Hybrid setup for stable magnetic fields enabling robust quantum control

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Well controlled and highly stable magnetic fields are desired for a wide range of applications in physical research, including quantum metrology, sensing, information processing, and simulation. Here we introduce a low-cost hybrid assembly of rare-earth magnets and magnetic field coils to generate a field strength of $\approx 10.9 \text{ mT}$ with a calculated spatial variation of less than $10^{-6}$ within a diameter of spherical volume of 150 $\mu \text{m}$. We characterise its tuneability and stability performance using a single Mg$^+$ atom confined in a radio-frequency surface-electrode trap under ultra-high vacuum conditions. The strength of the field can be tuned with a relative precision of $\leq 2 \times 10^{-5}$ and we find a passive temporal stability of our setup of better than $1.0 \times 10^{-4}$ over the course of one hour. Slow drifts on time scales of a few minutes are actively stabilised by adjusting electric currents in the magnetic field coils. In this way, we observe coherence times of electronic superposition states of greater than six seconds using a first-order field insensitive (clock) transition. In a first application, we demonstrate sensing of magnetic fields with amplitudes of $\geq 0.2 \mu \text{T oscillating at } \approx 2\pi \times 60 \text{ MHz}$. Our approach can be implemented in compact and robust applications with strict power and load requirements.
create quantisation fields can be beneficial in contrast to field coils. In the last years, such permanent magnets became more popular for a variety of applications in atomic physics research\textsuperscript{29–33}, in particular, due to their high magnetisation and despite their limited tunability of field strengths.

In our manuscript, we introduce a hybrid approach, using an assembly of rare-earth magnets and pairs of field coils, to generate well-controlled quantisation fields with strengths of more than 10 mT. To benchmark the performance of our approach, we use a single trapped Mg\textsuperscript{+} atom as a quantum sensor. Further, we implement a protocol to probe stray magnetic fields with amplitudes of \( \geq 0.2 \, \text{mT} \) oscillating at radio-frequencies enabled by the high stability of our magnetic field setup.

**Experimental Setup**

We equip our experimental setup with a combination of two sets of rare-earth ring magnets and three pairs of field coils (electro magnets) to generate, tune, and stabilise a quantisation field at a strength \( |B_0| \approx 10.9 \, \text{mT} \). In Fig. 1a, we sketch the geometry of this hybrid setup. Each set of the solid-state magnets consists of three neodymium (an alloy made of neodymium, iron, and boron) ring magnets that are axially magnetised. Each ring has the following dimensions: 58 mm inner diameter, 102 mm outer diameter, and 4 mm thickness. The vendor specifies the grade of this neodymium in-stock item to be N35, which corresponds to a remanence of \( B_r \approx 0.22 \, \text{T} \) and a temperature coefficient of \( \approx -1.2 \times 10^{-3} \, \text{K}^{-1} \). We numerically calculate the spatial magnetic field distribution of both sets that are aligned collinear at a distance \( d \approx 223 \, \text{mm} \) (distance between facing planes) using the open-source software package RADIA\textsuperscript{35,36}. Along their symmetry axis \( \hat{z} \), we can also analytically estimate the field distribution. The magnetic-field strength of a single axially magnetised ring is given by\textsuperscript{37}:

\[
B_{\text{ring}}(\hat{z}) = \frac{R_1}{2} \left( \frac{\hat{z}}{\sqrt{R_o^2 + \hat{z}^2}} - \frac{\hat{z} - D}{\sqrt{R_o^2 + (\hat{z} - D)^2}} \right) - \left( \frac{\hat{z}}{\sqrt{R_i^2 + \hat{z}^2}} - \frac{\hat{z} - D}{\sqrt{R_i^2 + (\hat{z} - D)^2}} \right),
\]

