Electric-field noise from ion-trap surfaces can cause motional heating and limit the coherence time of quantum operations to less than that required for fault-tolerant quantum information processing [1]. Heating rates tend to decrease with increasing ion-electrode distance \( d \), however smaller ion traps are desired for scalability and faster quantum gates. The motional heating rate \( \dot{\pi} \), defined as the time rate of change of the average motional-state occupation number, is related to the spectral density of the electric-field noise \( S_E \) by

\[
S_E(\omega) = \frac{4m\hbar \omega}{q^2} \tilde{\pi}(\omega),
\]

where \( \omega/2\pi \) is the motional frequency of the ion in the trap, \( m \) is the ion’s mass, \( q \) is its charge, and \( \hbar \) is Planck’s constant divided by \( 2\pi \) [2]. The electric-field noise that causes motional heating originates from thermally driven processes [3, 4], and can be significantly reduced by operating at cryogenic temperatures. For example, relative to room temperature, reductions in electric-field noise of 22 dB [5, 6], 19 dB [7], and 34 dB [8] have been reported, corresponding to cryogenic-electrode heating rates as low as 70 quanta/s (\(^{9}\text{Be}^+\), \( \omega/2\pi = 2.3 \text{ MHz} \)), 6 quanta/s (\(^{88}\text{Sr}^+\), 1.3 MHz), and 2 quanta/s (\(^{88}\text{Sr}^+\), 1.0 MHz), at ion-electrode distances of 40, 50, and 75 \( \mu \text{m} \), respectively. In addition, electric-field noise from room-temperature surface-electrode traps has been reduced by approximately 22 dB following in-situ treatments of ion bombardment, corresponding to heating rates as low as 43 quanta/s (\(^{9}\text{Be}^+\), 3.6 MHz, \( d = 40 \mu\text{m} \)) [6], and 3.8 quanta/s (\(^{40}\text{Ca}^+\), 1.0 MHz, \( d = 100 \mu\text{m} \)) [9]. For comparison, heating rate data and other experimental parameters for some traps are summarized in Table 1, and the corresponding normalized electric-field noise spectral densities \( \omega S_E \) are plotted in Fig. 1 as a function of \( d \) [6].

Despite this progress in reducing motional heating rates through cryogenic operation or in-situ treatments, electric-field noise in these traps typically remains well above estimates for thermal voltage noise (Johnson noise) from the electrode circuitry, and therefore is commonly referred to as “anomalous heating”. While this anomalous heating is thought to be related to surface contamination on the trap electrodes, a deeper understanding of its physical origin will help to solve this problem. In an experiment that tested the effects of contamination from air exposure and vacuum baking on a surface-electrode trap that was previously treated with in-situ Ar\(^+\) bombardment [6], heating rates were measured to increase from 50 to 930 quanta/s (\(^{9}\text{Be}^+, 3.6 \text{ MHz}, d = 40 \mu\text{m} \)) after a 48-h exposure to air followed by vacuum baking at 180 °C for approximately 100 h (see Fig. 5(c) in Ref. [10]). This corresponds to a 12 dB reduction in the electric-field noise spectral density as compared to that measured before the Ar\(^+\)-cleaning treatments (Table I, #9 and 10). These data indicate a potential benefit resulting from a precleaning treatment prior to trap assembly. While it is believed that in-situ treatments are required for full removal of the dominant source of this anomalous heating [10], it would be advantageous to implement an ex-situ precleaning treatment to reduce heating rates, thereby enabling new experiments, operating
TABLE I. Heating rates $\dot{\pi}$ from electric-field noise in some microfabricated ion traps of various sizes. Electrode treatments and experimental parameters are listed to compare the “frequency-normalized” electric-field noise spectral densities $\omega S_E$ for various ion-electrode distances $d$ and electrode temperatures. The data are grouped by electrode temperature and the following electrode treatments: untreated (UT), apart from typical microfabrication cleaning with solvents, in-situ treated (IT), and pretreated (PT), described in this work.

