A short response-time atomic source for trapped ion experiments

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Ion traps are often loaded from atomic beams produced by resistively heated ovens. We demonstrate an atomic oven which has been designed for fast control of the atomic flux density and reproducible construction. We study the limiting time constants of the system and, in tests with \(^{40}\text{Ca}\), show we can reach the desired level of flux in 12 s, with no overshoot. Our results indicate that it may be possible to achieve an even faster response by applying an appropriate one-off heat treatment to the oven before it is used.

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I. INTRODUCTION

Quadrupole ion traps find use in many areas of physics including the study of fundamental constants\cite{12}, building accurate clocks\cite{8}, and as platforms for quantum computation\cite{4}.

In these experiments, loading of the trap is usually accomplished by producing ions inside the trapping region from an atomic vapor, either by electron impact ionization or resonance-enhanced two-photon ionization\cite{9}, the latter providing a means for isotope-selective loading. Owing to the need for ultra-high vacuum conditions during operation of the ion trap, the vapor is usually provided by a collimated atomic beam from an oven which can be resistively heated when loading is desired.

An alternative method for producing an atomic vapor for loading is laser ablation of a coated target\cite{10}. Typically, a pulsed laser will be focused onto the target within line of sight of the trap. A single pulse with sufficient energy will ablate the surface of the target producing an atomic vapor. Once a vapor is present within the trapping region, atoms are ionized using either electron impact or resonant photoionization. This method has the advantage that the atomic flux can be created 'on demand' on the millisecond timescale.

Recent experiments have also demonstrated loading via ionization of a cold atomic beam emitted from a magneto-optical-trap (MOT) adjacent to the ion trap\cite{11}. Because the atoms are pre-cooled before ionization, efficient loading of shallow surface traps can be achieved with a far lower atomic flux than is produced by a conventional thermal oven.

As the applications of ion traps become increasingly diverse and the complexity of experiments rises, it is important to identify elements of the apparatus where well-engineered solutions can help produce reliable, stable and consistent performance across multiple units with minimal calibration. In order to load ion traps with complex multi-species ion chains it is important that the loading process meets certain requirements:

1. the system is capable of loading single ions of a chosen isotope with a high reliability,
2. the atomic flux incident on the trap surfaces is minimized, to reduce contamination which may generate stray fields or increased motional heating,
3. the loading mechanism is simple to reproduce consistently across many systems,
4. the time spent loading must not be a significant overhead in the operation of the system.

The final requirement is easily met in most current ion trap experiments owing to large storage times and relatively low ion numbers. However, when multi-species chains of several ions are desired\cite{7}, loading time can easily become an experimental bottleneck. For example, in a surface trap containing a string of 5-10 ions, a loss event will typically occur every few minutes. Typically, the resistively heated atomic ovens employed in our lab have required 2 to 5 minutes to heat up from room temperature, which would significantly impact the rate at which experimental data could be collected. If the oven is left on, the rise in background pressure causes an undesirable decrease in trap lifetime.

Although attractive for the simplicity of its in-vacuum components, extremely fast loading time, and good compatibility with cryogenic vacuum systems, laser ablation may not be suitable for all systems. The ablation plume produced by the pulse contains mainly neutral atoms, in combination with a small number of atomic and molecular ions of a variety of species and isotopes\cite{10}. Combined with the high kinetic energy of the ablation products, this limits the loading efficiency and will lead to an increased depletion rate of the ablation target\cite{10,11}. Combining ablation with resonant photoionization increases efficiency and selectivity, but may not completely avoid trapping of other charged ablation products.

MOT-based loading schemes are appealing due to their greatly reduced flux per loaded ion, but require more laser power and strong but well-shielded magnetic fields. These elements introduce additional experimental complexity and physical size, which may be undesirable when

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II. CONSTRUCTION

The atomic source presented here consists of a resistively heated stainless steel tube (outer diameter 1 mm, wall thickness 50 µm, length approximately 15 mm). The tube is held at either end by two flexure clamps made from stainless steel, which also form the electrical contacts. The central section of tube between the two clamps is crimped closed at two points, and the enclosed volume filled with calcium metal of natural isotopic abundance before the second crimp is made. Near the centre of the crimped section of tube is a 0.5 mm diameter aperture which allows the calcium vapor to escape when the tube is heated. The flexure clamps are mounted on an electrically and thermally isolating structure made from Macor, providing a stable and reproducible construction. This part contains a 2 mm diameter hole which is used for collimation of the atomic beam. The distance between the oven aperture and the exit of the collimation aperture is 13.5 mm, producing an atomic beam with a half-angle divergence of approximately 5 degrees.

In order to provide a measure of the temperature of the oven, a K-type thermocouple junction is spot-welded to the tube wall close to the aperture. The thermocouple wires are connected to two terminals of a standard high-voltage ceramic and copper feedthrough, which forms the cold junction of the thermoelectric circuit, as shown in Figure 2. Electrical connections for the heater current to a second pair of feedthrough terminals are made via two copper wires held with screw contacts to the flexure clamps. This construction, shown in Figure 1, is made from easily machined parts yet ensures the atomic oven can be accurately aligned to the trap, improving reproducibility. Furthermore, the low thermal mass of the tube permits the oven to be rapidly heated to its operating temperature, while its low thermal conductance prevents excessive heating of the surrounding structures. A variation on this design consists of two similar oven tubes held by individual pairs of flexure clamps, in turn mounted to a single, wider Macor support. This simple extension allows independent loading of two ion species from one compact assembly. The measurements we present here were made with the single-oven design, but are representative of the behaviour of either variation.