with inner radius \( R_i \), outer radius \( R_o \), and thickness \( D \). We calculate the corresponding field for our magnet assembly by summation of Eq. 1, geometrically offset for each ring. Results of our calculations are shown in Fig. 1b and we, further, numerically estimate the field homogeneity of our magnet configuration in the central region between both sets. Following, we calculate a diameter of spherical volume \( d_{\text{sw}} \approx 150 \, \text{\upmu m} \), where the relative strength of the magnetic field varies less than \( 1 \times 10^{-6} \). Note, the specific choice of materials in close proximity to the geometric centre can increase the field inhomogeneity significantly and needs careful consideration in order to estimate the homogeneity within the entire setup. In our setup, we mount each set on a threaded cylinder (one turn equals one millimetre travel) to fine tune \( d \). In this way, we can coarsely tune \( |B_0| \) by \( \approx 0.11 \, \text{mT \ cm^{-1}} \). For fine tuning of the spatial alignment and the strength, as well as, temporal stabilisation of \( |B_0| \), we deploy the three pairs of field coils (shim coils). All coil pairs can be fed by current-stabilised low-power supplies with a vendor-specified stability of 0.2 \( \times 10^{-6} \) A and a maximum current of 0.1 A. Two pairs can be used for spatial fine tuning and are aligned transversally to \( \hat{z} \); the first pair creates a magnetic field of \( \approx 0.24 \, \text{mT} \) for a current of 1 A in the horizontal direction and the second pair tunes the vertical direction with 1.3 mT A\textsuperscript{-1}. The third pair of shim coils is aligned along \( \hat{z} \) and we can apply a field strength of 0.26 mT A\textsuperscript{-1}. In addition, we control the current running in the longitudinal shim coils with our data acquisition system and a resolution of \( 3 \times 10^{-6} \) A.

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**Figure 1.** Experimental setup and spatial properties of the solid-state magnet assembly. (a) Cross-sectional view of an ultra-high vacuum chamber housing a surface-electrode trap (indicated at the centre), used for spatial manipulation of single atoms. Two sets of rare-earth, ring magnets generate a magnetic (quantisation) field \( B_0 \) along their symmetry axis \( \hat{z} \) (indicated by \( \cdots \)). In addition, three individual pairs of magnetic field (shim) coils are mounted on corresponding mechanical support structure, marked with \( \cdots \). The shim coils enter the chamber along \( B_0 \). A home-built biquad antenna (sketched in the top left corner) is used to apply microwaves around \( 2\pi \times 1.600 \, \text{MHz} \) for internal state manipulation of the atom. (b) The magnetic-field variation of the solid-state magnets close to their geometrical centre (inset shows larger region) along \( \hat{z} \), calculated using Eq. 1. From numerical calculations, considering all directions, we infer a diameter of spherical volume \( d_{\text{sw}} \approx 150 \, \text{\upmu m} \), where \( \Delta B/B_0 \leq 1 \times 10^{-6} \).
MHz is first-order insensitive to magnetic field changes, MHz and transition frequency, mT, the |3,3⟩ state splitting and, secondly, optimal state preparation in our experiments. For Δω MW,2 of the |3,3⟩ transition frequency ω MW,2/(2π) ≈ 1762.974 MHz as a function of ΔB0 and residual (measured - calculated Δω MW,0) plot. Tuning of the magnetic field strength (on site of a single trapped atom) via variation of the distance between the solid-state magnets within a full span of Δd ≈ 16 mm. The local magnetic field strength is probed with a relative precision of better than ≈0.2 × 10⁻⁴ via the |3,3⟩ to |2,2⟩ transition frequency, ω MW,0.

Our experimental apparatus for trapping and controlling single atoms is located in a ≈100 m² laboratory space that is specified with a temperature stability of better than ±0.3 K. We trap individual ²⁵Mg⁺ atoms under ultra-high vacuum conditions with a background gas pressure of below 2 × 10⁻⁹ Pa in a surface-electrode ion trap. The trap is microfabricated by Sandia National Laboratories and copies of the trap have been previously described. A maximum zero-to-peak voltage U RF ≈ 80 V oscillating at Ω RF/(2π) ≈ 57.3 MHz is applied to two ≈2.5 mm long radio-frequency (RF) electrodes that are 60 μm wide and are separated by ≈210 μm. This provides confinement of ions in the x-y (radial) plane at a distance h ≈ 83 μm above the surface. Further, electric (control) potentials are applied to several additional electrodes, in order to confine ions along the z (axial) direction. Correspondingly, we find single-ion motional frequencies of ≈2π × 0.8 MHz (axially) and ≈2π × 2.1 MHz (radially).

