Pulsed Ion Microscope to Probe Quantum Gases

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The advent of the quantum gas microscope allowed for the in situ probing of ultracold gaseous matter on an unprecedented level of spatial resolution. However, the study of phenomena on ever smaller length scales, as well as the probing of three-dimensional systems, is fundamentally limited by the wavelength of the imaging light for all techniques based on linear optics. Here, we report on a high-resolution ion microscope as a versatile and powerful experimental tool to investigate quantum gases. The instrument clearly resolves atoms in an optical lattice with a spacing of 532 nm over a field of view of 50 sites and offers an extremely large depth of field on the order of at least 70 µm. With a simple model, we extract an upper limit for the achievable resolution of approximately 200 nm from our data. We demonstrate a pulsed operation mode enabling 3D imaging and allowing for the study of ionic impurities and Rydberg physics.

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I. INTRODUCTION

The ability to observe natural phenomena on the single-particle level has led to major breakthroughs in modern physics. Prominent milestones in this context were the pioneering experiments in cloud chambers [1], the discovery of Rutherford scattering [2,3], the first imaging of a solid surface with atomic resolution [4], and the observation of quantum jumps for single trapped ions [5,6]. In the realm of quantum gases, time- and position-sensitive single-atom detection enabled Hanbury Brown-Twiss-type experiments for both bosons and fermions [7,8], and a scanning electron microscope was used for the first high-resolution in situ detection of individual atoms [9,10]. Nowadays, optical quantum gas microscopes offer the possibility to image strongly interacting atoms loaded into optical lattices with single-site resolution [11,12] and have been used to investigate Bose- and Fermi-Hubbard physics [13–16]. Image-stacking techniques have been employed for the reconstruction of three-dimensional atomic structures [17,18], and ensemble-averaged imaging with superresolution has been demonstrated [19,20]. All microscopes based on linear optics, however, are fundamentally limited in their resolution and depth of field by the wavelength of the imaging light. A high-resolution imaging method capable of extracting three-dimensional information from large-volume bulk gases is therefore highly desirable and would allow for the study of quantum correlations, impurity physics, and transport phenomena in unprecedented ways.

Here, we present a high-resolution imaging system based on ion optics, offering a multitude of intriguing features. Charged-particle optics is commonly employed in cold-atom experiments in the form of momentum-space spectrometers [21,22], but it has also been used to image neutral ground-state atoms [9,23,24] and Rydberg atoms [24–28]. Our instrument is especially inspired by the ion microscope presented in Ref. [23], for which a spatial resolution of smaller than 2.7 µm was demonstrated, and it is based on the following simple concept (Fig. 1). Neutral atoms are converted into ions and are subsequently imaged by means of a magnification process onto a spatially and temporally resolving detector. This scheme allows for the investigation of ground-state ensembles, Rydberg excitations, and ionic impurities with the very same apparatus. Owing to the excellent time resolution of the instrument on the order of a few nanoseconds (see Appendix D), both time-dependent measurements and 3D imaging via the time-of-flight information can be realized [29]. The choice of the ionization process constitutes a powerful experimental tool,
enabling the combination of the high spatial resolution with spectroscopic techniques and permitting weak measurement schemes. Furthermore, near-threshold photoionization offers the possibility to produce ultracold ions [30] and opens the door to the spatially resolved study of ionic impurities and ion-atom scattering in the quantum regime [31–35]. In this context, an exciting prospect is the observation of polaron formation and transport dynamics from the two-body collisional timescale to the few- and many-body timescales. We foresee further applications of our approach in the imaging of spatial ordering in three-dimensional Rydberg-blockaded ensembles [36], the detection of fine spatial structures in bulk Fermi gases (e.g., Friedel oscillations [37] and spatial correlations), and the probing of dynamic many-body processes with a high time resolution, just to name a few examples. In the following, we briefly describe our ion microscope and then focus on its performance and imaging characteristics. We begin by discussing a continuous operation mode, in which the object plane is permanently immersed in an extraction field, before demonstrating a pulsed extraction scheme especially suited for the study of ions and Rydberg atoms.

