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Trapping cold neutral atoms with an iron-core electromagnet

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Abstract. We have developed an iron-core electromagnet and used it to trap neutral atoms. The magnetic field can be switched from a spherical quadrupole configuration to a Ioffe configuration within 2 ms. We load 2×10^7 ^{87}Rb atoms from a vapor into a Magneto-Optical Trap (MOT) and transfer them into the purely magnetic trap with an efficiency of 95%. A strong radial compression is possible since we can generate quadrupole gradients up to 0.1 T/cm with an excitation current of 10 A (400 W of power consumption).

PACS. 32.80.Pj Optical cooling of atoms; trapping

The ability to magnetically trap neutral atoms has proven to be an essential step towards Bose-Einstein Condensation [1–4]. Magnetic trapping allows the use of evaporative cooling to reach quantum degeneracy, provided that the initial elastic collision rate is sufficiently high. For this purpose, tightly confining potentials are required to achieve high atomic densities. In addition, it is desirable to trap the atoms at a nonzero field minimum to avoid losses due to Majorana transitions [5].

To fulfill these requirements, many experiments have used variations of the Ioffe configuration [6]. For example, experiments with trapped Lithium atoms have been carried out in a static Ioffe trap using permanent magnets [2]. They produce a very steep potential but the magnetic field cannot be varied with time. Other setups use coils to generate similar magnetic field profiles [10,11]. In this case, the trapping potential can be varied but a significant electrical power and a sophisticated cooling system are required. The use of coils with ferromagnetic cores offers the possibility of combining the advantages of the above approaches. For example, reference [7] reports trapping of Lithium in a spherical quadrupole field created by two μ-Metal needles. In this paper, we describe a novel electromagnet inspired by that used in [2], but with the permanent magnets replaced by iron pole pieces.

As shown in Figure 1, the electromagnet consists of three pairs of 2 cm diameter cylindrical poles positioned along the X, Y and Z axes. A ferromagnetic yoke supports the poles and guides the magnetic flux by providing a low reluctance return path for the magnetic fields. Both poles and yoke are made with pure iron ($B_{\rm sat} = 2$ T, $\mu_r^{\rm max} = 7\times10^3$). The pole pieces are 20 cm long, with a 5 mm diameter hole along the symetry axis. The tip to tip spacing is 4 cm. Each pole is excited by a 440 turn coil of copper wire. The opposing poles in the XY plane are excited with equal and opposite currents. Near the center, these 4 coils generate a linear quadrupole field, given by: $\mathbf{B} = G(x\mathbf{e}_x - y\mathbf{e}_y)$ to first order in the coordinates. The quadrupole gradient G can be controlled with the current in the 4 quadrupole coils. The two poles along the Z

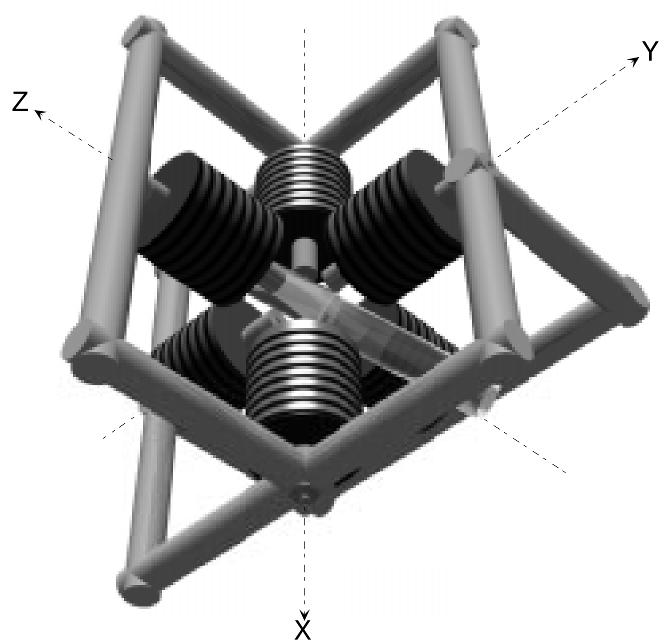

Fig. 1. Diagram showing the position of the poles and the vapor cell. The tip to tip spacing is 4 cm and the diameter of the cell 2.5 cm.

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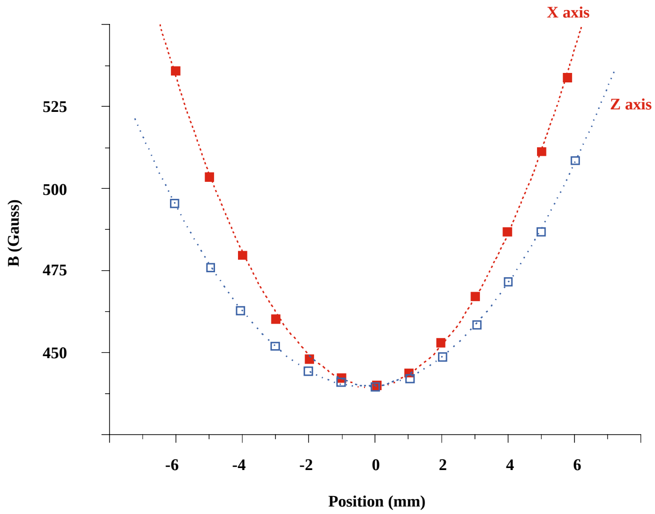

