Site-resolved imaging of beryllium ion crystals in a high-optical-access Penning trap with inbore optomechanics

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We present the design, construction and characterization of an experimental system capable of supporting a broad class of quantum simulation experiments with hundreds of spin qubits using ⁹Be⁺ ions in a Penning trap. This article provides a detailed overview of the relevant subsystems and their integration. We begin with a description of a dual-trap design separating loading and experimental zones. The experimental zone trap electrodes are designed to provide wide-angle optical access for lasers as required for the engineering of spin-motional coupling across large ion crystals while simultaneously providing a harmonic trapping potential. We describe a near-zero-loss liquid-cryogen-based superconducting magnet, employed in both trapping and establishing a quantization field for ion spin-states, and equipped with a dual-stage remote-motor LN₂/LHe recondenser. Experimental measurements via a nuclear-magnetic-resonance (NMR) probe demonstrate part-per-million homogeneity over 7 mm-diameter cylindrical volume, and confirm that the pulse tube does not have a discernible effect on the measured NMR linewidth. Next we describe a custom-engineered inbore optomechanical system which delivers UV laser light to the trap and holds multiple aligned optical objectives for top- and sideview imaging in the experimental trap region. We describe design choices including the use of non-magnetic goniometers and translation stages for precision alignment. Further, the optomechanics feature integration of UV-compatible fiber optics decoupling the system from remote light sources. Using this system we present site-resolved images of ion crystals and demonstrate the ability to realize both planar and three-dimensional ion arrays via control by rotating wall electrodes and radial laser beams. The paper concludes with a brief outlook towards extensions of the experimental setup and future experimental studies.

I. INTRODUCTION

Over recent decades significant progress, both theoretical and experimental, has been made towards building a fully-programmable quantum computer. Realizing such a device, however, remains a huge challenge requiring breakthroughs in many areas of science and engineering. Fortunately, this is not the sole approach for the implementation of important computational tasks where quantum advantages may be gained. Here we focus on the concept of an analog quantum simulator: namely, a controllable quantum system that mimics the behaviour, or evolution, of another less accessible system of interest. The simulator system must possess a Hamiltonian that captures the important features of the system being studied, and must be controlled, manipulated and measured in a sufficiently precise manner. Although lacking the universality of a general-purpose quantum computer, such problem-specific machines may provide computational advantages at intermediate scales that are likely easier to construct than comparable universal machines. It is therefore expected that practical quantum simulation may become a reality well before full-fledged quantum computers.

Interest in near-term mesoscale quantum simulators has grown as the technologies required for coherent manipulation of quantum systems have matured, and early practical applications have become feasible. A substantial body of proof-of-principle experiments has already been realized using a variety of physical systems, including nuclear spins, photonic systems, superconducting circuits, and cold atomic and trapped ions. New experimental demonstrations continue to this day and continue to validate the underlying potential of this computational paradigm for the simulation of physical systems.

Of particular interest are systems which support controllable Ising interactions exhibiting magnetic frustration. Here competing interactions between spins on a lattice prevent the realization of configurations which simultaneously minimize the energies of all pairwise interactions. Such a system can be realized using spins on a triangular lattice under an antiferromagnetic Ising interaction, in which spins cannot be simultaneously antiparallel to all neighbours, leading to competing forces and resulting in fluctuations in the spin orientations. In the classical limit this behaviour is posited to be central to understanding many complex systems, from social and neural networks to protein folding and magnetism. Quantum superposition and entanglement between spins in such a system give rise to long-range quantum spin correlations believed to underlie...
many exotic phenomena, such as quantum phase transitions, many-body localization, and even potentially high-temperature superconductivity. In quantum networks frustration leads to massively entangled and highly degenerate ground states with excess entropy even at zero temperature, underpinning exotic materials such as quantum spin liquids and spin glasses.

Among the various experimental platforms described above, trapped ions have many advantages in realizing the physics of Ising quantum spin simulation. Many experimental demonstrations have already been conducted using radiofrequency Paul traps, but these face technical limitations in realizing large ion numbers or multi-dimensional systems due to the trapping mechanism and resultant instabilities.

Penning traps, which employ a combination of static electric and magnetic fields to confine charged particles, provide substantial advantages when attempting to realize large, stable crystals of trapped ions for experiments with controllable Ising Hamiltonians. For instance, under the correct experimental conditions, laser-cooled ions in a Penning trap self-assemble into two-dimensional (2D) triangular lattices, and are amenable to high-fidelity spin-state control, long trapping times, and straightforward mechanisms for the generation of transverse-field Ising interactions. A number of important experiments have been carried out demonstrating these capabilities, including engineering and benchmarking of long-range Ising interactions, observation of quantum entanglement between spin-squeezed states, and measurement of out-of-time-order correlations as a signature of many-body quantum correlations.

This paper reports on the design, construction and characterization of a Penning-trap experimental setup capable of supporting quantum simulation research with hundreds of $^{9}$Be$^+$ ion spin qubits. This system contains several unique developments which we describe in detail. As such we focus on three primary subsystems: (i) the high-optical-access ion trap and vacuum chamber, (ii) a near-zero-loss wide-bore magnet with dual-stage reliquefier, and (iii) inbore non-magnetic optics for laser-beam delivery and simultaneous sideview and topview ion imaging with diffraction-limited resolution. Throughout our presentation we focus on unique aspects of our system and aim to provide sufficient detail for other teams interested in reproducing key functionalities. We present critical design considerations, information on subsystem performance, and demonstrations of site-resolved imaging of $^9$Be$^+$ ions in our system.

The remainder of this paper is organized as follows: Section II summarizes the theoretical background on Penning traps, the creation and manipulation of laser-cooled Coulomb crystals, and the atomic structure of beryllium allowing identification of the relevant optical and microwave transitions. The experimental setup is described in detail in Section III, addressing the three major subsystems identified above. Section IV presents details on trap operation, data on the production, confinement and imaging of cold ions, and analysis of their crystal structures. Finally, section V concludes with a brief summary and an outlook towards future work.

II. THEORETICAL BACKGROUND

We begin our presentation with an overview of the relevant background material to motivate the system design choices made in later sections. Here we present a summary of the operating principles of the Penning trap, and describe how crystals of laser-cooled beryllium ions may be realized therein. This includes a summary of the relevant atomic physics to understand the key optical transition frequencies for ion production, Doppler laser cooling, and Raman-mediated spin coupling. A more detailed discussion on these topics can be found in Refs. 58–60.

A. The Penning trap

In a Penning ion trap charged-particle confinement is achieved by the spatial superposition of an electrostatic quadrupole field $\vec{E} = -\nabla \Phi$ providing confinement along a “trap axis”, oriented parallel to a static, homogeneous magnetic field $\vec{B} = B_0 \hat{z}$ which provides radial confinement in the $xy$-plane via the Lorentz force. This trap therefore requires charged-particle dynamics to produce stable three-dimensional confinement.

The simplest version of the Penning trap employs only an axisymmetric center ring (CR) electrode and two axisymmetric endcap (EC) electrodes with hyperbolic surfaces to define a quadratic three-dimensional potential. In practice, as we will see below, additional correction electrodes are inserted between the CR and EC electrodes to compensate for field imperfections. The endcaps and center ring are biased with respect to each other by applying an external voltage $V_T$, resulting in an electric potential $\Phi_{T,i}$ at the position of ion $i$ whose ideal functional form is

$$\Phi_{T,i}(x_i, y_i, z_i) = V_T C_2 \left( \frac{z_i^2}{r_i^2} - \frac{x_i^2 + y_i^2}{2} \right),$$

where $C_2$ is a parameter that derives from the trap geometry. The equation of motion of a single particle in a Penning trap results in three fundamental motion modes: an axial mode oriented along the magnetic field with axial frequency

$$\nu_z = \frac{\omega_z}{2\pi} = \frac{1}{2\pi} \sqrt{2V_T C_2 \frac{q}{m}},$$

where $q/m$ is the ion’s charge-to-mass ratio, and two radial modes with eigenfrequencies

$$\nu_{\pm} = \frac{\omega_{\pm}}{2\pi} = \frac{1}{2} \left( \nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2} \right).$$

Here $\nu_{-} = \omega_{-}/2\pi$ is the magnetron frequency, $\nu_{+} = \omega_{+}/2\pi$ is the reduced cyclotron frequency and $\nu_c = \omega_c/2\pi = B_0 q/2\pi m$ is the cyclotron frequency. Stable trapping is achieved as long as $q V_T C_2 > 0$ and $\nu_{-} < \nu_c / \sqrt{2}$.

An additional potential is in general applied in order to provide an electrical means to tune the ratio of radial-to-axial confinement without modifying either the quantizing magnetic field or the axial potential. In the absence
of any external excitations, total angular momentum is conserved and the cloud can reach a stable equilibrium with rotation frequency $\Omega$ anywhere between the single-particle magnetron and modified cyclotron frequencies, or $\omega_{-} \leq \Omega \leq \omega_{+}$. The value taken by $\Omega$ depends on the initial conditions and the ion cloud density.

Within this range the rotation frequency can be precisely locked using a so-called “rotating wall” potential$^{51,62}$. The generation of such a potential, $\Phi_W$, in the radial plane involves applying phase-shifted radio-frequency (RF) signals across appropriately designed electrodes. This effectively distorts the radial trapping potential and imposes an external torque forcing a steady state rotation at the frequency of the applied signal$^{62,63}$.

It is advantageous to implement the rotating wall as a rotating azimuthal quadrupolar electric field, whose potential in the $xy$-plane is given by

$$\Phi_{W,i}(x_i, y_i, t) = V_W C_W \left(x_i^2 + y_i^2\right) \cos \left[2 \left(\Theta_i + \omega_W t\right)\right]$$  \hspace{1cm} (4)

In this equation $V_W$ is the amplitude of the sinusoidal signal applied to the electrodes, $C_W$ an electrode geometry dependent scaling factor, $\Theta_i$ the azimuthal angle at the position of the ion and $\omega_W = 2\pi \nu_W$ the angular frequency of the rotating wall. The combined potential at the position of the ion is therefore

$$\Phi_i(x_i, y_i, z_i, t) = \Phi_{T,i} + \Phi_{W,i} + \Phi_{C,i}.$$  \hspace{1cm} (5)

The final term above accounts for the Coulomb interaction between all ions

$$\Phi_{C,i}(x_i, y_i, z_i) = \frac{q}{8\pi \epsilon_0} \sum_{i \neq k} \frac{1}{r_{i,k}},$$  \hspace{1cm} (6)

with $r_{i,k}$ being the distance between ion $i$ and $k$.

We may transform into a frame co-rotating with the rotating wall frequency, $\omega_W$ which removes the explicit time-dependence, giving a potential

$$\Phi_{i}^R(x_i^R, y_i^R, z_i^R) = \frac{m}{2q} \left[\omega_z^2 (z_i^R)^2 + (\omega_{eff}^2 + \omega_{WA}^2) (x_i^R)^2 + (\omega_{eff}^2 - \omega_{WA}^2) (y_i^R)^2\right] + \frac{q}{8\pi \epsilon_0} \sum_{i \neq k} \frac{r_{i,k}^R}{r_{i,k}}.$$  \hspace{1cm} (7)

Here we have introduced an effective trapping frequency

$$\omega_{eff} = \sqrt{\omega_W \omega_c - \omega_W^2 - \omega_W^2/2}$$  \hspace{1cm} (8)

and a frequency scale associated with the rotating wall amplitude,

$$\omega_{WA} = \sqrt{2V_W C_W q/m},$$  \hspace{1cm} (9)

which results in ellipticity of the ion cloud. The presence of the rotating wall introduces an additional stability criterion such that $\omega_{WA} \leq \omega_{eff}$ must hold for stable trapping. This condition may be equivalently rewritten in terms of a deconfinement frequency

$$\omega_{de} = \frac{1}{2} \left(\omega_c - \sqrt{\omega_c^2 - 2\omega_W^2 - 4\omega_{WA}^2}\right),$$  \hspace{1cm} (10)

where for ion-cloud rotation frequencies below this value radial confinement is insufficient to maintain stable trapping.