II. ION MICROSCOPE

The design of our ion microscope is depicted in Fig. 2. The whole microscope column has a length of 135 cm and consists of three electrostatic three-cylinder lenses [38] connected via field-free drift sections. In order to compensate for mechanical tolerances, each lens is followed by an electrostatic quadrupole deflector (blue). The object plane lies above a repeller electrode and below an extractor electrode (pale yellow), which, at the same time, are part of a six-plate electric field control (radial field plates marked in blue). The repeller hosts an indium-tin-oxide-coated aspheric optical lens. The extractor also acts as the lower lens electrode of the first lens. (b) Detailed view of the second lens and the following deflection stage. (c) Spatially resolved ion detection is achieved via a delay-line anode on top of an MCP stack. (d) Schematic representation of the electrode configuration. Imaging properties and magnification are determined by the extraction voltages (\(V_{E}\) and \(V_{R}\)), the lens voltages (\(V_1\) to \(V_3\)), and the drift-tube voltages (\(V_{D1}\) and \(V_{D2}\)). The latter are referred to as \(V_D\) for all measurements for which \(V_{D1} = V_{D2}\).
In contrast to most conventional optical systems, electrostatic lens systems offer easy tunability of imaging properties via the electrode voltages. We explore the parameter space of our ion microscope by means of numerical trajectory simulations performed with a commercially available program [45] and find that our system allows for both 2D and 3D imaging. In a first step, we focus here on the performance of our microscope regarding 2D imaging. Nevertheless, a first proof-of-principle experiment demonstrating the 3D imaging capabilities of the optics is presented at the end of this paper. In the 2D mode, we keep all drift tubes at the potential of the MCP front plate ($V_E = -V_R = -500 \text{V}$), corresponding to an electric field of approximately $420 \text{ V/cm}$ in the object plane. An example of the axial electrostatic potential is shown in Appendix A.

Owing to their small initial velocity, the cold ions are extracted on trajectories almost parallel to the extraction field. Consequently, a sharp projection of the object plane can be observed in the detector plane even for voltage configurations for which no actual image formation occurs.

### III. CHARACTERISTICS OF THE IMAGING SYSTEM

In the following, we present experimental results on the characteristics of the previously described imaging system. For most of the measurements, $^{87}\text{Rb}$ atoms were loaded into a one-dimensional optical lattice with a spacing of 532 nm and photoionized in the crossing volume of two laser beams with wavelengths of 780 nm and 479 nm. The 780-nm beam was blue-detuned by 78 MHz from the $|5P_{3/2}, F = 3\rangle$ intermediate state and aligned parallel to the optical axis of the microscope ($z$ direction, see Fig. 2). The 479-nm beam was aligned perpendicular to the optical axis ($y$ direction) and tuned such as to realize a near-threshold ionization with typical excess energies on the order of $h \times 100 \text{ GHz}$ or below, where $h$ corresponds to the Planck constant. The setup described above was used to characterize the magnification, field of view (FOV), depth of field (DOF), and resolution of our microscope. The waists of the ionization beams were shaped to suit the specific measurement.

The study of the magnification behavior of the ion optics included magnifications too small to resolve the optical lattice. For the corresponding set of measurements, we held the atoms in an optical dipole trap and induced a spatial structure of the 780-nm light field by projecting the diffraction pattern of a double slit onto the atoms. The period of the resulting ionization pattern was measured to be $6.9 \mu\text{m}$ by employing a large magnification and using the optical lattice as a ruler. A similar approach was utilized in the proof-of-principle experiment demonstrating 3D imaging, and it is detailed in the corresponding section.

For all characterization methods, the imaged ion distribution was determined by the atomic density distribution and the intensity profiles of the ionization beams. The presented measurements are integrated over several experimental cycles and, as detailed later, compensated for phase drifts of the optical lattice as well as for minor distortions of the detected images. Additional information on the experiment and the data evaluation is given in the appendix.

