Magnetic field stabilization system for atomic physics experiments

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Atomic physics experiments commonly use magnetic fields of between a few and a few hundred Gauss to provide a quantization axis. As atomic transition frequencies depend on the amplitude of this field, many experiments require a stable absolute field. Most setups use electromagnets, which require a power supply stability not usually met by commercially available units. We demonstrate stabilization of a field of 146 G to 43 µG rms noise (0.29 ppm), compared to noise of ≥ 1 mG without any stabilization. The rms noise is measured using a field-dependent hyperfine transition in a single 43Ca+ ion held in a Paul trap at the centre of the magnetic field coils. For the 43Ca+ “atomic clock” qubit transition at 146 G, which depends on the field only in second order, this would yield a projected coherence time of many hours. Our system consists of a feedback loop and a feedforward circuit that control the current through the field coils and could easily be adapted to other field amplitudes, making it suitable for other applications such as magneto-optical traps.

I. INTRODUCTION

In many atomic physics experiments, the quantization axis is defined by a static magnetic field, typically between a few and a few hundred Gauss. In trapped-ion quantum information experiments, for example, hyperfine or optical transitions can serve as the basis for qubits, when orientational degeneracy is lifted by application of a static magnetic field. The transition frequencies usually depend on magnetic field to first order, through the Zeeman effect, which leads to qubit decoherence via magnetic field noise. At certain magnetic field values, particular transitions are field-independent to first order, giving so-called “atomic clock” qubits; these occur for example at 119 G in 9Be+, 146 G in 43Ca+, and 213 G in 25Mg+. However, to access the qubit state, transfer pulses on field-dependent transitions are used, which makes the qubit state preparation and readout operations susceptible to magnetic field noise. Hence there is a requirement for low absolute field noise at relatively large fields. Other applications, such as atomic clocks and precision tests of fundamental physics, also benefit from low magnetic field noise.

In most setups that use magnetic coils to generate the desired field, the field noise is dominated by the coil current noise. While the use of off-the-shelf low-noise power supplies can reduce this contribution, their noise levels are still too high for high-fidelity experiments. Electronic devices. Particularly at 50 Hz and harmonics, noise arising from the mains electricity is commonly observed in the laboratory. Unfortunately, this noise source can hardly be controlled directly, and environmental noise cannot be reduced by the use of permanent magnets. The most effective way to make the ions insensitive to external magnetic field fluctuations is by shielding, e.g., as provided by mu-metal enclosures, but this often reduces the optical access.

In this work, we demonstrate a feedback loop that stabilizes a coil current of approximately 60 A, providing a magnetic field of 146 G. To characterize the feedback loop’s performance, we measure the current noise electronically, and the magnetic field noise by probing a field-dependent qubit transition in a single 43Ca+ ion trapped at the centre of the coils. Contributions from the coil current are sufficiently suppressed by the feedback loop, leaving a magnetic field oscillation at the mains frequency due to ambient field noise. To tackle this remaining noise at 50 Hz and harmonics, we include a feedforward circuit that adds an additional out-of-phase signal to the coil current. The phase and the amplitude of this feedforward signal are calibrated using the ion as a probe. With feedback and feedforward combined, we reach an rms magnetic field noise of 0.29(1) ppm.

II. DESIGN OVERVIEW

Our approach to stabilizing the magnetic field has two parts: a feedback loop and a feedforward circuit. Both of them adjust the current through the magnetic field coils, which is provided by a low-noise constant current power supply Keysight 6671A (see Fig. 1 for the basic schematics).

The input to the feedback loop is derived from a current sensor in series with the field coils. The sensor output is processed by several filter stages. The control voltage generated by the feedback circuit then drives the base current of a transistor that bypasses both coils and sen-
sensor, thereby adjusting the coil current and the magnetic field. Since the feedback stabilizes only the coil current and not the magnetic field itself, the ion is still susceptible to ambient magnetic field noise. Measurements of the field at the ion (see below) reveal that this ambient noise consists mostly of an oscillation at 50 Hz and harmonics with a fixed phase offset from the mains electricity. We can then correct for these oscillations using the feedforward circuit, which modulates the coil current (but not the current through the sensor) in antiphase with the power line.

