light is delivered to the optics platform via single-mode optical fibers, and then directed to the atoms via free space optics. The beam path layout is analogous to that used in the lab-scale apparatus, with the addition of the push beam.

The MOT light is produced by a Toptica DL Pro laser. A portion of the output is double-passed through an acousto-optic modulator (AOM), and then delivered to a saturated absorption lock. The frequency of the laser can thus be fine-tuned by adjusting the frequency of this lock AOM. The remainder of the output light is coupled to a fiber electro-optic phase modulator (EOM), where modulation at 6.6 GHz produces a sideband used for optical pumping the $F = 1$ atomic ground state. The EOM output is amplified by a Toptica BoosTA (TA) tapered amplifier, to a total power of approximately 1.5 W. The light then passes through a series of AOMs and beam splitters that distribute beams to the various parts of the experiment.

The Bragg beams are produced by a Vescent DFB laser which can be phase locked to the MOT laser. A pair of AOMs are used to modulate the beam before it is delivered to the atoms. We did not have the opportunity to test Bragg splitting in the compact platform.

The optics platform itself consists of a stack of two 50 cm breadboards, with optics mounted on three layers. The vacuum chamber and coils are mounted to the bottom breadboard and enclosed by a cutout in the upper breadboard. The breadboards are aluminum, but the inner section of the upper breadboard is replaced by a non-conducting plastic material to minimize eddy currents from the oscillating TOP fields. The platform provides absorption imaging capabilities in the horizontal x and y directions, using the same beam paths as for the Bragg beams. The horizontal imaging axes are need to accurately align the Bragg beams and to ensure that the atomic wave packet trajectories close properly. A vertical imaging directions is also available, in which a probe beam is launched vertically upward into the vacuum cell, reflects at normal incidence from the silicon membrane mirror, and then exits the cell and is directed by a polarizing beam splitter onto the imaging camera. This imaging system is used to monitor the atom interferometer output.

An aspect of the compact system which differs from the lab-scale system is the use of a 3D mirror MOT. The optical layout for this MOT is complicated by the constraints of the coil structure needed for the TOP trap. One of the MOT beams is relatively simple, with a horizontal beam passing parallel to the silicon mirror surface and then retro-reflected from a free-space mirror. The other beams are incident on the silicon mirror at 45° angles. The delivery optics for these beams consist of two

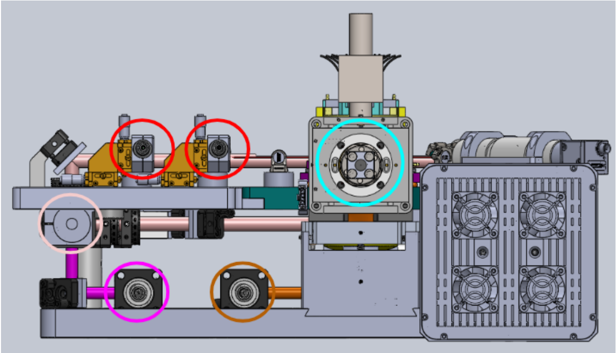

FIG. 7. CAD drawing showing fiber inputs for the entire system. Red circles show the Bragg beam and side imaging probe beam inputs. The light pink circle shows the 3D MOT input. The light blue circle shows the PICAS area where the 2D MOT and push beam inputs are. The hot pink circle shows the pumping beam input. The orange circle shows the bottom imaging probe beam input.

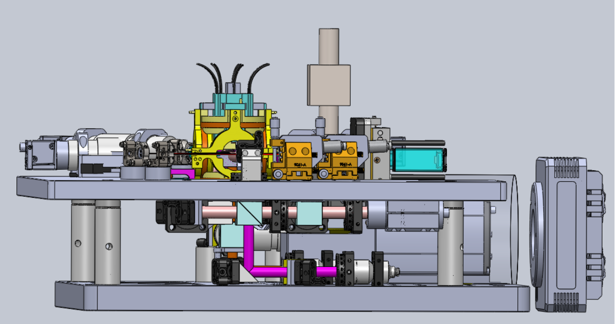

FIG. 8. CAD drawing of the compact system, side view. The 3D MOT beam is represented as light pink, and the optical pumping beam as hot pink.