#### A. Magnification

To explore the exceptional tunability of the magnification $M$ of our instrument, we fix all electrode voltages but $V_2$ and $V_3$ (see caption of Fig. 3) and use the latter two to tune the focal lengths of the second and third lens. Figure 3(a) shows a corresponding simulation of the total magnification revealing that high-quality imaging results can be obtained for magnifications ranging from below $\times 200$ to above $\times 1500$. Both higher and lower magnifications can be achieved if additional electrode voltages are adjusted. We compare the behavior of our microscope with the simulation for scans of either $V_2$ [Fig. 3(c)] or $V_3$ [Fig. 3(b)] for which the respective other voltage was fixed [see red lines in Fig. 3(a)]. As delineated above, the magnification was extracted by imaging either atoms in an optical lattice or a diffraction pattern of known period (see insets). Evidently, the simulations describe our imaging system accurately, with the largest deviation from the experiment being smaller than 10%. For our detector diameter (40 mm), the demonstrated magnification range maps to a FOV between approximately 30 $\mu\text{m}$ and 300 $\mu\text{m}$, which permits both high-resolution studies and the observation of large atomic ensembles.

#### B. Field of view

In order to confirm that the large magnifications suitable for high-resolution imaging can be used without any sacrifices concerning the FOV, we utilized our optical lattice as a test pattern. To this end, we employed a large 780-nm beam ($w_{780} \approx 36 \mu\text{m}$) and shaped the 479-nm beam to a horizontal light sheet with a waist of $w_{479} \approx 40 \mu\text{m}$. The measurement shown in Fig. 4(a) illustrates that the lattice can be clearly resolved over the whole detector area, corresponding to a FOV of 50 lattice sites. The data shown are postprocessed in two ways (see also Appendix F). First, we make use of the regular structure of the lattice to compensate for a local phase $\Phi_1$ caused by small distortions common to all measurements [Fig. 4(d)]. Second, we compensate for a time-
dependent global phase $\Phi_g$ caused by a thermal drift of the lattice over the measurement time of almost six hours [Fig. 4(c)]. We find that the local phase $\Phi_l$ stays below $2\pi$ over the whole detector, and we use the data shown in Fig. 4(d) to compensate for the observed distortion in all our measurements. A comparison between the raw data and the postprocessed data is shown in Figs. 4(b) and 4(e) for the marked region in Fig. 4(a). Even the raw data show a good contrast.

C. Depth of field

The FOV and DOF of an imaging system determine the maximum dimensions of the objects that can be imaged. In the case of high-resolution optical microscopes, the imaging volume is typically restricted by a small DOF originating from the large numerical aperture of the systems. In contrast, the DOF of our ion microscope is remarkably large, as demonstrated in the following. The DOF was probed for the same voltage configuration as used for the FOV measurement by employing a large 780-nm beam ($w_{780} \approx 36 \mu m$) and by shaping the 479-nm beam to a vertical light sheet ($w_{x,479} \approx 2 \mu m$, $w_{z,479} \approx 100 \mu m$). Because of the large extent of the light sheet in the $z$ direction, the height of the ionization region was primarily limited by the diameter of the atomic cloud ($1/e$ diameter of approximately 70 $\mu m$). Careful alignment of the lattice planes was required in order to attain a good imaging.
frequency is apparent [see, e.g., Fig. 5(b)]. We use the of our measured data, in which a signal at twice the lattice. The signature of this localization is found in the FFT the atoms caused by the tight confinement in the optical latticize the resolution, we take advantage of the localization of target given by the optical lattice. In order to still character-scope is significantly smaller than the period of our test magnifications, the resolution of the microscopemalike a quantative upper limit of $R$. Because of the finite detector resolution, we expect our imaging system to perform best at large magnifications. Consequently, the voltage configuration corresponding to the data shown in Fig. 3(b) was chosen for our resolution studies. In order to minimize the effects of residual distortions, a tightly confined photoionization volume was used for the measurement ($w_{780} \approx 2 \mu m$, $w_{179} \approx 5 \mu m$). Figure 5(c) shows the magnitude of the first- and second-order FFT peaks corresponding to the measured data as a function of $V_3$. The significant amplitude of the second-order peak indicates an excellent resolution over almost the whole measurement range. The drop of contrast at small magnitudes of $V_3$ is in accordance with our simulations and results from both imaging aberrations and a decrease of magnification.

