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Name of the recipient:
Department of Physics, University of Illinois at Urbana-Champaign
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1901 South First Street, Suite A
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Project title:
Atom chip microscopy: A novel probe for strongly correlated materials

Name of PI:
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November 3, 2011

FINAL REPORT for grant at UIUC, periods 1–3; grant is transferring to Stanford for Period 4:
This final report covers period from 09/15/2009 to 11/1/11.

1 Executive summary

Improved measurements of strongly correlated systems will enable the predicative design of the next generation of supermaterials. In this program, we are harnessing recent advances in the quantum manipulation of ultracold atomic gases to expand our ability to probe these technologically important materials in heretofore unexplored regions of temperature, resolution, and sensitivity parameter space. We are working to demonstrate the use of atom chips to enable single-shot, large area detection of magnetic flux at the 10^{-7} flux quantum (Φ_0) level and below. By harnessing the extreme sensitivity of atomic clocks and Bose-Einstein condensates (BECs) to external perturbations, the cryogenic atom chip technology developed here will provide a magnetic flux detection capability that surpasses other techniques—such as scanning SQUIDs—by a factor of 10^1–10^3. We are testing the utility of this technique by using rubidium BECs to image the magnetic fields emanating from charge transport and magnetic domain percolation in strongly correlated materials as they undergo temperature-tuned metal–to–insulator phase transitions.

Cryogenic atom chip microscopy introduces three very important features to the toolbox of high-resolution, strongly correlated material microscopy: simultaneous detection of magnetic and electric fields (down to the sub-single electron charge level); no invasive large magnetic fields or gradients; simultaneous micro- and macroscopic spatial resolution; freedom from $1/f$ flicker noise at low frequencies; and, perhaps most importantly, the complete decoupling of probe and sample temperatures. The first of these features will play an important role in studying the interplay between magnetic and electric domain structure. The last two are crucial for low frequency magnetic noise detection in, e.g., the cuprate pseudogap region and for precision measurements of transport in the high temperature, technologically relevant regime inaccessible to other techniques based on superconducting scanning probes.

In periods 1–3 of this grant, which we now close at the University of Illinois at Urbana-Champaign and restart at Stanford University where our new lab is being built, we have demonstrated the ability to rapidly create Rb BECs and trap them within microns of a surface in cryostat. Period 4 of this grant, to be performed at Stanford, will demonstrate the feasibility of using atom chips with a BEC to image transport features on a cryogenically cooled surface. Successful demonstration, in future funding cycles, will lead directly to the use of system for studies of transport in exotic and technologically relevant materials such as cuprate superconductors and topological insulators.

2 Accomplishments

The goal of this 4-period grant is to demonstrate cryogenic atom chip microscopy with rubidium. This entails: 1) creating and loading a Rb Bose-Einstein condensate (BEC) onto an atom chip; 2) testing the performance of the atom chip microscope with a microwire that generates a known magnetic field pattern; 3) demonstrating the ability to maneuver a BEC within microns of a substrate whose temperature is independently controlled and stabilized using a cryostat; 4) Attempting to image transport in a strongly correlated material such as VO2.

Comparison of actual accomplishments with the goals and objectives of the project:

This is the final report for Periods 1–3 of 4, which were performed at the University of Illinois