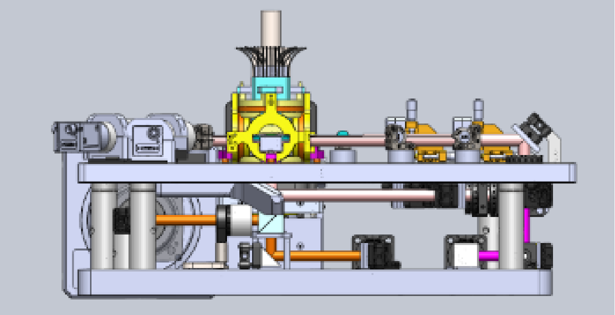

FIG. 9. CAD drawing of the compact system, front view. The vertical imaging probe beam is represented as orange.

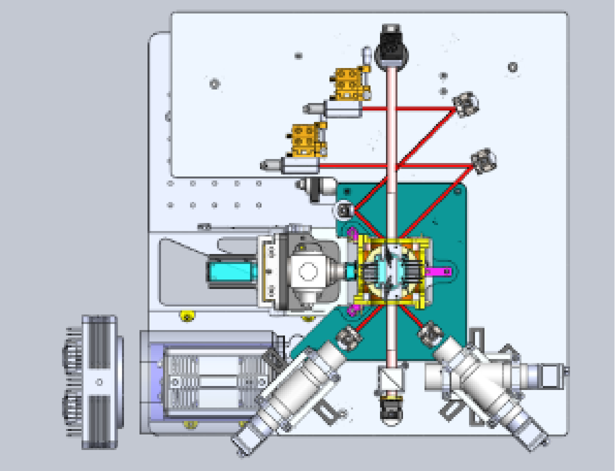

FIG. 10. CAD drawing of the compact system, top view. Bragg beams and side imaging probe beams represented as red. This figure also demonstrate the possible horizontal imaging camera locations.

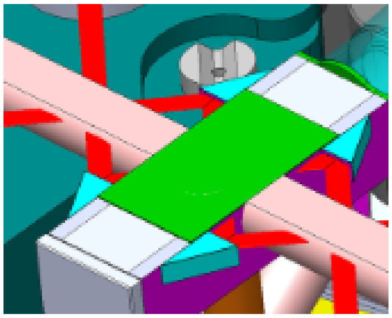

FIG. 11. CAD detail of cell and Bragg beam layout. The blue prisms are mirrors epoxied to the external cell wall.

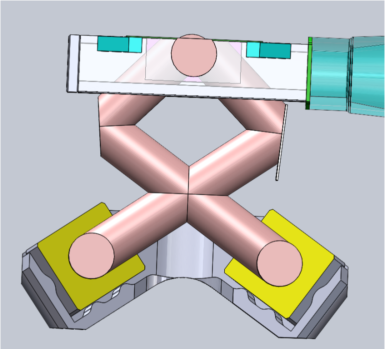

FIG. 12. CAD detail of the mirror MOT optics and beams.

FIG. 13. PICAS system. The push beam couples in to the central fiber jack the rear, and the 2D MOT beams couple in to the other two fiber inputs (one pictured). This system contains permanent magnets within and optics used to produce the 2D MOT beam. When mounted, it fully encloses the 2D MOT cell.

gold fold mirrors and two thin sapphire mirror which are mounted to the magnetic coil assembly as illustrated. In the initial design, all four of these mirrors were fixed in place, with no alignment adjustment possible.

The coil structure also impedes optical access for the two required Bragg beams. To overcome this, four mirrors are epoxied to the sides of the glass cell. The same beam paths are used for the horizontal imaging. Although this does provide the required access, the mirrors are small and nonadjustable, which places constraints on both the Bragg and imaging alignments.

D. Atom Chips and Coils

Although atom chips are by now a well-developed technique, the present effort is the first attempt to produce a TOP trap using an atom chip, and as such it has several

