Laser ablation loading of a surface-electrode ion trap

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We demonstrate loading of $^{88}Sr^{+}$ ions by laser ablation into a mm-scale surface-electrode ion trap. The laser used for ablation is a pulsed, frequency-tripled Nd:YAG with pulse energies of 1–10 mJ and durations of 4 ns. An additional laser is not required to photoionize the ablated material. The efficiency and lifetime of several candidate materials for the laser ablation target are characterized by measuring the trapped ion fluorescence signal for a number of consecutive loads. Additionally, laser ablation is used to load traps with a trap depth (40 meV) below where electron impact ionization loading is typically successful ($\gtrsim$500 meV).

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Trapped ions have been shown to be one of the most promising platforms for large-scale quantum information processing (QIP). Recently, development has begun on miniaturized and scalable ion traps [1–5]. While these efforts have met with some success, current designs suffer from technical challenges such as a relatively small trap depth and greater sensitivity to stray electric fields compared with the traps used in previous QIP experiments. Both of these problems make loading ions more difficult. For example, the loading of a surface-electrode printed circuit board ion trap with electron impact ionization presented in Ref. [6] was hindered by stray charges until buffer gas cooling was implemented and micromotion compensation performed. Photoionization has been used to load shallow ion traps [2,4,5], but it requires additional frequency stabilized lasers which are not readily available for every ion species. A new and elegant method in which atoms are photoionized directly from a MOT has been shown to efficiently load ions at a few mK [7], but the laser requirements are even more demanding than for standard photoionization loading.

Laser ablation of a solid target has been used to load ion traps as early as 1981 [8,9]. Ablation is a process in which a high-intensity laser strikes a surface, causing the rapid ejection of material that includes neutral atoms, ions, molecules, and electrons [10]. With other methods of ion loading, the neutral atoms are ionized inside the trapping region. This, however, is not the case with ablation. It was shown in Ref. [11] that the electrons from the ablation plume reach the ion trap first and short the trap electrodes for an amount of time on the order of 10 μs, and the ions from the ablation plume which are passing through the trapping region when the trap voltages recover may be captured. This shorting due to the electrons is necessary because the potential of a Paul trap is conservative in the pseudopotential approximation. The pseudopotential approximation is valid for any ions moving slowly enough to be captured by the trap. A recent paper demonstrated an alternative way to load ion traps with ablation which uses photoionization to ionize the neutral atoms in the ablation plume as they pass through the trap region [12].

Laser ablation loading is potentially advantageous for QIP for two reasons. First, it is very fast: ions can be loaded with a single laser pulse in much less than one second. And second, because the heat load is negligibly small ablation targets could be integrated with a multi-zone trap for localized loading. Thus far, however, no work has been done to determine whether ablation is a viable method for loading the miniaturized and scalable ion trap designs proposed for large-scale QIP.

This paper examines ablation loading of a shallow, surface-electrode ion trap similar to the designs proposed for large-scale QIP. We characterize several candidate materials for the ablation target to determine which materials are the most efficient and reliable for loading $^{88}Sr^{+}$, then proceed to find the minimum trap depth at which laser ablation loading is possible in this trap.

The ion trap used for this work is a printed circuit board surface-electrode Paul trap [6,7,13,14] shown in Fig. 1. The trap is typically operated with 200–600 V rf amplitude at 8 MHz. The trap is mounted in a ceramic pin grid array (CPGA) chip carrier, which is plugged into a custom built ultra-high vacuum (UHV) compatible CPGA socket [2]. The socket is installed in a vacuum chamber evacuated to 2×10^{-9} Torr. A schematic of the experimental setup is shown in Fig. 2.