To extract an upper limit of the resolution, we assume that all atoms occupy the lowest band of the optical lattice and employ a Gaussian approximation for the single-site wave function (see Appendix H for details). We then convolve the density profile with a Gaussian point spread function (PSF), scale it according to the magnification of the microscope, and bin the profile with the bin size used for the experimental data (100 $\mu m$). Expectedly, the FFT of the model profile shows a second-order peak at twice the lattice frequency, enabling comparison with the experiment. We identify the full width at half maximum of the PSF as the resolution $R$ and find that, for the highest magnifications, we get good agreement with our experimental data for $R \approx 200$ nm [see solid line in Fig. 5(c)]. In consideration of the nonoptimized loading procedure of the optical lattice, the atoms most certainly occupy several bands instead of only the lowest band. Since this leads to a less-confined wave function (and therefore to a smaller amplitude of the second-order FFT peak), the actual resolution of our microscope is probably significantly smaller than 200 nm. Indeed, numerical simulations accounting for realistic mechanical tolerances and voltage noise suggest that a resolution on the order of 100 nm is achievable [29], which permits the in situ observation of phenomena taking place at the length scale of the healing length of Bose-Einstein condensates [46] or the Fermi wavelength of ultracold Fermi gases [37].

D. Resolution

From the measurements presented above, it is evident that, for large magnifications, the resolution of the microscope is significantly smaller than the period of our test target given by the optical lattice. In order to still characterize the resolution, we take advantage of the localization of the atoms caused by the tight confinement in the optical lattice. The signature of this localization is found in the FFT of our measured data, in which a signal at twice the lattice frequency is apparent [see, e.g., Fig. 5(b)]. We use the amplitude of this second-order peak as a qualitative measure of the resolution $R$ of our microscope, and we use a simple model to give a quantiative upper limit of $R$. A powerful feature of our ion microscope is the ability to directly image ions and field-ionized Rydberg atoms. Both the study of Rydberg and ion physics, however, would be hindered by a constant extraction field. Therefore, our instrument is designed such as to allow for a pulsed extraction. In the measurements presented in the following, a fast high-voltage switch was employed to toggle between small compensation voltages and large extraction voltages.
being applied to the extractor and repeller [Fig. 2(a)]. By the additional use of four radial field plates, this procedure enables us to precisely cancel stray electric fields while the extraction field is switched off. The pulsed operation mode was tested for the same optical configuration as was used for the measurements discussed in the previous paragraph and slightly different voltage settings resulting in a magnification of $M = 1467$ (see Appendix G). In every experiment, 6000 ionization cycles were realized, each consisting of a 1-$\mu$s-long photoionization pulse followed by a variable wait time $t_{\text{wait}}$, after which the extraction field was switched on. A measurement result for $t_{\text{wait}} = 0$ $\mu$s is shown in the inset of Fig. 6(a), together with the corresponding FFT. As for the data measured in the continuous operation mode, second-order Fourier peaks are clearly observable and indicate a resolution on the order of half the lattice spacing. For increasing wait time $t_{\text{wait}}$, the visibility of the lattice structure decreases, and a decay of the first-order Fourier peak, which serves as an indicator for the blurring of the lattice structure as a function of $t_{\text{wait}}$. The timescale of the decay reveals the low temperature of the produced ions in the few tens of microkelvin range. Error bars correspond to a conservative estimate of the statistical error (see Appendix F).

![Image](image-url)

**FIG. 6.** Pulsed operation mode. (a) Imaging result for $t_{\text{wait}} = 0$ $\mu$s and magnitude of the FFT corresponding to the integrated lattice profile. The clear signature of a second-order Fourier peak indicates a resolution on the order of half the lattice spacing (266 nm). (b) Decay of the first-order FFT peak, which serves as an indicator for the blurring of the lattice structure as a function of $t_{\text{wait}}$. The timescale of the decay reveals the low temperature of the produced ions in the few tens of microkelvin range. Error bars correspond to a conservative estimate of the statistical error (see Appendix F).