Fig. 2. Measured field along the X and Z axes for an excitation current $I = 3.5$ A in the quadrupole and dipole coils. The experimental data are fitted with second order polynomials. The bias field is 440 Gauss, the dipole field curvature 170 Gauss/cm^2 and the X axis curvature 270 Gauss/cm^2. We estimate a 5% accuracy of the measurements due to sampling noise of the data acquisistion system and to the fact that the 3 Hall probes are not perfectly orthogonal and are separated by 1 mm.

axis are excited with equal currents, making a dipole field whose Z component varies as $B_z = B_0 + C(z^2 - \frac{x^2+y^2}{2})$. The bias field B_0 and the dipole field curvature C are determined by the current in the dipole coils. The magnitude of the total magnetic field can be approximated by:

$$|\mathbf{B}| = B \simeq B_0 + (\frac{G^2}{2B_0} - \frac{C}{2})(x^2 + y^2) + Cz^2. \quad (1)$$

We have mapped the magnetic field using a 3D Hall probe. Figure 2 shows the variation of the magnetic field magnitude along different axes for excitation currents $I = 3.5$ A in the 6 coils. Near the center, the field magnitude is found to be well described by equation (1) with a 440 Gauss bias field and curvatures of $\mathrm{d}^2B/\mathrm{d}x^2 = \mathrm{d}^2B/\mathrm{d}y^2 =$ 270 Gauss/cm^2, $\mathrm{d}^2B/\mathrm{d}z^2 = 170$ Gauss/cm^2. From these curvatures, we calculate oscillation frequencies $\nu_{x,y} =$ 30 Hz, $\nu_z = 24$ Hz for ^{87}Rb trapped in the $F = 2, m_F =$ 2 state.

When the current is turned off, the field drops by 30% within 1 ms and then falls off with a 8 ms time constant limited by eddy currents in the iron structure. Because of hysteresis in the iron, a remanent bias field of about 20 Gauss and a remanent quadrupole gradient of 15 Gauss/cm remain after eddy currents are dissipated. Small compensation coils provide the coercive excitation necessary to reach zero magnetic field when the excitation current is turned off.

In order to trap the atoms, the electromagnet is placed around a 2.5 cm diameter cylindrical glass vacuum cell. The axis of the cylinder is aligned with the 111 direction of the electromagnet. The cell is pumped with a 30 l/s ion pump and contains about 10^{-9} hPa pressure of Rb. We first load atoms from the vapor into a Magneto-Optical Trap (MOT) by supplying current to the 2 coils of the electromagnet along the X axis only. A current of 200 mA generates a spherical quadrupole field with $\mathrm{d}B_x/\mathrm{d}x = 20$ Gauss/cm. A 100 mW laser diode produces 6 independent circularly polarized trapping beams, each with a power of 6 mW and a diameter of 15 mm. They are detuned by 2Γ to the red of the $5S_{1/2}$, $F = 2 \rightarrow 5P_{3/2}$, $F = 3$ optical transition at 780 nm. Because of the pole pieces, the beams cannot propagate along the symetry axes of the magnetic field but the MOT works satisfactorily with the beams tilted by 15 to 40 degrees. A repumping beam, on resonance with the $5S_{1/2}$, $F = 1 \rightarrow 5P_{1/2}$, $F = 2$ transition at 794.7 nm, overlaps the trapping beams. The density and number of trapped atoms were measured with a CCD camera by absorption imaging of a weak resonant probe beam. After 5 s of loading, the MOT contains about 2.0×10^7 atoms. We measure the temperature in the MOT by a ballistic expansion method: we switch off the beams and the magnetic field, and let the cloud expand for a variable delay time before taking an absorption image. We find a temperature of about 100 μK.

In order to optimize the phase-space density before turning on the Ioffe trap, we reduce the temperature by increasing the detuning and decreasing the intensity of the laser beams, after switching off the magnetic field. After 12 ms, the atoms are cooled to 20 μK ($\mathrm{v}_x\mathrm{rms} = 7.5 v_{\mathrm{rec}} =$ 4.5 cm s^{-1}) with a density at the center of the trap of 3×10^{10} cm^{-3}. We then block the trapping beams and optically pump the atoms into the $5S_{1/2}$, $F = 2$, $m_F = 2$ state. We do this by creating a small bias field along the Z axis and applying a 250 μs pulse of laser light which propagates along the Z axis through the 5 mm hole in the pole tips. This beam is on resonance with the $5S_{1/2}, F =$ $2 \rightarrow 5P_{3/2}, F = 2$ transition and σ^+ polarized (this choice minimizes heating because the trapped state is dark). The repumping beam on the $5S_{1/2}, F = 1 \rightarrow 5P_{1/2}, F = 2$ transition remains on during this procedure and is turned off after the optical pumping pulse.