The external quantisation field is aligned at an angle of approximately 30° with respect to the z axis and lies within the x-z plane (see Fig. 1a). In Fig. 2a, we illustrate the level scheme of the S_{1/2} ground state manifold of ²⁵Mg⁺ with a nuclear spin of 5/2. Near the field strength |B₀| ≈ 10.9 mT, the |F = 3, m F = 1⟩ to |F = 2, m F = 0⟩ hyperfine transition frequency ω MW,2/(2π) ≈ 1762.974 MHz is first-order insensitive to magnetic field changes, while the quadratic frequency deviation is ≈2π × 217 kHz mT⁻². Here, F denotes the total angular momentum and m F is the projection of the angular momentum along the magnetic field axis. We keep this notation for labeling purposes only. In case of |B₀| ≫ 0, F and m F are inappropriate quantum numbers and, therefore, we calculate level splittings and inter-state coupling strengths numerically. Laser beams (with wavelengths close to 280 nm and σ⁻ polarised) for Doppler cooling to a temperature of ≈1 mK and state preparation via optical pumping into |3,3⟩ of the S_{1/2} ground state propagate parallel to the magnetic field. For state detection, a single laser beam induces resonant fluorescence and we can discriminate the |3,3⟩ (bright) state from the other hyperfine ground (dark) states. Fluorescence photons are detected by a photon-multiplier tube (PMT) detector; more details on our laser setups, state preparation and detection techniques are described in refs. Further, we can coherently manipulate the internal states via a pulsed application of microwaves between ω MW/(2π) ≈ 1,300 MHz and ≈1,850 MHz or radio-frequency waves at ω RF/(2π) ≈ 55.3 MHz. The microwaves are applied via a home-built biquad antenna that is geometrically optimised for 2π × 1,600 MHz, while the radio-frequency waves are capacitively coupled onto the RF electrodes.

Individual experimental sequences are comprised by about 500 μs of cooling and state preparation, zero to 1.5 s of state manipulations or (near) free evolution, and 100 μs of state detection. Sequences are repeated N exp ≈ 100 to 500 times to yield averaged data points (including statistical uncertainties) for fixed parameter settings. More details on raw data analysis in our experiments can be found in ref. In the following experiments, state preparation can include population transfer from the bright state to any other state of the hyperfine manifold, e.g., |3,1⟩ state, via microwave (or radio-frequency) pulses. In turn, state detection, will then include reversed application of pulses to transfer population back into the bright state. After optimisation, we further neglect infidelities of these transfer pulses in the analysis of our experiments; in similar experimental setups infidelities below 10⁻⁴ have been reported.

**Results**

**Tuning and long-term stability of the quantisation field.** In dedicated calibration measurements, we tune the orientation and strength of B₀ to enable optimal experimental conditions; We require, firstly, first-order field insensitivity of the |3,1⟩–|2,0⟩ state splitting and, secondly, optimal state preparation in our experiments. For these calibration experiments, we probe the magnetic field with a single ion via the |3,3⟩ to |2,2⟩ transition.
frequency $\omega_{\text{MW},0}$ with a field sensitivity of $\approx -2\pi \times 21.764\text{ MHz mT}^{-1}$, cf. Fig. 2 and Table 1. We apply either a single microwave $\pi$ pulse (Rabi sequence, i.e., full population transfer from $|3,3\rangle$ to $|2,2\rangle$) or two $\pi/2$ pulses separated by the duration $T_{\text{Ramsey}} \leq 20\mu$s (Ramsey sequence).

A coarse setup of the orientation of $B_0$, i.e., superposition of the magnetic field with the wave vector of our laser beams for optimal optical pumping into the $|3,3\rangle$ state, is ensured by mechanical/geometrical constraints and adjustments of the beam polarisation. Further, we coarsely tune the strength of $B_0$ by mechanical adjustments of $d$, while monitoring $\omega_{\text{MW},0}$ via Rabi sequences. In addition, we record $\omega_{\text{MW},1}$ via Rabi sequences to find the field strength corresponding to the first-order field-independent transition, see Fig. 2b.