Locking the global rotation frequency provides advantages in trapping as it prevents the plasma from spinning down under the ambient drag from static field errors and collisions with background neutrals$^{64}$. In addition, when moving towards the realization of laser-cooled Coulomb crystals as described in the next section, stabilizing the ion rotation frequency enables spatially resolved crystal images via stroboscopic measurements$^{53}$.

B. Light-matter interaction in $^9$Be

Quantum simulation using ion crystals in Penning traps mandates the use of various light-matter interactions in order to perform critical tasks including: (i) Resonantly enhanced multi-photon photoionization (REMPI); (ii) Doppler cooling; (iii) repumping ions that leave the Doppler-cooling cycling transition; (iv) Raman interactions to mediate spin-spin couplings; and lastly (v) millimeter-wave interactions to drive qubit transitions. In this subsection we identify the relevant aspects of the beryllium energy level structures that motivates downstream design choices permitting appropriate optical access. This summary is supplemented by detailed atomic physics calculations presented in Appendix A.

The production of ions from neutral beryllium constitutes the first step of any experiment and may proceed along various approaches. We focus on photoionization as it provides elemental and isotopic selectivity and minimizes electrode charging as occurs in electron bombardment. Direct photoionization of $^9$Be requires a wavelength of 133 nm, which lies in the inconvenient vacuum ultraviolet (VUV) spectral region. It is therefore advantageous to utilize a REMPI scheme where the efficiency of a multi-photon process is greatly enhanced by tuning the first excitation to a resonant transition of $^9$Be before exciting to the continuum$^{65}$. We generate 235 nm light by doubling the output of a high-power multimode diode with output at 470 nm, which is in turn injection locked from a singlemode 470 nm laser. The details of this laser setup will be described elsewhere. Beryllium-9 has a nuclear spin of $I = 3/2$, which couples to the electron spin ($S = 1/2$) to form hyperfine structure. The relevant energy level diagram for neutral $^9$Be is shown on the left side of Fig. 1 including magnetic field corrections from the approximately 2 T superconducting magnet. The relevant transition frequencies for photoionization of neutral beryllium are summarized in Table I. The calculated uncertainties are dominated by the magnetic field contribution for the $\Delta m_L \pm 1$ transitions and the uncertainty in the field-free line of 2 MHz for the $\Delta m_L = 0$ transition.

The relevant atomic transitions in $^9$Be$^+$ for qubit manipulation, Doppler cooling, repumping, and Raman interactions, are illustrated on the right hand side of Fig.
TABLE I. Upper: Transition wavelengths and frequencies for neutral \(^9\)Be in a 1.998 T magnetic field. While the central \(m_L = 0\) line has the attractive feature of not shifting proportionally to the magnetic field, polarization requirements mean it cannot be excited axially. Lower: Calculated transition wavelengths and frequencies for \(^9\)Be\(^+\) in a 1.998 T magnetic field. Uncertainties are dominated by the uncertainties of the literature value of the field-free transitions (90% and 80% for the cooling and repump transitions, respectively), and the magnetic field strength uncertainty of 1 mT. The qubit transition uncertainty is almost entirely due to the uncertainty in magnetic field strength.

| Transition | Wavelength (nm) | Frequency (THz) |
|------------|----------------|-----------------|
| Cooling    | 313.123624(39) | 957.42523(12)   |
| Repump     | 313.117541(46) | 957.44383(14)   |
| Qubit 5    | 5.4447(28)     | 55.062(28)      |

For simplicity the ionic energy levels are depicted in the \(|m_I, m_J\rangle\) basis omitting hyperfine states that do not take part in the desired transitions. The qubit is encoded in the Zeeman-split ground states of the valence electron spin of \(^9\)Be\(^+\) namely the 2\(s^2\)\(S_{1/2}\) states parallel \(|\uparrow\rangle = |m_J = +1/2\rangle\) and anti-parallel \(|\downarrow\rangle = |m_J = -1/2\rangle\) to the confining magnetic field of the Penning trap. The \(B_0 \approx 2\) T magnetic field used in this setup produces an energy splitting \(\approx 55\) GHz. This transition is addressed using a custom-designed U-band horn antenna and elliptical mirror which will be described elsewhere.

The primary optical transitions in \(^9\)Be\(^+\) are all around 313 nm, including the primary Doppler cooling transition. In addition to cooling, the Doppler transition is also used for state-selective readout through fluorescence detection as the \(|\uparrow\rangle\) state will scatter 313 nm photons while the \(|\downarrow\rangle\) is dark. The Doppler transition is not perfectly closed so that ions have a finite chance of leaving the cooling manifold, although this process is strongly suppressed. The repump transition is therefore driven from \(|\downarrow\rangle\) to \(|2P_{3/2} m_J = +1/2\rangle\) mainly for quickly pumping all ions to the \(|\uparrow\rangle\) state during qubit-state initialization. The final optical transition is used in engineering Ising-type Hamiltonians by generating effective spin-spin interactions between ions across the crystal. This is accomplished using Raman lasers which off-resonantly excite modes of motion in the ion trap\(^5\). The wavelengths and frequencies relevant to our experiment appear in Table I. The laser systems used to generate the various laser beams broadly follow the approach of Wilson et al.\(^6\).

III. EXPERIMENTAL DESIGN

In this section we focus on the detailed presentation of the critical design drivers and choices made in realizing our Penning trap experimental platform. This involves, as in any atomic physics experiment, consideration of the relevant atomic transitions, frequencies, and the like. However, the Penning trap brings with it considerable additional constraints arising from the underlying mechanisms of both trapping and light-matter interaction.

For instance, the Doppler and repump beams will in general be oriented parallel to the trap axis while an additional transverse Doppler cooling beam is employed to apply a torque to the ion crystal as described above. This mandates both on-axis optical access as well as the ability to steer a laser beam through the trap orthogonal to the trap axis and in the center of the magnetic field. The Raman beams, similarly, must enter the trap at a relatively shallow angle (< 35\(^\circ\)) to the transverse plane where the ion crystal resides. The comparatively long wavelength microwaves must also be brought into the trap with microwave magnetic field transverse to the trap axis. Finally, ion state detection must be performed by the collection of light both parallel to the trap axis (topview imaging) and also perpendicular to it (sideview imaging) as indicated in Fig. 2.

These requirements overall mandate high optical access in the trap - an objective which competes with the need for harmonicity of the trapping potential and magnetic field homogeneity. Further, they conflict with the challenging geometric constraints imposed by the use of a superconducting solenoid magnet, common in precision metrology applications requiring high field homogeneity and stability. In this section we describe the design and assembly of a system meeting these competing constraints.

![Energy levels and relevant transitions in atomic and ionized beryllium in a 2 T magnetic field (not drawn to scale). Left: Resonantly enhanced, two-photon ionization process of one valence electron from \(1S_0\) to \(3P_1\) in neutral \(^9\)Be, the excited-state-to-continuum wavelength is \(\approx 307\) nm. Right: \(^9\)Be\(^+\) energy level diagram with transitions for Doppler cooling, repump, and Raman transitions shown. Only the \(m_L = +3/2\) levels are shown. This diagram is only valid after the nuclear dynamics have been frozen out by optically pumping the \(m_I\) states to the \(m_I = 3/2\) manifold through the cooling transition with properly chosen polarization.](image-url)
demands and supporting our objective of building a robust system for quantum simulation experiments with large crystals of trapped ions. We focus on three primary subsystems, the Penning trap and associated ultra-high-vacuum (UHV) chamber, the near-zero-loss superconducting magnet, and the inbore optomechanics for laser delivery and ion imaging.

### A. Penning trap system

Our trap design focuses on the segregation of critical tasks in a manner that permits high fidelity quantum simulation experiments with efficient loading of ions. As a result, the Penning trap system consists of two traps, referred to as the loading trap (LT) and science trap (ST), stacked coaxially. Ions are initially created and confined in the LT, then shuttled into the ST where Coulomb crystals are created, manipulated and imaged. Separating these functions permits greater optical access in the ST by freeing room needed for the beryllium sources, and prevents the experimental zone from being contaminated by beryllium plating generated during ion creation. An overview of the trap assembly is shown in Fig. 3, including beryllium ovens and lasers.

#### 1. Loading trap

The LT consists of an axisymmetric center ring (CR) and two end cap (EC) electrodes with hyperbolic surfaces, see Fig. 4(a).

The central diameter of CR is $r_0 = 4.95$ mm and the half distance between the EC is $z_0 = 5.49$ mm. This geometry approximates an ideal Penning trap as only limited optical access is required. Nonetheless, both axial and radial beam access are allowed in this trap; on-axis holes of 5 mm diameter in both EC electrodes serve to deliver the axial Doppler beam and photoionization beam into both sections of the trap, and to facilitate transfer of the ions between the traps. All trap electrodes are machined from oxygen-free high conductivity (OFHC) copper and assembled in a stacked formation, separated by machined Macor rings for electrical isolation.

As mentioned above beryllium atoms are created and ionized in the LT; two beryllium ovens as sources of $^9$Be are mounted in $(5 \times 8 \times 10)$ mm$^3$ cavities milled in the exterior of the CR. The ovens reside in the resultant gap and the output atomic flux is roughly collimated by passing through an $\varnothing 2.0$ mm aperture of 2.3 mm length limiting the solid angle of the atomic flux cone into the trap center, see Fig. 4. The ovens consist of a $\varnothing 50$ $\mu$m beryllium wire tightly wound around a coiled filament of $\varnothing 100$ $\mu$m tungsten wire. The filament length and coil number is set to ensure that upon heating thermal expansion does not cause inadvertent shorts between adjacent coils. The filament is spot-welded to a pair of $\varnothing 1.0$ mm tungsten electrodes using a leaf of constantan foil. The electrodes are then glued into a custom Macor base using a UHV-compatible ceramic adhesive. To avoid a deformation of the filament structure, the resulting torque on the coil is minimized by choosing the alignment of the coil and the polarity of the heater current such that its magnetic moment is parallel to that of the superconducting magnet. For full details on construction method see Ref. 57.

#### 2. Science trap

The structure of the science trap is developed with the primary objectives of providing high optical access for laser beam delivery and ion imaging while maintaining high harmonic of the trapping potential. Lasers must enter and exit the trapping region without clipping electrode surfaces to avoid photo-induced damage (and consequently distortion of the potential), unwanted charging effects, and laser scatter. Apertures must therefore provide sufficient clearance for beam alignment, including a large angular separation $\theta_R$ in the case of the two Raman beams for tuneable ODF configurations. The 55 GHz or $\approx 5.5$ $\mu$m millimeter wave beam used for qubit manipulation also sets a lower bound on its entry aperture size to minimize diffraction, as does the requirement of high numerical aperture (NA) for high-resolution imaging.