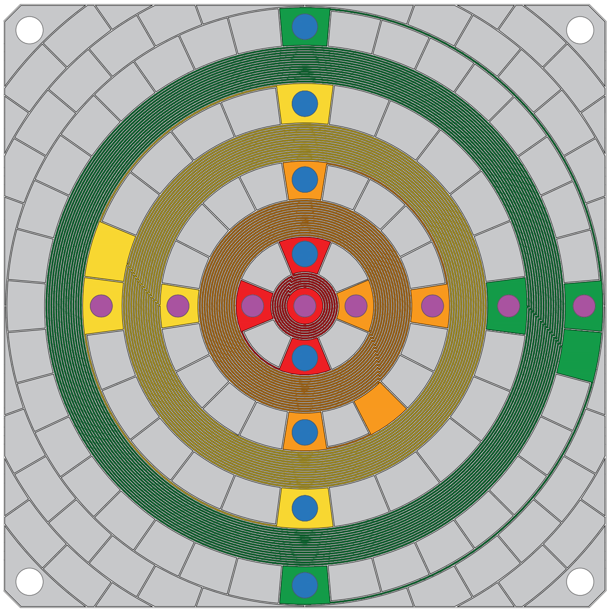

FIG. 14. Spiral chip design. Red, orange, yellow and green colors designate four independent spiral circuits. Purple circles represent vias connecting to matching spirals on the other side of the chip. Blue circles represent contact points for pogo pins. Grey sectors are neutral copper with no current connections.

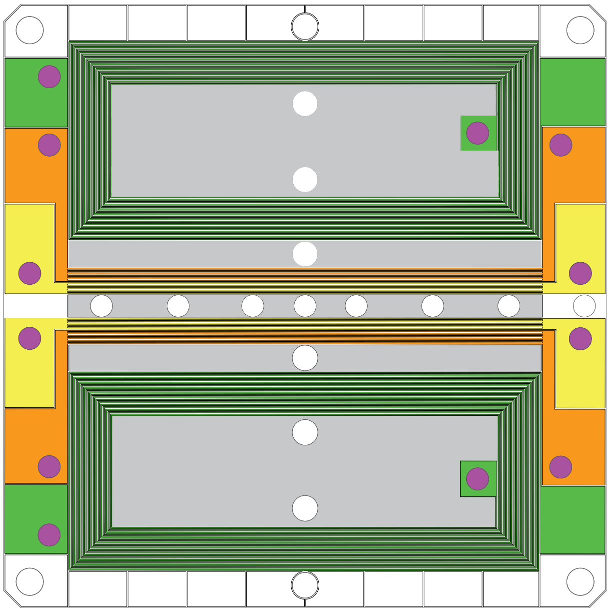

FIG. 15. Linear chip design. Orange and yellow colors designate linear wires used to produce the MOT. Green colors designate rectangular coils designed for trap tilt compensation. Purple circles represent vias to matching circuits on the other side of the chip. Gray blocks are neutral copper machined into thin strips to suppress eddy currents. White circles are holes providing access to the spiral chip and clearance for the vias there.

novel requirements. Our apparatus uses a stack of two double-sided chips: the chip closest to the atoms features spiral coils that are used to produce the magnetic trap for evaporative cooling at atom interferometry, while the more distant chip features linear wires that are used to produced the mirror MOT and to compensate for tilts of the apparatus with respect to gravity. The two chips are separated by a thin Kapton film, and then mounted onto a heat sink block machined from Shapal ceramic. Shapal is an electrical insulator with good thermal conductivity, so that the chip heat can be managed while avoiding eddy currents. Electrical contact to the chips is made via solderless pogo-pin spring connections. The pogo pins are mounted in the heat sink block, and access to the spiral chip is provided by holes in the linear chip. Lead wires to the pogo pins are delivered through holes in the top surface of the block.

Both atom chips were fabricated at AFRL, by laser machining of direct-bonded copper on aluminum nitride. The copper layers on both sides are 0.12 mm thick, and the aluminum nitride substrate is 0.76 mm thick. Each chip is 35 mm square. Both chips have areas containing conducting wires for producing trap fields, and other areas with no current carrying elements. To suppress eddy current effects, the passive areas are machined into small non-contiguous elements; on the spiral chip these are trapezoidal regions about 3 mm across, while the linear chip uses wire-like patterns. A version of the spiral chip that lacked the eddy current remediation was initially incorporated into the lab-scale vacuum chamber for testing, but we found that the eddy currents were sufficiently asymmetric to prevent the interferometer from working and the chip was removed.

The trap bias fields are produced by six orthogonal coils mounted on a Delrin frame. The frame itself is mounted to the upper optical breadboard. The configuration allows the vacuum chamber to slide in and out of the assembly so that either the chamber or coils can be accessed independently when needed. The mounting points for the coil structure and chip heat sink block are designed such that the position of the current elements does not change, to first order, under the modeled heat load of the trap.

