Active cancellation of stray magnetic fields in a Bose-Einstein condensation experiment
C. J. Dedman, R. G. Dall, L. J. Byron, and A. G. Truscott

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Magnetic trapping, evaporative cooling, and Bose Einstein Condensation
Active cancellation of stray magnetic fields in a Bose-Einstein condensation experiment

C. J. Dedman
Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

R. G. Dall, L. J. Byron, and A. G. Truscott
ARC Centre of Excellence for Quantum-Atom Optics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

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A method of active field cancellation is described, which greatly reduces the stray magnetic field within the trap region of a Bose-Einstein condensation experiment. An array of six single-axis magnetic sensors is used to interpolate the field at the trap center, thus avoiding the impractical requirement of placing the sensor within the trap. The system actively suppresses all frequencies from dc to approximately 3000 Hz, and the performance is superior to conventional active Helmholtz cancellation systems. A method of reducing the field gradient, by driving the six Helmholtz coils independently, is also investigated. © 2007 American Institute of Physics.

I. INTRODUCTION

In 1995 a dilute gas Bose-Einstein condensate (BEC) was experimentally realized for the first time. In these early demonstrations the atoms were confined in a magnetic trap with subsequent evaporative cooling leading to the formation of a BEC. Ten years on, magnetic traps are still the workhorse for most BEC experiments, although optical confinement has also been demonstrated. One of the appealing features of a magnetic trap is the inherent stability that it offers, after all one need only to carefully stabilize the trap coil currents to generate stable magnetic trapping fields. To attain BEC a magnetic trap current stability of $10^{-3}$ is adequate, which equates to a magnetic stability of $\sim 1$ mG for a 1 G bias field. In general, a stability of $10^{-3}$ in coil currents is easy to achieve, most commercial power supplies meet such specifications. However, due to background magnetic field fluctuations, which are of order $\sim 1$ mG in most laboratories, an ultimate magnetic trap stability of better than $10^{-3}$ is difficult to reach. This limit places restrictions on the type of experiments that are possible, in particular, continuous wave (cw) “atom laser” experiments.

In our experiment we control the currents in our trap coils to around one part in $10^7$, which amounts to $10 \mu$G of magnetic field noise. However, we have measured our ac field noise and determined it to be approximately $1$ mG peak-to-peak (P-P) due to background B-field fluctuations mainly at the mains power frequency of 50 Hz. A typical magnetic noise spectrum is shown in Fig. 1, where it is seen that active field suppression is required to around 500 Hz. Without suppression of these background fields cw atom laser experiments would be impossible in our system. In this article, we describe a high-performance active magnetic field cancellation scheme which is suitable for use with complicated experimental setups, such as a BEC experiment.

II. MAGNETIC SHIELDING

Before describing the field cancellation system employed here, it is useful to briefly review existing methods of reducing unwanted magnetic fields.

A. High-permeability shielding

The region-of-interest (ROI) is enclosed within a box or cylinder constructed of “mu-metal,” or similar material having extremely high permeability. The stray magnetic flux travels preferentially through the magnetic shield, greatly reducing the field within the enclosure. Potentially, this method is simple and capable of very high performance. Many formulas are available for calculating the dc field reduction ratio for simple geometries, typically yielding 50–200 for a single long cylinder, and $\geq 1000$ for multiple nested shields. A mu-metal cylinder of length 550 mm and diameter 120 mm, used in our laboratory as a field-free region for testing residual magnetism of small components, reduces the Earth’s magnetic field by a factor of $\sim 500$ parallel to the cylinder axis, and $\sim 100$ perpendicular to the axis. In practice, mu-metal shielding around complex experimental apparatus rarely achieves this level of performance, due to the necessity of access holes and mechanical joins. A quick measurement of several complex single-layer mu-metal shields in our laboratories revealed dc field reduction ratios from 10 to 40. However, the suppression of ac stray fields, mainly at the power mains frequency of 50 Hz and harmonics, is frequently less. For 50 Hz ac fields, our shielding cylinder provided a reduction of only $\sim 10$ parallel to the cylinder and $\sim 40$ perpendicular to the axis. Complex shields with access...
holes and joins provided near-useless ac reduction ratios from 4 to 10. A mu-metal enclosure around our BEC trap would be mechanically complex to build, extremely inconvenient due to restricted access to the experiment, and would not achieve the required reduction of stray magnetic fields, particularly at ac frequencies.

