

An optically heated atomic source for compact ion trap vacuum systems

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S. Gao,¹ W. J. Hughes,^{1,a)} D. M. Lucas,¹ T. G. Ballance,² and J. F. Goodwin¹

AFFILIATIONS

¹Clarendon Laboratory, Department of Physics, University of Oxford, Parks Rd., Oxford OX1 3PU, United Kingdom

²ColdQuanta UK, Oxford Centre for Innovation, Oxford OX1 1BY, United Kingdom

^{a)}Author to whom correspondence should be addressed: william.hughes@physics.ox.ac.uk

ABSTRACT

We present a design for an atomic oven suitable for loading ion traps, which is operated via optical heating with a continuous-wave multimode diode laser. The absence of the low-resistance electrical connections necessary for Joule heating allows the oven to be extremely well thermally isolated from the rest of the vacuum system. Extrapolating from high-flux measurements of an oven filled with calcium, we calculate that a target region number density of 100 cm^{-3} , suitable for rapid ion loading, will be produced with 175(10) mW of heating laser power, limited by radiative losses. With simple feedforward to the laser power, the turn-on time for the oven is 15 s. Our measurements indicate that an oven volume 1000 times smaller could still hold enough source metal for decades of continuous operation.

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I. INTRODUCTION

Cold trapped atomic ions are an ideal platform for quantum computing beyond the fault tolerant threshold, having demonstrated the highest fidelity operations (preparation, readout, and single- and two-qubit gates) and the highest ratio of coherence time to gate period^{1–4} of any qubit candidate. Although trapped ion qubits can be manipulated with exquisite precision, the translation of these techniques to a larger-scale processor capable of operating at the ~1000-qubit level has yet to be demonstrated. The technical challenge of building and controlling a large system is significant and a number of approaches have been proposed to address this.^{5–7}

One approach to achieving the necessary scaling is to produce a large number of relatively simple quantum processor nodes, each of a size which permits high-fidelity operation, connecting the nodes together to form a large quantum network. Entanglement between modules can be generated and distributed remotely via photonic interconnects.^{8,9} By taking a modular approach, the complexity of each node is reduced to a manageable level, thereby transforming the scaling challenge from a problem of quantum physics to one of classical systems engineering and integration.

Present-day proof-of-principle ion trap systems do not have particular size requirements; however, in the construction of these

larger networks or other applications demanding compact or portable ion trap systems, the per-node footprint will become increasingly critical. The ultra-high vacuum system which houses the ion trap typically dictates the overall size of each node, and therefore pursuing compact and scalable technologies for this particular component is important.

A number of technical aspects of system design are improved when the vacuum system is scaled down, including reduced imaging system working distance, increased mechanical and thermal stability, and lower power requirements for magnetic field coils. On the other hand, there are aspects which become more challenging, primarily achieving a suitable quality of vacuum with limited pump rates, putting a strong imperative on making vacuum-side components as simple and clean as possible and minimizing localized heating of the system to reduce outgassing. One such in-vacuum component is the atomic source used to load the ion trap, which typically consists of a resistively heated oven connected to a pair of high-current vacuum feedthroughs. This approach to construction leads to a relatively complex and poorly thermally isolated assembly, increasing both the in-vacuum surface area and unwanted heating of the surrounding system. In this paper, we demonstrate how optical heating of the oven mitigates these issues and demonstrate an effective miniaturized atomic source compatible with ultra-compact ion trap systems.