II. RESULTS AND CHALLENGES

The initial goal for the compact apparatus was to produce a BEC in the spiral chip trap. Based on comparisons to other atom-chip systems, we expected cooling times of 5 s or less. Unfortunately, we were unable to achieve this goal during the A-PhI project. Although we were able to implement a MOT, the number of atoms trapped was inconsistent, and the best numbers achieved, of order 10^7, was a factor of ten lower than what we estimate was required for BEC.

We discuss here the challenges encountered, but the fundamental issue was the difficulty of modifying the

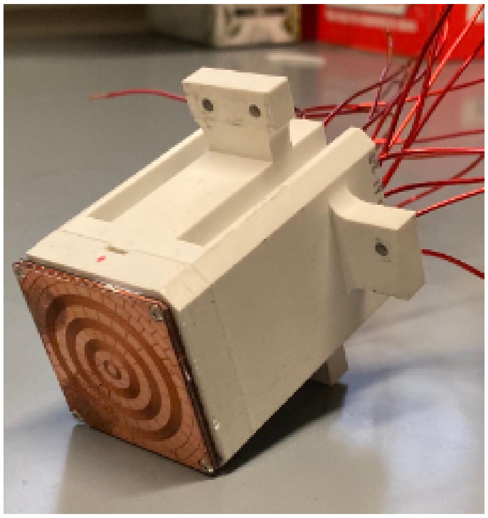

FIG. 16. Photograph of assembled chip tower showing spiral chip

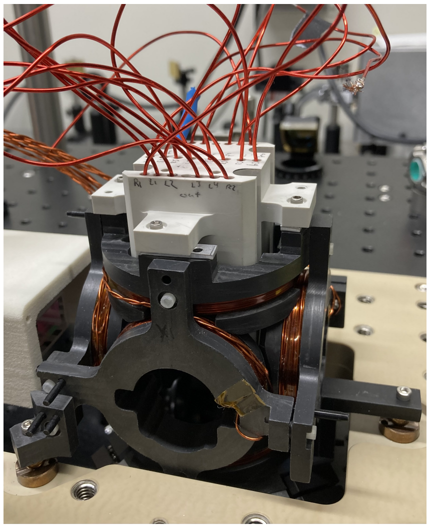

FIG. 17. Photograph of full coil assembly with chip tower. The vacuum cell is not in place.

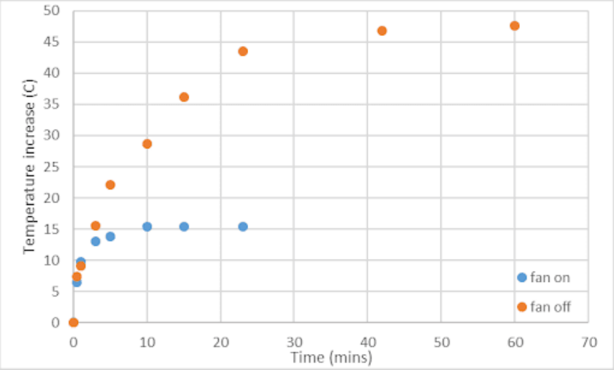

FIG. 18. Chip heating measurements.

compact system to diagnose and correct problems encountered. In retrospect, we would have been better off implementing an intermediate system using the compact cell and chip with a lab-scale optics platform that permitted easier modification and testing.

A. Chip heating

One source of MOT inconsistencies was heating of the chip. The MOT magnetic field configuration requires a dc linear gradient field of about 10 G/cm, which can be generated by wires on the linear chip. The chip has a total of four independent linear traces that were wired in series with a total resistance of 1.6 Ω. A current of 6.0 A was required to achieve the MOT gradient. During steady operation, the heat load of 10 W caused a significant temperature increase in the heatsink block. We measured the chip temperature itself by monitoring the resistance of one of the spiral chip coils and assuming the normal copper temperature coefficient of 0.4%/K. Over the course of 30 minutes, the chip temperature increased by about 50 K, and as this occurred, the MOT was observed to diminish or disappear altogether. To mitigate this problem, we installed a small electric fan on the apparatus to improve air cooling of the block. This reduced the temperature increase to about 15 K, and eliminated obvious effects on the MOT performance. However, forced air cooling typically degrades the stability of nearby laser beam paths, making this undesirable as a permanent solution.