For the optimum feedback loop design, we start with a low-noise current sensor and design the subsequent input stage so as to minimize degradation of the sensor performance. We chose to use the LEM IT 400-S fluxgate current probe as this was the lowest-noise sensor commercially available (specified maximum rms noise of 1 ppm in 0...1 kHz, at 400 A). Since its relative output noise decreases with increasing current, it is advantageous to maximize the primary current. By winding up 6 turns of the cable around the sensor, we increase the effective primary current to 360 A. The output current of the fluxgate sensor is measured with a four-terminal resistor and an instrumentation amplifier for common-mode noise rejection. By subtracting the DC setpoint, we generate an error signal, i.e. the deviation of the sensed current from the setpoint. We measure this error signal with an FFT analyzer to obtain noise spectra. In the following section we will discuss different contributions to these noise spectra and how we generate a feedback signal from this input.

III. ELECTRICAL CHARACTERIZATION AND CIRCUIT DESIGN

Before designing the feedback loop and the feedforward circuit, we characterize the the sensor, input stage, power supply unit and coils. These measurements will determine the required feedback bandwidth and the eventual noise floor of the closed-loop system.

The first stages of the feedback circuit have to be designed carefully since the expected AC signals (i.e. noise of the coil current) are of the same order as the intrinsic noise of the components. The setpoint voltage is provided by two digital-to-analog converters (DACs) that are supplied by a low-noise voltage reference. They allow for separate coarse and fine tuning of the DC setpoint, with a resolution of 0.09 ppm (13 µG for our application at 146 G). In the subtraction stage, the error signal is also amplified by a gain of 200, after which the signal is much larger than the typical noise from electronic components in the circuit, and standard design techniques can be used for the subsequent stages.

We characterize the sensor with the primary current circuit detached by measuring the error signal of the input stage with the FFT analyzer. The measured sensor noise spectrum shows white noise of 1 µG/√Hz between 10 Hz and 80 kHz (see Fig. 3, blue curve, and Table 1). Spurs at 17 kHz and harmonics (∼ 9 ppm rms) are sensor artefacts arising from the fluxgate operation. As a comparison, we emulate an ideal current sensor by shorting the four-terminal resistor (i.e. no output current noise at 0 A). The resulting spectrum does not show the fluxgate clock noise but the same white noise of 1 µG/√Hz (0.26 ppm in 1 Hz...1 kHz, equivalent to 38 µG at 146 G). This shows that this measured noise level is dominated by the instrumentation amplifier or the setpoint subtractor, and not by the fluxgate sensor. Any stabilization by the feedback loop can reduce the noise no lower than this noise floor.

We next connect the sensor to the coils and the power supply unit, without the feedback or feedforward shunts, and apply a current of 60 A to measure the initial coil current noise without any stabilization (Fig. 3, red curve). The noise of the power supply is mainly located at frequencies below 5 kHz, leading to 960 µG rms noise between 0.4 Hz and 1 kHz. Spurs at 50 Hz and harmonics (> 500 µG rms) are fluctuations of the coil current with the mains electricity.

From these pre-characterization measurements we derive a required bandwidth of the feedback loop between 1 kHz and 10 kHz: on one hand, the bandwidth should be no lower than 1 kHz since otherwise a major part of the power supply noise would not be attenuated. As the bandwidth increases, the attenuation factor at lower frequencies increases, too. On the other hand, the feedback must not respond to the fluxgate clock noise at 17 kHz and harmonics by imposing a supposed cancellation current on the coils – which would add noise. For this reason, we add notch and low-pass filters to the feedback circuit after the error-signal generation. These filters, however, reduce the phase margin of the feedback loop, which could result in instability if the bandwidth was close to the notch frequency (17 kHz). Therefore, a trade-off has to be found between the suppression of any 17 kHz fluxgate clock noise, and the suppression of broadband noise. We choose 3 kHz as the target bandwidth.