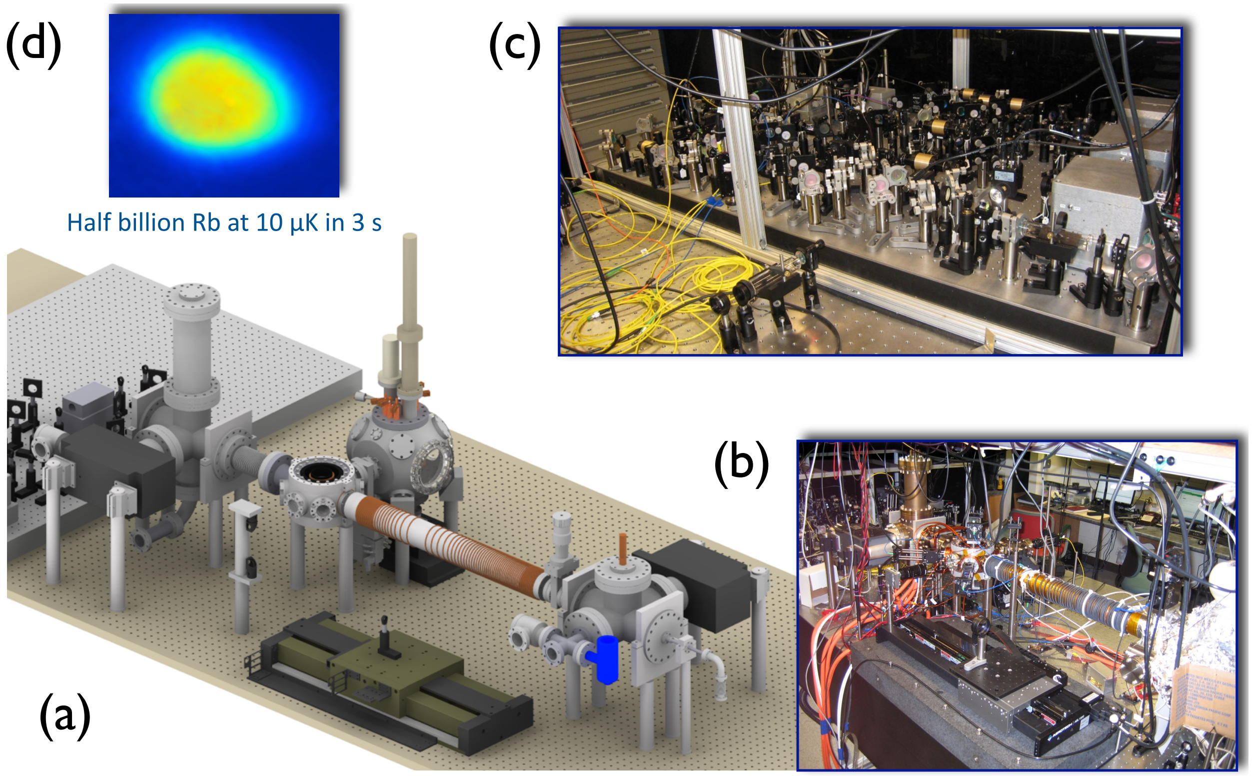

Figure 1: **Rb BEC production machine.** (a) The 3D CAD design of the cryogenic atom chip microscope UHV chamber. From right to left: Rb oven; Zeeman slower; BEC production chamber (this is also where the MOT is formed); UHV pumping section. Shown additionally are the air bearing translation stage for the optical tweezer and the UHV cryogenic atom chip chamber. (b) The fully operational UHV chamber including optical tweezer. (c) The completed home-built Rb laser cooling system. (d) An example image of ultracold Rb atoms produced in our BEC chamber.

at Urbana–Champaign. My group and this project are moving to Stanford University in January 2012, and this grant, per the request of Dr. Jane Zhu, the program manager, will restart at Stanford for period 4. We have met all milestones up to year 3 set out in our original grant proposal including BEC production, atom chip macrowire loading, and the demonstration of cryostat operation from room temperature to 7 K. The only exception is the demonstration of high resolution BEC imaging near the sample surface, which we hope to accomplish by year's end. (Period 3 ends 6 months from now, so we are well within our period 3 milestone range.) Year 4 will see the demonstration of the full imaging system at cryogenic temperatures.

Accomplishments prior to period 3:

At the time of the last progress report, we had demonstrated the fully operational Rb laser cooling and trapping system and were producing ultracold (1 μK) Rb samples every 3 s (see Fig. 1). Evaporative cooling to BEC was nearly complete, we were waiting on the installation of a new RF amplifier to complete the RF knife evaporation to degeneracy. The optical dipole trapping laser was installed and aligned to the ultracold atoms. The cryogenic atom chip trapping chamber was fully complete, and we had begun microfabricating our first atom chips. We identified topological insulators and cuprate superconductors, rather than VO_2, as the most interesting materials to investigate once we have completed the atom chip microscope calibration experiments.