B. Beam polarization

Another source of instability was polarization drift of the 3D MOT beams. This occurs because it is difficult to precisely couple input light to the correct mode of a polarization-maintaining fiber, and then temperature changes can cause the polarization of the fiber output to vary. Although small, these variations had a significant effect on the MOT beam balance, since the beams are generated using polarizing beam splitters. To mitigate this, we installed a polarizer to fix the beam polarization before reaching the beam splitters. The variations in beam power caused by transmission through the polarizer were small enough to neglect. Although this is a straightforward solution to a common problem, it required considerable modification of the optics platform to install the polarizer, since initially there was insufficient space for it. Owing to this, it was not possible to mount the polarizer in an independently rotatable stage, so in order to set the orientation it was necessary to repeatedly remove the optic, adjust the mount, and then replace it. Further, the half-wave plate used to set the beam splitter balance used a mount that was too large to bolt directly to the optics breadboard, so the board featured an indentation to accommodate it. It was neces-

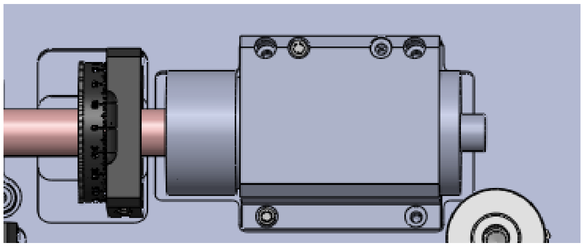

FIG. 19. CAD drawing of fiber launch and half-waveplate mount. It was necessary to insert a polarizer between these two elements.

sary to design a mount for the polarizer that worked with the same indentation. Ultimately, the problem was satisfactorily resolved, but what would have been an hour's work in the laboratory system required roughly a week of effort.

C. Beam alignment

In the course of fixing the polarization problem, it became evident that the MOT performance was unusually sensitive to the MOT beam alignment. Adjusting this alignment carefully presented several challenges. First, many of the relevant optics were mounted on the bottom side of the upper breadboard, making them difficult to adjust. Second, the final set of mirrors for the vertical beams was the complicated coil assembly of Fig. 12. There was no simple way to visualize or evaluate the resulting beam alignment at the location of the atoms. Because of these problems, any time an optics layout change was required, it took an inordinate amount of time to realign the beams to recover the MOT.

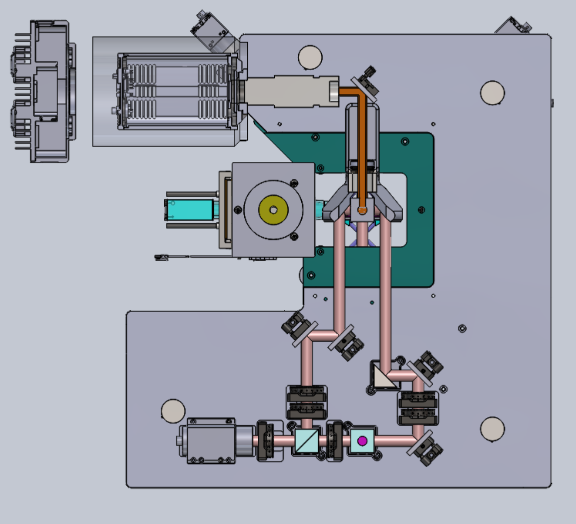

FIG. 20. Optics mounted on the bottom of the top breadboard. 3D MOT beams in light pink, probe beam in orange.

The method we developed to overcome these alignment challenges consists of removing the top breadboard and flipping it over for better access to all of the relevant optics. To perform this procedure, we (carefully) slid the vacuum chamber out of the coil assembly so that the breadboard could be removed. Optical posts were mounted to the top of the to support it while it was inverted. In this configuration, it was straightforward to direct beams into the coil assembly. In order to establish the position of the beams at the MOT, we first placed a card on the exposed bottom surface of the atom chip, and ensured that both beams reached the card reasonably centered. We then replaced the card with a thin mirror, substituting for the silicon membrane mirror of the cell. We then align the beams so that the reflections from the chip mirror exited the coil assembly well overlapped with the corresponding input beams. When the breadboard and chamber were reinstalled, the beam alignment was typically good enough to observe a MOT.

While exploring this issue, we found that it was not possible to align the beams so that they were centered on the atom chip and also able to propagate through the coil assembly without clipping on mirrors. We attribute this to small misalignments of the fixed mirrors in the assembly. To correct for it, we remachined the forked mount holding the two lower mirrors of the assembly to replace the fixed mounts with adjustable kinematic mounts. This enable the beams to be better centered on the chip and also facilitated adjustment of the beam alignment to optimize the MOT performance.