For fine tuning of $B_0$, we adjust current amplitudes fed into the shim coils guided by Ramsey sequences probing $\omega_{\text{MW},0}$ in multiple iterations: The currents in the vertical and horizontal shim coils are adjusted to minimise $|B_0|$; i.e., optimising superposition of $B_0$ with preparation laser beams, while the current in the longitudinal shim coils is optimised for setting $|B_0|$ to its target value within a relative precision of $\approx 0.1 \times 10^{-4}$. We perform multiple long-term measurements of the passive magnetic-field stability over the course of up to 8 hours with a single ion without re-loading or other systematic variations of experimental parameters. We find maximal variations of the magnetic field strength of $\approx 0.3 \times 10^{-4}$ within five minutes and $\approx 1.0 \times 10^{-4}$ within one hour.

In literature several mechanisms are discussed to influence the stability of fields from permanent magnets and it is distinguished between reversible and irreversible effects. Irreversible effects that lead to a degradation of the magnetisation can be triggered, e.g., by heat, external magnetic fields, and mechanical force. Timescales of this ageing vary strongly with effective amplitudes of these disturbances and are difficult to assess. For example, in our case, a longterm demagnetisation due to the room temperature surrounding may be of about 0.01 within one year, as studied in ref. 37. On shorter timescales (from minutes to hours), reversible effects due to variations of the surrounding temperature need to be considered. First of all, magnetisation varies proportional to the reversible temperature coefficient and we calculate that in our case (assuming a temperature stability of $\pm 0.3$ K) it yields a relative magnetic field stability of better than $3.6 \times 10^{-4}$. Another effect results from thermal expansion of the supporting structure of the magnets with increasing temperature. We estimate this effect to contribute not more than $1.5 \times 10^{-4}$ of field variations. Note, that both of these reversible effects add up in our current setup.

During the following measurement runs, we track magnetic-field strength drifts every five to 20 minutes via variations of $\omega_{\text{MW},0}$ within a Ramsey sequence, and adjust current amplitudes of the longitudinal shim coils, accordingly. In this way, we actively stabilise the magnetic field to $|B_0| = 10.9584(2)\text{ mT}$.

Finally, we conservatively estimate spatial magnetic field gradients in the vicinity of a single trapped ion from final mechanical setup tolerances and based on the numerical field simulations of the solid-state magnets. We assume that the ion is displaced by less than 2 mm from the geometric centre position $\vec{x} = 0$ of the magnet assembly. Therefore, we expect spatial gradients of less than $11 \text{ mT mm}^{-1}$ in any direction, neglecting additional contributions, e.g., from contaminating magnetic materials in the trap chip and the surrounding support structures. Note, this corresponds to a spatial variation of $\omega_{\text{MW},0}$ of less than $2\pi \times 26 \text{ MHz mm}^{-1}$.

### Measurements of coherence times.

In the following, we determine coherence times $\tau$ in some literature referred to as the $T_1$ relaxation duration of four different sets of internal state superpositions within the ground state hyperfine manifold, cf. Fig. 2a, in order to further benchmark the performance of our overall setup. In Table 1, we quantify and summarise relevant properties of the probed transitions. We apply the following experimental sequences to measure coherence times: After preparation of the initial state, we create internal state superpositions, e.g., from contaminating magnetic materials in the trap chip and the surrounding support structures. We find maximal variations of the field-independent superposition states.