The science trap design is shown in Fig. 5. All electrode dimensions have been designed via numerical optimization to ensure the competing objectives identified above are met. Details on the optimization procedure and resulting geometric constants appear in Appendix C. The trap electrodes are again machined from OFHC copper: Endcap 1 (EC1), rotating wall (RW), center ring (CR), and endcap 2 (EC2). Electrodes are assembled in a stacked formation separated by Macor rings for electrical isolation, as in the loading trap.

An eight-fold array of radial apertures of dimension $(5 \times 10)$ mm$^2$ is machined in the center ring. This permits a maximum angular separation of $\theta_R = 32^\circ$ for the Raman beams, around 1.5 times the value used in previous work$^{35}$. Our design implements the RW electrodes, an eight-fold-symmetric radial array sandwiched between the Macor rings, on either side of the CR, see Fig. 5. The sixteen rotating wall electrodes are electrically connected in four groups of four, each comprising vertically- and radially-opposing electrodes.

The CR electrode has a length of 14.5 mm and is separated from the RW electrodes by 1.1 mm. Each RW electrode has a length and width of 2.1 mm and 3.9 mm, respectively. Their inner surface has a radius of 10 mm, identical to the other ST electrodes. The distance between the RW electrodes and adjacent end caps is 0.8 mm, the length of the 20 mm-diameter part of the end caps is 8.2 mm. After that the inner diameter of EC 1 is reduced to 5 mm to form a transition to the LT.

A wire mesh (5.6 $\mu$m grid spacing) strung on a titanium ring structure is mounted on Macor spacers above EC2 of the science trap. This structure closes the Penning trap electrostatically and therefore prevent distortions of the trapping potential due to static charges on the interior surface of the glass cuvette. The wire mesh is centred on the trap axis (Fig. 3a) providing a clear path for axial lasers exiting the trap without scattering off the
wire grid. The mesh presents a far-out-of-focus occlusion for topview imaging and as such does not significantly impact imaging performance.

3. Trap and UHV Assembly

We perform the mechanical assembly of the various trap electrodes and insulators in a clean environment and integrate additional alignment and mechanical support structures into the assembly. Figure 6 shows the assembled ST and LT, where the stacked electrodes and Macor rings are clamped together with threaded titanium rods. The trap assembly is bolted onto an alignment tube, itself clamped at its base in a groove grabber mounted in a CF63 through flange. This mechanical assembly requires critically tight tolerances as the trap assembly will be cantilevered from the vacuum flange in a horizontal configuration. As such the alignment tube is machined from OFHC copper and Au-plated to avoid cold welding to e.g., trap electrodes or other alignment structures in the presence of snug mechanical fits.

The CF63 flange shown on the trap assembly is sandwiched between similar flanges on the main vacuum chamber and a glass vacuum cuvette encasing the trap assembly (Figs. 7 and 8). The cuvette consists of a $\varnothing 50$ mm ID double octagonal cell, with an eight-fold symmetric array of apertures for radial optical access, each covered with 15 mm $\times$ 37 mm flat rectangular windows externally bonded to the main glass body. The top is sealed with a $\varnothing 60$ mm OD window providing axial optical access. All
FIG. 3. Trap assembly and laser orientation overview. (a) Rendering of trap electrodes (colored) and Macor spacers (white), showing relative orientations of ovens, trapping region, and laser orientations. Electrodes used in the science trap (ST) and loading trap (LT) are colored differentially for clarity (b) Cross-section through trap electrodes (hatched) inner electrode surface geometry and optical access in the science trap. All electrodes in the LT exhibit hyperbolic surfaces to approximate the ideal potential described in Eq. 1. The ST electrodes are cylindrical with radial optical access ports for Raman lasers and millimeter waves highlighted. At far left is the wire mesh serving as a charge screen to prevent trap instability.

windows are made from UV-grade fused silica, and antireflection (AR) coated on both sides for 313 nm. The cuvette neck is mated via a glass-metal interface onto a 316 LN stainless steel tube welded to a CF63 flange.

In order to ensure mechanical stability of the trap assembly in a horizontal orientation, just above the CF63 flange in the trap assembly, the outer diameter of the alignment tube enlarges to fit snugly with the inner diameter (ID) of the stainless steel neck of the cuvette, see Fig. 6 (15) and (16). The OD of this section of the alignment tube is $54.03 \text{ mm}$, providing a H7/h6-class fit with the $54.00 \text{ mm}$ ID of the cuvette’s stainless steel neck. Venting channels in the enlarged section allow cabling from the traps to reach the vacuum feedthroughs downstream.

The trap assembly and cuvette mate to an UHV chamber consisting of a number of standard vacuum components, two permanently attached vacuum pumps, and a number of electrical feedthroughs, see Fig. 7. All standard vacuum components are made from 316 LNS stainless steel, and custom parts from either OFHC copper, grade 2 titanium, or Macor, satisfying the dual requirements of low magnetic permeability and vacuum compatibility.

The main vacuum chamber is constructed from a 316L stainless steel hexagon with six CF63 flanges arranged around the sides, and two CF160 flanges on top and bottom. The trap assembly and cuvette are connected to this hexagon via a CF63 full nipple. A pair of CF160 zero length reducer flanges are mounted on the top and bottom of the hexagon, supporting a CF40 all-metal valve on the top, and a 24-pin CF63 D-SUB UHV feedthrough on the bottom. A CF63 5-way cross is attached to the hexagon opposite the 5-way cross along the axial direction on the back flange, hosting a $20 \text{ L s}^{-1}$ ion getter pump on top, a Bayard-Alpert ion gauge on the side, and an AR coated vacuum viewport at the back for axial optical access. The system includes a non-evaporative getter (NEG) pump mounted on one of the four CF63

FIG. 4. (a) Loading trap design and assembly showing relevant electrodes (colored), Macor spacers (white), and oven assemblies. (b-d) Beryllium oven assembly and mating to center ring electrode. (b) Filament coil spot-welded to tungsten electrodes glued into Macor base. (c) Underside of assembly with tungsten electrodes protruding through Macor base. Different electrode lengths identify correct polarity for heater current. (d) Cavity milled into side of LT CR for housing beryllium ovens. Beryllium plating is observed on interior surfaces of oven housing after running oven. $22.0 \text{ mm}$ aperture through CR allowing an approximately collimated atomic flux to reach trap center is shown in the middle of the image.
FIG. 5. Exploded view of the Science trap. As above metal electrodes are represented in color while Macor spacers are white. Relevant components are labeled. Inset: Photograph of ST center ring electrode oriented to highlight eight large apertures for wide optical and millimeter wave access.

The remaining three side flanges of the vacuum chamber are equipped with 7-pin power feedthroughs for delivering high voltage to the LT, ST and rotating wall electrodes. Kapton-coated wires are used to connect internal feedthrough pins to all trap surfaces, electron guns (not used or discussed further), and beryllium ovens. A perforated $\varnothing 50$ mm OFHC copper tube is mounted inside the hexagon along the trap axis via internally attached groove grabbers to prevent feedthrough cabling from obstructing optical access along the trap axis. For full details on component designs see Ref. 57.
FIG. 6. Trap assembly mounted on alignment tube (gold) and attached to UHV flange at bottom. Assembly is performed in a vertical orientation to ensure proper alignment and to facilitate electrical connections. (1) Wire mesh. (2, 4, 7) ST – EC2, CR, EC1. (3, 6) Rotating wall electrodes (vertically-opposite). (5, 9) Titanium rods. (8, 10, 12) LT – EC2, CR, EC1. (11) Beryllium oven. (13) Trap assembly mounting plate. (14) Au-plated copper alignment tube. (15) Enlarged OD for mating with cuvette neck. (16) Groove grabber. (17) CF63 through flange.
FIG. 7. Vacuum system assembly. Trap tower assembly (10) is encased in a glass cuvette (19, 20) connected to hexagonal vacuum chamber (1). Trap voltages and rotating wall controlled by high-voltage power supplies are routed to SHV connectors on custom breakout boxes (16, 17, 18) associated with respective power feedthroughs (13, 14, 15). Beryllium ovens are driven by power supplies connected to the SUB-D feedthrough (5). After bakeout and with the ion getter pump (7) and NEG (12) activated an ultimate vacuum of order $2 \times 10^{-11}$ mbar was reached, as read off the ion gauge (8). For parts list see table VI.

B. **Superconducting magnet and dual-stage reliquefier**

In our Penning-trap system a superconducting solenoid magnet provides the means of radial confinement of charged particles, but also establishes a stable physical environment for precision experiments which could not easily be performed in a similar way in other ion traps. Such experiments include, for example, high-precision mass spectrometry$^{67,68}$, determination of fundamental constants$^{69-71}$, CPT tests$^{72,73}$ and quantum simulation with large ion crystals$^{53,55}$. These capabilities arise from the high temporal stability and self-shielding effects of superconducting solenoid magnets operated in persistent mode$^{74}$. By use of additional so-called shim coils, spatial field inhomogeneities originating from the geometry and mechanical tolerances of the main solenoid coil can be compensated, resulting in a dedicated region at fields of several Tesla with high field homogeneity and a spatial extent of a few cubic-millimeters.

For the Penning trap described in section III A, we employ a homogeneous magnetic field of a $B_0 \approx 2$ T, in a 150 mm-diameter horizontal-bore superconducting magnet. The magnet itself is an after-market system originally manufactured by Oxford for use in small-animal imaging experiments. It is charged to below its design field strength of 3 T such that the resulting qubit frequency remains in a frequency band where commercial low-phase noise, high-power millimeter wave sources are available.

The magnet cryostat boils off LN$_2$ at a rate of 7.451/d and LHe at a rate of 0.481/d. With vessel capacities of about 321 for LN$_2$ and about 751 for LHe, the 50% evaporation times are about 2.2 d and 156 d, respectively. Despite the relatively long hold time of LHe, frequent refill cycles for LN$_2$ reduce the maximum duty cycle of an experiment. This is because the magnetic field during the filling process will change due to permittivity variations of the material in thermal contact with the cryostat, as well as pressure changes in the cryostat. The time for the magnetic field to resettle varies for each individual system and environmental conditions but can be of order hours. In addition, even LN$_2$ refilling can cause disruption to standard experimental procedures due to the common buildup of condensation and icing.
FIG. 8. Trap assembly in glass cuvette showing relationship between electrode structures, optically contacted windows, and UHV chamber. (a) Cuvette mounted on vacuum system during UHV bake, with pumping line still attached (top). (b) On-axis “topview” highlighting laser beampath on axis (bright spot) using back illumination, shielding mesh preventing cuvette charging from distorting trap potential, and eight-fold symmetric cuvette window pattern. (c) Angled side view showing thickness of optical flat vacuum window constituting first element of topview imaging system (lower left) and alignment of windows to trap apertures.

To reduce cryogen losses and minimize the impact of cryogen refilling on system up-time, a novel dual-stage reliquefier (DSR) system is used to recondense both helium and nitrogen boil-off and return the reliquefied gas directly to the cryostat. This hybrid near-zero-loss system provides the advantage over fully cryogen-free systems of persistent operation in the absence of power for several days and, as we demonstrate below, limited observed impact of reliquefier operation on the temporal stability of the magnetic field. Here we provide an overview of system configuration and performance measured over an approximately 12 month period; for detailed schematics and performance specifications of comparable cryomechanical coolers dedicated exclusively to Helium, see Ref. 75.