Even with all of these improvements it was challenging and tedious because if I adjusted something too much or didn't have the cell in quite the right place, I would have to the flip the whole thing over again and redo it to varying degrees because the alignment through the mirror MOT optics was very tight. To give ourselves some additional ability to align the beam without the need to flip it over multiple times, we added mirror mounts to the fold mirror mount so that we have better adjustment of the beam through the mirror MOT optics. Additionally, you could use the chip to align the beam in real time with these mirror mounts to ensure the beam isn't clipping or the overlap is near the middle of the chip.

D. MOT Monitoring

Although the improvements discussed above did make the mirror MOT more reliable and easier to work with, the atom number remained too low, with a peak observation of 10^7 atoms and typical performance of about half that. A persistent difficulty in addressing this problem was the lack of a useable real-time monitor of the atom number. In the lab-scale system, we implement a monitor by imaging the MOT fluorescence onto a photodiode, which can then be tracked using a voltmeter or oscilloscope. The compact system was not designed with a fluorescence monitor, and we found no good way to implement one. Collection lenses placed on the upper

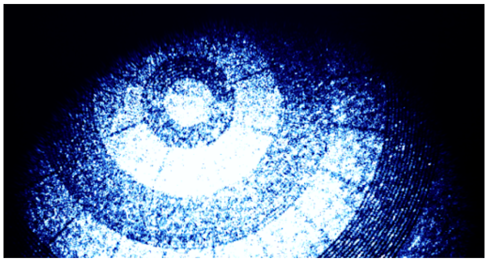

FIG. 21. Misalignment of MOT beams on chip with original forked mount. Here the chip is illuminated by the off-center MOT beams.

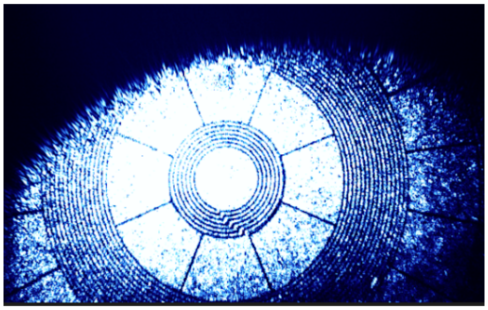

FIG. 22. Improved alignment with new mount.

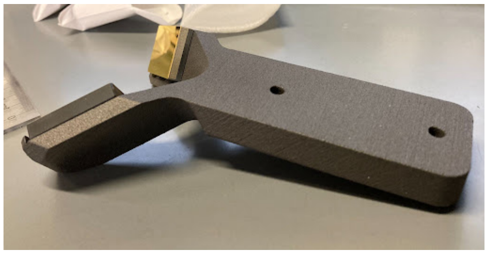

FIG. 23. Forked mirror mount with fixed mirrors.

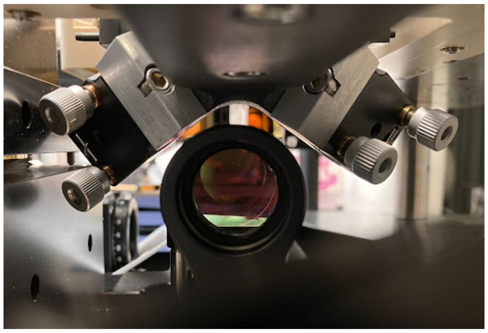

FIG. 24. New fold mirror mount, installed.

breadboard had low efficiency and suffered from large amount of background light from scatter MOT beams and the pushing beam. We attempted to add a photodiode to the vertical imaging beam path using the other output of the probe beam splitter, but given the constraints involved we were unable to collect enough fluorescence to provide a reliable signal. As an alternative to a photodiode, we modified the bottom imaging camera to provide a continuous video update, and developed a computer program to provide a real-time measure of the total light in the image. This monitor was useful, but it was rather slow and could not easily be synchronized to other experimental time controls. For instance, it could not be used to monitor the decay of the fluorescence after the pushing beam was turned off.