III. CONTROL

The temperature of the oven is controlled with a digital feedback loop implemented in a microcontroller. The voltage across the thermocouple junction is measured via a high-impedance differential analogue input stage, sampled with an analogue-to-digital converter at a rate of 1 kHz, and the current is supplied by a buck-type voltage regulator controlled with a pulse-width modulated signal from the microcontroller. The resistance of the oven tube when cold is approximately 200 mΩ, with additional lead resistances totalling approximately 50 mΩ. The controller circuit can supply up to 20 A into this load, while approximately 3 A is required to maintain the tube at a temperature of 400 °C. With the feedback loop optimized for a fast rise-time with no over-shoot, it is possible to heat the oven to 400 °C in ≈ 3 s.

Since the vapor pressure is an exponential function of temperature, the absence of over-shoot in the step re-
IV. MEASUREMENT OF ATOMIC FLUX

To validate our design as an atomic source, we measure the atomic flux by laser resonance fluorescence as a function of time after oven turn-on and turn-off. The oven is placed inside a vacuum chamber at approximately $10^{-6}$ mbar. A laser at 423 nm is focused to a waist of 100 µm at a position approximately 10 mm from the oven collimation aperture. The angle of the laser beam is aligned so that it is perpendicular to the direction of the atomic beam in order to minimize Doppler broadening and shifts of the atomic resonance with respect to the laser, as shown in Figure 4.

In Figure 5 we show the current, temperature and detected fluorescence when the oven is turned on for 21 s. The controller regulates the current to reach a steady temperature at the thermocouple in 4 s with minimal overshoot. Detected fluorescence shows that the emission of atomic flux begins after 8 s, increasing to its equilibrium rate after 12.5 s. We attribute the delay in this response to the thermal mass of the calcium and the relatively poor thermal conductivity between the calcium and the walls of the oven. When the current is switched off, the atomic flux drops to zero after 2 s. Note that for these experiments the optical detection efficiency has not been precisely calibrated and the exact number density of the atomic beam is not known, but was made substantially greater than would be necessary for loading ions in order to generate a high rate of fluorescence. The emission rate is can be reduced to any value desired via adjustment of the temperature setpoint.

The loading rate in a real trap will depend strongly on the trap depth and details of the photoionisation process, which both vary greatly between experiments. As such we have not conducted a comprehensive study of the performance of this oven in a particular trap, which would be less useful than the measurements we present of the stability and temporal response of the flux produced. However, we have used this oven design to load a surface trap in our latest experiments, and observe that the average loading time is similar to the equilibration time of the atomic flux.

Repeated firings of the oven at a given temperature set point yield stable and consistent results over a long...
period of time. In order to test the long term stability of the atomic flux generated by the oven, we fired the oven repeatedly at close to 100% duty-cycle at over a period of 15 hours. The steady-state fluorescence count rate was measured at regular intervals, as shown in Figure 5. The atomic flux appears stable for the first few hours, before starting to steadily decrease with a time constant of approximately 60 hours. We note that after 15 hours, the total number of atoms which have passed through the oven is estimated to be $\sim 10^{10}$. In our surface traps this would be sufficient to load a total of $\sim 10^7$ ions, many more than are necessary over the lifetime of any typical experiment. Considering the geometry of the collimator, this integrated flux corresponds to emission of a significant fraction of the calcium mass heats and begins to vaporize, while the deposits on the walls are rapidly depleted. Subsequent repeats of the experiment exhibit the normal behaviour, as shown in Figure 5, while repeating the high temperature pre-treatment leads again to the dynamics we have just described.

This behaviour suggests a means to produce an oven with a faster response. If the calcium inside were heated under vacuum to melting point ($842^\circ C$) before drilling the oven aperture, a thicker but relatively uniform and well thermally-contacted layer could be deposited on the inside of the oven tube. For the experiments described here, this would allow for the production of controlled atomic flux in 2 s.

V. CONCLUSION

We have presented and tested a design for an atomic oven suitable for loading of ion traps, which is compact and easy to reproduce. By controlling the oven current to stabilize the temperature of a thermocouple mounted next to the oven aperture with a digital feedback loop, we are able to reach a steady level of atomic flux in 12 s with no overshoot. We have successfully used this oven system to load ions in a surface trap.

The closed-loop control allows the the oven to be run at a higher temperature for a shorter period of time when loading ions. Because the number density in the atomic beam is a strong exponential function of temperature, the time-integrated flux required to load a single ion can thus be achieved with less total energy delivered to the trap environment. Combined with the low thermal mass and conductivity of the oven, this will reduce heating of the neighbouring trap and vacuum systems, reducing
FIG. 7. Behaviour of oven after heat treatment. (a) Oven current (blue) and thermocouple temperature (red) vs. time. (b) $^{40}$Ca fluorescence signal vs. time. The initial strong peak (arrowed) is indicative of redistribution of calcium within the oven tube, which could allow for a reduction in the turn-on time of the oven.

thermally-driven electrical and mechanical variations.

We hope other researchers may find this design useful for their own work; detailed schematics are available on our online repository[12]

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