We now have to ensure correct operation of the current shunt over the target bandwidth of the feedback loop. If the power supply were an ideal constant-current source with a DC output current \( I_{\text{PSU}} \), any AC signal \( I_{\text{shunt}} \) through the shunt would induce the same signal but with opposite sign in the current \( I_{\text{sens}} \) through sensor and magnetic field coils, since \( I_{\text{sens}} = I_{\text{PSU}} - I_{\text{shunt}} \). The supply’s large output capacitance, however, leads to a deviation from an ideal constant current source at higher frequencies and gives resonant effects by coupling to the coils’ inductance. We characterize this behaviour by measuring the transfer function \( I_{\text{sens}} / I_{\text{shunt}} \), which shows a drop in amplitude of nearly two orders of magnitude from 10 Hz to 100 Hz. To correct for this, we add a compensation stage after the notch filters of the feedback circuit. We find that a bi-quadratic filter works well for our setup, with components chosen so that the filter’s transfer function is the inverse of the measured one. Note that the measured transfer function depends strongly on the power supply (and also on the coil inductance, which is ≈ 0.6 mH in our experiment), and therefore the components in the compensation stage would have to be adapted to different setups.

The final stage of the feedback circuit provides gain and defines the bandwidth; its output is taken to the cur-
FIG. 1. Schematic view of the feedback loop (solid) and the feedforward circuit (dashed). The power supply runs in constant-current mode. For the feedback loop, a sensor measures the total current through the coils, from which a control voltage $V_{\text{shunt}}$ is derived. This control voltage is then fed into a shunt that bypasses sensor and coils. A block diagram of the feedback circuit is shown in fig. 2. A line-trigger provides a phase-locked reference for synchronization of the feedforward correction with the mains. Full details of the circuits will be made available.

TABLE I. Summary of rms magnetic field noise under various conditions. Values in parentheses are derived from measurements of the error signal with an FFT analyzer; others are deduced from measurements on the $^{43}\text{Ca}^+$ qubit.

| Condition                        | Rms Noise (µG) | Dominant Noise Source                  |
|----------------------------------|----------------|----------------------------------------|
| No stabilization                 | 960            | power supply unit                      |
| Feedback alone                   | 161            | ambient 50 Hz line noise               |
| With feedback and feedforward    | 43             | limited by noise floor and feedback bandwidth |
| Sensor noise floor                | 38             | instrumentation amplifier, reference subtraction |

The current shunt, which can shunt up to 100 mA away from the coils. We use a double integrator to reduce low-frequency noise without degrading the phase margin near the unity-gain cross-over. A complete block diagram of the feedback loop is shown in fig. 2.

The overall temperature coefficient of the feedback circuit is expected to be about 250 µG/K, dominated by the voltage reference.

**IV. RESULTS**

For initial characterization, we measure the current noise with the feedback loop closed (Fig. 3, yellow curve) and compare it to the previous measurements without any stabilization (red curve). When the feedback loop is closed, the noise is clearly suppressed for frequencies below 3 kHz. It appears to be below the noise floor because we are measuring the in-loop error signal; the actual current noise will not be lower than the noise floor as determined before (blue curve). Around 10 kHz, a small bump in the noise spectrum is only present with feedback enabled: it arises where the phase margin is $< 90^\circ$ as a result of the trade-off chosen between the cancellation of any 17 kHz fluxgate clock noise and the suppression of broadband noise around 10 kHz.

Next, we characterize the magnetic field noise using a single trapped $^{43}\text{Ca}^+$ ion as a point probe. The ion is held in a blade-type Paul trap in ultrahigh vacuum and is located approximately at the geometrical centre of the magnetic field coils. We measure the coherence time of a qubit stored in the ground level hyperfine $4S_{1/2}^1$ and $4S_{1/2}^3$ states, whose frequency splitting is first-order dependent on the magnetic field via the Zeeman effect, with coefficient 2.45 kHz/mG.

The qubit coherence is measured by Ramsey experiments. Magnetic field noise will shift the qubit frequency and cause fluctuations in the phase shift accumulated in each measurement shot, which results in a drop of the Ramsey fringe contrast $c$ when averaged over many shots. Correlated noise on a time scale longer than the Ramsey delay time $\tau_R$ leads to a Gaussian decay $c = \exp(-\tau_R^2/2T_c^2)$, with a time constant $T_c$ to which the magnetic field rms noise $\sigma_B$ is related by

$$\sigma_B = \frac{\sqrt{2}}{T_c} \left( \frac{2\pi \times 2.45 \text{kHz/mG}}{\text{rms}} \right).$$

With the feedback loop enabled, we measure a coherence time of 0.57(1) ms, implying an rms field noise of 161(3) µG.