The DSR system consists a two-stage cryocooler pulse tube cold head (Cryomech PT407-RM) with remote motor and a 4.5 kW helium compressor (Cryomech CP2800). The main reliquefier assembly is shown in Fig. 9 and has been customized for our application. The pulse tube cryocooler is mounted inside the vacuum-sealed condensing chamber of the reliquefier. The first stage of the cold head provides cooling capacities at the temperature range of 30 K to 70 K for recondensing LN$_2$ boil-off. The second stage provides cooling capacities of 0.5 W at 4.2 K for recondensing LHe boil-off.

FIG. 9. Reliquefier and remote motor assembly (shown 90° rotated): (1) Vacuum-sealed condensing chamber, (2) Base plate for pulse-tube cold head, (3) Remote motor assembly, (4) External Helium reservoirs, (5) Nitrogen gas bleed inlet, (6) LN$_2$ return line, (7) Helium gas recovery inlet, (8) LHe return line, (9) 1.5 m flex line connecting pulse tube to remote motor assembly, (10) Aeroquip fitting for low-pressure flex line, (11) Aeroquip fitting for high-pressure flex line.

The DSR assembly is mounted above the magnet on a gondola structure decoupled from the walls and floor of the laboratory to mitigate the coupling of vibrations into the magnet. One key feature of the cold head design is the separation of the remote motor assembly from the pulse tube. This permits a helium expansion cycle in the cold head without directly using a displacer or piston, thereby reducing vibrations in the magnet, known to limit the trapped-ion spin coherence times$^{76}$. The remote motor is also mechanically fixed to the overhead gondola system such that it is decoupled from the magnet system. It sits on a sliding shelf which permits strain management in the flex line during reliquefier insertion or removal.

The compressor package uses 99.999 % pure helium as the refrigerant gas and is installed in the service room adjacent to the lab with vibration-dampening feet used for suppressing low-frequency vibrations. Two flexible stainless steel lines carry low- and high-pressure helium from the compressor to the remote motor, which in turn is connected to the cold head via a 1.5 m flex line. The remote motor controls a valve which sets the pressure changes inside the pulse tube, creating the necessary cooling power to achieve temperatures below 4 K at the heat exchanger.

The two drain legs of the reliquefier are inserted into the fill ports of the magnet and make primary physical contact to the magnet cryostat through rubber O-rings. Helium boil-off from the magnet cryostat enters the condensing chamber via a flexible vapor line connecting the LHe vessel to a gas inlet on the reliquefier. The vapor line is equipped with a needle valve setting the helium flow rate and hence permitting control over the pressure in the magnet cryostat. Helium gas entering the chamber contacts the 3.9 K cold head on the second stage of the cryocooler where it condenses. The liquefied helium is then funneled into a 12.7 mm-diameter vacuum-insulated return line inserted into the helium fill port of the magnet cryostat, forming a closed helium loop. For the nitrogen cycle, the return line consists of a coaxial tube permitting both capture of LN$_2$ boil-off and its return after recondensing through the same port. Nitrogen boil-off flows up the outer jacket toward the condenser surface and the recondensed liquid flows back through the center tube returning to the magnet cryostat.
The differential pressure between cryostat and laboratory, and the temperature at the two cooling stages, are monitored by sensors. A stable cryo-siphon loop is achieved when the liquefaction rate is slightly lower than the boil-off rate. The helium cycle is regulated at a temperature of 3.9 K measured at the cold head. By setting the needle valve mentioned above, a stable overpressure of about 1 psi in the helium cryostat can be maintained. The nitrogen cycle is regulated at an over-pressure of 0.5 psi, resulting in a temperature of about 64 K at the first stage of the cold head. Stable operation is achieved using a PID controller (Stanford Research Systems CTC100) to regulate heaters at the nitrogen and helium condensing stages. Maintaining a positive pressure in the cryostat vessels is imperative since atmospheric gases can freeze inside and subsequently clog the two cryogenic vessels. All sealings between the reliquefier and the cryostat are compression fittings using FKM O-rings. The cryostat features non-return (pop-off) valves and a burst disc to permit emergency decompression of the vessels in the event of a superconducting quench, which likely constitute the largest component of the overall system leak rate.

Manually refilling LHe or LN$_2$ is not possible with the reliquefier installed as it occupies the relevant liquid cryogen fill ports. A top-up of cryogens to compensate residual system losses is achieved by slowly bleeding gaseous helium and nitrogen into the recondenser. Helium gas is injected via a flange on the magnet cryostat’s helium manifold connected in tandem to the helium vapor line of the reliquefier. Nitrogen gas is bled in directly through an inlet on the condenser chamber. As such the system’s liquid cryogen levels may be maintained without the need to interrupt system performance.

We measure the effective loss rate of cryogens from our system by calculating the total input gas volume that becomes liquefied using a digital flow meter (Bronkhorst MV-392-He) installed on the helium inlet line. Once a sufficient amount of helium gas is liquefied, the rising LHe contacts warmer system components at the top of the vessel resulting in an increase in boil-off rate. The helium pressure therefore increases in the magnet cryostat, reducing the flow rate of injected gas to zero. Integrating the flow rate up to this point, and converting from gas to liquid volume yields the estimated volume of LHe added to the system. Using this method we calculate the total volume of added LHe after 77 days of continuous operation at 0.6 L, or a loss of 7.8 mL/d. Over a year this implies a loss of less than 5 % of the helium vessel capacity. The loss rate for liquid nitrogen determined from the level meter is 160 mL/d. Thus, the loss rates for LHe and LN$_2$ are decreased by more than a factor 60 and 46, respectively. This results in a time-to-empty of about 9600 days for LHe and 200 days for LN$_2$. We have periodically repeated this procedure over more than a year of continuous operation and found the loss rate to be approximately consistent.

Pulse-tube cryocoolers are known to produce mechanical vibrations which can negatively impact the performance of sensitive experimental systems$^{77}$. In order to address characterize the impact of the DSR on magnet performance, the homogeneity of the magnetic field in the center of the bore, and its temporal stability with the reliquefier running were mapped using a commercial nuclear magnetic resonance (NMR) probe. Free induction decay (FID) measurements were performed on a sample consisting of an aqueous 0.15 mol/L copper sulphate solution. The sample was contained in a $\varnothing 7.0 \times 8.0 \text{mm}^3$ nylon capsule mounted inside the NMR probe. The NMR probe was mounted inside the bore in a translating and rotating structure, providing fine control of the sample position.

The NMR signal’s optimal full-width-half-maximum (FWHM), with the cryomechanical reliquefier off, and following standard shimming procedures, was $\Delta \nu_{\text{FWHM}}^{NMR} = 91 \text{ Hz}$ at a Larmor frequency of $\nu_{\text{Larmor}}^{NMR} = 85.064 094 \text{ MHz}$. This measurement is repeated with the reliquefier turned on and the resultant NMR lineshapes compared in Fig. 10. We observe minimal deviation between the two cases, thus indicating no significant increase in magnetic field inhomogeneity due to the operation of the reliquefier at this scale of inhomogeneity. The measured NMR linewidth indicates a fractional inhomogeneity of approximately 1 ppm over a volume approximately seven orders of magnitude larger than the typical volume occupied by an ion crystal in this trap. The measured NMR linewidth is broadened due to the concentration of the copper sulfate solution, and this figure represents a likely upper bound on field inhomogeneities.

The measured NMR center frequency implies a magnetic field of $B_0 \approx 1.997 \text{ T}$. Due to the gradual formation of magnetic domains in the stainless steel structure of the magnet, the field intensity in the bore slowly decreases over time. To quantify this the center frequency of the NMR signal was measured over a 24-hour period, resulting in a drift rate of $dB_0/dt = -3 \times 10^{-8} \text{ T h}^{-1}$. 

C. Inbore optomechanics and imaging system

In this section we describe the custom inbore optomechanics used to route laser light to and from the trapping
region, deliver millimeter waves to the ions, and capture the ionic fluorescence used for diagnostics and qubit-state readout. This subsystem joins (in a non-contact fashion) with the trap at the center of the magnet bore and also connects to external optical systems as shown in Fig. 2. Below we introduce key design elements of the optomechanical assembly, describe the alignment procedure employed, and provide detailed characteristics of the custom imaging system designed for site-resolved top-view imaging.

1. Optomechanical system design

The design of this subsystem is heavily constrained by the geometry of the trap and the limited magnet-bore diameter. All components must fit within the 150 mm horizontal bore, and components which are radially aligned to the trap itself must fit within a radial shell constrained centrally by the 68 mm outer diameter of the trap cuvette. The construction must permit independent adjustment of all pertinent degrees of freedom in order to ensure good optical alignment with trap apertures, as well as positional repeatability. The optomechanics also face the stringent requirement of high mechanical stability to ensure lasers remain aligned to the ion cloud to within tens of microns over long experimental runs, and must be sufficiently rigid to maintain good alignment while the assembly is inserted into the magnet bore. These requirements are further complicated by the limited mounting options arising from the system geometry. The assembly may only be mechanically anchored outside of the magnet bore, meaning it must either be cantilevered inside the bore or stabilized against the ID of the bore itself. Unfortunately the bore is neither perfectly round nor uniform, complicating self-centering techniques.

The inbore optomechanics section that was designed and constructed to fulfill all requirements outlined above is shown in Fig. 11. Construction materials are required to be non-magnetic in order to prevent distortions to the magnetic field homogeneity or pose a mechanical risk to the glass vacuum cuvette. In practice we have found that even austenitic steel variants are not acceptable for inbore construction as they alter the optimal shim configuration after the assembly is inserted into the magnet bore. Our system features a central, eight-fold symmetric frame design that matches the symmetry of the underlying trap electrodes. The core mechanical components are a central frame tube and two inbore discs affixed using radially oriented grub screws. This tube also attaches to an external plate that fixes the frame to the extrabore optomechanics (Fig. 12), and possesses an inner diameter machined to allow insertion of a standard 2" optics beam tube. The three discs feature eight radially arranged cutouts that allow insertion of seven standard 1" beam tubes and one WR-19 waveguide. Two of these seven circular extrusions have slightly enlarged diameters to allow 1.2" beam tubes. This general geometry brings the additional benefit that it fully occludes the open end of the magnet bore, mitigating the risk of magnetic items being pulled into the bore by the fringing field.

The assembly is approximately self-centering in the magnet’s bore by means of captured, spring-loaded ball-bearing grub screws inserted radially into the two discs. These are adjusted in height prior to assembly of the full frame from the inside of the discs, and fixed in position by additional fastening grub screws as indicated. All grub screws used in the assembly are grade 2 titanium.

The seven tubes affixed to the inbore discs are used for beam delivery and are terminated at the trap with deflector prism mounts. The use of each tube is indicated in Fig. 12 and ranges from beam delivery to the ions to positioning of imaging elements. Deflectors employed for radial Doppler beams in either trap are Thorlabs CCM5 cubes with custom, high-reflectivity right angle prisms and Nylon screws. The two imaging tubes feature a custom prism mount that does not limit achievable numerical aperture and positions the prisms more accurately. Imaging tubes consist of an outer 1.2" Thorlabs SC1800RL dust cover onto which the prism holder is press-fitted and glued, and an inner 1" beam tube. The outer tube allows optimization of the deflector's axial alignment with the trap, while the inner tube permits independent adjustment of the image focus.

