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TOWARDS A DUAL SPECIES COLD ATOM BASED PRESSURE SENSOR

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Abstract:
This article describes the conceptual design of a dual species cold-atom based pressure sensor to be built at the Center of Applied Space Technology and Microgravity (ZARM) in cooperation with the Physikalisch-Technische Bundesanstalt (PTB) and supported by the University of British Columbia (UBC). It shall be capable of pressure measurements based on the loss rate of magnetically trapped rubidium and potassium atoms and shall lay the foundation for commercial applications of this measurement method.

Keywords: cold atoms; magneto-optical trap; quantum sensor; ultra-high vacuum

1. INTRODUCTION

The fundamental advantage of cold-atom based pressure sensors is that atoms constitute immutable sensor elements that never age, degrade or change with use. As a consequence, atoms are the basis for modern-day time and frequency standards. All other technologies capable of measurements in the ultra-high vacuum (UHV) and extreme-high vacuum (XHV) ranges, such as ionization gauges, are limited by sensor degradation and drift between calibrations. Using atomic sensors to detect gas molecules in vacuum and thus measure the absolute pressure or particle flux offers a solution to this problem.

2. OPERATIONAL PRINCIPLE

The loss of atoms from a magnetic trap (MT) or magneto-optical trap (MOT) due to collisions with the background gas is a well-known phenomenon that was observed when the first MOTs were developed [1]. This decay of trapped atoms over time t follows an exponential curve

$$N(t) = N_0 \mathrm{e}^{-\Gamma \mathrm{t}}, \tag{1}$$

where N_0 is the initial number of atoms and Γ is the collision induced loss rate. Based on the velocity dependent collision cross section σ_i and the averaged thermal velocity v_i of a gas species i, the loss rate

$$\Gamma = \sum_i n_i \langle \sigma_i v_i \rangle \tag{2}$$

is directly proportional to the background gas density. The values of $\langle \sigma_i v_i \rangle$ are species dependent atomic properties and therefore a suitable foundation for this measurement principle. For a known $\langle \sigma_i v_i \rangle$, a measurement of Γ can be used to determine the background gas density by inverting equation (2) [2].

Currently, there are three methods of determining $\langle \sigma_i v_i \rangle$: Klos and Tiesinga used *ab initio* calculations to find values for collisions of rubidium and lithium with different background gases [3]. At NIST these values are used for calibrating their sensor, which is then validated using a second standard [4]. The second standard could also be used to measure $\langle \sigma_i v_i \rangle$ independent of the calculations of Klos and Tiesinga. A third method first explored at UBC makes use of the finding that collisions are dominated by Van der Waals interactions, such that the trap loss rate versus trap depth of a sensor atom caused by different background gas species can be scaled to the same universal function using a single parameter. This universal relation is called the quantum diffractive universality (QDU) [5].

Typically, MTs are used for precision measurements of the number density of the background gas. This is because atoms in a MT can be prepared in a single quantum state and thus MTs avoid the complication of sensor atoms in a MOT where the action of the trap constantly cycles atoms between their ground and excited electronic states. Measuring the fluorescence of atoms gives a quantity, which is directly proportional to the number of atoms. Fluorescence detection however requires excitations of the trapped atoms, which occurs inside a MOT. A measurement of the loss rate therefore requires the following fundamental steps:

1. Load atoms in MOT
2. Detect atom number by fluorescence
3. Transfer atoms from MOT to MT
4. Hold atoms in MT for duration t
5. Transfer of atoms from MT to MOT
6. Detect atom number by fluorescence.

Considering the transfer efficiency from MOT to MT and systematic error sources like straylight, this will yield one datapoint on a plot of the relative atom number over the time in the trap. Repeating the measurement for multiple hold times t maps out equation (1) giving rise to Γ and, in case of a single background gas species with known $\langle\sigma_i v_i\rangle$, n_i [2].