II. ATOMIC SOURCES IN ULTRA-COMPACT VACUUM SYSTEMS

Loading of ion traps requires ionization of atoms of the desired species within the trapping region, commonly through a two-photon ionization process.¹⁰ A variety of methods are used to produce sufficient atomic density in the loading region, including collimated thermal beams,¹¹ laser ablation,¹² and cold beams from magneto-optical traps (MOTs).¹³

Collimated thermal beams are the most widely used due to the simplicity with which they can be produced: a small tube filled with the target species can be heated with an electric current with high reliability and loaded with sufficient source metal to last for thousands of years of loading if used conservatively. A highly compact Joule-heated thermal source has been demonstrated;¹⁴ however, high-current electrical feedthroughs remain a potential point of failure for ultra-compact systems. Furthermore, Joule heating is inherently inefficient as the low-resistivity electrical connections needed to deliver the heating current also act to conductively sink the generated heat. This greatly increases overall power dissipation and attempts to integrate such ovens with cryogenic systems have either resorted to mounting the oven outside the low-temperature stage^{15,16} or faced problems during operation, such as large temperature drifts after loading.¹⁷

Laser ablation loading has gained popularity in recent years due to the cryo-compatible heat load and the lack of warm-up time, allowing near-instantaneous ion loading.¹⁸ However, this comes at the cost and complexity of including a high-intensity pulsed laser source and, in the case of many-node networked quantum computers, directing the emitted pulses to each node. The very high stream velocities of ablated atoms also mean that the technique is not well suited to low-depth traps, where only a small fraction of the atoms have low enough kinetic energy to be successfully confined after photoionization.¹⁹

MOT-based loading provides a clean, cold, and well-controlled source of atoms on demand, but the considerable experimental overheads make it all but unfeasible for scaling to large networks of small traps.

In this paper, we investigate an alternative approach to producing the atomic beam, using an optically heated thermal source, which combines the low-velocity output associated with Joule-heated sources with greatly improved efficiency and a reduced complexity of construction.

III. CONSTRUCTION

The oven consists of a stainless steel tube with a length of 10 mm, a diameter of 2 mm, and a wall thickness of 0.1 mm. The oven is filled with ~20 mg of calcium in granular form and both ends are closed with stainless steel plugs, one of which has a 0.75 mm aperture drilled through its center. The oven is mounted on a framework of glass rods and folded steel supports (of proprietary design) which ensures thermal conductivity between the oven and the surrounding room-temperature vacuum system is extremely low.

The completed assembly is mounted in a custom-built ultra-compact vacuum system using ColdQuanta's "Channel Cell" technology, of volume <10 cm³, with an integrated ion pump (see Fig. 1). The oven is directed through a second 0.75 mm aperture fixed to

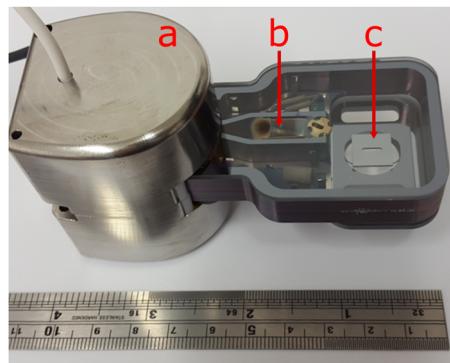


FIG. 1. Ultra-high vacuum system used in this work, including (a) integrated Penning cell ion pump, (b) optically heated calcium oven, and (c) target region with dummy trap. Internal volume of the cell is <10 cm³.

an internal silicon partition of the chamber, reducing deposition of calcium outside the target region. This target region consists of a fiducial in the form of a silicon wafer with a 5 × 0.5 mm² slot cut through it, representing the intended location of the ion trap.

Heating of the atomic oven is achieved via a multimode continuous-wave diode laser with wavelength 780 nm, capable of up to 7 W output power, but typically operated at 100 mW–500 mW. The heating laser is focused and directed onto the oven tube with *ex vacuo* bulk optics, targeting a small region of the tube, which is intentionally darkened to increase absorption (via a proprietary technique). For improved performance, the remainder of the oven tube can be electroplated in gold to reduce the radiative emissivity, although this has not been performed for the results reported here.

IV. CHARACTERIZATION OF OVEN PERFORMANCE

To validate the performance of the oven, we evaluate the dynamic and equilibrium number density of atoms produced within the target region vs heating laser power via spectroscopic measurements. We target a nominal number density of 100 cm⁻³, sufficient to achieve ion loading within a few seconds in typical trap geometries with ~1 mW of power applied via the second-stage ionization laser.^{10,20} We also infer the temperature of the oven from the measured number density and system geometry and use this to produce a simple thermal model of the oven and give a prediction of its operating lifetime under normal conditions.

