Building a Portable Cold-Atom Pressure Standard

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Pressure Metrology Needs Modernization

The second is defined by the hyperfine transitions in Caesium, and the metre is defined by the speed of light. By contrast, vacuum pressure is defined using an orifice flow standard involving an inert gas inside a box with a small hole of known conductance, a flowmeter, and a pump [1]. This method is confined to the low vacuum regime due to outgassing in the chamber and a reliance on a Maxwell-Boltzmann distribution in the gas and can only be implemented for inert gases. Lower pressures have no defined standard, and rely on ion gauges to provide accurate measurement. A better standard is needed to improve measurements in areas such as

- surface analysis of materials.
- thin-layer deposition on semiconductors.
- atmospheric pressure and constituent determination as a function of altitude.
- atomic physics and nuclear fusion by finding collision cross sections.
- vacuum metrology.

It is possible to define and measure pressure using cold atoms, bringing pressure measurements into the age of quantum standards.

Cold Atom Pressure Measurement

Collisions between trapped atoms and background particles limits the lifetimes of trapped species. The number of atoms in a Magnetic Trap (MT) roughly follows $\frac{dN}{dt} = -\Gamma N$, where N is the number of atoms. Pressure can be found using $P = \frac{\Gamma}{\sum_i n_i \langle\sigma_{\text{loss}} v_i\rangle_{X,i} k_B T}$ where n_i is the density of background species i, k_B is Boltzmann's constant, T is temperature, and $\langle\sigma_{\text{loss}} v_i\rangle_{X,i}$ is the velocity-averaged collisional loss cross section, a value that can be measured [2].

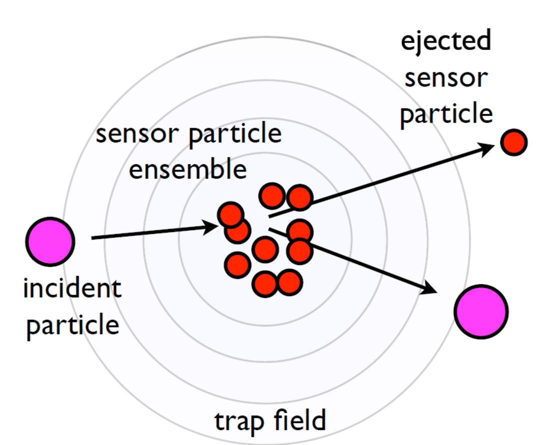

Fig. 1: Sensor particle ejection from trap due to collision with a background particle

The loss rate, Γ, is measured by determining the number of atoms left in the trap as a function of hold time. The procedure to measure a single data point is illustrated in figure 2:

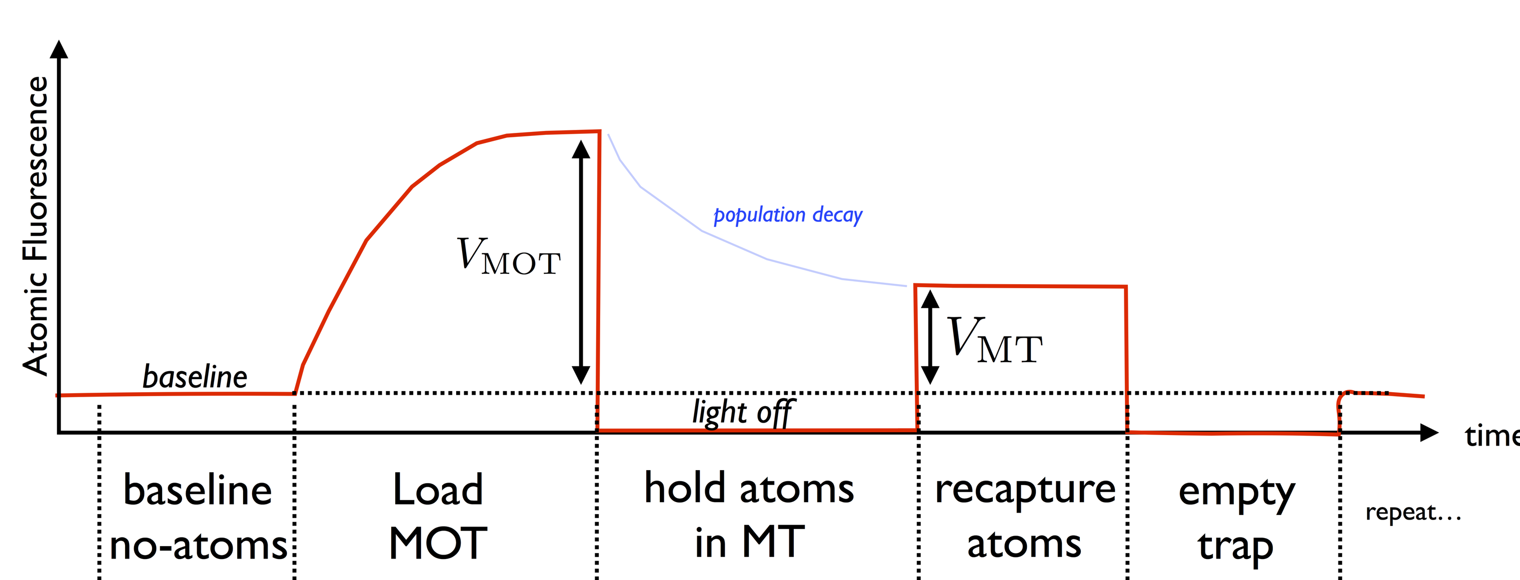

Fig. 2: Timing of a single data point measurement

- We trap ^{87}Rb in the F=1, m_s=-1 state.
- We use a MT rather than a Magneto-Optic Trap (MOT) to hold the atoms, as a MT has a better-defined trap depth.
- We use a MOT to capture atoms as it has a superior loading rate.
- We use a MOT to read the number of atoms as magnetic traps do not use optical pumping, so we cannot view the number of atoms in the trap.