B. Eddy current shielding

The shielding enclosure is constructed from sheets of aluminum or copper, having high-electrical conductivity. Stray ac fields induce circular “eddy currents” within the material, creating an opposing field, and limiting penetration of the original field within the material. The shielding effectiveness is zero at dc, and increases with frequency, so for optimum screening at all frequencies it is common to construct shields from alternating layers of high-permeability and high-conductivity materials, such as mu-metal and aluminum. For example, Zimmerman\(^\text{10}\) describes a shielded room for biomagnetic experiments, constructed from 38 mm thick aluminum plate, and achieving a field reduction ratio of 46 dB at 60 Hz. It is not practical to enclose our entire BEC experiment in a magnetically shielded room. Apart from the prohibitive cost of providing a sufficiently large screened room, most of the vacuum pumps and field-producing electronic equipment would need to be inside the room, and little benefit would be obtained.

C. Active Helmholtz coils

In the classic passive Helmholtz arrangement, a pair of magnetic coils in each axis is used to create a uniform dc field, thus canceling the unwanted field. An obvious improvement is to place a three-axis magnetic sensor at the ROI near the center of the coils, and use a proportional or proportional Integral and differential (PID) controller in a feedback loop for each axis, driving the coil currents so as to oppose the original field. An early high-performance system of this type was described by Marzetta\(^\text{11}\) and this same basic arrangement has been built and described many times since. Major advantages are that the system attenuates both dc and ac fields, and adapts to changes in the perturbing field. Commercial “active shielding” systems of this type are available,\(^\text{12}\) targeted at applications such as electron microscopes, which require small stray fields for optimum resolution. Broadly speaking, the systems described provide useful attenuation from dc to 1 kHz, with an attenuation ratio of 100 at 50 Hz, measured at the feedback sensor. In general, it is not possible to place the sensor at the point where zero field is desired, such as within an electron microscope, or BEC trap. As a result, and depending on the uniformity of the perturbing field, the field reduction at the point of interest is usually well less than the quoted factor of 100 or so attained at the feedback sensor.

III. EXPERIMENTAL SETUP

Figure 2 illustrates the cancellation method presented here. For simplicity, only a single axis is shown, subsequently referred to as the x axis. The cancellation coils for each axis are identical to conventional Helmholtz coils, except that the two coils are driven independently, rather than being wired in series. It is possible to simultaneously zero both the field magnitude \(B_x\) and gradient \(dB_x/dx\), by driving different currents through the two coils. If the coil currents are equal, as for conventional Helmholtz coils, then the resultant field is uniform. However, if the currents are unequal, then any desired linear field gradient can be produced, and the perturbing field and gradient can be exactly canceled at a single point. In each axis, a pair of single-axis magnetic sensors is placed symmetrically on each side of the BEC trap center, as close together as possible, as in Fig. 2. The high-gain feedback action of the two controllers ensures that the magnetic field \(B_x\) is brought to zero at both sensors. If the perturbing field, \(B_x\), varies linearly along the x axis, then both the field magnitude and gradient will be zeroed in the ROI between the sensors. In simple terms, if \(B_x\) is brought to zero at two points, then \(B_y\) should be small anywhere between those two points. The exact performance will vary greatly depending on the shape (uniformity) of the perturbing field. The second axis, referred to here as the y axis, is arranged identically, with a pair of sensors, controllers, and coils. Thus, \(B_y\) and \(dB_y/dy\) are also zeroed at the ROI.