Lastly, we designed a novel type of atom chip that allows atoms (or molecules) to be confined in their absolute ground state. This is crucial for the future of cryogenic atom chip microscopy with dysprosium, the most magnetic atom. Dy's 10x larger magnetic moment translates into at least a 20x better sensitivity to magnetic fields than Rb, but also means that it is much more susceptible to trap loss from dipole-induced spin relaxation. Trapping near-cryogenic-surfaces in the absolute (Zeeman) ground state, which our new trap allows for the first time, eliminates this inelastic loss channel while providing trapping architecture for Dy-based atom chip microscopy.

Cumulative accomplishments up to period 3:

- **Production of ultracold Rb:** We have successfully completed all of the laser cooling steps necessary for creating a Rb BEC:
  - Zeeman slowing a fast atomic beam from 300 m/s to 10 m/s.
  - Capture of atoms in a MOT. We load 7×10^8 Rb atoms in 3 s at $\sim$100 μK.
  - Optical molasses cooling of atoms to 10 μK by 1) rapidly shutting off the magnetic quadrupole field; 2) field zeroing to sub-10 mG, 3) detuning and decreasing the intensity of the cooling light; and 4) decreasing the intensity of the repumper light.
  - Optical pumping of Rb atoms to the $|2,2\rangle$ or $|1,-1\rangle$ state depending on the particular experiment.
  - Recapture of ultracold Rb into a magnetic quadrupole trap of 40 G/cm.
  - Adiabatic compression of atoms into a 160 G/cm trap.
  - Creation of hybrid trap consisting of a magnetic quadrupole and an optical dipole trap.
  - Observed signatures of evaporative cooling after application of a swept RF field.
  - Absorption imaging diagnostics.
- **Created a Rb BEC in the production chamber:** We succeeding in creating a Rb BEC using a hybrid trap formed by the intersection of a focused 7 W 1064 nm optical dipole trap beam and the quadrupole magnetic field of the MOT. We can produce BECs of population between 10^5 and 10^6 atoms at 100 nK in less than 20 s.
- **Transferred nearly condensed Rb to science chamber:** We used the very same 1064 nm laser to optically tweeze the ultracold Rb (a factor of two in temperature from BEC to reduce heating and loss from 3-body collisions) 40 cm from the production UHV chamber to the gate valve-issolated science chamber.
- **Assembled and installed the cryogenic atom chip science chamber:** The science chamber houses the He-flow cryostat, atom chip assembly, high NA imagining optics viewport, and provides access to the Rb ultracold gas production chamber (see Fig.2). This chamber has been installed onto the BEC production apparatus. (See Fig.3.)

- **Capture of Rb ultracold gas by macrowire atom chip:** The science chamber houses the He-flow cryostat, atom chip assembly, high NA imagining optics recessed viewport, and provides access to the Rb ultracold gas production chamber. This chamber has been installed onto the BEC production apparatus.
- **Atom chip microfabrication:** We microfabricated have our first atom chips for re-Bose condensing the atoms near a cryogenically cooled surface. (See Fig. 4.) We are now working to load the ultracold atoms into these chips.
- **Crystat operation down to 7 K:** We were able to cool the UHV copper cold head of the He-flow cryostat down to 7 K, and we have designed heat shields to allow cooling with lower cryogen flow and to lower temperatures. Copper braids will be attached to cold head and cool condensed matter sample to at least 20 K in current version of experiment.
- **Strong field seeking atom chip (SSAC) trap:** We have invented an atom chip that allows the trapping of atoms (or molecules) in their absolute ground state. Maxwell's equations dictate that atoms (or molecules) confined in magnetostatic (or electrostatic) traps must be in a metastable Zeeman state. In such a state, these atoms a susceptible to inelastic collisions that lead to trap heating or loss. Highly magnetic atoms like Dy or atoms with peculiar collisional properties like Cs (the time standard) are particularly susceptible to this detrimental collisional loss. Traditional atom chips cannot tightly confine Dy near a surface since the loss rate will be too high. Optical dipole traps can trap near a surface, but the $\sim$10 W of scattered light can quench the superconducting state of nearby superconductors. Our new SSAC trap gets around both problems by allowing confinement near a surface using superconducting wires and confining the atoms in their absolute ground state. This is possible because the SSAC trap employs AC (microwave) fields, for which Maxwell's equations do not place such restrictions on the trappable state. Figure 5 describes this novel trap in more detail, and we are working on a forthcoming publication.
- **Achievements not related to grant:** In an unrelated project, we have successfully created the world's first BEC of dysprosium, the most magnetic element. We mention this because Dy is a prime candidate for dysprosium-based atom chip microscopy in the future (i.e., beyond this current grant's scope), which promises to enhance the sensitivity of the atom chip microscope by a factor of 20-1000. This result has been published in Phys. Rev. Lett.