Apparatus

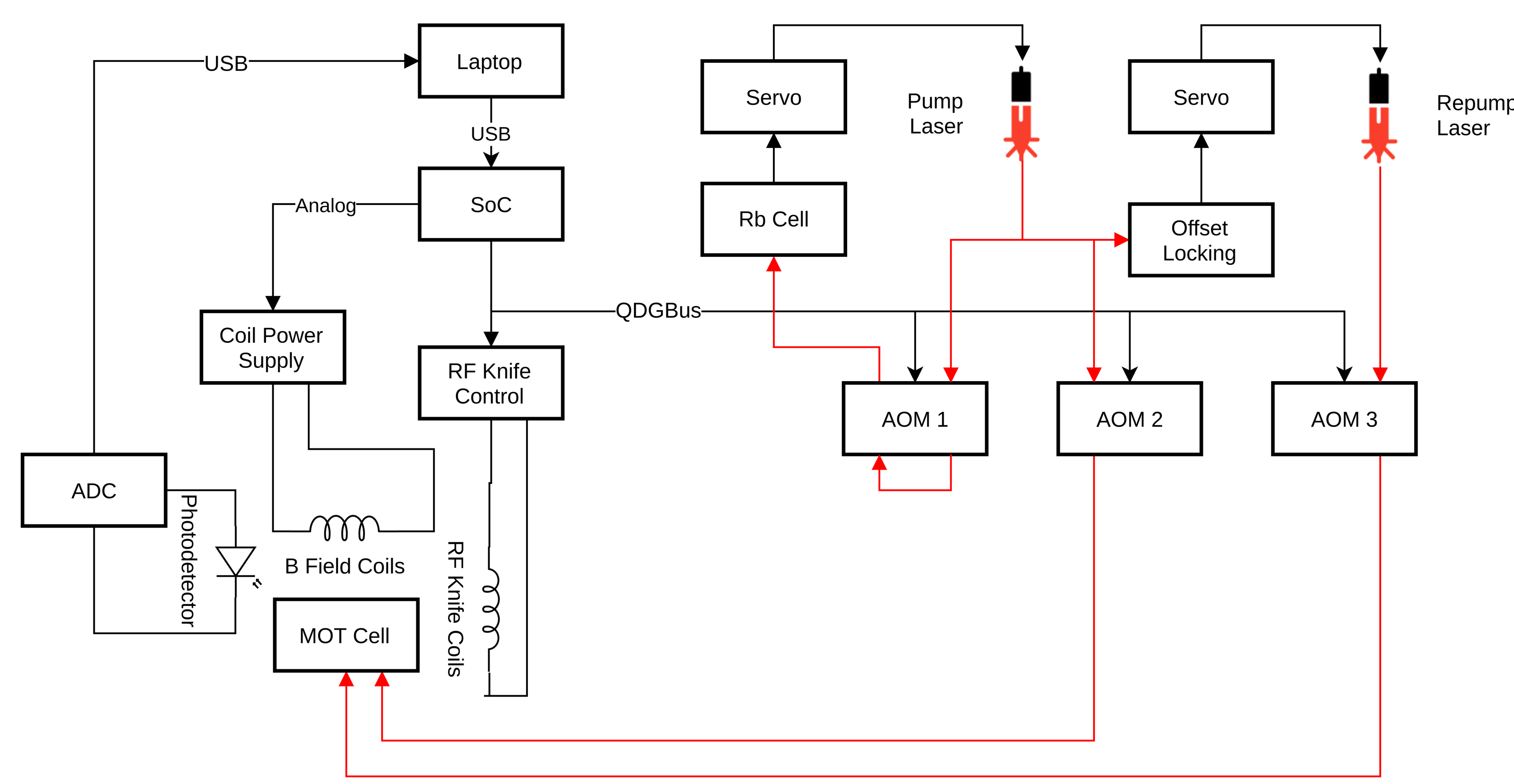

Fig. 3: High-Level diagram of the pressure measurement apparatus

- The laptop runs a Python script that controls the System on a Chip (SoC), which controls the hardware.
- The pump laser drives the F=2 to F'=3 transition; the repump laser drives the F=1 to F'=2 transition of ^{87}Rb.
- The RF knife controls the trap depth of the MT, which is important for determining $\langle\sigma_{\text{loss}} v\rangle$.
- The measurement MOT will be loaded using a push laser from a second 'loading' MOT that gets its Rubidium from dispensers. The loading MOT design will be similar to the measurement MOT.
  - It will not have an RF Knife or fast-switching coil power supply.
  - The pump laser will also be used to push atoms into the measurement trap.
  - It will be controlled by the same computer and SoC as the measurement system.