The third axis (z axis) must be treated differently, because it is not possible to independently control the field gradient in all three axes. One of Maxwell’s equations states that

\[
\begin{align*}
\frac{d}{dx} \left( \frac{1}{\mu} \frac{d}{dx} \right) B_x + \frac{d}{dy} \left( \frac{1}{\mu} \frac{d}{dy} \right) B_y + \frac{d}{dz} \left( \frac{1}{\mu} \frac{d}{dz} \right) B_z = J_x + J_y + J_z
\end{align*}
\]

with \(J_x, J_y, J_z\) the sources of current. For zero field, \(B_x = B_y = B_z = 0\), and the only terms are:

\[
\begin{align*}
\frac{d}{dx} \left( \frac{1}{\mu} \frac{d}{dx} \right) B_x + \frac{d}{dy} \left( \frac{1}{\mu} \frac{d}{dy} \right) B_y + \frac{d}{dz} \left( \frac{1}{\mu} \frac{d}{dz} \right) B_z = 0
\end{align*}
\]

which can only be true if

\[
\begin{align*}
\frac{d}{dx} \left( \frac{1}{\mu} \frac{d}{dx} \right) B_x &= 0, \\
\frac{d}{dy} \left( \frac{1}{\mu} \frac{d}{dy} \right) B_y &= 0, \\
\frac{d}{dz} \left( \frac{1}{\mu} \frac{d}{dz} \right) B_z &= 0
\end{align*}
\]

This implies that

\[
\begin{align*}
\frac{d}{dx} B_x &= 0, \\
\frac{d}{dy} B_y &= 0, \\
\frac{d}{dz} B_z &= 0
\end{align*}
\]

and

\[
\begin{align*}
\frac{d}{dx} B_x &= 0, \\
\frac{d}{dy} B_y &= 0, \\
\frac{d}{dz} B_z &= 0
\end{align*}
\]

FIG. 1. Typical background B-field noise spectrum measured near the BEC experiment.

FIG. 2. Schematic of the active stabilization scheme. Only the x axis is shown for clarity.
\[ dB_x/dt + dB_y/dy + dB_z/dz = 0. \]  

Thus, if the field gradient is actively zeroed in two axes, then the gradient must also be zero in the third axis, and any attempt to actively set the gradient in all three axes will fail. Hence for the z axis, the outputs from the two sensors are averaged, and the two coils are wired in series, as per conventional Helmholtz coils. In principle, it makes no difference which axis is chosen as the “third axis.” As the field gradient is not directly zeroed in this axis, we chose the axis having the smallest component of the perturbing field.

In summary, the array of six sensors interpolates the field at the trap center, ensuring that the field magnitude at the ROI is brought to zero. Driving the Helmholtz coils independently reduces the field gradient and produces a larger field-free region, because the cancellation field closely matches the perturbing field. In contrast, conventional Helmholtz coils produce a uniform correction field, and thus do not alter or reduce the field gradient.

In a conventional active Helmholtz arrangement, the feedback control systems in the three axes are independent, meaning that a change in coil current in one axis does not affect the field strength measured in the other two axes. However, in the method described here, a change in current in any given coil alters the field strength at every sensor. It may seem that this interaction would cause instability or “fighting” between controllers, but in fact the system is perfectly well behaved.

### IV. Magnetic sensor

Due to the mechanical complexity of the BEC trap, there is very little free space available to place the magnetic sensors. Thus, simplicity and small size were a high priority. Single axis fluxgate sensors, Stefan Mayer Instruments model FLC100, were chosen due to small size (45 mm \( \times \) 14 mm \( \times \) 5.5 mm), low cost, and adequate performance. Zero drift is quoted as \(<0.02\) mG/K, and noise is less than \(0.03\) mG P-P from 0.1 to 10 Hz. As the stray ac field is around \(1\) mG P-P, sensor noise will limit the effective field attenuation to a factor of around \(33\), which is satisfactory here. Higher-performance fluxgates are available, but are larger and more expensive. For the following reasons, we decided to use the fluxgate sensor for low frequencies (<16 Hz) and an inductive pickup coil for higher frequencies. First, the fluxgate sensor requires heavy filtering to remove 17 kHz “hash” from the electrical output. This causes phase lag at higher frequencies, limiting the performance of the feedback loop. The fluxgate sensor also generates significant magnetic noise at 17 kHz, which may reach the trap center, given the close proximity. The 17 kHz field can be screened by enclosing the sensor in an eddy current shielding sleeve, but this creates further phase lag in the sensor response. Finally, pickup coils are simple to construct, and have superior sensitivity and phase fidelity at higher frequencies, permitting high-feedback gain.