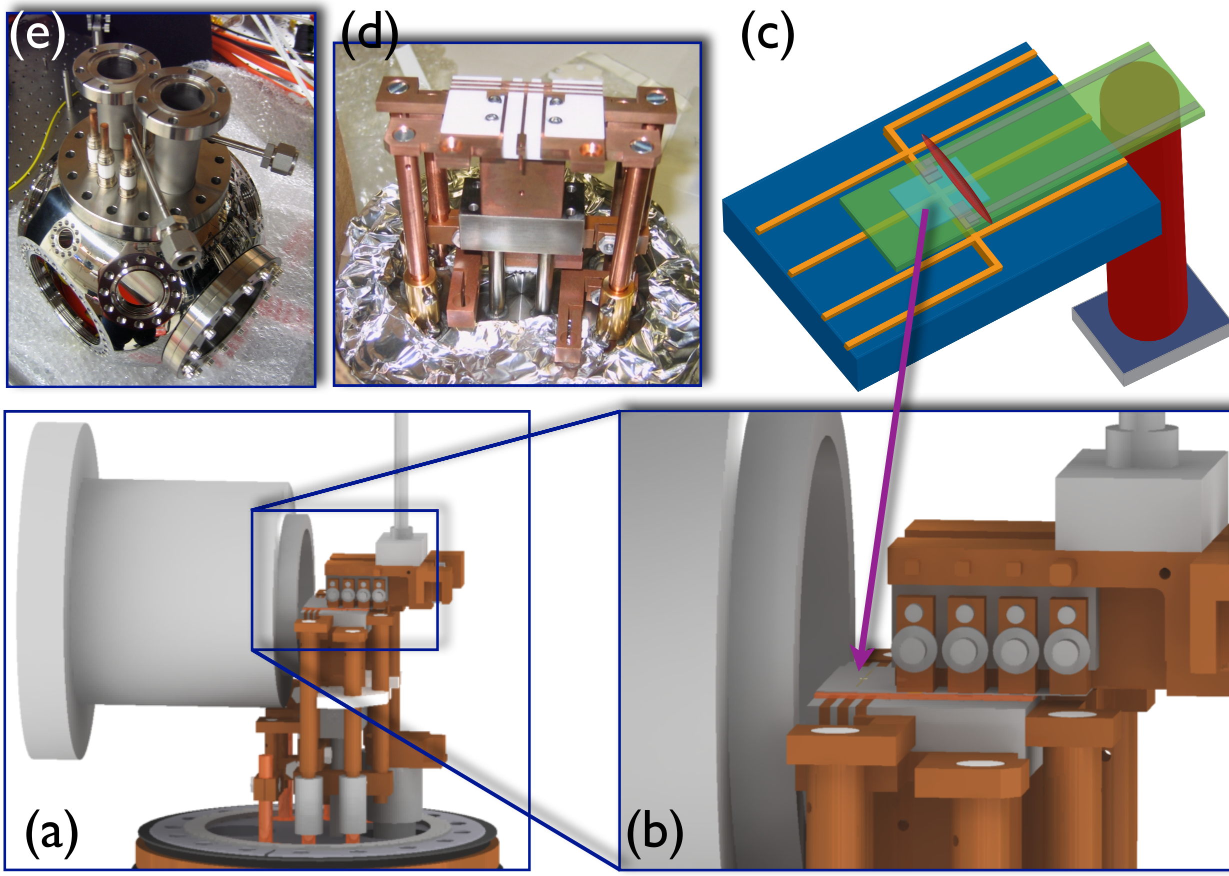

Figure 2: **The cryogenic atom chip chamber.** (a) 3D CAD rendering of the inside of the cryogenic atom chip chamber. The bucket window at left allows the placement of a high NA lens system within 1 cm of the BEC. The large Cu feedthroughs support the high currents necessary for the base atom chip, while the small Cu feedthroughs provide the low noise, fast-switching atom chip microwire currents. A stainless steel heat sink provides high-pressure chilled-water cooling to the atom chip and base wires. (b) A close-up of the atom chip and ^{4}He flow cryostat. (c) Sketch of the cryogenic atom chip (dark blue with gold wires) with BEC (red) above sample (light blue on a green substrate). The sample is attached to a cantilevered substrate that provides both thermal contact to the Cu cryostat feedthrough and also electrical feedthroughs for a four-point contact array and platinum thermometer. The substrate can be maneuvered on a 3-axis piezo translation stage (the substrate is attached via Cu braids to the fixed