A. Measurement of atomic flux

The oven tube is optically heated by the 780 nm laser, producing a wide beam of neutral calcium atoms from the first of the two 0.75(2) mm collimation apertures, the second of which selects a narrow beam of atoms directed toward the target region. We detect the presence and number density of neutral calcium atoms via resonance fluorescence spectroscopy on the 4s²1S₀ → 4s4p¹P₁ transition. The atomic beam passing through the target region interacts with the beam from a 423 nm single-mode external-cavity diode laser, which is focused to a waist of 1/e radius $w_0 = 40 \mu\text{m}$ and aligned with wavevector orthogonal to the neutral atom flux, minimizing

Doppler effects. The resonance fluorescence emitted by the atoms passing through this target region is collected by an NA = 0.299(3) imaging system with optical axis at 45° to the spectroscopy beam and relayed with magnification $m = 10$ to a photon-counting photomultiplier tube (PMT) for detection. A 500 μm aperture is placed immediately before PMT, such that detection is limited to photons emitted from a ($\lesssim 50 \mu\text{m}$)³ target region, where the spectroscopy laser and atomic beam intersect. A schematic diagram of the oven and optical systems is given in Fig. 2.

From the imaging system photon detection efficiency, the interaction and fluorescence collection volumes, and the physics of the laser–atom interactions, we can convert the measured photon count rate to a number density of atoms in the target region. Note that the experiments reported here are conducted in the absence of any strong bias field, so the dipole transition quantization axis is defined by the polarization state of the spectroscopy laser. This polarization is stable but unknown, introducing a significant uncertainty ($\pm 33\%$) in the conversion from count rate to number density. Despite this large uncertainty, we are able to establish an effective model of the oven’s thermal performance, response time, and required operating power, as we will show in Sec. IV B.

In the remainder of this section, we provide a summary of the physics relevant to the spectroscopic determination of the atomic beam number density and the assumptions that are made. Throughout these experiments, the intensity of the excitation laser is kept much smaller than the saturation intensity,

$$I_{\text{sat}} = \frac{\hbar\omega_0^3\Gamma}{12\pi c^2}, \quad (1)$$

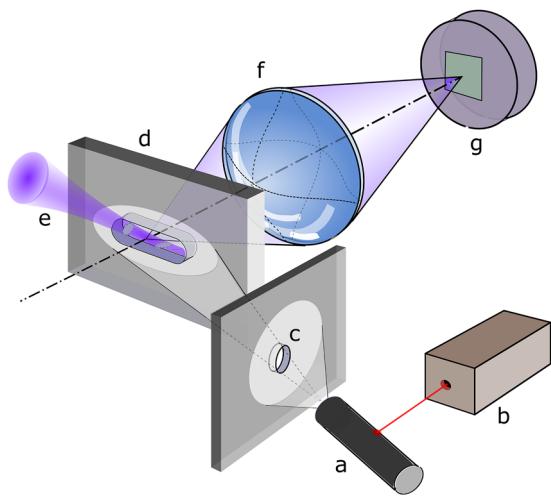


FIG. 2. Schematic diagram of apparatus for optical heating of calcium oven and resonance fluorescence spectroscopy of emitted atomic beam. (a) Calcium-filled stainless steel oven tube; (b) a 780 nm optical heating laser; (c) beam of calcium atoms passing through second collimation aperture; (d) silicon wafer target, approximating a microfabricated wafer-type ion trap chip; and (e) a 423 nm spectroscopy laser beam aligned with wavevector orthogonal to the neutral atom flux; (f) NA ~ 0.3 collection lens, imaging with magnification $m = 10$ to (g) a photon-counting PMT detector.