The pickup coil we used had 10 000 turns, with an outer diameter of 44 mm. The coil winding capacitance should be kept as low as possible, because this stray capacitance interacts with the winding inductance, creating a response peak at the resonant frequency, and a phase lag below the resonant frequency. To eliminate electrical hum and noise pickup, the pickup coil must be screened. This can be achieved by winding the coil on a conductive former, and/or by wrapping the completed coil with conductive tape. The stray capacitance can be reduced by spacing the screen several millimeters away from the winding. The fluxgate sensor is located inside the coil, and the two are separated by a copper eddy-current shielding sleeve. The coil sensitivity is \(0.34\) V/G at 50 Hz. The crossover frequency between sensors is 16 Hz, and a high-order low-pass filter completely removes the 17 kHz hash on the fluxgate output.

### A. Controller

Five high-gain proportional controllers were constructed, each with a bipolar current driving capability of 2.0 A. The output stage is a voltage-to-current converter, monitoring the current across a 1.0 \(\Omega\) sense resistor, and employing local feedback to ensure that the output current is proportional to the input voltage, at all frequencies. Thus the Helmholtz coil inductance creates no frequency dependence or phase lag in coil current. The pickup coil generates a voltage proportional to \(dB/dt\). Therefore the low-noise (LT1007) coil preamplifier is configured as an integrator above 10 Hz, to give an output proportional to \(\phi(t)\). The pickup coil has a dc resistance of 4.7 k\(\Omega\) and is loaded with 22 k\(\Omega\), which helps suppress the coil self-resonance. The controller response is deliberately arranged to roll off at 20 dB/decade, creating a phase lag of 90°. For stable operation, any additional unwanted phase lags must not exceed 90° at the frequency where the gain has fallen to 1.0. In practice, this simply means that to maximize the usable feedback gain at the frequencies of interest, one must minimize the unwanted phase lags at higher frequencies, for example, by reducing pickup coil capacitance. Slight further improvements can be obtained by tailoring the gain and phase response of the controller, for example, by adding a small amount of phase lead at higher frequencies to compensate for sensor lag. To test the performance of the controller and feedback loop, a single controller was used to drive two coils in conventional Helmholtz arrangement, with the sensor placed midway between the coils. A second pair of Helmholtz coils, connected to a signal generator, was used to produce a perturbing field, at a variety of frequencies between dc and 50 kHz. At each frequency, the field strength measured by the feedback sensor was measured with and without the controller enabled. The field attenuation ratio thus measured is plotted in Fig. 3. With an attenuation ratio of 800 (58 dB) at 50 Hz, this is an excellent result that would not be possible using a fluxgate sensor alone. The high attenuation means that for all practical purposes the field at each feedback sensor is reduced to zero, and any field remaining at the trap center will be purely as a result of field nonuniformity. The slight amplification of field noise at around 10 kHz is of no consequence, as the original field noise at that frequency is negligible. Integral action was not included in the controller because it was not necessary, and because simple integrator circuits degrade the controller overload recovery time, which is important in our application.
region of interest. is just adequate to provide good field uniformity over our dimension. The mechanical complexity of the BEC experi-
ment restricted the coil dimension to around 500 mm, which is 0.59, where \( S \) is the coil separation, and \( D \) is the coil dimension. The mechanical complexity of the BEC experiment restricted the coil dimension to around 500 mm, which is just adequate to provide good field uniformity over our region of interest.

B. Helmholtz coil design

The purpose of Helmholtz coils, when used in pairs, is to produce a highly uniform magnetic field, over a usefully large region at the center of the coils. If the coil currents are unequal, for example in the \( x \) axis, then the purpose is to produce a uniform field gradient \( dB_x/dx \). In both cases, the best results are obtained when the coil dimension is large compared to the region of interest inside the coils. Square Helmholtz coils were employed for mechanical simplicity, and because performance is similar to round coils. Our modeling showed that for square coils, the optimum \((S/D)\) ratio is 0.59, where \( S \) is the coil separation, and \( D \) is the coil dimension. The mechanical complexity of the BEC experiment restricted the coil dimension to around 500 mm, which is just adequate to provide good field uniformity over our region of interest.