Tubes are arranged in pairs and fixed in orientation by means of tube-pair clamps. The clamps maintain alignment while pairs are adjusted with extrabore adjusters, i.e. translation stages. The tubes and clamps are fixed by Nylon-tipped grub screws made from grade 2 titanium opposite extrusions that guarantee good line contact between clamp and tube. The central 2" beam tube that houses the topview imaging system is joined with one of the seven 1" beam tubes by means of a clamp. An axial deflector prism is glued onto the first element of the imaging system to deflect axially propagating laser beams away from light-sensitive cameras and PMTs. The prism is located behind the retaining lip of the imaging system housing which prevents contact of the sharp edge of the prism with the cuvette window. The deflected light travels down the associated 1" tube and is used for alignment diagnostics of the axial beams outside of the magnet bore. All positioning features were machined to H7/h6 locating transition fits with medium interference that allow repeatable positioning without undue pressure on extrabore actuator stages.

The millimeter wave routing takes the remaining slot in the eight-fold-symmetric frame and features a loose transition fit cutout for WR-19 waveguides (see position 7 in Fig. 12). The waveguide and custom delivery system are restrained by another ball-bearing grub screw on the last tube clamp, joining it to the 2" tube perpendicular to the trap axis, but leaving axial translation unrestricted. The inbore assembly is connected to an Aluminium breadboard mounted to a custom goniometer as shown in Fig. 12. The goniometer allows global rotation of the optomechanical assembly coaxial with the magnet's bore in order to compensate for any rotational misalignment (roll). The goniometer is mounted on height-adjustable feet with fine-pitch threads to set the vertical position of the assembly. This also allows adjustment of the optomechanical system's pitch relative to the trap axis. Non-
FIG. 11. Section view of inbore optomechanics. Assembly of eight-fold tube frame with captured ball bearing screws and fastening grub screws indicated. Note that three of the seven tubes are not shown and the millimeter wave parts are omitted. Inset: Photograph of trapping and optomechanics sections joined extrabore during alignment.

magnetic linear translation stages are also mounted on the breadboard and connected to the tube-pair clamps allowing individual axial translation of these tubes. The tubes employed for sideview imaging in the science trap have two translation stages to allow individual fine positioning and focusing. A second horizontal platform on top of the goniometer (mounting posts not shown) sits above the bore which hosts fiber collimation and beam steering optics.

All laser light is delivered to the trap via solarization-resistant, UV-cured, polarization maintaining fiber patch cords followed by beam-shaping optics, all mounted external to the magnet bore (Fig. 12). The use of fibers for this purpose provides robust beam pointing stability as well as spatial and polarization filtering, while also decoupling the alignment of the optomechanical system from external laser systems. The fibers are connected to collimators which are purged with dry N$_2$ gas to prevent UV-induced accretion of particles onto the fiber facet.

The primary laser beam delivered by the inbore optomechanical system is the radial Doppler cooling beam. Light from the collimator passes beam shaping optics whose final element is a long-focal-length lens in a x-y-translation mount. The lens both focuses the radial beam to a waist of $w_0 \approx 45 \mu$m, and allows pure translation of the waist in the direction parallel and perpendicular to the trap axis, which is crucial for Doppler cooling. As a consequence of the arrangement of deflectors the beam translation axes are rotated by 45° with respect to the translation mount. An adapter plate (not shown) can be used to rotate the translation mount to account for this. After the translation mount the beam passes a half-wave plate and is then deflected down the Doppler beam tubes using the same CCM5 deflector cubes as mentioned above.

2. Optical alignment

The optical alignment procedure for the trap system is complicated by both tight tolerances and the fact that the interaction region between the trap subsystem and the optomechanical assembly resides inside the magnet bore, hidden from view. We therefore align the optomechanical assembly before inserting into the bore, perform test alignment of the optomechanics to the trap outside the bore, independently align the trap relative to the magnet, and finally simultaneously align the optomechanical
FIG. 12. Side and front projection view of extrabore optomechanics. Purple indicates propagation of Doppler cooling beams. Light leaving the optomechanics, supporting posts for top platform, and magnet in front projection omitted for clarity. Eight-fold positions are: (1) Loading trap radial Doppler beam entry, (2) Science trap radial Doppler beam entry, (3) Axial beam exit, (4) Science trap sideview imaging, (5) Loading trap sideview imaging or radial Doppler beam exit, (6) Science trap radial Doppler beam exit, (7) millimeter waveguide port, and (8) Science trap sideview alignment port or additional sideview port.

Beam delivery and imaging tubes are paired extrabore using tube clamps to form groups \{1, 5\}, \{2, 6\}, \{4, 8\} and 3 together with the center tube. To set the rotational and translational orientation of the tubes pinholes are placed on the exit apertures of the beam deflector cubes and a pilot laser beam is aligned through both apertures, i.e. on all prism mounts as shown in the inset of Fig. 11. We avoid centering pilot beams through the beam tubes as machining and other tolerances can make this a misleading procedure. The absolute axial position of beam tubes cannot be prealigned extrabore since there is no physical stop or other reference point known to sufficient precision. Therefore these positions are measured from the system models and later aligned in-situ using the trap apertures.

Alignment of the deflector prism pair that guides the axial laser beams out of the bore requires special attention. The position of axial beams on either screens or electronic position detectors outside is important for a number of diagnostics, including coarse alignment to ensure the laser does not impinge on sensitive detectors. A pilot beam that passes a central aperture on the exit of the deflector tube (counterpropagating to the typical orientation of the axial Doppler laser beam, entering at position 3 in Fig. 12) will hit the axial deflector prism in the center of the imaging system and be deflected away from it. Accordingly the prism is glued in-situ which allows precise control over the deflection angle.

The extrabore optomechanics are similarly aligned with the inbore optomechanics before insertion into the magnet bore. A pilot beam is used to align all optical elements with the mechanical cage system. Apertures are placed on the entry of radial Doppler beam tubes for both traps at positions 1 and 2 in Fig. 12, and on the exit apertures of the inbore deflector cubes. To retain positional information relative to trap-electrode apertures, the radial beam alignment lens and subsequent deflecting mirrors are aligned such that the center of the lens translation mount’s dynamic range is close enough to one edge of the trap aperture to ensure clipping, accounting for limited dynamic range of lens translation. The absolute position of the beam as well as the relationship between external translation to motion in the target region can be obtained by using an alignment target positioned at the nominal trap center. On the Doppler beam exit tubes, positions 5 and 6 in Fig. 12, similar targets can be placed to mark the beam position during proper alignment.

Final alignment of the assembled optomechanical sub-system is undertaken with the trap in place. The cuvette is centered in the bore by placing optical apertures on the axial view port and the exit of the magnet’s bore, and aligning a visible pilot beam through both. The optomechanical assembly frame is self-centering in the magnet’s bore due to the action of the ball-bearing grub screw. We use fiber-delivered UV light passing through the optomechanics while the assembly is inserted in the bore to compensate pitch and yaw errors between the optomechanics and the bore. The appropriate axial locations of the tubes can then be found by centering the
Finally, as shown in Fig. 2, the aligned trap and optomechanical subsystems are mounted on a pivotable table with center of rotation under the trapping region. Through this table, the base plates on which these two subsystems are mounted are joined permitting angular deflection of the trap relative the magnet bore without disturbing the optical alignment secured above. This flexibility is useful in ensuring any misalignment of the magnetic field (which may result in trapping instability) is easily compensated.

3. Diffraction-limited imaging system

In this subsection we describe the optical imaging system designed and constructed to provide flexible and complete characterization of ions in the Penning trap. The system was constructed in two parts: topview imaging along the trap axis allows site-resolved ion imaging, and sideview imaging along a radial direction permits simplified diagnostics, determination of ion-crystal dimensionality as well as global fluorescence measurements. Overall we target high numerical aperture (NA) systems in order to allow spatial resolution with ion spacing approximately 15 µm and state discrimination on microsecond timescales (limited by off-resonant decay processes).

Our approach to the design of this system incorporates generic considerations such as tolerance to misalignment of optical elements, and preference for stock optical items to reduce cost. However, we also encounter a number of unique challenges posed by the structure and geometric constraints of our system:

- The vacuum cuvette windows form the first optical element in either path where they set a minimum distance and add aberration.
- The topview path must incorporate an optical flat and UV-opaque deflector prism to prevent axial laser beams from passing to the detectors. This produces a rectangular obstruction in the center of the image and sets a minimum distance to the cuvette.
- Co-location of the top- and sideview imaging systems in the magnet bore significantly constrains the size of available lenses.
- For simplicity the sideview imaging systems in science and loading trap are to be identical as their NA is limited by the cuvette windows.
- Active imaging elements must be positioned far from the fringing field of the magnet requiring an at least one-meter imaging path.
- Imaging magnification is constrained by the low fill factor of high-speed detectors (our design is based on a Micro Photon Device’s SPC3 - a 96 kHz frame rate camera with single photon counting ability on a 64 x 32 pixel array, but low fill factor of 4%).

The imaging system we designed to simultaneously fulfill these constraints is shown in Fig. 13(a) with respective orientations and distances to scale. For our design magnifications of ×30 and ×13 (topview and sideview), ion crystals of hundreds to thousands of ions (depending on crystal conformation) can be imaged onto detector cameras within respective fields of view of 275 µm and 550 µm, within which both are above the diffraction limit. In the final design we achieved numerical apertures of 0.32, and 0.12 (f/# 1.56, and 4.17) at working distances of 50.8 mm and 73.9 mm, for top- and sideview systems respectively. These compare favorably with the geometric limitations on the achievable NAs of 0.34 and 0.13. Characteristics of the lens positions constituting the imaging objectives, and defined by fixed machined spacers, are summarized in Table II. Production of the spacers and housing, as well as assembly and interferometric testing were performed by Sill Optics GmbH & Co KG. In addition a simplified imaging system was installed in the sideview port of the loading trap which allows for higher transmission of 235 nm light to monitor atomic along with ionic fluorescence on a PMT, but does not provide diffraction-limited imaging.

Our designs were realized using numeric optimization with the initial aim of maximizing the Strehl ratio of the collimating section of the imaging objectives (up until and including SPC025AR.10 and SPC019AR.10, respectively, see Fig. 13(a)). This is a convenient measure of the quality of the optical system which compares the peak intensity of the imperfect, i.e. aberrated, optical system to that of a perfect system limited only by diffraction. The starting point for our optimization was derived from published approaches to designing imaging systems for vacuum chambers, and lens separations and focal lengths were iteratively adjusted, constrained by available stock selections. Next, we proceeded to optimize the image forming elements, again with the aim of maximizing Strehl ratio for a fixed distance to the magnet and fixed magnification.

The collimated output of the topview imaging is incident onto a beam-shrinking telescope consisting a long focal length plano-convex singlet (Thorlabs LA4337-UV) and a plano-concave singlet (Newport SPC019AR.10, not shown) with lens spacing of 1197 mm. This enables a target image magnification of ×30 when used in conjunction with a plano-convex singlet (Thorlabs LA4579-UV, not shown). Inserting additional flat, normal-incidence optics in the beam-shrinking telescope does not alter the performance characteristics of the imaging system due to the very low convergence angles in that section of the beam. This is a feature of great practical utility since it offers flexibility with respect to, for example, the number and thickness of optical filters or polarizers installed to reduce unwanted background light scatter.