where $\omega_0 = 2\pi \times 707 \text{ THz}$ is the frequency of the spectroscopy transition and $\Gamma = 2\pi \times 35 \text{ MHz}$ is the transition linewidth. The total scattering rate, for an ensemble of atoms with Doppler-shifted transition frequencies at detuning Δ from the excitation field frequency, is then given by

$$R = \iint_V I(r, z)\kappa(\Delta)n(\Delta)dVd\Delta, \quad (2)$$

where

$$\kappa(\Delta) \approx \frac{\Gamma}{2I_{\text{sat}}\left(1 + 4\frac{\Delta^2}{\Gamma^2}\right)} \quad (3)$$

and $I(r, z)$ is the excitation field intensity as a function of radial and axial positions within the spectroscopy beam, $n(\Delta)d\Delta$ is the number density of calcium atoms with Doppler-induced transition frequency shifts $\Delta + d\Delta$ from the laser frequency, and the inner integral is taken over the volume V of the region imaged onto the detector.

The excitation field is orthogonal to the atomic beam axis, so the only Doppler shifts are those due to the divergence of the atomic beam across the interaction region, with

$$\Delta(\theta, T) \approx 2\pi\theta\left(\frac{\bar{v}(T)}{\lambda}\right), \quad (4)$$

where θ is the small angle between the atom velocity and the axis of the atomic beam in the plane containing the axis of the excitation beam, $\bar{v}(T) = \sqrt{8k_B T/m\pi}$ is the mean speed of atoms with mass m in a beam emitted from a gas at temperature T , and λ is the wavelength of the excitation field.

For the purposes of estimating the Doppler shift number density $n(\Delta)$, we consider the target region to be point-like, a good approximation given its size and distance from the source. The direction of the velocity of an atom reaching the target region is thus associated with the region of the source aperture from which it originates. As the collimation aperture is circular, we calculate the Doppler-shift spectral number density

$$n(\Delta) = N * p(\Delta) = \frac{2N}{\pi\Delta_{\text{max}}} \sqrt{1 - \left(\frac{\Delta}{\Delta_{\text{max}}}\right)^2}, \quad (5)$$

where N is the total number density in the target region and $p(\Delta)$ is the Doppler shift probability distribution with domain $-\Delta_{\text{max}}(T) < \Delta < \Delta_{\text{max}}(T)$, where $\Delta_{\text{max}}(T)$ is determined by the temperature and the collimation of the atomic beam.

In our setup, $\theta_{\text{max}} = 0.044$, given by the first aperture diameter (0.75 mm) and its distance to the target region (17 mm).

We can evaluate the integrals separately for each term in Eq. (2). The intensity profile is near-constant as it passes through the interaction region, so evaluating the volume integral (see the Appendix for details) we find

$$\iint_V I(r, z)dV = LP_{423}, \quad (6)$$

where $L = 46.4 \mu\text{m}$ is an effective length of the imaging system collection volume in the direction of the laser beam and P_{423} is the total optical power. We find

$$\begin{aligned} R &= LP_{423} \int \kappa(\Delta)n(\Delta)d\Delta \\ &= LP_{423}N(T)\tilde{\kappa}(T), \end{aligned} \quad (7)$$

where $N(T)$ is the number density and

$$\begin{aligned}\tilde{\kappa}(T) &= \int_{-\Delta_{\max}(T)}^{\Delta_{\max}(T)} \kappa(\Delta) p(\Delta) d\Delta \\ &= \frac{\Gamma^3}{4I_{\text{sat}}[\Delta_{\max}(T)]^2} \left(\sqrt{1 + \frac{4[\Delta_{\max}(T)]^2}{\Gamma^2}} - 1 \right).\end{aligned}\quad (8)$$