3. STATE OF THE ART

At the UBC, a sensor using ^{85}Rb and ^{87}Rb was developed. This laboratory setup uses electromagnets as well as a glass cell as the vacuum chamber [2]. Furthermore, researchers at UBC created a sensor setup with co-located rubidium and lithium MOTs to allow measurements of ^{87}Rb and ^{6}Li loss rates from a MT exposed to the same background gas species [6, 7].

The National Institute of Standards and Technology (NIST) developed one laboratory setup which was used to conduct pressure measurements with rubidium and lithium [8]. Furthermore, a compact sensor head was developed for measurements with lithium. The system is based on a single laser, which provides light for two sensor heads [9].

4. GOALS AND CONCEPTUAL DESIGN

The sensor developed by ZARM and PTB shall be capable of measuring pressures in the UHV and XHV regime using cold ^{87}Rb and ^{41}K atoms. Doing so, the collaborators aim to help develop the technology for commercial applications while also providing data for fundamental research on collisions between trapped atoms and background gas particles: Measurements with rubidium atoms will provide additional data on $\langle\sigma_i v_i\rangle$ contributing to an international consensus on its values for ^{87}Rb. Measurements with potassium have not yet been realized at all and will provide valuable data for exploring the limits of QDU.

Aiming for a broad field of commercial applications, the sensor shall meet the following requirements: A transportable and compact system shall be realized, which can operate outside of a controlled laboratory environment. The planned sensor shall therefore consist of a small sensor head and a compact laser and electronics system. The latter shall fit into 6 shelfs of a 19″ rack. For operation independent of environmental conditions, thermal stability is essential. This mostly applies to the laser and electro-magnetic coil system, where temperature changes can lead to changes in the light frequency and the magnetic field gradient, respectively. Reducing costs and complexity, the system shall mostly be based on commercial and modular components. Additionally aiming for a wide range of applicants, a user interface for the operation of the sensor shall be developed.

The following sections discuss those subsystems in further detail, that have the biggest impact on the aforementioned design goals.

4.1 Vacuum System

Providing interfaces to all other subsystems of the sensor, the design of the vacuum system is largely dependent on the overall operational concept. ZARM plans to use a free-space MOT which is loaded from a 2D MOT via a push beam. A differential pumping stage shall minimize the partial pressure of the sensor atom species in the main chamber. The center of the design will be a cylindrical aluminum chamber providing optical interfaces for trapping and detection as well as mechanical interfaces to the 2D MOT. The chamber is $34\,\mathrm{mm}$ high, has a diameter of $102\,\mathrm{mm}$ and weighs $0.25\,\mathrm{kg}$. Aiming for compactification, the optical interfaces shall be based on plane windows sealed with indium wire. This allows for a larger cross section of optical access compared to CF windows with the same cross section of the overall interface. As sources for rubidium and potassium, compact prefilled ovens with a CF16 interface developed at ZARM are used.

4.2 Magnetic Field System

This system shall be capable of providing a magnetic field gradient of more than $2.5\,\mathrm{T\,m^{-1}}$ along all axial directions at the center of the chamber. Figure 1 shows a rendering of the sensor head with all attached subsystems including two electromagnets in an anti-Helmholtz configuration. These are based on copper flat wire rated for a current of 76 A.

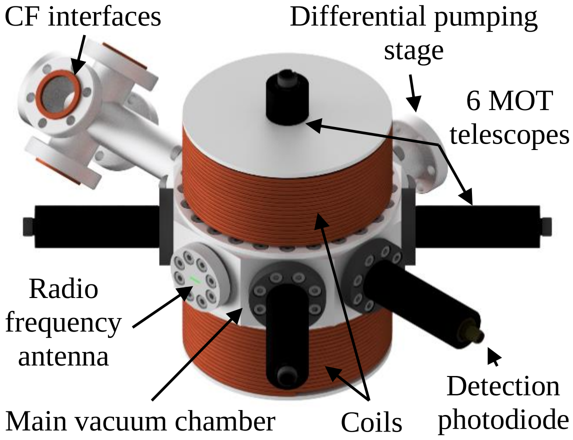

Figure 1: Rendering of the conceptual design of the sensor head with external coils; other sensors and a pump are attached to the CF interfaces; the radio frequency antenna is used for setting the trap depth