We find that for the sideview system any single plano-convex spherical singlet with sufficiently long focal length can be used for diffraction-limited imaging at any point in the outgoing beam. The finite remaining divergence from imaging an extended source means, however, that the beam will start to clip progressively on the light-tight enclosures the farther out the imaging lens is placed. The final imaging element for the sideview system was a Thor-
FIG. 13. (a) Section through top- and sideview imaging systems around the ion trap. The relative orientation of the section planes in both views has been altered for clarity. Topview lens spacers are labeled T1 - T5, the extrabore imaging section with spacer T6 is not shown (see text). Sideview lens spacers are labeled S1 - S3, the extrabore imaging plano-convex lens is not shown. Lenses starting with L are Thorlabs stock items, lenses starting with SPC are Newport stock items. Spacer parameters are ring thickness $d$, distance $x$ between lens contact points, and contact angles $\theta$ and $\phi$. Both imaging systems are secured within lens tubes by a retaining ring pushing onto an O-ring to avoid scoring, or breaking the lenses upon fastening. The deflector prism minimizes light leakage by including an optically flat Si wafer on the front side which has high reflectivity in the UV and is sufficiently thick to mitigate transmission. (b,c) Modulation transfer function of topview and sideview imaging as a function of object side spatial frequency. Solid lines are in the tangential plane, dashed lines in the sagittal plane. The black dashed line is the diffraction limited performance in both planes. Note that the topview frequency axis covers twice the range of the sideview. (d) Strehl ratio for topview and sideview imaging systems as a function of field coordinate. Dashed black line corresponds to a ratio of 0.8 which is often used to define diffraction-limited performance. Inset: On-axis point spread function for topview and sideview as a function of detector coordinate. The peak value gives the Strehl ratio where diffraction limitation is indicated by the black dashed line. Note that the object side point spread function will be narrower by the magnification of the imaging systems.
lands LA4663-UV, which sets the magnification to about \( \times 13 \). The sideview lenses are housed in a positioning tube that translates axially independent of the prism used to deflect ionic fluorescence, permitting independent alignment and focusing, see Fig. 11.

| \( x \) (mm) | \( \theta \) (°) | \( \phi \) (°) | \( x \) (mm) | \( \theta \) (°) | \( \phi \) (°) |
|--------------|---------------|---------------|--------------|---------------|---------------|
| T1           | 2.22          | 90.0          | 90.0         | S1            | 3.85          | 104.3         |
| T2           | 7.30          | 121.5         | 90.0         | S2            | 4.25          | 100.3         |
| T3           | 28.10         | 90.0          | 105.4        | S3            | 14.08         | 94.0          |
| T4           | 27.56         | 90.0          | 105.4        |               |               |               |
| T5           | 10.73         | 90.0          | 90.0         |               |               |               |
| T6           | 44.13         | 80.0          | 80.0         |               |               |               |

TABLE II. Lens spacer parameters for topview and sideview imaging system. Distance between lens contact points \( x \) and lens contact angles \( \phi \) and \( \theta \) (refer to Figure 13). Spacer thickness \( d \) for topview spacers is \( d = 1.5 \) mm and for sideview spacers \( d = 1.0 \) mm. Spacer outer diameter is \( 2'' \) for topview spacers and \( 1'' \) for sideview spacers, except for T6 which is \( 1'' \) and has \( d = 2.5 \) mm. Note that spacer T1 has an additional chamfer to avoid collision with the meniscus lens.

The imaging performance of both systems can be characterized by the modulation transfer function (MTF), the Strehl ratio, and the on-axis point spread function (PSF). For well-corrected optical systems all three quantities scale with the wavefront error, but can be used to highlight different aspects of imaging performance.

The modulation transfer function is a measure of image contrast. The image of a unit step for a MTF of unity will be perfectly resolved with no smearing, whereas a vanishing MTF means aberration smears the image to be uniformly grey. A MTF of 0.5 or above is commonly considered sharp, while the lower end is highly subjective, but \( \approx 2-6\% \) is often still considered resolvable by eye. The modulation transfer function is commonly plotted as a function of spatial frequency as this allows to gauge the loss in contrast for finer features or sharper edges. The highest attainable spatial frequency is a direct measure of smallest spatial resolution. The overall shape of the ideal, non-obstructed MTF is governed by the field stop (aperture) shape only. For real imaging systems the MTF becomes a function of field position and plane of incidence, i.e. sagittal or tangential, as well. The design modulation transfer functions for both topview and sideview imaging systems are presented in Fig. 13(b)-(c). Both follow very closely the ideal shape for a circular field stop, where the topview imaging has additional structure for mid-range spatial frequencies from the presence of the deflection prism. The stronger dependence on field position and incidence plane in the sideview stems mainly from clipping on the center ring electrode before the imaging system. Note that the MTF is given in object space, i.e. demagnified, to give a direct indication of resolving power.

The Strehl ratio is a convenient measure for well-corrected objectives to quantify closeness to a system limited only by diffraction since it combines all effects into a single number. Conventionally a value of 0.8 is considered diffraction-limited as most observers will have difficulty distinguishing improved image quality beyond that point. The Strehl ratio is often given as a function of field coordinate to extract the field of view within which it remains above a threshold. Such a plot is presented in Fig. 13(d) for both the topview and sideview systems with an inset that shows the on-axis point spread function for both systems in detector coordinates, i.e. scaled by system magnification. The Strehl ratio gives information only about the relative performance to an aberration-free system of otherwise identical construction. The consistently high Strehl ratio for large field values in the sideview imaging indicates that performance can not be much improved. However, the observed decrease in spatial cut-off frequency for large field points in the MTF plot shows that the expected image quality will fall towards the outer edges of the field of view.

Inspection of Fig. 13(b)-(d) clearly demonstrates that the design target for resolution with fixed magnification and geometrical constraints have been met as the contrast at the nominal ion-ion distance of \( \approx 15 \) µm or 70 cycles/mm is close to the unaberrated case for all field points and remains high for magnified crystal sizes surpassing the available detector areas.

IV. TRAP OPERATION

In this section we describe the operating conditions employed in our efforts to observe first light in the trap as well as site-resolved ion crystals. We begin with a discussion of the trapping potential employed in our experiments, describe ion loading procedures, report the measured ion and atomic transition frequencies, and present site-resolved images of ion crystals.

A. Trap potential tuning and configuration

The electrostatic potential created by the Penning-trap electrode structure deviates from the ideal quadrupolar potential given by Eq. 1 due to anharmonicities originating from the finite size of the trap, application specific modifications as well as mechanical tolerances. For instance, in the LT the potential in the trapping region is affected by the finite size of the hyperbolic electrodes as well as the apertures present for laser beam access and shuttling. Deviations from the ideal Penning trap are more significant in the science trap, due to the high optical access and cylindrical electrode geometry. We address anharmonicities in this trapping region by applying a constant electric potential \( V_{STRW,DC} \) to the rotating wall electrodes, in addition to the rotating wall radio-frequency drive \( V_{W} \).

To find the optimum tuning ratio \( T = \frac{V_{STRW,DC}}{V_{STCR}} \), the ratio between the science trap rotating wall DC and center ring electrode voltage, the simulation package SIMION\textsuperscript{81} has been used. First, the Laplace equation of the complete electrode structure is solved on a 3D anisotropic grid with 100 µm spacing in both radial directions, and 5 µm spacing in the axial
direction. Second, the equation of motion is solved for ions starting with different axial and zero radial kinetic energy in the electrostatic center of the trap. In an ideal situation, Eq. 2, is independent of the ion’s kinetic energy and therefore its motional amplitude. To obtain the axial frequency, the necessary time of flight $t_n$ of an ion to perform $n$ oscillations is computed, which results in $\nu_z = n/t_n$. This is performed for different axial kinetic energies, and for a variety of tuning ratios $T$, resulting in an axial frequency $\nu_z(T,E_{\text{kin}})$. The relative axial frequency deviation has been calculated as the standard deviation of the axial frequencies of an ion ensemble with kinetic energies between $E_{\text{kin,min}} = 0.03 \text{eV}$ and $E_{\text{kin,max}} = 0.05$ to $1 \text{eV}$, normalized by the axial frequency at minimal energy, $\nu_z(T,E_{\text{kin,min}})$, shown in Fig. 14. For our trap geometry, a tuning ratio of $T_{\text{opt}} = 0.09$ minimizes the axial frequency dependence with respect to kinetic energy and therefore motional amplitudes around the center of the trap. The analysis employs the sum effect of all orders of anharmonicities and is not limited to the evaluation of the lowest orders as typically done. However, a separate analysis shows that the first even order coefficient $C_4$ (Ref. 82) becomes zero at around $T_{\text{opt}}$.

Ultimately, we elect to operate the science trap at a trap voltage of $V_{\text{STCR}} = V_T = -65 \text{V}$ applied to the ring electrode and $V_{\text{STRW,DC}} = V_{\text{STCR}}T_{\text{opt}} = -5.85 \text{V}$ while all other electrodes are held at ground. This voltage choice is somewhat arbitrary but corresponds to a compromise between trap depth and the desire to limit voltage swings during the shuttling procedure transporting ions from the LT to the ST while reducing fluctuating patch potentials. In this configuration, and with the calculated geometric quadratic coefficient $C_2 = -4.68 \times 10^{-3} \text{mm}^{-2}$, we find single-ion motional frequencies as shown in Tab. III.

### B. Ion loading

Ion loading commences with energization of the electrodes for the LT via low-noise computer-controlled high-voltage power supplies. The loading trap center ring voltage is held at only a few volts (typically $\geq -10 \text{V}$) while other LT electrodes are held at ground. This results in a shallow potential which restricts the kinetic energy distribution of ionized beryllium captured during the loading process. The final science trap endcap is negatively biased (typically $-100 \text{V}$) to repel any electrons produced during the loading procedure either from the ionization process or photoemission arising due to stray light impinging on trap electrodes.

The beryllium oven described in section III A 1 is driven by application of a heating current of $\approx 1 \text{A}$ to the tungsten filament, indirectly heating the beryllium wire to $\approx 920 \degree \text{C}$. This produces a flux of neutral $^9\text{Be}$ estimated to be of order $1 \times 10^{14} \text{s}^{-1}\text{m}^{-2}$ near the trap center, taking into account the geometry of the LT. In test setups we have operated the oven with currents up to $\approx 1.5 \text{A}$ before significant beryllium plating was observed on a proximal window.

Atomic beryllium is ionized upon irradiation with $1 \text{mW}$ to $4 \text{mW}$ of $235 \text{nm}$ light and its fluorescence is monitored via a PMT aligned to the sideview imaging port of the loading trap. The axial Doppler cooling laser is turned off during the loading cycle to prevent heating of radial motional modes when ions are created. The integrated atomic fluorescence observed on the PMT provides a proxy measure for the number of ions created in the trap. At PI laser powers around $4 \text{mW}$ we are able to obtain tens to about one hundred ions within ten minutes of ionization time in the science trap (accounting for ion losses induced in the shuttling procedure described below). We have observed that higher atomic fluorescence can be achieved with small increases to the oven current but focus on conservative operating conditions. After reaching an approximate target ion number the oven current and PI laser are turned off.

Ion shuttling to the science trap proceeds as a sequential change in the voltages on all intermediate electrodes to create a moving potential well. The shape and temporal distribution of these potentials is simulated in SIMION such that the well moves at a constant velocity and depth along the trap axis, in order to minimize

| Eigenmotion Frequency (kHz) |
|-----------------------------|
| axial $\nu_z$               | 406.4 |
| magnetron $\nu_-$           | 24.4  |
| cyclotron $\nu_+$           | 3381.5|

TABLE III. Motional frequencies of a $^9\text{Be}^+$ ion in a magnetic field of $B_0 = 1.998 \text{T}$ and at a science trap potential of $V_{\text{STCR}} = -65 \text{V}$ and a tuning ratio of $T_{\text{opt}}$. The free cyclotron frequency is $\nu_c \approx 3406 \text{kHz}$. 