The photon count rate is $C = \eta_d \eta_g \eta_p R$, where $\eta_d = 25(3)\%$ is the detection efficiency including losses in the optics, $\eta_g = 2.28(5)\%$ is the geometric collection efficiency calculated from the numerical aperture [NA = 0.299(3)] of the photon-collecting lens, and $\eta_p = 1.1(4)$ is the likelihood of emission per solid angle in the direction of collection relative to isotropic emission, on which the large systematic uncertainty is due to the unknown but stable polarization of the 423 nm beam. The number density $N(T)$ can be determined from the measured count rate and the temperature of the beam

$$N(T) = \frac{C}{\tilde{\kappa}(T) P_{423} L \eta_d \eta_g \eta_p}. \quad (9)$$

B. Thermal performance

The temperature of the oven could be determined by scanning the laser to measure the Doppler broadening, but the intentionally near-Doppler-free geometry of the system means this provides limited sensitivity. However, the very strong dependence of vapor pressure on temperature means that by comparing the measured number density with that predicted to be found within the interaction region, we are able to infer the oven temperature to within a few kelvin, even when considering the substantial uncertainty in N due to the uncalibrated polarization.

The atomic vapor pressure within the oven is given by

$$p(T) = N_o(T) k_B T, \quad (10)$$

where N_o is the number density inside the oven and T is the oven temperature. The vapor pressure can be obtained from standard tables.²¹ The atomic flux density at the hole is $\Phi = N_o(T) \bar{v}(T)/4$, where $N_o(T)$ is the number density in the oven, $\bar{v} = \sqrt{8k_B T/m\pi}$ is the mean speed of atoms in the oven (equal to that in the emitted beam). The atomic flux density on the sphere r away from the source is $\phi(r, \beta) = \phi_0(r) \cos \beta$, where β is the angle to the atomic beam axis, and flux conservation of the half sphere with radius r determines the axial flux density $\phi_0(r)$,

$$\Phi A_o = \int_0^{\pi/2} \phi(r, \beta) (2\pi r \sin \beta) r d\beta = \phi_0(r) \pi r^2, \quad (11)$$

where A_o is the area of the oven aperture. The flux density along the axis is also related to the target region number density N by $\phi_0(r_o) = \bar{v}N$, where r_o is the distance between the oven aperture and the target region. The target region number density is then

$$N(T) = \frac{\phi_0(r_o)}{\bar{v}(T)} = \frac{N_o(T) A_o}{4\pi r_o^2} = \frac{p(T) A_o}{4\pi k_B T r_o^2}. \quad (12)$$

Using Eqs. (12) and (9), we can calculate the number density in the target region and the temperature of the oven from the measured photon count rate. In Fig. 3, we show how steady-state number

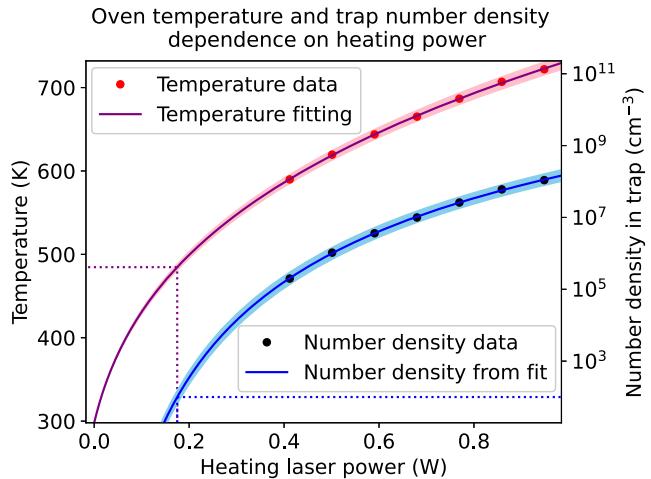


FIG. 3. Dependence of oven output on optical heating power. We measure steady-state number density in the target region as a function of incident power and convert this to a projected oven temperature via the geometric properties of the system and standard calcium vapor pressure curves.²¹ We fit a simple thermal model of the oven to this data, finding that radiative processes dominate the power loss. The shaded regions around the fit line indicate the $\pm 1\sigma$ bounds of the model fit, with the uncertainty dominated by the unknown but constant spectroscopy beam polarization. Using the same known properties of the system to convert the temperature fit to number density allows us to find the power necessary to achieve the target number density (100 cm^{-3}) in the trap region, which is too low to easily measure via resonance fluorescence spectroscopy. We predict that 175 mW of optical power is sufficient to run the oven at the desired level of flux.