However, since the ion is sensitive to the magnetic field and not just to the coil current, we still have contributions from ambient field noise. A dominant contribution to ambient noise arises from the mains electricity, at 50 Hz and harmonics thereof. While the feedback loop suppresses current noise at these frequencies sufficiently, the ambient field noise is not attenuated, as it is not detected by the current sensor.

To measure the effects of magnetic field modulation in
phase with the 50 Hz power line cycle, we use the zero-crossing of the power line cycle as a trigger for our experiments. The accumulated phase shift caused by oscillations of the magnetic field at 50 Hz and harmonics is now the same for all experiments with the same delay from the trigger. In line-triggered Ramsey experiments, we measure a coherence time of 1.93(7) ms, which translates to a magnetic field noise of $\sigma_B = 48(2) \mu$G. Spin-echo measurements, which are less sensitive to noise at frequencies below $2/T_R$, show coherence times of 11.3(2) ms (8.1(1) $\mu$G magnetic field rms noise).

The increase in coherence time found in line-triggered experiments already shows the presence of magnetic field noise at 50 Hz, but we can also measure these oscillations more directly. We run experiments that determine the qubit frequency, for a series of different delay times from the line-trigger. Since the qubit frequency follows the magnetic field, these experiments therefore reveal the oscillations of the magnetic field at the ion within each mains electricity cycle. With the feedback loop enabled, we measure a 50 Hz modulation with an amplitude of 262(5) $\mu$G (Fig. 4, red dataset) (for comparison, the current noise at 50 Hz and harmonics without any stabilization corresponds to 500 $\mu$G rms). This is in approximate agreement with the result from the coherence time measurement without line-triggering (Table II).

This coherent modulation is clearly distinguishable from broadband noise and fortunately does not change significantly over periods of weeks. This allows us to program a feedforward circuit to modulate the coil current in (anti)phase with the power line to counteract the magnetic field oscillation measured at the ion. With this feedforward circuit, we measure a remaining modulation by the mains electricity of only 14(5) $\mu$G rms, limited by the measurement accuracy (Fig. 4, black dataset).

The fully-stabilized experiments with both feedback and feedforward enabled show an rms field noise of 45(1) $\mu$G (coherence time of 2.03(5) ms, or 9.6(1) ms with spin-echo) without the need for line-triggering, which is similar to the result obtained from line-triggered experiments without a feedforward circuit (see Table II for comparison). Thus the feedforward circuit eliminates the need for line-triggering, which can greatly improve the rate of data acquisition, as the experimental repetition rate is not limited to 50 Hz.

The longer coherence times obtained by spin-echo measurements indicate that the main source of decoherence is low-frequency noise. We investigate this by monitoring the drift of the qubit frequency on an hour timescale (see Fig. 5). With the feedback enabled, the slow drift corresponds to an rms noise of 43 $\mu$G, or 0.29ppm (for frequencies $< 0.05$ Hz), which is similar to the results obtained from the coherence time measurements without spin-echo. We attribute the observed level of 0.29 ppm low-frequency rms noise to the voltage reference used in the feedback loop (specified peak-to-peak noise, 0.1 Hz – 10 Hz: 0.25 ppm typical, rms noise 10 Hz – 1 kHz: 0.67 ppm typical).

For comparison, without any stabilization, the noise was predominantly at frequencies below 10 Hz (see Fig. 4), with a low-frequency (< 1 Hz) rms noise of about 14 ppm.
Reduced using eq. 1. The noise values for the spin-echo experiments were synchronized with the 50 Hz mains cycle.

All experiments were line-triggered, and the feedback was enabled for both datasets. The solid curves are fits to modulation with components at 50 Hz and 150 Hz. The rms noise on an hour time scale is 43 µG.

The coherence times that we measured for the field-dependent qubit in $^{43}$Ca$^+$ at a stabilized field of 146 G are comparable to those obtained for field-dependent qubits at low magnetic fields without stabilization (e.g. 11(2) ms in line-triggered spin-echo measurements on a $^{40}$Ca$^+$ Zeeman qubit at 3.7 G, indicating that we have achieved similar absolute field stability at 146 G as is typically obtained at fields of a few Gauss. This is also advantageous for experiments using multiple ion species, as the different species do not possess atomic clock transitions at the same magnetic field.