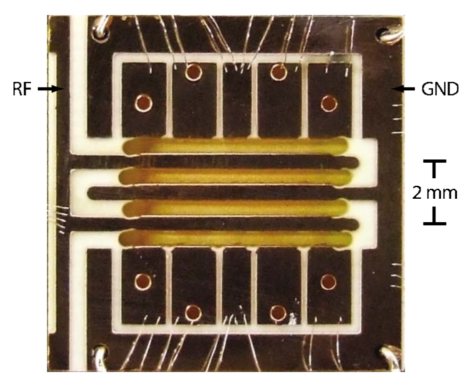

FIG. 1. (Color online) The surface-electrode ion trap used for testing ablation loading. The rf electrodes are spaced by 2 mm center-to-center, leading to an ion height above the trap of 0.8 mm. The long center electrode is held at rf ground, but may have a dc offset applied to it. The segmented electrodes on the sides carry dc potentials for confinement along the long axis of the trap, as well as elimination of stray electric fields.

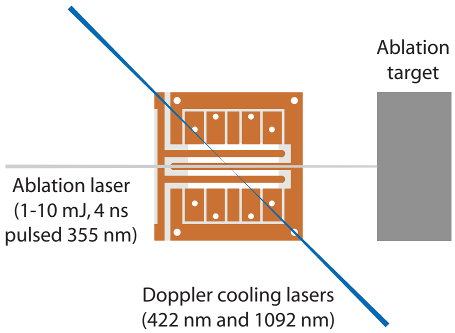

FIG. 2. (Color online) A diagram of the setup showing the position and orientation of the ablation target relative to the ion trap. The surface of the ablation target is approximately 25 mm from the trap center and is orthogonal to the direction to the ion trap. Not to scale.

We detect $^{88}Sr^+$ ions using laser-induced fluorescence on the 422 nm $5S_{1/2} \rightarrow 5P_{1/2}$ transition, with a 1092 nm repumper beam addressing the $4D_{3/2} \rightarrow 5P_{1/2}$ transition to prevent electron shelving in the metastable $4D_{3/2}$ state. Fluorescence is observed using either a photon counting photomultiplier tube (PMT) or an electron-multiplying CCD camera.

The laser used for ablation is a pulsed, frequency-tripled Continuum Minilite Nd:YAG laser at 355 nm. No additional photoionization lasers are used. We load ions using a single laser pulse of energy 1–10 mJ and duration 4 ns. Ion numbers ranging from one to a few hundred are obtained with a single pulse.

Firing the ablation laser ten times in ten seconds raises the vacuum pressure from the base pressure of 2×10^{-9} to 3×10^{-9} Torr. The vacuum pressure drops back down to the base pressure in a few seconds in this system.

The efficiency of laser ablation loading is strongly dependent on the ablation target material. We study several target materials by measuring the trapped ion signal as a function of the number of ablation laser pulses fired on a single spot of the target. Each ablation laser pulse knocks the ions from the previous pulse out of the trap, so the trapped ion signal is roughly proportional to the number of ions loaded by a single ablation pulse. An ideal ablation target would load a constant number of ions per pulse. In practice we find that the number of ions per pulse is not constant and that eventually the target stops producing ions. The target lifetime is different for each target material. Similar changes in yield are observed after many ablation pulses in pulsed laser deposition and is attributed to ablating a profile into the target surface which modifies the ablation process [15]. Note that a finite ablation target lifetime is not a fundamental problem because the position of the ablation laser spot on the target can be dithered. This measurement provides a benchmark of the loading efficiency, consistency, and lifetime of the target.

The target materials studied here are Sr (99% pure random pieces from Sigma-Aldrich), Sr/Al alloy (10% Sr, 90% Al by mass from KB Alloys), single crystal $SrTiO_3$ ($\langle 100 \rangle$ crystal orientation from Sigma-Aldrich), and $SrTiO_3$ powder in an epoxy resin (5 μm $SrTiO_3$ powder from Sigma-Aldrich mixed with Loctite 5 min epoxy). While Sr metal is a natural