density and oven temperature vary as a function of optical power. Considering in particular how the temperature varies with power, we can fit a thermal model of the oven and extract estimates of its radiative emissivity ϵ_{rad} and the thermal conductivity K of its mechanical supports. For an oven at temperature T mounted in a vacuum system at room temperature $T_0 = 298 \text{ K}$, the total heat loss power is

$$P_{\text{loss}} = K(T - T_0) + \epsilon_{\text{rad}} \sigma S(T^4 - T_0^4), \quad (13)$$

where σ is the Stefan–Boltzmann constant and S is the surface area of the oven. The fraction of heating laser power absorbed ϵ_{abs} may differ from the total surface emissivity (due to both the difference in wavelength and local variation in surface roughness or composition). From energy conservation, we find

$$P_{\text{laser}} = \frac{P_{\text{loss}}}{\epsilon_{\text{abs}}} = \frac{K}{\epsilon_{\text{abs}}} (T - T_0) + \frac{\epsilon_{\text{rad}}}{\epsilon_{\text{abs}}} \sigma S(T^4 - T_0^4). \quad (14)$$

Fitting this to the data in Fig. 3, we find the values of the parameters

$$\frac{K}{\epsilon_{\text{abs}}} = (5.7 \pm 6.2) \times 10^{-5} \text{ W K}^{-1}, \quad (15)$$

and

$$\frac{\epsilon_{\text{rad}}}{\epsilon_{\text{abs}}} = 0.89 \pm 0.07. \quad (16)$$

From our fitted thermal model and the results in Eqs. (12) and (9), we can then predict how number density will vary with laser power, as shown by the blue line in Fig. 3. This allows us to extrapolate from our measured data to number densities, which would not

produce enough fluorescence to permit direct detection—our target number density of 100 cm^{-3} corresponds to an average number of atoms in the loading region at any one time of < 0.0001 . According to the fitted thermal model, a heating power of $175(10) \text{ mW}$ is predicted to achieve the oven temperature of $485(1) \text{ K}$ necessary to produce this target density of 100 cm^{-3} .

Thermal losses from the system are primarily radiative at typical operating temperatures. The fitted conductive losses are consistent with zero, and even at the 485 K target temperature comprise $\lesssim 10\%$ of the total losses, within errors.

C. Temporal response

We now consider the temporal response of the oven immediately after the heating laser is switched on. The blue data series shown in Fig. 4 shows the number density measured in the trap region after applying 500 mW of laser power from $t = 0 \text{ s}$ to $t = 440 \text{ s}$. The number density begins to rise after about a minute of heating and reaches 80% of its steady-state value ($\sim 6.8 \times 10^5 \text{ cm}^{-3}$) after 181 s . To reduce the turn-on time of the source, we apply very simple feedforward in the form of a two-level, three-stage heating profile, with 3 W of laser power applied from $t = 0 \text{ s}$ to 11.5 s , 0 W from 11.5 s to 18 s , and 500 mW from 18 s until turn-off. This results in the response shown in black in Fig. 4, with 80% of the steady-state value reached in 15 s . More sophisticated power profiles could doubtless achieve even faster turn-on and less overshoot, but it is likely that this simple approach is sufficient for most applications.

Note that the turn-off response is rapid (reducing to 20% of the steady-state level in 11 s) because the initial stages of cooling are fastest, and the flux is reduced by 80% after just 30 K of cooling. However, the fitted thermal model, along with the calculated heat capacity of the system (0.055 J K^{-1}), predicts that the *temperature*