The displayed coils weigh 3.2 kg, which is more than 70% of the sensor head's overall mass. Also, in terms of the volume and power budget, the coils are the main driver. Furthermore, the coils would require an active cooling system. To reduce mass, size and power consumption, the coils must be positioned closer to the center of the chamber. ZARM is currently investigating an in-vacuum magnetic field system, which could be realized with electromagnets or permanent magnets. The latter would mitigate magnetic field fluctuations due to heating of the system at the cost of an invariable magnetic field gradient.

4.3 Laser System

The laser system shall provide at least 100 mW of power for both, pumping and repumping of the atoms. The used transition is $5^2\mathrm{S}_{1/2} \rightarrow 5^2\mathrm{P}_{3/2}$ for rubidium and $4^2\mathrm{S}_{1/2} \rightarrow 4^2\mathrm{P}_{3/2}$ for potassium.

Both species shall be cooled with the same laser system. The current design is shown in Figure 2 and will consist of two lasers. One laser provides the light for the repumping transition. It serves as the master laser, as it is locked using a spectroscopy cell (Spec). The second laser shall be offset locked to the respective pumping transitions. Amplitude and frequency modulation shall be provided by acousto-optical modulators (AOM). To achieve the required power, tapered amplifiers (TA) are implemented.

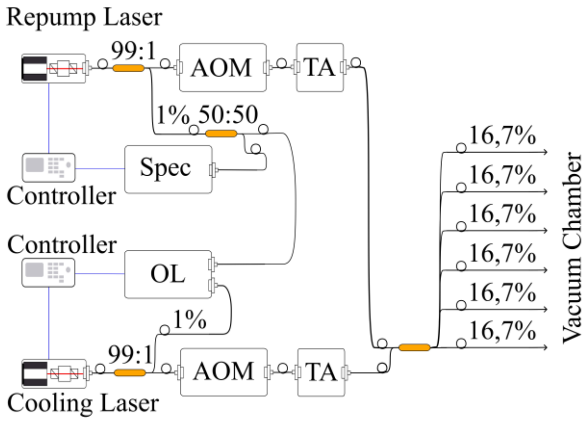

Figure 2: Schematic of the laser system; Spec: Spectroscopy unit, OL: Offset locking, TA: Tapered Amplifier; depending on the MOT design the number of fibers attaching to the vacuum chamber can change

The lasers, the spectroscopy module and the offset locking module will be provided by an industrial partner. This system is compact, will fit into a 19” rack and can change between the cooling frequencies using stepper motors.

The beam diameter for trapping the atoms shall be bigger than 6 mm and will be achieved by telescopes mounted to the vacuum chambers. Circular polarization is implemented via quarter-waveplates within the telescopes. A design decision on the use of a 3D MOT or a mirror MOT is outstanding.

5. PLANNED MEASUREMENTS

During the characterization of the sensor a transfer standard calibrated at PTB will be used as a reference. In the final phase of the project a characterization at the continuous expansion system CE3 of the PTB is planned. This primary standard has a relative uncertainty of below 2×10^{-2} in the UHV regime [10]. The characterization is performed with He, Ne, Ar and other gases, which are yet to be selected. Due to the findings of Barker et al., measurements with Ar yield the largest inaccuracy and are therefore of the biggest interest [3].

6. SUMMARY

ZARM and PTB aim to design a cold atom vacuum sensor that can measure pressures in the UHV and XHV regime based on collisions of trapped cold ^{87}Rb and ^{41}K atoms with the background gas. The measurement principle is based on $\langle \sigma_i v_i \rangle$, an immutable property of the collision partners. Aiming for commercial applications, the planned design focusses on a compact setup with an in-vacuum magnetic system and a commercial and modular laser system.

This project is currently in the preliminary design phase. At the end of the three-year project a fully characterized sensor shall be in operation at ZARM.

7. REFERENCES

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