FIG. 14. Simulated relative axial frequency deviation as a function of the maximum kinetic energy of an ion ensemble, calculated for different tuning ratios. At a tuning ratio of about $T_{\text{opt}} = 0.09$, the deviation is smallest over a wide energy range. The uneven structure at small energies is due to numerical inaccuracies in the simulation. For further details see text.
heating-induced ion losses. The shuttling potential sequence only determines the relative values for the potentials, which can be scaled to accommodate different ramping speeds in power supplies or desired final voltages. The slew rate with which the electrode potentials are changed should stay well below the motional periods of the ions to keep the process adiabatic. However, regions with comparatively small potential gradients, i.e., between the endcaps, should be passed rapidly due to possible patch potentials on the electrodes. A schematic illustration of the sequence of shuttling voltages employed is shown in Fig. 15. In this work shuttling typically finishes after one minute with a moving potential depth throughout the procedure of \(-50\) V. We start with a loading trap center ring voltage \(V_{LT\text{CR}} = -67.55\) V to produce this and finish with the science trap voltages of \(V_{ST\text{CR}} = -65\) V and \(V_{ST\text{RW,DC}} = -5.85\) V as described above. Table IV lists all voltages applied during ionization in the loading trap, shuttling from loading to science trap and trapping in the science trap.

Upon completion of the automated shuttling sequence the ions have moved into the radial Doppler cooling beam present in the Science Trap, at which time the axial cooling beam is turned on. Initial cooling proceeds by repeatedly sweeping the cooling-laser frequency from several GHz red-detuned towards the transition frequency. Ionic fluorescence from resonant excitation can be monitored on a PMT or camera on either side- or topview imaging ports. After a few scanning cycles ions occupying large magnetron radii have converged on the trap center, and the cooling lasers are moved to the optimum Doppler cooling frequency; \(\gamma/2 \approx 10\) MHz below resonance.

C. Measured optical transition frequencies

The center of the atomic transition is experimentally determined by monitoring the maximum of the atomic fluorescence for a given flux and laser power during the loading process. Likewise, the center of the cooling transition is determined by monitoring the maximum of fluorescence peaks during the cooling procedure either in the LT or ST. The center frequencies for the photoionization and Doppler cooling transitions are given in Tab. V.

| Electrode  | Voltage (V) during: | Loading shuttling trapping |
|------------|---------------------|----------------------------|
| LT EC1     | 0                   | 0                          |
| LT CR      | -10                 | -67.55                     |
| LT EC2     | 0                   | -50                        |
| ST EC1     | 0                   | -50                        |
| ST RW,DC   | 0                   | -57.86                     |
| ST CR      | 0                   | -57.86                     |
| ST EC2     | 0                   | 0                          |

TABLE IV. Voltages applied on electrodes during ion loading, shuttling (maximum values given, for time dependence see Fig. 15) and trapping. For electrode abbreviations see Sec. III A.

Laser frequency measurements are taken with a HighFinesse WSU-10 wavemeter measuring at the respective fundamental wavelengths around 626 nm and 470 nm. The wavemeter is periodically calibrated using a frequency stabilized Helium-Neon laser from SIOS Messtechnik GmbH with standard deviation \(\leq 500\) kHz. The experimental uncertainty is dominated by the wavemeter measurement uncertainty at the fundamental frequency. Owing to the thermal creation process of the atomic flux, Doppler shifts will have a strong influence on the center of the photoionization line. The PI laser nominally strikes the flux at right angle, but for atoms of \(\approx 1000\) K even sub-degree deviations from normal incidence will provide Doppler shifts of order of the linewidth. Our measured value for the PI transition deviates from the calculated normal incidence (or rest) transition frequency in neutral \(^9\)Be by \(\approx 61\) MHz, i.e., less than one linewidth, which is consistent with Doppler shifts caused by angular misalignment of the center of the atomic emission cone by less than 1°. In the Doppler transition the deviation between theory and experiment is 226 MHz outside the first confidence interval of 121 MHz. This deviation may be explained by the change in magnetic environment through insertion of the trapping and optomechanics sections as magnetic field determination and shimming were done prior. Shimming using the qubit transition will allow for a more accurate determination of the magnetic field and thus a correction of the theoretical value.

![FIG. 15. Potential sequence for quasi-adiabatic shuttling procedure simulations in SIMION. The Science trap center ring and rotating wall electrodes are kept on the same potential throughout the sequence. Their final values, determined by the desired ion motional frequencies and the tuning ratio, are set at the end. \(V_{ST\text{CR}}\) is the final center ring voltage, while \(V_{LT\text{CR}}\) is the loading trap voltage at the start of the shuttling procedure and produces the same central potential in the LT as is required in the ST, numerical values are given in Tab. IV. The potential depth as well as the total shuttling time are scalable. Electrodes not shown remain on ground throughout the procedure.](image-url)
FIG. 16. Images of $^9\text{Be}^+$ crystals taken with topview (a) and sideview (b - d) imaging systems. (a) Site-resolved ion crystal showing triangular lattice structure when camera is gated at the crystal rotation frequency $\Omega$. The crystal rotation frequency is locked to the rotating wall at about 26 kHz with 100 ns exposures per trigger over 9 s. (b-d) Single-plane, double-plane and multi-plane ion crystal conformations as seen on the sideview for several seconds of continuous exposure. Images (a) and (b) show the same crystal. Axes indicate orientation in space, size bars are 20 $\mu$m long in all images.

D. Site-resolved imaging of ion crystals

Ions crystallize within a few seconds of the completion of ion shuttling and application of the correctly aligned Doppler cooling beams. Time-averaged sideview imaging may be performed directly; the sharp focus of the sideview imaging system restricts light collection to a narrow volume in space. This results in a sectional view with clearly distinguished ion planes, and indicates that ion trajectories are stable over many seconds, as required for light collection in Fig. 16 via an Andor iXon Ultra 897 camera.

The crystal conformation is determined by the torque applied from cooling lasers, field imperfections, and the rotating wall potential, while the typical ion spacing is also a function of trap potential depth. Crystals rotating at frequencies $\Omega$ close to the high or low frequency deconfinement edges will have lenticular shapes, reducing to a single plane for sufficiently low rotation frequencies as in Fig. 16(b). By contrast crystals rotating at frequencies closer to the middle of the permissible range will have larger axial extent as in Fig. 16(d).

Continuous exposure to perform topview imaging result in concentric rings due to the temporal smearing of the ion locations from the ion rotation about the trap axis. To overcome this we apply the quadrupole rotating wall and synchronize a gateable camera to image stroboscopically; here an Andor iStar ICCD. This requires precise knowledge of the rate of rotation as set by the rotating wall drive. In addition, our application requires planar crystals such that the RF drive frequency must be on either end of the permissible range where we chose the lower to maximize light collection. The ion crystal is locked to the rotating wall by first positioning the cooling lasers appropriately such that its torque drives the crystal towards low rotation frequencies and lenticular shapes. Then the rotating wall torque is increased by either increasing the amplitude of the drive close to and above twice the magnetron frequency, or by decreasing the frequency of the rotating wall drive towards twice the magnetron frequency for a fixed amplitude. Increasing the torque from the RF drive gradually elongates the crystal from lenticular towards planar where the crystal rotation locks whenever stable configurations are achieved. An image of a locked, planar ion crystal is shown in Fig. 16(a) with about 70 ions in a triangular lattice. We observe locked, stable crystals over many seconds to tens of minutes. Radial cooling laser misalignment can be a major source of crystal destabilization as this results in competing torques applied to the crystal by the laser and rotating wall potential.

Once a crystal is locked at the rotating wall frequency, a gateable camera can be used to produce stroboscopic images. Due to the quadrupolar rotating wall geometry, the camera is triggered at half the rotating wall drive frequency to match the crystal rotation frequency. The gating period determines the arc subtended by individual ions during the imaging period and should be kept short to permit single-ion resolution at the crystal periphery where velocities are highest. These velocities in turn depend nonlinearly on the rotation frequency of the crystal (and hence the imaging trigger frequency) as the inter-ion distance also changes with rotation rate. A trade-off between improved angular resolution and reduced exposure time must be optimized for a particular crystal radius and applied trapping potential. For Fig. 16(a) we restricted the gate width to 100 ns at a rotation frequency of about 26.6 kHz, yielding an angular resolution of $\approx 1^\circ$.

| Transition      | Wavelength (nm) | Frequency (THz) |
|-----------------|-----------------|-----------------|
| Cooling         | 313.123695(7)   | 957.425014(20)  |
| Photoionization | 234.937 476(2)  | 1276.052 09(1)  |

TABLE V. Measured transition wavelength and frequency for neutral and ionized beryllium in a 1.998 T magnetic field.
Preliminary investigation showed that the ion lifetime, which is dominantly limited by charge-exchange reactions with $\text{H}_2$, during Doppler cooling to the $2p^2P_{3/2}$ excited state\(^\text{83}\), is consistent with our background gas pressure of $\sim 6 \times 10^{-11}$ mbar (this pressure reading differs somewhat from the one given in Fig. 7 due to the proximity of the superconducting magnet, altering the measurement of the pressure gauge and/or pumping efficiency). Under constant application of both Doppler cooling beams with total intensity of approximately $0.8 \times$ the saturation intensity, we observe the mean ion lifetime is about 1.1 hours, extracted via the observation of fluorescence with a photomultiplier connected to the science trap sideview imaging system. As centrifugally-separated contaminant ions are only sympathetically cooled, a buildup of contamination ultimately destabilizes the ion crystal over several hours of continuous cooling.

\section*{V. CONCLUSION}

In this manuscript we have reported on the design, construction, and characterization of an experimental system for quantum simulation based on trapped-ion crystals in a Penning trap. Our presentation focused on novel elements, such as the development of high-optical access trap and optomechanical subsystems designed specifically for the laser configurations needed in quantum simulation. In addition, we introduced a world-first dual-stage liquid cryogen reliquefier enabling uninterrupted operation over many months without measurable degradation in magnet performance. We successfully demonstrated the realization of ion crystals as well as site-resolved imaging using a custom objective and phase-locking of the crystal rotation to a rotating-wall potential.

The system we have presented represents a highly flexible and extensible platform for experiments in quantum simulation using ion crystals. The optomechanical system is an area of particular importance for targeted upgrades as we seek to improve stability and flexibility. In an effort to enhance our ability to align optical beams to the trap axis and simultaneously align the trap axis to the magnetic field, we have procured a non-magnetic, absolute-encoding hexaglide system allowing precise positioning of the trap in all spatial degrees of freedom with 5 $\mu$m resolution for translation and 0.01° angular resolution. Moreover our customized hexaglide is engineered such that when deactivated the final position is locked in order to prevent the cuvette from crashing into optical elements or the magnet bore.

To date we have focused on the implementation of laser-cooling and imaging using axial and radial Doppler cooling, and repump beams. Moving forward requires more detailed consideration of the delivery and control over Raman lasers which must be actively aligned to the ion crystal. For instance, we plan to upgrade the deflector mirrors to be mounted on piezo-actuated goniometers equipped with resistive encoders for computer-controlled precision beam alignment. This will permit automated beam-position searches when performing alignment, and will also provide an opportunity for Raman laser beam angles to be adjusted \textit{in situ}. Additionally, it will permit computer control over the orientation of the wavefronts of the Raman beam relative to the crystal, a key challenge in ensuring spatial homogeneity of the Raman-mediated interaction across the ion crystal\(^\text{53}\).

