National Aeronautics and Space Administration

Spaceborne quantum sensors based on magnetically insensitive atomic gases

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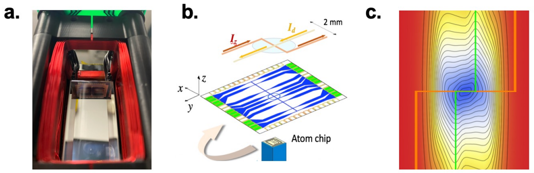
Objectives

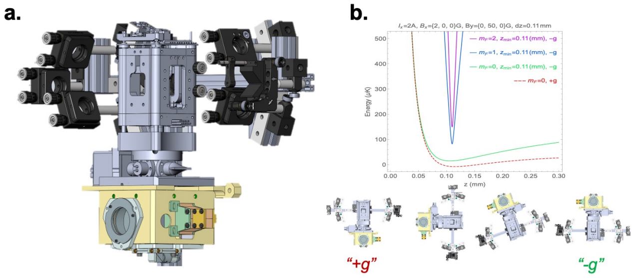
We are developing novel techniques to produce, trap and control ultracold neutral atoms in magnetically insensitive Zeeman states (magnetic quantum number, mf = 0), in order to improve the capabilities of spaceborne quantum sensors. The primary goal is to develop a unique source of ultracold atoms with magnetic quantum number of zero, making them insensitive to weak magnetic fields. Additionally we plan to leverage this source of atoms and magnetic techniques for atom interferometer designs. Novel trap shapes can be tailored to achieve 3D geometries ideally suited for inertial and force gradient sensing while remaining immune to stray magnetic fields and residual fields from the apparatus. Our objective is to prepare a compact breadboard device as a proof-of-concept to demonstrate application of these unique trapping potentials for Bose-Einstein-condensates (BECs).

Background

The technology of cooling and manipulating ultracold atomic gases has matured to such a degree that gases prepared as at sub-nanoKelvin temperatures enable quantum sensors for unprecedented clocks, accelerometers and rotation sensors, and gravity sensors. The next generation of entanglement-enhanced quantum systems promise to further revolutionize fundamental physics experiments, position, timing, and inertial sensing technologies. Such quantum sensor applications can benefit from sourcing large numbers of ultracold atoms specifically in a magnetically insensitive state.

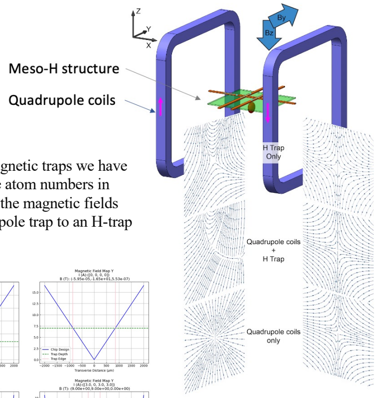


An atom chip located at the top of a dual-celled vacuum chamber (a.) is capable of forming a trap for neutral atoms by running currents through micro-wires on the semiconductor chip. The “z-d” planar geometry (b.) produces a [1.0 , 1.0 , 0.2] kHz trap for Rb atoms in the mf=2 state. A simulated atom chip trap shown here (c.) uses a BECCAL-like chip design.

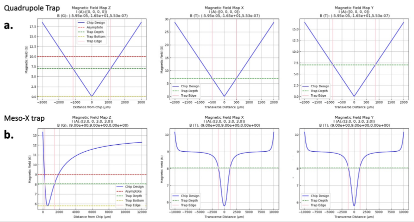


CAD image (a.) of the CAL-like vacuum chamber with optomechanical structure that allows an invertible configuration. By operating the chip inverted (b.) we can effectively levitate the magnetically insensitive atoms (the green solid curve shows a stronger trap than the red dashed plot)

Modeling the atomic trap potentials



Through modeling and analysis of the magnetic traps we have developed a new approach to improve the atom numbers in atom chip systems. This figure illustrates the magnetic fields and how we can transform from a quadrupole trap to an H-trap and yield more efficient transfer.



Modeling results that show the comparison of a quadrupole trap (a.) with a meso-X trap (b.) formed by a medium-sized chip structure located behind the atom chip. In the quadrupole trap, the magnetic fields are created by running 7.5 A of current through a pair of coils in an Anti-Helmholtz configuration. Augmenting the system with a mesoscopic trap, a higher atom number can be loaded to the final atom chip trap by improving the mode-matching during trap configuration transitions.

Approach and Results

A prime example of such a system is the Cold Atom Lab (CAL), in which the atom chip’s (Fig. 1) current-carrying wires produce very strong magnetic field gradients near the surface so the trap confinement is strong [1]. Atoms in a magnetically insensitive state are immune to smaller perturbations of magnetic fields due to imperfections in the wires and fluctuations in the external environment. They are, however, strongly guided and trapped spatially by quartic-scaling walls of the trap potential. In a spaceborne sensor, microgravity makes trapping of insensitive states is readily achievable. These novel traps can be demonstrated on the ground by trapping atoms above the chip wires. The closer atoms “sag” towards the chip, the stronger the magnetic field and gradient. In this manner, the spin zero cloud can be levitated instead of falling.

Significance/Benefits to JPL and NASA

There has been a strong resurgence of interest to perform microgravity experiments aboard the International Space Station (ISS), as well as the Lunar Gateway. NASA’s JPL-built Cold Atom Lab (CAL) has now been in routine operation in space for over three years. Independent from on-going CAL activities, this proposed project allows JPL to prepare for future funding opportunities for space-based quantum sensors with NASA SMD, while at the same time demonstrate the suitability of this piece of technology for a number of scientific investigations. It will directly benefit microgravity-based science studies such as follow- on missions to CAL, including the potential adoption into investigations with the Bose-Einstein Condensate Cold Atom Lab (BECCAL), a joint NASA-DLR mission currently planned for 2025 deployment on ISS. Additionally, there is preliminary planning of creating a fourth Science Module, “SM4,” for another CAL upgrade that could be in operation within the next 2-3 years. Furthermore, our proposed studies could develop techniques that would benefit future planetary missions for gravity mapping and inertial sensing. JPL’s 7X program office is interested and involved in BECCAL and follow-ons for CAL. The proposed quantum sensors could greatly advance research opportunities in fundamental physics (Dark Energy, Dark Matter, Gravitational Waves).

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