1. I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091 (1995)
2. A. Steane, Appl. Phys. B 64, 623 (1997)
3. D. Wineland, C. Monroe, W. Itano, D. Leibfried, B. King, and D. Meekhof, J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998)
4. C. Langer, R. Ozeri, J. D. Jost, J. Chiaverini, B. Démartore, A. Ben-Kish, R. B. Blakestad, J. Britton, D. B. Hume, W. M. Itano, D. Leibfried, R. Reichle, T. Rosenband, T. Schaeetz, P. O. Schmidt, and D. J. Wineland, Phys. Rev. Lett. 95, 060502 (2005)
5. F. P. Harty, D. T. C. Allcock, C. J. Ballance, L. Guidoni, H. A. Janacek, N. M. Linke, D. N. Stacey, and D. M. Lucas, Phys. Rev. Lett. 113, 220501 (2014)
6. C. Ospelkaus, U. Warring, Y. Colombe, K. R. Brown, J. M. Amini, D. Leibfried, and D. J. Wineland, Nature 476, 181 (2011)
7. F. P. Harty, High-Fidelity Microwave-Driven Quantum Logic in $^{43}$Ca$^+$, Ph.D. thesis, University of Oxford (2014).
8. P. Treutlein, P. Hommelhoff, T. Steinmetz, T. W. Hänsch, and J. Reichel, Phys. Rev. Lett. 92, 203005 (2004)
9. R. Szmul, V. Dugrain, W. Maimeult, J. Reichel, and P. Rosenbusch, Phys. Rev. A 92, 012106 (2015)
10. M. Niedermayer, K. Lkahmanskii, M. Kumph, S. Partel, J. Edlinger, M. Brownutt, and R. Blatt, N. J. Phys. 16, 113066 (2014)
11. M. Brownutt, M. Kumph, P. Rabil, and R. Blatt, Rev. Mod. Phys. 87, 1419 (2015)
12. M. E. Poitzsch, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Rev. Sci. Instr. 67, 129 (1996)
13. M. F. Brandl, M. W. van Mourik, L. Postler, A. Nolf, K. Lkahmanskii, R. R. Paiva, S. Möller, N. Danilidis, H. Häffner, V. Kaushik, H. Ruster, C. Warschburger, H. Kaufmann, U. G. Poschinger, F. Schmidt-Kaler, P. Schindler, T. Monz, and R. Blatt, Rev. Sci. Instrum. 87, 113103 (2016)
14 C. D. J. Sinclair, E. A. Curtis, I. L. Garcia, J. A. Retter, B. V. Hall, S. Eriksson, B. E. Sauer, and E. A. Hinds, Phys. Rev. A 72, 031603 (2005).
15 T. Ruster, C. T. Schmiegelow, H. Kaufmann, C. Warschburger, F. Schmidt-Kaler, and U. G. Poschinger, Appl. Phys. B 122, 254 (2016).
16 S. R. Woodrow, Linear Paul trap design for high-fidelity, scalable quantum information processing, Master’s thesis, University of Oxford (2015).
17 P. J. J. O’Malley, J. Kelly, R. Barends, B. Campbell, Y. Chen, Z. Chen, B. Chiaro, A. Dunsworth, A. G. Fowler, I. C. Hoi, E. Jeffrey, A. Megrant, J. Mutus, C. Neill, C. Quintana, P. Roushan, D. Sank, A. Vainsencher, J. Wenner, T. C. White, A. N. Korotkov, A. N. Cleland, and J. M. Martinis, Phys. Rev. Applied 3, 044009 (2015).
18 S. Brouard and J. Plata, Phys. Rev. A 68, 012311 (2003).
19 M. J. Biercuk, a. C. Doherty, and H. Uys, J. Phys. B: At. Mol. Opt. Phys. 44, 154002 (2011), 1012.4262.
20 C. J. Ballance, V. M. Schafer, J. P. Home, D. J. Szeber, S. C. Webster, D. T. C. Allcock, N. M. Linke, T. P. Harty, D. P. L. Aude Craik, D. N. Stacey, A. M. Steane, and D. M. Lucas, Nature 528, 384 (2015).
21 T. R. Tan, J. P. Gaebler, Y. Lin, Y. Wan, R. Bowler, D. Leibfried, and D. J. Wineland, Nature 528, 380 (2015).