We are looking forward to future demonstrations of site-resolved imaging with single-photon sensitivity as we integrate our APD-array into the main topview imaging system. Integration of a microlens array can boost collection efficiency considerably in order to partially compensate for the relatively low fill-factor of the detector’s active area. This will allow us to move towards studies of the dynamic evolution of quantum correlations in real space, leveraging the unique capabilities of the platform we have developed.

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A. APPENDIX: BERYLLIUM LEVEL STRUCTURE CALCULATION

The energetic structure of ion crystals in a Penning trap is intimately tied to the trap geometry and present potentials, which mandates simulations to make quantitative predictions of mode frequencies. However, the field-free transition frequencies in neutral and singly charged $^9\text{Be}$ are well known and magnetic-field-induced corrections to the level structure can be readily calculated due to the comparatively simple Hamiltonian for low mass number alkali-earth atoms and ions. Only $S$ and $P$ orbitals need to be considered in these calculations since all relevant transitions take place in the ground- and first excited state manifolds. In order to find the required frequencies for the resonant light-ion interactions, we need to find the eigenenergies of the ionic Hamiltonian for the $2s^2S_{1/2}$ and $2p^2P_{3/2}$ states. This Hamiltonian is given by:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}$$

$$\mathcal{H}_0 = \mathcal{H}_{SO} + \mathcal{H}_{Ze} + \mathcal{H}_{Zn} + \mathcal{H}_{HF},$$

where $\mathcal{H}_0$ is the field-free Hamiltonian whose eigenenergies are known, and $\mathcal{H}$ is the Hamiltonian that describes the perturbation by the magnetic field. It is has four contributions: $\mathcal{H}_{SO} \propto \mathbf{L} \cdot \mathbf{S}$ is the electronic spin-orbit coupling term, $\mathcal{H}_{Ze} = \mu_B (g_L \mathbf{L} + g_S \mathbf{S}) \cdot \mathbf{B}$ is the Zeeman interaction of the electron’s spin and orbital magnetic moments with the external magnetic field, $\mathcal{H}_{Zn} = \mu_B g_I \mathbf{I} \cdot \mathbf{B}$ is the Zeeman interaction of the nuclear magnetic moment with an external magnetic field, and $\mathcal{H}_{HF} \propto \mathbf{I} \cdot \mathbf{J}$ is the hyperfine interaction. $\mathbf{hL}$, $\mathbf{hS}$, and $\mathbf{hI}$ are the orbital, spin, and nuclear angular momentum operator, respectively, $\hbar$ is Planck’s constant, $\mu_B$ is the Bohr magneton, and the $g$s denote associated $g$-factors of angular momenta. In the following we will briefly outline the derivation of transition frequencies.

In our intermediate field strengths, where neither $\mathcal{H}_{SO} \gg \mathcal{H}_{Ze}$ nor $\mathcal{H}_{SO} \ll \mathcal{H}_{Ze}$, we find the excited $(2p^2P_{3/2})$ state energies by exact diagonalization of the electronic part of $\mathcal{H}$ in the $[L, S, m_L, m_S] \equiv [m_L, m_S]$ basis, and treat the contributions arising due to nuclear magnetic moments as first order perturbations afterwards. This is a good approximation because the energy scales in these two Hamiltonians differ by several orders of magnitude for the $2p^2P_{3/2}$ state. The pertinent energies $E_{m_{J}}$ (as $m_I$ from this are those whose $m_J$ are $3/2$ for Doppler cooling and readout, and $1/2$ for the repump transition. They are given by

$$E_{3/2} = \frac{1}{3} \Delta E + \mu_B (1 + \frac{1}{2} g_S)B,$$

$$E_{1/2} = \frac{1}{6} \left( -\Delta E + 3 \mu_B B + \left[ 9 \Delta E^2 + 6 \mu_B \Delta E (g_S - 1)B + 9 \mu_B^2 (g_S - 1)^2 B^2 \right]^{1/2} \right),$$

where $\frac{1}{2} \Delta E$ is the constant of proportionality in $\mathcal{H}_{SO}$. The nuclear magnetic moment perturbation introduces additional additive terms

$$E_{m_I} = h A m_I + \mu_B g_I m_I B,$$

where $A$ is the hyperfine constant of proportionality in $\mathcal{H}_{HF}$.

We cannot follow the same treatment for the ground state $(2s^2S_{1/2})$ however, because the zero orbital angular momentum means the spin-orbit term $\mathcal{H}_{SO}$ vanishes, therefore no longer dominating the energy scale. To find the ground state energies we consequently perform exact diagonalization arriving at a Breit-Rabi equation. The full Hamiltonian for the ground state is

$$\mathcal{H} = \hbar A \mathbf{I} \cdot \mathbf{J} + \mu_B (g_J \mathbf{J} + g_I \mathbf{I}) \cdot \mathbf{B}$$

$$= \frac{1}{2} \left[ (I_- J_+ + I_+ J_-) + I_z J_z \right] + \mu_B (g_J J_z + g_I I_z)B,$$

where in the last step we have rewritten it in terms of ladder operators. From this representation it is clear that the stretched states with $m_F = \pm F$ are eigenstates in the $[F, m_F]$ basis for all magnetic field strengths. To find the other energies we chose the $|\pm\rangle \equiv |m_J = \pm \frac{1}{2}, m_I = m_F = \pm \frac{1}{2}\rangle$ basis to conserve $m_F$ (as $\mathbf{F}$ commutes with $\mathcal{H}$ for all magnetic field strengths) and diagonalize the matrix representation. The resulting energies are

$$E_{F, m_F} = -\frac{\hbar A}{4} + g_I m_F \mu_B B - \frac{1}{2} \left[ h^2 A^2 F^2 + 2 \hbar A m_F \mu_B (g_J - g_I)B + \mu_B^2 (g_I - g_J)^2 B^2 \right]^{1/2}.$$

By using the same approach we can also find the resonant step transition energies required for photoionization. The Hamiltonian is significantly simpler because neutral $^9\text{Be}$ has electrons with anti-parallel spins in both ground $^1S_0$ and excited $^1P_1$ state such that the total spin $S = 0$ and therefore $\mathcal{H}_{SO} = 0$. Likewise $J = 0$ in the ground state, such that the hyperfine interaction $A \mathbf{I} \cdot \mathbf{J}$ vanishes. The $^1P_1$ hyperfine interaction additionally can be neglected since for a singlet state it can be shown quite generally that the hyperfine $A(1L_J) = 0^{84}$. This yields the simple Hamiltonian
\[ \mathcal{H} = \mu_B \mathbf{L} \cdot \mathbf{B} + \mu_B g_I \mathbf{I} \cdot \mathbf{B} \]
\[= \mu_B L_z B + \mu_B g_I I_z B \]
\[\text{(19)}\]
which has eigenenergies of
\[E = \mu_B m_L B + \mu_B g_I m_I B. \]
\[\text{(20)}\]

B. APPENDIX: UHV PARTS LIST

Here we provide the detailed parts list associated with Fig. 7.

| No.  | Description                        | Supplier                        |
|------|------------------------------------|----------------------------------|
| 1    | hexagonal vacuum chamber           | Kimball Physics Inc. MCF800-SphHex-G2E6 |
| 2    | CF160/40 adaptor, 2xCF40 flanges   | Vacom GmbH SPE-10058267-10       |
| 3    | CF160/63 adaptor                   | Vacom GmbH ZL160063-316LNS       |
| 4    | all-metal valve                    | MDC 314004                       |
| 5    | feedthrough – 25-pin SUB-D         | Vacom GmbH SPE-CF63L-SUBD-25-DE-CE-CBG-316L |
| 6    | 5-way cross                        | Vacom GmbH FWX63R-316LNS         |
| 7    | ion getter pump                    | Varian/Agilent VacIon Plus 20 StarCell 9191145 |
| 8    | Bayard-Alpert ion gauge            | Granville Phillips 274042        |
| 9    | vacuum viewport                    | Torr Scientific Ltd. 16121-1     |
| 10   | trap tower assembly                | Fig. 6                           |
| 11   | CF63 through flange                | Vacom GmbH MCF450-PWF/GG         |
| 12   | non-evaporative getter (NEG)       | SAES Capacitorr D400-2           |
| 13,14,15| feedthrough – 7 pin/12 kV/13 A  | Vacom GmbH CF40-MPCHV12- 7-SE-CE-MO |
| 16,17,18| SHV/BNC breakout boxes         | custom                           |
| 19 & 20| CF63 flange & glass cuvette      | Precision Glassblowing Inc.     |

TABLE VI. Vacuum system part index for Fig. 7.

C. APPENDIX: TRAP ELECTRODE OPTIMIZATION

The trap-electrode design described above significantly departs from the ideal electrode geometries, inevitably distorting the ideal quadrupole potential. We characterize anharmonic contributions to the potential using an expansion in spherical harmonics about the trap center
\[\Phi = \sum_{n=0}^{\infty} \Phi_n = V_T \sum_{n=0}^{\infty} C_n \rho^n P_n \left( \frac{z}{\rho} \right), \]
\[\text{(22)}\]
where \(\rho = \sqrt{x^2 + y^2 + z^2}\), \(z/\rho = \cos \theta\) in spherical coordinates and \(P_n(\cos \theta)\) are the Legendre polynomials of order \(n\). Assuming rotational symmetry, odd-ordered coefficients \(C_n\) vanish, so that the first 4 non-zero terms take the form
\[\Phi_0 = V_T C_0 \]
\[\Phi_2 = V_T C_2 \left( \frac{z^2 - r^2}{2} \right) \]
\[\Phi_4 = V_T C_4 \left( z^4 - 3r^2z^2 + \frac{3r^4}{8} \right) \]
\[\Phi_6 = V_T C_6 \left( z^6 - 15r^2z^4 + \frac{45r^4z^2}{8} - \frac{5r^6}{16} \right). \]
\[\text{(23)}\]
\[\text{(24)}\]
\[\text{(25)}\]
\[\text{(26)}\]
Nonzero terms for \(n > 2\) capture higher order perturbations on the ideal quadrupole term \(\Phi_2\), while the zeroth order term \(\Phi_0\) captures a DC offset associated with the applied voltage.

The specific dimensions appearing in our design, as highlighted above, were selected by a process of optimization on the electrode geometry, minimizing anharmonicities \(C_4\) and \(C_6\) with terms beyond eighth order ignored. In practice (see Sec. III A 2) this involved performing a variational search over any free parameters, e.g. trap dimensions or electrode separation distances, while maintaining the design constraints on aperture sizes and additional electrode structures. For a given choice of design parameters, the trapping potential was simulated and the result fitted to Eq.
\begin{table}
\centering
\begin{tabular}{l c}
\hline
$C_0$ & 0.78133 \\
\hline
$C_2$ & $-4.68 \times 10^{-3}$ mm$^{-2}$ \\
\hline
$C_4$ & $-1.58 \times 10^{-7}$ mm$^{-4}$ \\
\hline
$C_6$ & $1.10 \times 10^{-7}$ mm$^{-6}$ \\
\hline
\end{tabular}
\caption{Multipole expansion coefficients for the potential in a $\Delta z = \pm 5$ mm region about the center of the ST.}
\end{table}

The values of the expansion coefficients $C_n$ for $n > 2$ extracted from this fit were then iteratively minimized and shown in table VII.