cryostat) to provide wide area imaging ability. (d) Image of the Cu and Macor atom chip base wire assembly and the stainless steel water cooled base. The atom chip is glued on top of this assembly and its current feedthroughs are guided around fixtures (not shown) mounted to the sides. (e) Image of the cryogenic atom chip chamber. The top shows the electrical feedthrough ports as well as the chilled water ports and the 2.75" CF port for the Janis ^{4}He flow cryostat (not shown) that we have already tested. Though difficult to see, the chamber has mounted on it the recessed bucket 6" CF window that provides the high NA access for the lens system. The BEC is optically tweezed between the production chamber and this chamber using a focused 10 W 1064 laser.

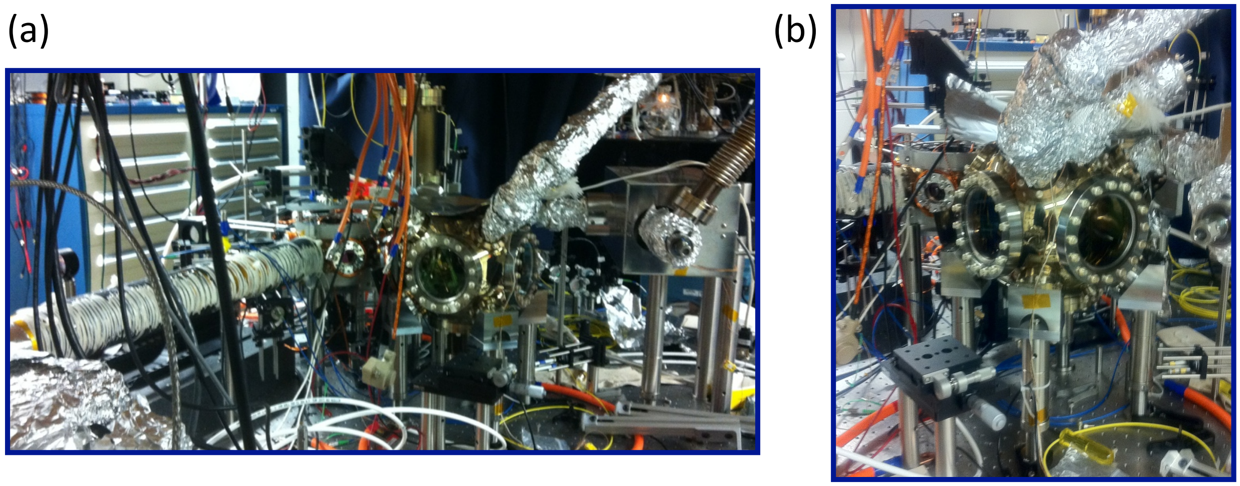

Figure 3: **Cryostat with atom chip chamber attached to BEC production chamber:** (a–b) View of atom chip chamber attached to BEC production chamber. BECs are created in lefthand chamber and optically tweezered into atom chip cryostat chamber at right.