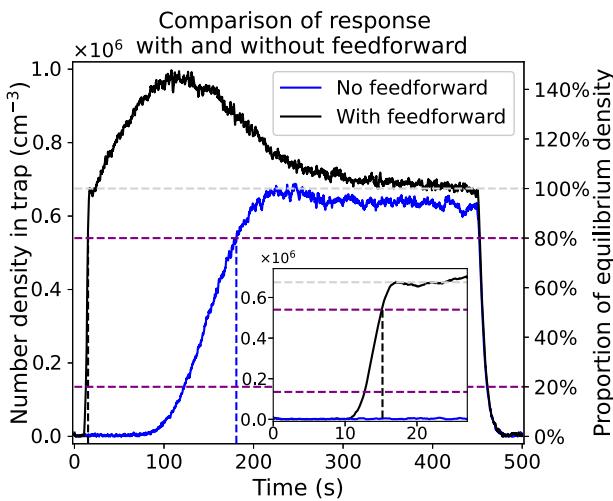


FIG. 4. Temporal response of number density in loading region after heating laser turn-on, with and without feedforward to optical power. Operating at constant heating power, the oven takes $\sim 3 \text{ min}$ to reach 80% of its steady state output; with a simple two-level turn-on profile, this response time can be reduced to $\sim 15 \text{ s}$, shown in more detail in the inset. The number density drops rapidly after turn-off, reaching 20% of its steady state value in 11 s .

response will be significantly slower, cooling with a characteristic timescale of $\sim 2 \text{ min}$. This residual heat would have to be taken into account if using the oven frequently and with feedforward, to avoid excessive overshoot.

D. Predicted lifetime

Using Eq. (12), the total flux of atoms leaving the oven, given in Eq. (11), is

$$J_{\text{atom}} = \Phi A_o = N(T) \bar{v}(T) \pi r_0^2. \quad (17)$$

Operating at 485 K , sufficient to produce the 100 cm^{-3} target number density, the oven emits atoms at a rate of $J_{\text{atom}} = 46 \times 10^6 \text{ s}^{-1}$. The 20 mg of calcium in the oven consists of $\sim 3 \times 10^{20}$ atoms, giving an expected lifetime under the continuous operation of $200\,000$ years.

V. CONCLUSION AND OUTLOOK

We have produced a compact optically heated atomic oven. By avoiding the increased thermal conductive losses associated with the wiring required for electrical heating, the oven may be extremely well thermally isolated from the surrounding vacuum system, and we predict that 175 mW of optical power will be sufficient to heat the oven to 485 K and produce atomic flux density suitable for rapid loading of an ion trap. The power required could be further reduced through gold electroplating of the oven tube. Running at high steady-state flux levels and with a maximum of 3 W of laser power, we achieve 80% of equilibrium flux within 15 s with simple two-level feedforward to the laser power; an even faster response is likely possible when operating at the much lower flux levels required for ion loading, by using a higher optical power or with a smaller oven with lower thermal mass. While demonstrated here with calcium, the oven could be used as a thermal source of popular ion species, such as magnesium, strontium, barium, or ytterbium, at similar but lower operating temperatures. It could also be used for beryllium, but owing to its lower vapor pressures, heating laser powers in the range of 1 W – 2 W would be required to reach the desired number densities.

The extremely high lifetime of the current source implies the mass of calcium in the oven, and thus its size, could be greatly reduced without any meaningful impact. Looking ahead, we are investigating far smaller optically heated sources, integrated within the structure of the trap itself. By also moving the source much closer to the target region, the overall flux required to reach a suitable number density for loading is greatly reduced, and the source mass may still be reduced further. Combined with the measures to reduce radiative losses, the necessary heating power could likely be reduced by an order of magnitude or more, reducing the heating laser requirements and presenting the possibility of operation within a cryogenic system.

While such reductions in mass also provide the potential for reduced turn-on time, another approach worthy of consideration is to forgo the question of temporal response altogether by running the oven continuously at a very low flux. For suitable choice of oven materials and location within a multi-zone trap, this may be feasible without significant reduction in vacuum quality in the qubit operation regions. Loading would then be achieved by applying a short pulse of both photoionization lasers, with ion production

rate limited only by the second stage power available. This approach would also bring the benefit of reducing temporal fluctuations of the temperature throughout the trap, which can introduce problematic drifts in the electric properties and micromotion compensation.

In summary, we believe that efficient, optically heated thermal atomic sources provide a promising solution to the problem of ion loading in compact ion trap vacuum systems, where the low power dissipation and simplicity of construction and assembly represent considerable benefits.