between two electrodes essentially resembling a plate capacitor [Fig. 2(a)]. Owing to the linear variation of the extraction potential along the $z$ direction, the ions pass the extractor electrode with a kinetic energy depending on the initial position along the optical axis. As a consequence, the axial position directly maps to a small variation of the overall time of flight of the ions. Our simulations show that, for a broad range of operating conditions, the mapping between the object coordinate $z$ and the time of flight $t_{\text{tof}}$ is accurately described by the relationship

$$t_{\text{tof}}(z, r) = \alpha z + t_r(r) + t_0.$$  

Here, $\alpha$ is a distance-to-time conversion factor, $r$ is the initial radial distance from the optical axis, $t_r(r)$ describes a radially symmetric curvature of the time of flight, and $t_0$ is on the order of tens of microseconds, whereas the contribution of the other two terms is in the nanosecond range. While $t_r$ constitutes an unwanted distortion, the associated curvature only needs to be measured once and is then easily compensated for during postprocessing.

For a given time resolution (see Appendix D), the achievable axial resolution depends on $\alpha$ and increases with the overall time of flight of the ions. Consequently, it is beneficial to employ drift-tube voltages of small magnitude. While all drift tubes were kept at the potential of the MCP front plate ($-2.4$ kV) for the measurements presented in the preceding part of this paper, our microscope is specifically designed such as to allow for a tuning of $V_{\text{D1}}$ [see Fig. 2(d)]. Figure 7(a) shows a simulation of the transverse magnification $M$ of the microscope, demonstrating that a large range of $M$ is also accessible for $V_{\text{D1}} = -550$ V. Details on the performed simulations can be found in Appendix A.

As a first test of the 3D imaging capabilities of the microscope, we performed a proof-of-principle experiment in which we resolved the diffraction pattern of two crossed double slits. For the chosen electrode voltage configuration [marked with a red dot in Fig. 7(a)], the transverse magnification was experimentally determined from an optical lattice measurement to be $M = 1026$, which is in good agreement with the simulated value of $M_{\text{sim}} = 1080$. The atomic cloud was prepared similarly to the procedure detailed in Appendix B, but it was transported and held in a single-beam 1064-nm optical dipole trap oriented along the $x$ direction ($w_{1064} \approx 38$ $\mu$m). As for the pulsed measurements shown in Fig. 6, every ionization cycle consisted of an approximately 1-$\mu$s-long photoionization pulse, after which the extraction field was switched on. The complete ionization sequence lasted 1.3 s and comprised approximately 4300 ionization cycles. During the photoionization pulse, the central part of the atomic cloud was illuminated homogeneously by a large 780-nm beam. The 479-nm light

F. 3D imaging

The 3D imaging capability of our instrument is based on the time-of-flight information of the ions. For the following discussion, it is worth recalling that the ions are created...
field was spatially structured in both the $x$ and $z$ directions by projecting the diffraction pattern of two crossed double slits onto the atoms [see Fig. 7(b)]. The $x$ period of the cross-shaped diffraction pattern was measured to be 6.9 $\mu$m. In order to resolve several diffraction orders in the $z$ direction, the atomic cloud with a 1/4-e-diameter of approximately 20 $\mu$m was repositioned several times during the measurement.

Figure 7(c) shows the experimental result as a function of the detector coordinates $x$ and $t$, where, except for an offset, $t$ corresponds to the time of flight of the ions. As expected from Eq. (1), the data exhibit a curvature, the asymmetry of which we attribute to a displacement of the ionization region from the optical axis and to small mechanical asymmetries within the ion optics. In a postprocessing step, we compensate for the temporal distortion by the subtraction of a fitted fourth-order polynomial $p(x, y)$. By assuming equal $x$ and $z$ periods of the diffraction pattern, the distance-to-time conversion factor $\alpha$ can be estimated to be $\alpha \approx 1.12$ ns/$\mu$m, which is in good agreement with our simulations. The postprocessed data are shown in Fig. 7(d) as a function of the object coordinates. The diffraction pattern is clearly resolved in the $z$ direction, corresponding to the optical axis of the microscope.

Because of detrimental effects broadening the arrival time distribution of the ions (see Appendix D), we do not expect the axial resolution to match the transverse resolution in the presented operation mode. As our simulations suggest, axial resolutions significantly better than 1 $\mu$m can be achieved, however, for drift-tube voltages $V_{D1}$ even smaller in magnitude. The corresponding operation modes will be investigated in future studies.