V. RESULTS

A. Reduction of field magnitude

There are two types of results that could be quoted—academic and real. Academic results, as sometimes shown in the specifications of commercially available field reduction systems, are obtained by using a large pair of Helmholtz coils to generate a uniform perturbing field, and measuring the reduction in that field when the feedback loop is enabled. The results appear excellent, but are irrelevant to real world applications where the perturbing field is nonuniform. We measured the reduction in ac field strength in three typical real-world situations, as described below. The results are also compared with a conventional active Helmholtz arrangement, obtained by reconfiguring the system with three controllers and three single-axis sensors.

The stray ac field strength in an electronics workroom was \(~3.0\) mG P-P, and the sensor spacing was set to \(~120\) mm in all axes. At the ROI, midway between all sensors, the ac field strength was reduced by a factor of \(>100\). When configured as a conventional active Helmholtz system, the reduction factor was \(~14\), or about seven times worse. With a 20 W mains transformer placed 450 mm from the ROI, the field strength was reduced by \(~50\), also \(~7\) times better than achieved with a conventional system. Final magnetic testing was performed in the BEC Laboratory. Due to the bulky vacuum shell and other experimental hardware around the trap, the sensors had to be placed further apart, at an average spacing of 200 mm. The stray ac background field was around 1.0 mG but, compared with the electronics workroom the gradient was larger. The waveform was distorted and “spiky,” and there was a noticeable 800 Hz field from a nearby turbo pump. A large mild steel optical bench top, directly under the experiment, distorted stray fields, and increased their gradient. In short, this is an unusually stringent environment for active reduction of magnetic fields. It was not possible to place an independent test sensor at the trap center. Instead, two small pickup coils, of 8000 turns and 15 mm diam, were placed either side of the trap location, separated by a distance of \(~25\) mm. The outputs from these sensors were averaged, giving an accurate interpolated estimate of the ac field at the trap center. We confirm that the averaged output is an accurate estimate of the field at the trap center in the following way. First, the outputs appear almost identical on an oscilloscope, indicating that the field gradient has little effect over a 25 mm separation. Second, in a region nearby the experiment, the averaged output appears identical to that measured midway between the sensors. Unfortunately it is impossible to place the feedback sensors at 25 mm separation, as they would obscure laser beam access into the trap. With the active feedback system enabled, the field strength is reduced in all axes, by a factor of \(~25\), as shown in Fig. 4.

To quantify the dc performance of the system we monitored the background field in the workroom over a period of several hours with a Meda FVM400 digital magnetometer placed at the ROI, see Fig. 5. The large spikes in the dc background, each lasting several seconds, are caused by a nearby “Heliac” experiment, employing large coils carrying several thousand amperes. The origin of the slow variations is unknown. A dramatic improvement is observed, with re-

![FIG. 3. Plot of magnetic field attenuation measured at the feedback sensor.](image1)

![FIG. 4. B-field measurements for all three components of the ac magnetic field present at trap center. Two plots are shown for each axis, one with the stabilization and one with out. The ac noise in each axis is suppressed by a factor of ~25.](image2)
remains variations being within the fluxgate drift specification of 0.02 mG/K. The net dc field can be set to zero at any point, by adjustment of dc offset controls on each controller.

B. Reduction of field gradient

For measurement of ac field gradients, a simple gradiometer was constructed, consisting of two small ac pickup coils as previously described, separated axially by a distance of 11.7 mm. A difference amplifier provided a measurement of the field gradient. As expected, the field gradient components $dB_x/dx$, $dB_y/dy$, and $dB_z/dz$ were significantly reduced, typically by a factor of 5. However, what really matters in most applications is the field gradient $dB/ds$, meaning the rate of change of the field magnitude, with respect to distance in the direction of maximum change. This was measured approximately by tilting the gradiometer for maximum signal. In favorable situations, such as when a perturbing current-carrying coil was placed parallel to one of the Helmholtz coils, the field gradient $dB/ds$ was substantially reduced. However, for randomly oriented perturbing fields, the gradient was typically reduced by around 20%, presumably because six independently driven coils are insufficient to accurately match the shape of a general perturbing field. We conclude that passive shielding is the only practical means of substantially reducing field gradient. Reduction in the gradient of dc fields was not measured, but is expected to be similar. As the reduction in gradient is not dramatic, the additional cost and complexity of providing five controllers, rather than three, may not be justified in many applications. The use of six sensors would still be advantageous in reducing the field magnitude. For each axis, the outputs from the two sensors would be averaged, and the two Helmholtz coils wired in series. Each pair of sensors produces an interpolated estimate of the field at the ROI. One axis in the five-controller system already uses this scheme of averaging two single-axis sensors, and performs as expected. It would be relatively easy to modify existing “single three-axis sensor” active Helmholtz systems in this way, with considerable improvement in the reduction of field magnitude at the ROI. There are no unusual issues with feedback stability or interaction between controllers, because the system is functionally equivalent to a conventional three-controller system, with the sensor placed at the ROI.