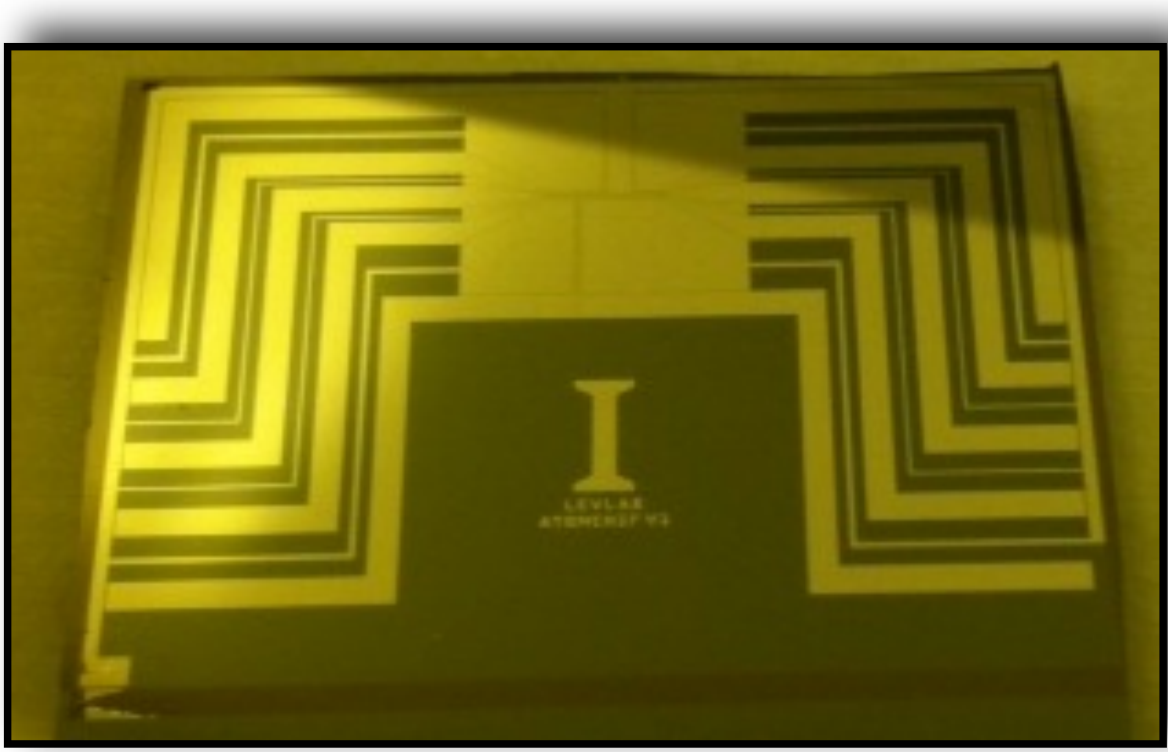

Figure 4: Atom chip fabricated by our group in the Illinois microfab lab.