### IV. CONCLUSION AND OUTLOOK

We have presented a high-resolution ion microscope allowing for the time-resolved probing of quantum gases on a single-atom level. The magnification of the imaging system was shown to be highly tunable, enabling the investigation of both isolated microscopic few-body processes and extended many-body systems. With a resolution better than 200 nm and an exceptionally large DOF of more than 70 $\mu$m, our microscope is excellently suited for the study of bosonic and fermionic bulk quantum gases on the length scale of the healing length and the Fermi wavelength, respectively. A pulsed operation mode enables the spatially resolved investigation of ion-atom hybrid systems and Rydberg ensembles and permits the ultraprecise measurement and subsequent compensation of stray electric fields.

We believe that charged-particle optics holds great promise for the field of ultracold quantum gases and will allow for a whole range of new experimental techniques as well as an unprecedented level of precision. Key aspects in this respect are the exceptional spatial and temporal resolution, the possibility of 3D imaging, and the freedom to combine the spatial resolution with spectroscopic techniques. For example, the latter possibility enables spin-resolved detection by employing a Zeeman-sensitive and narrow-line optical transition to a Rydberg state, which is subsequently field ionized.

As a next step, we plan to use the 3D imaging capabilities of our apparatus in combination with near-threshold photoionization to create and study ultracold ionic impurities in a degenerate quantum gas [31,33]. Using the same experimental tools, we also aim for the observation of individual ion-atom collisions in the quantum regime [35].

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APPENDIX A: TRAJECTORY SIMULATIONS

The imaging properties of the ion optics were simulated by propagating test patterns through the electrostatic potential corresponding to a given electrode voltage configuration. An example of the axial potential is shown in Fig. 8. As the ions remain well separated under typical experimental conditions, no Coulomb repulsion was considered. For the simulations shown in Figs. 3(a) and 7(a), two test patterns with a lateral line spacing of \( L = 100 \text{ nm} \) and an extent of \( 10 \mu\text{m} \) along the optical axis were employed [see inset of Fig. 3(a) for the shape of the patterns]. Each pattern consisted of 800 ions, given an isotropic velocity distribution corresponding to an initial kinetic energy of \( k_B \times 10 \mu\text{K} \). One of the patterns was centered on the optical axis, whereas the other one was offset by a distance corresponding to 42.5% of the FOV. Here, the FOV is defined as the detector diameter divided by the magnification. For the displayed data points, the line spacing is clearly resolved and the local magnification extracted from the off-axis pattern differs by less than 5% from the on-axis case. The latter condition aims to ensure a low distortion of the imaging result. Since the effects of mechanical asymmetries and voltage noise are not captured by the simulations presented, no quantitative prediction can be made for the resolution.

![Example of the axial electrostatic potential. The curve shown corresponds to an electrode voltage configuration of \( [V_R, V_E, V_1, V_2, V_3, V_D] = [500, -500, -3200, -250, -110, -2400] \text{ V} \). The shaded regions mark the position of the main electrodes of the three lenses. The potential stays flat for the remaining distance to the detector, which is located at 1350 mm.](011036-8)

APPENDIX B: PREPARATION OF THE ATOMIC CLOUD

Except for the 3D measurement, for which further information can be found in the main text, the following experimental details apply. Each experimental cycle started with the loading of approximately \( 4 \times 10^8 \) \(^{87}\)Rb atoms from an effusive oven into a magneto-optical trap (MOT). For this, a double-element Zeeman slower was employed, which in the future will allow us to perform experiments with lithium [47]. The atoms were then optically transported along the \( x \) axis (Fig. 2) from the MOT chamber into a separate science chamber, above which the ion microscope is located. The transport was accomplished by the use of a transport trap consisting of two 1064-nm laser beams passing through a lens mounted on an air-bearing translation stage [48]. The beams crossed under a small angle of 2.3°, producing a transverse intensity profile with a \( 1/e^2 \) waist of approximately 70 \( \mu\text{m} \) at the crossing point. For the measurements performed at low magnifications [Fig. 3(c)], we typically held \( 2 \times 10^6 \) to \( 3 \times 10^6 \) atoms at a temperature on the order of 10 \( \mu\text{K} \) in the transport trap. For the experiments performed in an optical lattice, we ramped down the power of the transport trap on a timescale of 1.5 s and ramped up the lattice within 100 ms. The latter was produced by a retroreflected 1064-nm laser beam oriented along the \( y \) axis (Fig. 2) and possessing a \( 1/e^2 \) waist of \( 110 \mu\text{m} \). After the ramping process, the atoms were solely held by the optical lattice potential with a depth of about 1100\( E_r \), where the recoil energy is defined as \( E_r = \hbar^2 k^2/(2m) \). Here, \( m \) corresponds to the atomic mass, \( \hbar \) is the reduced Planck constant, and \( k \) is the wave vector of the lattice light. All experiments were performed in unpolarized samples with the atoms being pumped to the \( F = 2 \) hyperfine state. Depending on the specific measurement, a complete experimental cycle lasted between 10 and 13 s.