C. Implementation in a Bose-Einstein condensation experiment

Implementation of the active stabilization scheme, in a complicated experimental setup like ours, has many potential pitfalls. First, for the system to be useful it must work while our magnetic trap is on. Our trap produces fields with enough strength to easily saturate our fluxgate sensors (saturation for our sensors is 1 G), however, due to our BiQUIC trapping geometry and the relatively small size of the trapping coils these fields fall off quickly enough such that the field increase at the sensors is only ~100 mG. Care must also be taken with the trap lead in wires, as they pass within a few centimeters of the sensors and thus any motion of these wires is converted in to magnetic noise by the active stabilization. For our requirements, we cannot have the active stabilization on for a complete run of our experiment. Rather we wait until the atoms have been transferred into the magnetic trap, and then switch on the active stabilization. The system settles in around 50 ms, and the switching has no adverse effects on the experiment.

In our BEC experiment the trap field is altered during the evaporation ramp to vary the confinement strength. This change in trap field, produces a small change in the dc field measured at our sensors, which then alters the bias field of the trap. However, this is a small effect in our system, and has no effect on BEC production.

To test the performance of the active field stabilization scheme we measured the intensity stability of a cw atom laser generated in our experiment. The atom laser beam is comprised of metastable $^2\text{S}_1^\text{S}$ helium atoms ($\text{He}^*$) and produced using rf radiation to flip the magnetic spin of some of the atoms in the BEC. The magnetic moment of $\text{He}^*$ atoms in the $m=1$ trapped state is $2\mu_B$, which is four times larger than that of the most commonly used atom laser state in Rb. As such we are four times more sensitive to magnetic field fluctuations than previous atom laser experiments. These atoms are then untrapped and fall under gravity where they are detected by our multichannel plate (MCP). Figure 6 shows a comparison of two atom laser beams produced in this way, one with the active stabilization (b) the other without (a). The lower plots of Fig. 6 show the power spectral density of the atom laser intensity produced in each case. Without the active stabilization we measure a hundred-fold increase in the power of 50 Hz atom laser intensity noise. This measurement is limited by the signal-to-noise on our atom laser beam; we expect that the suppression of magnetic noise is greater, however, at present it is below the measurement resolution of our experiment. Note that care was taken to ensure that in each case atoms were output coupled from the same location within the BEC.

In terms of our atom laser experiments, the dc stability is required for shot-to-shot reproducibility. By tuning the atom
laser frequency to the edge of the BEC, it is possible to give an upper limit on the shot-to-shot bias field fluctuations. With the active stabilization on, we see less than 100 μG variation, over several hours, considerably better than with no stabilization.

VI. DISCUSSION

We have described a scheme that actively reduces stray magnetic fields from dc to 3000 Hz. Implementation of the system in a complicated BEC experiment, where the sensor cannot be placed at the ROI, has been successfully demonstrated, reducing the effects of stray magnetic fields to below the resolution of our experiment. Although the field gradient was only slightly reduced, the field magnitude was reduced ~7 times lower than with a conventional active Helmholtz arrangement using a single three-axis sensor. The use of six single-axis sensors could be advantageously applied to existing three-controller active Helmholtz systems in situations where the sensor cannot be placed at the ROI. Finally the scheme has proven to be remarkably robust, able to work in an environment where other magnetic fields are being switched on and off, as well as being relatively insensitive to placement of the sensors.

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