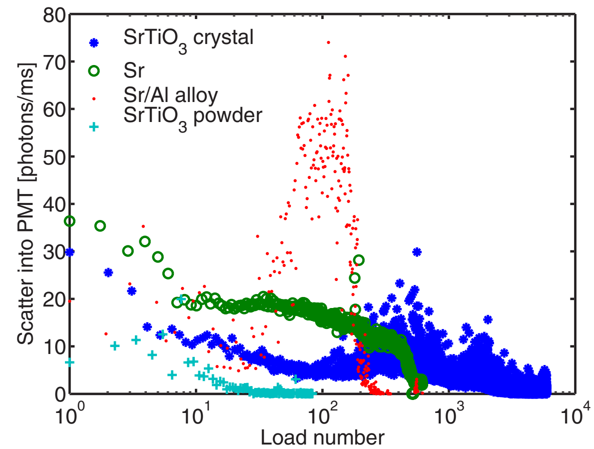

FIG. 3. (Color online) A plot of the trapped ion signal as a function of the number of ablation pulses fired on a single spot of the target for several ablation target materials. Each point represents the signal due to a single ablation pulse of energy 8 mJ. The ions from the previous pulse are lost when the electrons in the ablation plume short the trap, so the trapped ion signal is roughly proportional to the number of ions loaded by a single pulse of the ablation laser. For this experiment, the ablation laser was focused to a spot size of 300 μm. For reference, a single ion scatters roughly 0.2 photons/ms into the PMT in this setup.

choice of target material, it is difficult to work with because it oxidizes quickly in air. None of the other targets we consider here have that problem. In Fig. 3 we plot experimental results for each target. It is clear that from a standpoint of lifetime and consistency that the $SrTiO_3$ crystal is the best choice of target material for loading $^{88}Sr^+$. We are not concerned about the relatively lower efficiency of $SrTiO_3$ because we are primarily interested in loading small numbers of ions.

We proceed to measure the dependence of the trapped ion signal on the trap depth. In this experiment, ions are loaded into the trap at a series of decreasing rf voltages which correspond to decreasing trap depths. We calculate the trap depth using a boundary element electrostatics solver [14,16], and verify that the solution is accurate by checking that it predicts secular frequencies which match the experiment at each rf voltage. The trapped ion signal for each trap depth is plotted in Fig. 4. The ablation laser pulse energy of 1.1 mJ and spot size of 680 μm are chosen to maximize the ion signal at low trap depth. We found that the lowest trap depth at which we can load using laser ablation is 40 meV. In contrast, the same experiment using electron impact ionization of a thermal atomic beam loaded a minimum trap depth of 470 meV.

The 40 meV trap depth loaded here with ablation is similar to the shallowest trap depths loaded with photoionization of a thermal atomic beam [2]. Additional criteria to consider when selecting a loading method for QIP include isotope selectivity, matter deposited onto the trap electrodes, charge deposited onto nearby dielectric surfaces, and the ability to load single ions on demand. Photoionization loading is isotope selective [17,18], generates much less matter and charge than electron impact ionization loading [19], and is capable of loading single ions on demand [17,20].

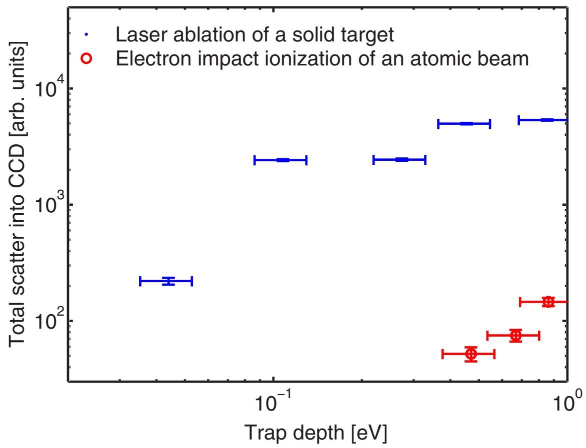

FIG. 4. (Color online) A plot of the trapped ion signal as a function of the computed trap depth for both ablation and electron impact ionization loading. An ablation pulse energy of 1.1 mJ was used with a spot size of 680 μm. Each point is the ion signal obtained either from a single pulse of the ablation laser or from loading using electron impact ionization until the ion signal stops increasing.