APPENDIX C: PHOTOIONIZATION SEQUENCE

After the preparation of the atomic cloud, a photoionization phase followed. For the measurements performed in the continuous operation mode of the microscope, the ionization sequence lasted 200 ms, during which time the 780-nm laser was switched on continuously. Because of technical reasons, the 479-nm laser was pulsed with a duty cycle of 95% and a frequency of 50 kHz. For the pulsed measurements shown in Fig. 6, the ionization sequence lasted 1.8 s and consisted of 6000 ionization cycles. In each cycle, a 1-\( \mu\text{s} \)-long photoionization pulse was followed by a variable wait time \( t_{\text{wait}} \) (see main text) before the extraction field was pulsed on. In order to minimize the effect of dark counts that occur at a typical rate of a few Hz, the detector was gated such as to register only signals compatible with the employed ionization sequence. The number of detected ions per
experimental cycle (i.e., for one atomic cloud) depends on the specific measurement and typically ranges between a few tens and a few hundreds of ions. As an example, the measurement shown in Fig. 5(a) consists of 18 400 ion counts, which were acquired over the course of one hour.

**APPENDIX D: ION DETECTION**

The employed delay-line detector offers a spatial and temporal resolution on the order of 100 μm and 200 ps, respectively, and features a maximum continuous detection rate of 1 MHz with a multihit dead time on the order of 10 ns. For the pulsed operation mode, the time resolution of the ion detection is not limited by the detector but by the temporal jitter of the pulsed extraction and the voltage noise of the lens electrodes, which directly translates into a broadening of the time-of-flight distribution of the ions. From our experimental data, we determine a typical time resolution on the order of a few nanoseconds for drift-tube voltages of typical time resolution on the order of a few nanoseconds. From our experimental data, we determine a maximum continuous detection of drift-tube voltages of 1000 V.

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For the measurements performed in an optical lattice [see Fig. 3(b)], the FFT corresponding to the integrated lattice profile was fitted assuming a Gaussian shape of the first- and second-order peaks evoked by the periodicity of the lattice. The magnification was then determined from the fitted peak positions and the known wavelength of the lattice laser $\lambda_{\text{latt}} = (1063.93 \pm 0.01) \text{ nm}$. Error bars were determined by considering the conservative estimate of the systematic error of $\lambda_{\text{latt}}$ and the standard error of the fitted peak positions. For the characterization of small magnifications for which the lattice could not be resolved [see Fig. 3(c)], a spatial structure was induced into the 780-nm photoionization beam by passing the beam through a double slit (slit separation and width of $3 \text{ mm}$ and $1 \text{ mm}$, respectively) before focusing the beam onto the atoms. To this end, an in-vacuum aspheric lens with an effective focal length of 26 mm was used. The described setup resulted in an image of the far-field diffraction pattern of the double slit in the focal plane of the lens. The period of the diffraction pattern $\lambda_{\text{diff}}$ was measured at a known magnification previously calibrated with the optical lattice. In comparison with the measurements performed in an optical lattice, the 479-nm beam was enlarged in the $x$ direction to $w_{479x} \approx 100 \text{ μm}$ and the 780-nm beam measured approximately $w_{780x} \approx 2 \text{ μm}$ at the position of the atoms. The magnification was extracted by fitting the imaged diffraction pattern. Error bars were determined by considering the error of $\lambda_{\text{diff}}$ and the standard error of the fitted pattern period. All error bars in Fig. 3 are significantly smaller than the marker size.