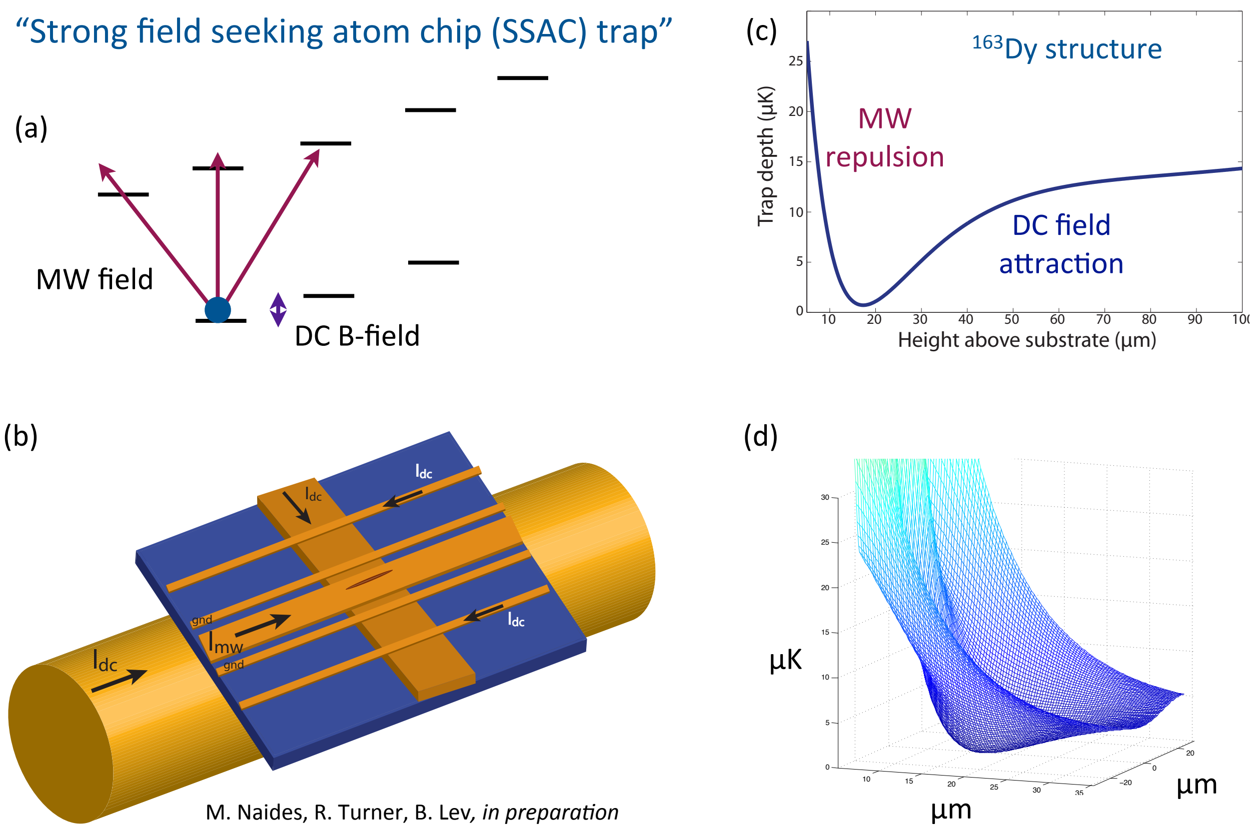

Figure 5: **Strong field seeking atom chip (SSAC) trap.** (a) The SSAC trap works by using a near-field microwave field to repel atoms in their absolute lowest ground state from the surface of the conductor supporting the AC current. A DC currents in separate wires attract the atoms to the surface of the atom chip. The MW field mixes into the ground state $< 1\%$ of the metastable states. This suppress inelastic collision channels. (b) The 3D trap minimum (other axes not shown) is formed when the repulsive MW potential is balanced by the attractive DC potential. Trap frequencies exceeding 1 kHz are possible. (c) Atom chip microwire layout. (d) Full numerical simulation of trapping potential including simulation of potential from MW co-planar waveguide. (To be published.)

3 Publications

None published or submitted, but one in preparation:

- M. Naides, R. Turner and B. L. Lev, "Atom chips for highly magnetic atoms" (to be submitted to PRA 2011). This paper describes our novel SSAC trap design and presents supporting data.
- B. Dellabetta, T. L. Hughes, M.J. Gilbert, and B. L. Lev, "Detecting Signatures of Topologically Protected States with Quantum Degenerate Gases," (to be submitted to PRL 2011). This paper describes the use of the cryogenic atom chip microscope to image surface transport in a topological insulator in a manner that allows for the determination of the bulk to surface conductance ratio.

4 Project personnel

- Matthew Naides, Graduate student, 100%
- Richard Turner, Graduate student, 100%
- TianMin Liu, Rotating graduate student, 25%
- Brian Kasch, Visiting scholar, 100% (Employment ended 4/30/2010.)