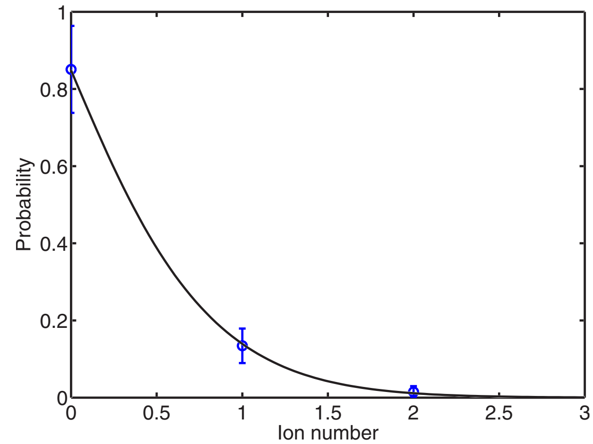

FIG. 5. (Color online) Probability distribution of the number of ions loaded with a single ablation laser pulse. The circles are experimental data and the line is a Poisson fit with a mean ion number of 0.16. The experiment was performed in a smaller ion trap than the one used for the other experiments in this paper with an ablation pulse energy of 2 mJ and a spot size of 500 μm.

The isotope selectivity of ablation loading is similar to that of electron impact ionization loading when loading the ions in the ablation plume as in this work. It is possible, however, to implement ablation loading in an isotope selective manner by preventing the ions from reaching the trap and photoionizing the neutral atoms in the ablation plume. Hendricks *et al.* [12] demonstrated isotope selective loading with a low energy ablation laser, which does not have enough energy to produce ions. Alternatively, one could use a high energy ablation laser in conjunction with an electrostatic filter that prevents the ions from reaching the trap.

Matter deposited onto the trap electrodes is suspected to increase the heating rate of the motional state of trapped ions [21–23]. After 5000 ablation laser pulses we do not observe any change in trap behavior. This establishes an upper bound on the amount of matter deposited on the trap electrodes of one monolayer, because if there were more matter it would short the trap electrodes. In a separate experiment we measured the ion heating rates in cryogenic ion traps loaded with laser ablation and found them to be quite low [24]. These results suggest that ablation does not deposit enough matter onto the trap electrodes to hinder QIP experiments.

Charge deposited onto dielectric surfaces near the trap generates stray electric fields which must be compensated in order to perform precision quantum operations [25]. In extreme cases stray electric fields can make it impossible to load the ion trap [6]. We find that ablation loading generates similar magnitudes of stray electric fields to electron impact ionization loading, and that photoionization loading generates somewhat smaller stray electric fields. In principle, however, it should be possible to reduce the amount of charging caused by ablation loading by using ion optics to remove the electrons from the ablation plume and focus the ions.

Finally, the data presented in Figs. 3 and 4 corresponds to loading hundreds of ions per ablation pulse. We load single ions with ablation by setting the ablation laser energy such that on average less than one ion is loaded per pulse and alternating ablation laser pulses with ion signal measurements until a single ion is observed. If more than one ion is observed they are ejected from the trap and the loading process restarts. Figure 5 shows an example probability distribution of the number of ions loaded with a single ablation laser pulse. This experiment was performed in a smaller ion trap than the one used for the other experiments in this paper with an ablation pulse energy of 2 mJ and spot size of 500 μm. The experimental probability distribution fits well to a Poisson distribution with a mean ion number of 0.16. With these parameters it takes on average seven pulses to load and the probability of loading more than one ion is 8%. The probability of loading more than one ion can be reduced by using a lower ablation laser pulse energy.

In conclusion, we have used laser ablation of a solid target to load a surface-electrode ion trap. Several candidate materials for the ablation target are characterized, and single crystal $SrTiO_3$ is found to give the best performance for loading $^{88}Sr^+$. Laser ablation is demonstrated to work for loading surface-electrode ion traps at trap depths as low as 40 meV. If isotope selectivity is required or stray electric fields are a problem, ablation can be used as a neutral atom source for photoionization. Either as a stand-alone ion source or as a neutral atom source for photoionization, these results suggest that laser ablation is a viable loading method for large-scale ion trap QIP.

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