**APPENDIX F: DATA PROCESSING**

The employed detector delivers a time stamp and a position for each detected ion. We compensated for minor distortions of the detector image in the $y$ direction (Fig. 2) by applying a spatially dependent shift to the detected $y$ position of all ions. The spatial distribution of this shift was found by using the regular density modulation of the atomic cloud in the optical lattice as a test pattern (Fig. 4). The local distortion could be interpolated from the discrepancy between the observed lattice phase and the phase expected for an ideal lattice structure [Fig. 4(d)]. We checked that the influence of wave-front aberrations of the lattice beams is small by shifting the image along the $x$ direction of the detector using the electrostatic deflector after the third lens (Fig. 2). At least partly, we attribute the observed distortions to nonlinearities of the detector.

The global phase $\Phi_g$ of the detected lattice pattern [see Fig. 4(c) for a specific measurement] is determined by the phase of the retroreflected optical lattice and thus depends on the relative phase between the two counter-propagating lattice beams. Therefore, $\Phi_g$ is susceptible to a thermally...
caused position drift of the retroreflecting mirror. To compensate for this effect, we sorted the detection events into groups of 100 consecutively detected ions and calculated the FFT corresponding to the integrated lattice profile for each of the groups. We then extracted the global phase of the lattice from the complex amplitude of the first-order FFT peak and corrected for the drift accordingly. Subsequently, the data were binned with a bin size of 100 μm.

For measurements for which the magnitudes of the FFT peaks were extracted, we determined a statistical error of these by considering again groups of 100 consecutively detected ions. For each of the groups, the complex amplitudes of the first- and second-order FFT peaks were determined. An estimate for the error of the peak magnitudes was then found by dividing the standard deviation of the amplitudes by $\sqrt{n_g}$, where $n_g$ is the number of groups.

**APPENDIX G: PULSED OPERATION MODE**

The measurements shown in Fig. 6 were acquired using the following electrode voltages: \( [V_R, V_E, V_1, V_2, V_3, V_D] = [400, -400, -2800, -200, -110, -2400] \) V. For the pulsed measurements shown in Fig. 6(b), the magnitude of the first-order FFT peak decreased with increasing $t_{\text{wait}}$. In order to still accurately compensate for the thermal drift of the lattice, a measurement for $t_{\text{wait}} = 0 \, \mu s$ was performed in every second experiment cycle. The thermal drift of the lattice was then deduced only from these additional measurements and corrected for according to the procedure detailed in the previous paragraph.

**APPENDIX II: APPROXIMATION OF THE SINGLE-SITE WAVE FUNCTION**

For atoms occupying the lowest energy band of our deep optical lattice, we approximate the single-site wave function by a ground-state harmonic oscillator wave function. To this end, we consider the Taylor expansion of the lattice potential around an energy minimum $V(x) \approx V_0 k^2 x^2$ and find the probability density of the lowest harmonic oscillator state to be

\[
|\psi(x)|^2 = \frac{(2mV_0k^2)^{1/4}}{(\pi \hbar)^{1/2}} \exp \left( -\frac{\sqrt{2mV_0k}}{\hbar} x^2 \right).
\]  

Here, $V_0$ is the depth of the lattice potential, $m$ is the atomic mass, and $k$ is the wave vector of the 1064-nm lattice light.

**APPENDIX I: COMPENSATION OF STRAY ELECTRIC FIELDS**

For the pulsed measurements presented in Fig. 6, stray electric fields within the ionization volume were compensated by applying suitable voltages to the six compensation electrodes. In order to calibrate these voltages on the order of a few tens of millivolts, free ions were observed for up to 70 μs. The compensation voltages were adjusted such as to minimize the displacement of the detected ion distribution as the observation time was increased. For the field component along the optical axis, the time-of-flight information from the ion detection was employed. From the observed spread of the ion cloud, the typical magnitude of residual fields in the transverse direction can be quantified to be on the order of 100 μV/cm over a spherical volume with a diameter of 10 μm.

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