We plot the population probability $P_{\Delta \phi}$ of state $|3,1\rangle$ as a function of $\Delta \phi$ for two different values of $T_{\text{Ramsey}}$. From sinusoidal model fits to the data, we determine the contrast of such Ramsey sequences for all four sets of superposition states for variable $T_{\text{Ramsey}}$ and show these results in Fig. 3b. In a final analysis step, we determine $\tau$, i.e., the duration $T_{\text{Ramsey}}$ after which the initial contrast decayed to $e^{-1}$, by exponential model fits to each data set. We find a coherence time of $6.6(9)$ s for the field-independent superposition states, while coherence times are shorter than two milliseconds for all other superposition states; all results are summarised in Table 1. Measured decoherence rates $\Gamma = 2\pi \tau^{-1}$ increase linearly as a function of the corresponding magnetic-field sensitivities and suggest significant magnetic-field fluctuations on time scales between a few hundred microseconds and a few seconds. From additional experiments with less stable power supplies feeding the shim coils, we estimate that

| Label | Transition | Trans. frequency $\omega_{\text{MW},0}$ | Field sensitivity $\Omega_{\text{Coupl}}$ | Coupling strength $\omega_{\text{MW},0}$ | Coherence time $\tau$ |
|-------|------------|--------------------------------------|----------------------------------|----------------------------------|------------------|
| MW, 0 | $|3,3\rangle \rightarrow |2,2\rangle$ | 1541.066(4) | -21.764 | 161(3) | 0.42(6) $\times 10^{-3}$ |
| MW, 1 | $|2,2\rangle \rightarrow |3,1\rangle$ | 1655.815(2) | -10.116 | 38.3(8) | 0.9(1) $\times 10^{-3}$ |
| MW, 2 | $|1,1\rangle \rightarrow |2,0\rangle$ | 1762.97381160(1) | $\pm 0.1 \times 10^{-4}$ (+0.217 mT$^{-1}$) | 28.5(6) | 6.6(9) |
| RE, 0 | $|2,2\rangle \rightarrow |3,1\rangle$ | 55.260(1) | +5.381 | 0.28(6) | 1.8(2) $\times 10^{-3}$ |
noise levels from the relevant current supplies contribute less than $2\pi \times 0.002$ Hz to the lowest decoherence rates of $2\pi \times 0.15(3)$ Hz (for the field insensitive transition). Further, we assume that the limited thermal stability of the permanent magnets contributes significantly to field noise in our setup. A temperature variation of about 45 mK on timescales faster than the bandwidth ($\approx 1$ mHz) of our active stabilisation translates to a field variation of $\approx 0.8 \mu T$ and would suffice to explain the observed decoherence rates. For reference, we infer the amplitude of background/stray magnetic field noise to be $\lesssim 0.1 \mu T$ from another experimental setup in our laboratory. Note, we ensure that leakage from our laser beams contribute less than $2\pi \times 0.08$ Hz (for all probed transitions).

**Sensing of oscillating magnetic fields.** In a first application, we use the clock transition for sensing of oscillating magnetic fields $B_{osc}$ that originate from stray currents with unknown amplitude ($\propto U_{RF}$) in the two RF electrodes. We consider that these fields predominantly lie in the $x$-$y$ plane, due to the symmetry of the electrode structure. Under this assumption and from basic atomic properties, we calculate the frequency dependent a.c. Zeeman shift of the probed transition, and find a quadratic sensitivity of $2\mu Hz$ on timescales faster than the bandwidth ($\approx 1$ mHz) of our active stabilisation translates to a field variation of $\approx 0.8 \mu T$ and would suffice to explain the observed decoherence rates. For reference, we infer the amplitude of background/stray magnetic field noise to be $\lesssim 0.1 \mu T$ from another experimental setup in our laboratory. Note, we ensure that leakage from our laser beams contribute less than $2\pi \times 0.08$ Hz (for all probed transitions).

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In subsequent measurements, we vary $T_{rf}$ up to 1.2 s for fixed $\Delta U_{RF}$ to determine the phase accumulation from differential a.c. Zeeman shifts. Corresponding results as a function of $\Delta U_{RF}$ are shown in Fig. 4a. A quadratic model fit to this data yields a slope of $2\pi \times 20.77(7)$ mHz$^{-1}$ and from this we infer an oscillating magnetic field strength of $B_{osc} = 5.239(8) \mu T$ for $U_{RF} = 79.5 \mu V$.