We were able to quantitatively probe the MOT using absorption imaging with the vertical probe, as seen in Fig. 25. However, this provides only a snapshot and requires significant image processing time, so it is ineffective to use when optimizing a parameter. We attempted to use the horizontal absorption imaging system as well, which would be useful for determining the distance from the MOT to the atom chip. Unfortunately, the small mirrors affixed to the vacuum chamber provided too limited a field a view for this purpose, and this was compounded by a small chip we inadvertently introduced into one mirror when removing the chamber from the coil assembly.

Separately from the 3D MOT, we also had no good tool to evaluate the performance of the 2D MOT. In principle the slow atomic beam could be detected with a transverse absorption probe, but the system lacked sufficient optical access for this.

E. Magnetic Trapping

Although we were unable to achieve a sufficient number of atoms in the mirror MOT, we did attempt to load atoms into the chip-based magnetic trap. However, the chip circuits were designed to be driven by the Northrop Grumman current amplifiers. These amplifiers were unavailable due to delivery delays, so we instead developed a simple switching system using standard current supplies. The Northrop system will be more effective since it will allow the switching profiles to be controlled precisely. This can be important since, for instance, it is necessary to ensure the MOT fields are fully turned off before turning the chip fields on.

It is also important to align the position of the chip trap with that of the MOT. For vertical alignment, this requires the horizontal imaging system which as noted above did not work well.

When we did try to load the chip trap, we generally observed that the atoms were launched by the magnetic force away from the trap center. It is not clear why this happened, but it would be expected if the chip fields turned on before the MOT bias fields turned off, since the non-zero bias fields would significantly displace the trap center from the expected location.

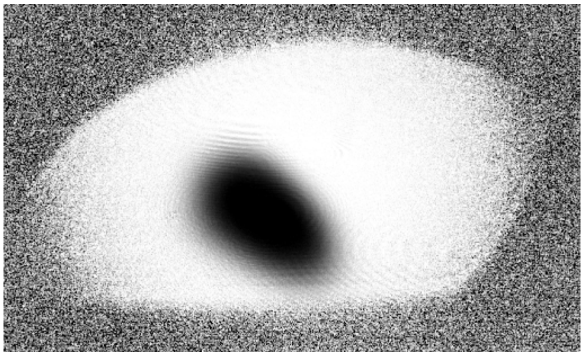

FIG. 25. Absorption image of a 3D MOT.

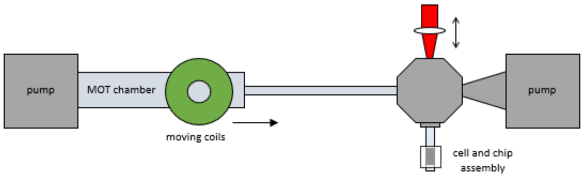

FIG. 26. Block diagram of the proposed hybrid experiment. The red beam is a high power laser producing an optical trap that can be translated to carry atoms from the main chamber into the CQ cell.

III. CONCLUSION AND FUTURE WORK

The compact system has many advantages over the lab-scale experiments, and it could serve as a significant step towards an atom interferometer system suitable for use in a field environment. Unfortunately, it seems to have been too large a step away from proven techniques, and despite working on it over an extensive period from May 2021 to December 2022, there remain significant shortfalls.

Moving forward, we hope to decouple the atom-chip interferometer studies from the MOT system performance, so that we can determine if the chip interferometer performance warrants further development on the compact system. To achieve this, we plan to mount the CQ cell and coil assembly onto our lab-scale apparatus. Rather than loading it with a surface MOT, we will transfer cold atoms into the cell using a translatable optical trap. This will remove the need for MOT and pushing beams which relives much of the pressure on optical access. It is possible to load atoms directly from the optical trap into the chip trap, simply by ramping up the chip fields once the atoms are positioned appropriately. We will then be able to test evaporative cooling and operation of the Sagnac interferometer.

Also, we have now finally obtained the Northop Grumman current amplifiers, so these will be available for operation in the 'hybrid' system. This will allow us to test novel capabilities such as TOP waveform shaping, dynamic trap modification, and to some extent tilt control.

To facilitate this effort, CQ has provided us with additional MOT cells, including the silicon membrane. We will use one of these cells for the hybrid system, so it will not be necessary to break vacuum on the compact chamber. If the chip interferometer results are positive, we plan to return to the compact chamber but set it up on a full-size optics table with conventional optics control. It would also be possible to design a simplified coil system capable of producing the MOT fields but not the chip trap. This could permit greater optical access and permit better diagnostics for the 3D MOT and 2D MOT performance.

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