| Treatment | $\pi$ (s$^{-1}$) | $d$ (µm) | $\omega/2\pi$ (MHz) | Ion | Electrode Material | $\omega S_E$ ($10^{-6}$ V$^2$/m$^2$) | Reference |
|-----------|----------------|----------|----------------------|-----|---------------------|---------------------|-----------|
| 1         | UT (300 K)     | 16,000   | 40                   | $^{25}$Mg$^+$ | Au                  | 340          | [10]      |
| 2         | IT (300 K)     | 930      | 40                   | $^{9}$Be$^+$ | Au                  | 5.4          | [8]       |
| 3         | (300 K)        | 3.8      | 100                  | $^{40}$Ca$^+$ | Cu/Al               | 0.15         | [9]       |
| 4         | UT (300 K)     | 70       | 40                   | $^{9}$Be$^+$ | Au                  | 5.4          | [9]       |
| 5         | (5 K)          | 6        | 50                   | $^{88}$Sr$^+$ | Au                  | 1.0          | [7]       |
| 6         | (300 K)        | 2.1      | 100                  | $^{88}$Sr$^+$ | Nb                  | 0.025        | [15]      |
| 7         | IT (300 K)     | 100      | 40                   | $^{9}$Be$^+$ | Au                  | 5.4          | [8]       |
| 8         | (300 K)        | 3.8      | 100                  | $^{40}$Ca$^+$ | Cu/Al               | 0.15         | [9]       |
| 9         | UT (300 K)     | 387      | 62                   | $^{25}$Mg$^+$ | Au                  | 170          | [13]      |
| 10        | (300 K)        | 30       | 60                   | $^{25}$Mg$^+$ | Au                  | 14           | This Work |

at either room or cryogenic temperatures, without the need for in-situ cleaning capabilities. It may be that in-situ cleaning treatments can be combined with cryogenic cooling to reduce heating rates further; however, implementing in-situ ion-bombardment treatments in a cryogenic ion-trap setup is challenging, given the necessity to provide optical access, and to incorporate cryogenic, vacuum, and gas-handling components.

Ion bombardment tends to redeposit sputtered metal into the interelectrode gaps. This redeposited metal can cause electrical shorts in regions of the gaps that are shielded by the electrodes from ion bombardment. Since the etch rate from sputtering is observed to be greater than the rate of redeposition, designing the trap-electrode and ion-beam geometry to eliminate the shielding of the gaps can mitigate this problem. One could also optimize the dose of the in-situ treatment required to achieve the desired heating rate by employing treatment parameters (i.e., beam energy, mass, and incident angle) that minimize the sputter yield of the electrode material and concurrently maximize that of the surface contaminants [11]. In addition, one could perform an ex-situ precleaning treatment just prior to final trap assembly, allowing ion bombardment from multiple angles to remove any metal redeposited in the gaps. There is evidence from Ref. [6] that higher sputtering energies may be necessary to achieve very low heating rates at room temperature. This suggests a requirement for relatively high-energy surface modifications, e.g., removal of constituents with relatively low sputter yield [12]. However, higher sputtering energies likely exacerbate the redeposition problem. In addition to the potential benefit to traps without in-situ cleaning capabilities, ex-situ precleaning treatments may also help to reduce this redeposition problem by allowing a gentler in-situ treatment.

In this work, we used a multi-angle precleaning procedure using high sputter doses to remove contaminants while simultaneously removing redeposited metal from the gaps between electrodes. We compare heating rates in two similar (but not identical) stylus-type ion traps, one with and one without the precleaning treatment (Table I, # 12 and 11, resp.), and find a heating rate in the precleaned trap lower by an order of magnitude. Making use of in-situ Auger electron spectroscopy, we correlate this reduction in electric-field noise with the reduction in surface contaminants due to the precleaning procedure.

Using a microfabricated stylus trap, described in detail in Ref. [13] (Table I, # 11), we reported an untreated trap-electrode heating rate of $387 \pm 15$ quanta/s for $d = 62$ µm above an 80-µm diameter Au stylus post (Fig. 1, hexagon symbol). The corresponding electric-field noise, which is well above estimates for thermal voltage (Johnson) noise, is thought to arise from dynamical processes of contaminants on the surface that cause contact-potential fluctuations. These contaminants have many potential sources, including residues from the fabrication processing, vacuum baking for ultra-high vacuum (UHV) operation, or other adventitious contamination from air exposure.