ACKNOWLEDGMENTS

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APPENDIX: CALCULATION OF EFFECTIVE FLUORESCENCE COLLECTION REGION VOLUME

In Eq. (6), the total integrated intensity of the collected volume $\int_V I(r, z) dV$ is converted to the product of the power P_{423} and an effective length L . This effective length L is determined by the area over which the excitation beam and the collection overlap in space as the atomic beam is sufficiently wide that its properties can be assumed constant over the relevant region.

The excitation beam has a $1/e$ waist of $w_0 = 40 \mu\text{m}$, and thus a Rayleigh range of $z_0 = 12 \text{ mm}$. This is much longer than the extent of the beam in the collection region, and thus, the beam radius will be considered constant over the entire collection region.

The imaging system has a magnification of $m=10$ through a $500 \mu\text{m}$ diameter aperture before the PMT. Therefore, counts can be collected from up to $25 \mu\text{m}$ away from the imaging axis in the imaging plane. The imaging system is assumed to have infinite depth of field because the depth of field is much larger than the imaging axis length over which atoms are excited by the laser.

With these assumptions, the volume integral of intensity in the collection region $\int_V I(r, z) dV$ can be calculated by setting up two coordinate systems according to Fig. 5. The coordinates x , y , and z are associated with the imaging system, with z defining the imaging axis and the origin in the focal plane. The coordinates x' , y' , and z' are associated with the excitation beam, with z' along the beam axis and x' and y' in the transverse plane. The two coordinate systems share a common origin. Without loss of generality, x' is chosen to coincide with x .

The intensity of the excitation field in its coordinate system can be written as

$$I(x', y', z') = \frac{2P_{423}}{\pi w_0^2} \exp - \frac{2(x'^2 + y'^2)}{w_0^2}, \quad (\text{A1})$$

where there is no z' dependence because the Rayleigh range is large compared to the width of the collection region. To transform into the collection coordinates, we use $x' = x$ and $y' = y \cos \alpha + z \sin \alpha$

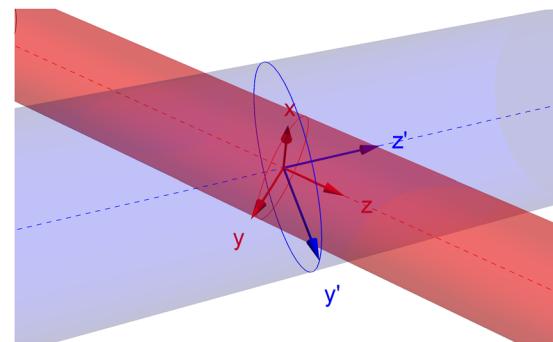


FIG. 5. Diagram of the coordinate system geometry used to calculate the effective length L of the imaging system. The collection region is shown in red, and the excitation beam (shown here as a cylindrical contour) is shown in blue. The target region is formed at the overlap of the excitation beam and the collection.

with $\alpha = 45^\circ$ the angle between the excitation beam axis and imaging axis. Finally, we convert the transverse coordinates x and y to polar coordinates ρ, ϕ using $x = \rho \cos \theta$ and $y = \rho \sin \theta$. This leaves the integral of Eq. (6) as

$$\begin{aligned} \int_V I(r, z) dV &= \frac{2P_{423}}{\pi w_0^2} \int_{-\infty}^{\infty} \int_0^{\rho_m} \int_0^{2\pi} \\ &\quad \times e^{-\left(\frac{2}{w_0^2}\right)^{[(\rho \cos \phi)^2 + (\rho \cos \alpha \sin \phi + z \sin \alpha)^2]}} \rho d\phi d\rho dz, \end{aligned} \quad (\text{A2})$$

where $\rho_m = 25 \mu\text{m}$ is the radial extent of the collection region from the imaging axis. Evaluated numerically, this leads to $\int_V I(r, z) dV = LP_{423}$, with $L = 46.4 \mu\text{m}$.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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