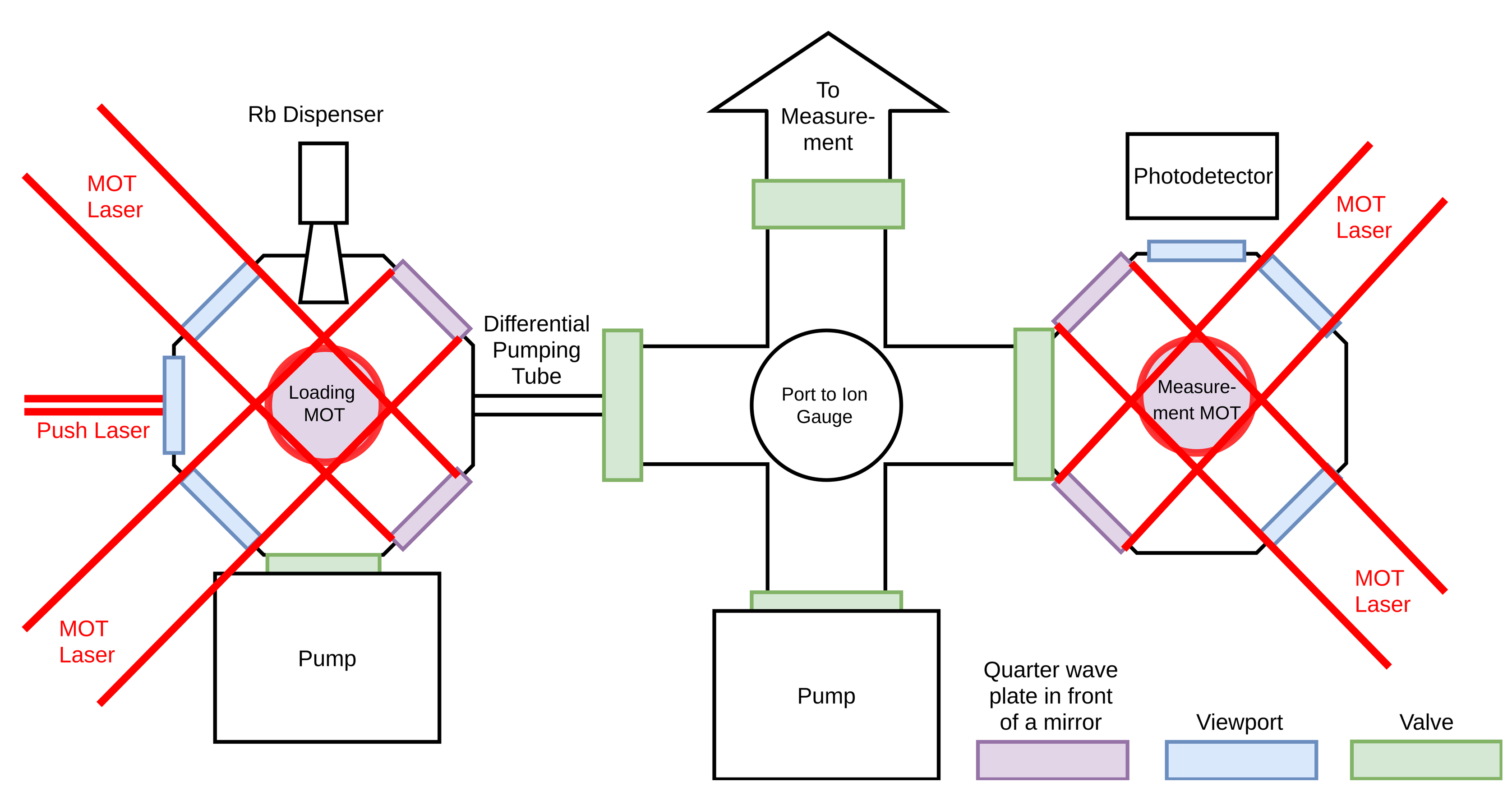

Fig. 4: Sketch of proposed vacuum chamber design

- Each MOT will be ∼1cm across as a smaller MOT allows for greater magnetic field gradients.
- The differential pumping tube consists of a small diameter tube connecting the source and measurement chambers.The small diameter inhibits the flow of gas between the two vacuum sections, except for the well-controlled, directed flux of Rubidium atoms from the source.

Advantages

- Our recent discovery that quantum diffractive collisions are universal means that the device can be used to define pressure and can be applied to the measurement of any gas species [3].
- This technique relies only on fundamental atomic properties, making it immutable.
- This portable apparatus is designed to be assembled and stored on a rack the size of a refrigerator for direct, on-site comparison with existing standards.

Currently, metrologists benchmark pressure standards by comparing the calibration factor of an ion gauge sent between sites. A limitation of ion gauges is that their calibration can shift when transported between sites [4]. Our apparatus can instead be compared directly to orifice flow standards around the world.

Additionally, ion gauges can only be calibrated to a standard for Argon and Nitrogen, are only linear for inert gases, and every gauge requires a unique calibration factor for every gas it is used on [5]. Our apparatus can be used with any gases and requires no calibration.

Roadmap

We expect to finish assembling the portable apparatus by September 2019, and to complete validation by December 2019.

To facilitate the adoption of a cold-atom pressure standard, we plan to compare our measurements with the existing orifice flow standard and similar cold-atom device at the National Institute of Standards and Technology (NIST). Following that, we plan to visit other standards organizations around the world to unite competing definitions for pressure.

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References

[1] K. Jooya, *Progress towards a primary pressure standard with cold atoms.* PhD thesis, University of British Columbia, 2017.

[2] J. Van Dongen, *Study of background gas collisions in atomic traps.* PhD thesis, University of British Columbia, 2014.

[3] J. L. Booth, P. Shen, R. V. Krems, and K. W. Madison, "Universality of quantum diffractive collisions and the quantum pressure standard," *submitted to NJP*, 2019.

[4] J. A. Fedchak and D. R. Defibaugh, "Long-term stability of metal-envelope enclosed bayard–alpert ionization gauges," *Journal of Vacuum Science & Technology A*, vol. 30, no. 6, p. 061601, 2012.

[5] A. Calcatelli, "The development of vacuum measurements down to extremely high vacuum -xhv," *Measurement*, vol. 46, 02 2013.