In order to test the dependence of ion motional heating on the amount of surface contamination, and the benefits of a precleaning treatment, in this work we prepared two nominally identical traps that were fabricated on the same wafer. Both traps were precleaned as described...
next, exposed to air for \( \sim 24 \) h, and then vacuum-baked together in the ion-trap chamber. The precleaning consisted of a series of treatments of \( \text{Ne}^+ \) bombardment at three different angles: 10 min at \( +30^\circ \), 10 min at \(-30^\circ\), and 20 min at \( 0^\circ \), all treatments using 2 kV and \( 30 \mu\text{A/cm}^2 \) with a \( \sim 3\)-mm focus diameter of the incident ion beam, at a Ne pressure of \( \sim 6 \times 10^{-3} \) Pa [14]. The initial angled treatments are intended to remove most of the contaminants away from the surface and minimize any embedded contaminants. The final normal-incidence treatment cleans shadowed redeposition of metal (and other deleterious impurities) from the gaps in the electrodes. One of the traps, shown in Fig. 2, was used to trap ions and compare heating rates with the untreated trap of Ref. [13]. The duplicate trap was mounted to a sample transfer stage in the ion-trap chamber and subsequently transferred, in UHV, to a surface-science chamber for the post-bake analysis.

Prior to the precleaning treatment or vacuum baking, Auger electron spectroscopy (AES) of the untreated Au electrodes on the as-fabricated duplicate trap chip indicates the presence of carbonaceous contamination (1-2 carbon monolayers (ML) thick), previously correlated with anomalous heating [6], along with small amounts of other contaminants (S, O, Fe) from the electroplating bath used for gold deposition (Fig. 3-a). Immediately after applying the \( \text{Ne}^+ \) precleaning treatment to the duplicate trap-electrode surfaces, Auger spectra collected in situ signify a clean Au surface free of these contaminants (Fig. 3-b). Before vacuum baking, air exposure of these precleansed surfaces for \( \sim 24 \) h typically results in a reacquiring of less than 0.5 ML of oxygen-free adventitious carbon. The level of contamination on the actual ion-trap electrodes was also monitored using AES during the steps of the precleaning treatment to confirm comparable results. Upon vacuum baking for UHV processing of the assembled ion-trap chamber, the thickness of the carbonaceous layer grows slightly, presumably from hydrocarbons desorbing from the vacuum-chamber walls and other surfaces. Nevertheless, vacuum baking of these precleaned and air-exposed surfaces typically results in less surface contamination than the untreated, as-fabricated electrodes. The approximate carbon coverage on the precleaned, air-exposed, then vacuum-baked duplicate trap chip was determined from in-situ AES to be \( \sim 0.6 \) ML (Fig. 3-c). Since the actual trap chip and the duplicate trap chip were exposed to air and vacuum baked together in the assembled ion-trap chamber, we assume that the actual trap chip has the same level of contamination as the duplicate trap.

The lowest motional heating rate of the precleaned ion trap was measured to be \( 30 \pm 2 \) quanta/s (Table I, #
faces. Assuming either a 1/$d^4$ or 1/$d^2$ distance scaling for the noise, we estimate that the precleaned trap should have 10% or 15% less noise, respectively, due to geometrical considerations. Therefore, we conclude that these geometric differences cannot account for the observed reduction in heating rate.

We checked that the heating rate in the precleaned trap was not limited by extraneous technical noise. This can arise from voltage noise from the computer-controlled digital-to-analog converters and amplifiers that apply static potentials to the trap. Therefore, to exclude this possibility, we applied static (dc) potentials generated by batteries. We also checked for ion state de-pumping during the wait period in the heating rate measurements by using a fast shutter to eliminate possible stray light from the acousto-optical switches. During these tests, we observed no measurable differences in the heating rate.

Preliminary tests of the cleaning procedure on other electrode materials indicate that, in addition to gold, Cu and Al electrodes may also benefit from such a precleaning treatment. However, for Nb electrodes, our Auger analysis indicates the presence of a very low-sputter-yield refractory-metal carbide following the precleaning treatment. Niobium carbide forms when the native oxide of Nb is covered with adventitious carbon and undergoes ion bombardment [15]. This may preclude the use of ion-bombardment precleaning treatments on Nb electrodes.

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* Present Address: Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

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