Next, we measure the spatial dependence of this field along the $y$ axis. We deploy a similar spin-echo sequence as described above, but vary the position $\Delta y$ of the ion, respectively to its initial position $y_0$, within the second free evolution duration for fixed $U_{RF}$. In such sequences, the ion position is varied by applying electric control fields. We calibrate relative ion displacements in dedicated measurements to within $\pm 0.2 \mu m$ and ensure that displacements in all other directions are less than $\approx 1.0 \mu m$. We observe a linear variation of $\Delta y$ as a function of $\Delta y$ with a slope of $2\pi \times 327(7)$ mHz$^{-1}$ and attribute this to differential field gradients. Zeeman shifts, Note, to explain the observed frequency shift by a spatial variation of static magnetic fields only, it would require local gradients of $\approx 1.2 \mu T \mu m^{-1/2}$. In comparison, we refer to our estimation of global linear gradients of less than $11 \mu T \mu m^{-1}$ (see above) and judge the presence of such large (static) local gradients to be unlikely in our setup. Consequently, we show in Fig. 4b the variation of $B_{osc}$ with a non-linear slope of $\delta B_{osc}/\sqrt{\delta y} = 0.261(3) \mu T \mu m^{-1/2}$.

**Discussion**

We describe a hybrid approach for generating stable magnetic fields, with a field strength around 10.9 mT and a calculated spatial variation of less than $10^{-6}$ within a diameter of spherical volume of 150 µm, using a combination of rare-earth magnets and magnetic field coils powered by stable low-power current supplies. We coarsely tune the magnetic field by mechanical adjustments of the permanent magnets and use the field coils for fine
tuning. In our experiments, we use a single trapped Mg\(^{+}\) atom to probe the field characteristics. We find a passive long-term temporal stability of \(\times - 1104\) over the course of one hour. In addition, we implement a feedback loop for active field stabilisation with a bandwidth of about 1 mHz to better than \(2 \times 10^{-5}\) via re-adjustments of currents in the field coils. Further, we benchmark the short-term performance of our setup by measurements of coherences of internal state superpositions and find coherence times of up to \(6.6(9)\) s. We assume that the short-term stability is limited by the passive (thermal) stability of the permanent magnets and the bandwidth of the active field stabilisation. In a first quantum sensing application, we probe magnetic fields oscillating at \(2 \pi \times 60\) MHz that originate from currents running in our trapping structure. We measure the magnitude with a quadratic sensitivity of \(2 \pi \times 4.783\) Hz mT\(^{-2}\) and spatial variation within about ten micrometers. In an extension of our measurements, complete, i.e., local amplitude and phase information of the oscillating field can be recorded. Numerical simulations of the oscillating magnetic fields can be compared to our results and, in turn, would yield detailed understanding of electronic properties of trapping structures that are used for quantum simulation and related fields of research.

The stability of our hybrid approach can be further increased in several ways. First of all, we can increase the bandwidth and accuracy of the active stabilisation. In addition, we can combine permanent magnets with different reversible temperature coefficients in arrays that create magnetic fields that are intrinsically robust against thermal variations. Another way to be use a support structure that is engineered to counteract the change of magnetisation due to thermal drifts by a change in the distance between the magnet sets. The magnetic field noise floor can be improved via implementation of shielding against stray magnetic fields as, e.g., demonstrated in ref. Another way can be to use a support structure that is engineered to counteract the change of magnetisation due to thermal drifts by a change in the distance between the magnet sets. The magnetic field noise floor can be improved via implementation of shielding against stray magnetic fields as, e.g., demonstrated in ref. Finally, adapted and optimised geometries of the solid-state magnets can yield smaller footprints, while increasing regions of homogeneous field distribution, and variable field strengths. We conclude that improved versions our hybrid approach are of particular importance for setups that have strict power and load requirements, while being cost effective. Thus, it enables more compact and robust developments in a variety of applications.

Data availability. The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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Author Contributions

F.H., P.K., M.W., U.W., and T.S. developed the experimental apparatus. F.H., P.K., and U.W. conceived, conducted, and analysed the experiments. All authors carefully discussed the results and reviewed the manuscript.

Additional Information

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