We switch to the Ioffe trap by applying an equal current to all the coils. The field reaches the final value in 2 ms. This rise time is obtained by putting a 50 μF capacitor charged to 700 V in parallel to the power supply in order to deliver a strong pulse of current when switching on. The trapped atoms are monitored through their interaction with a probe beam. This beam propagates along the axis of the cell and has a well controlled σ^+ component with respect to the direction of the bias field. Because of the strong bias field B_0, the optical transitions experience large Zeeman shifts. We thus can monitor selectively the atoms trapped in the $5S_{1/2}, F = 2, m_F = 2$ ground state by detuning the probe beam 600 MHz above the zero field resonance. This laser beam selectively couples the trapped ground state to the $5P_{3/2}, m_I = 3/2, m_J = 3/2$ level of the excited manifold. Since this excited state is a pure $m_F = 3$ state, this forms a two-level cycling transition. From the analysis of absorption images, we can infer the number of trapped atoms. We have measured 1.9×10^7 atoms trapped in the $m_F = 2$ state which corresponds to a transfer efficiency of 95% from the MOT to the Ioffe trap (without any optical pumping, the measured transfer efficiency is about 20%). After loading, we observe an exponential decay of the number of atoms remaining in the trap with a time constant of 2.5 s. This value is consistent with the Rb vapor pressure and the background gas pressure which is measured with an ion gauge near the trap (P = 7×10^{-9} hPa).

If the equilibrium position of the atoms in the MOT and in the Ioffe trap do not overlap, for example due to the effect of gravity or imprecise positioning of the poles, the atoms acquire extra energy during the transfer. Optimum transfer is achieved by carefully positioning the MOT with the help of three additional pairs of coils along the X, Y, Z axes. These coils generate a small bias field which translates the center ($B = 0$) of the MOT. Even for our best overlap, a residual mismatch of order a few hundred microns remains. This leads to oscillations of the atomic cloud. If the atoms were permitted to thermalize (which they do not in our experiment because of the short lifetime), the final temperature would be of order 100 μK.

By modulating the current in the coils we are able to excite various modes of motion in the trap and measure their frequency [8,9]. When we modulate the quadrupole field for example, we change the curvature of the trap and excite parametric resonances (breathing modes) at $2\nu_y$ along the X and Y axes. Because the minimum of the potential is determined by the magnetic field and gravity, a modulation of the quadrupole field also results in a modulation of the position of the potential minimum at the same frequency. This excites a sloshing motion of the atoms at ν_y. Using the latter type of excitation, we modulate the current in the quadrupole coils for 500 ms, and monitor the oscillating position of the atomic cloud in the $Y-Z$ plane. The observation is made by imaging the fluorescence induced by a saturating probe beam, onto a CCD camera. In Figure 3 we show a resonance curve of the amplitude of oscillation along Y. Instead of scanning the excitation frequency, we scan the curvature of the trap while keeping the modulation frequency constant at 27.5 Hz. We observe a resonance for a current in the quadrupole coils of 3.2 A. From this measurement, we calculate a resonance frequency of 29 Hz for a current of 3.5 A, consistent with the 30 Hz value calculated from the Hall probe measurement. The width of the resonance is determined by the duration of the modulation period: because we are in the transient regime of forced oscillation, we observe a beating between the excitation frequency and the resonance frequency of the system. As shown in Figure 3, the amplitude of oscillation almost vanishes for $\nu - \nu_y = \pm 2$ Hz, which is consistent with the 500 ms modulation length.

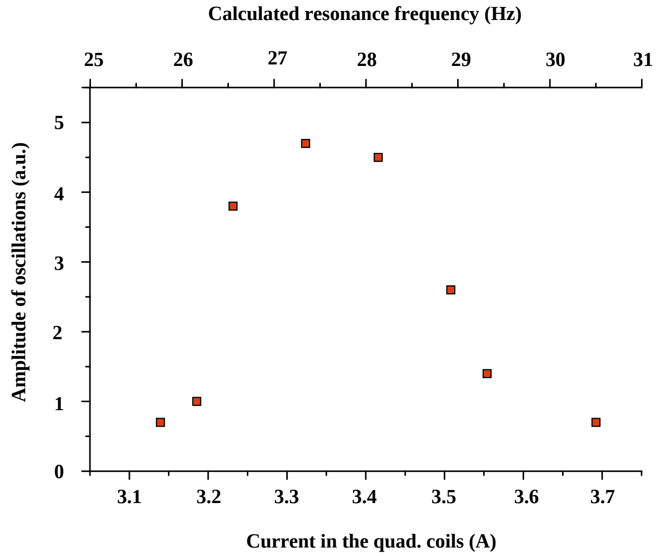

Fig. 3. Amplitude of oscillation of the atoms *versus* the current in the quadrupole coils with the modulation frequency kept constant at a value of 27.5 Hz. The upper scale shows the calculated resonance frequency at each value of the current. The width of the resonance is determined by the length of the modulation period (500 ms).

It is useful to evaluate our trap performance with a view towards Bose-Einstein condensation. Once the atoms have thermalized in the trap, they undergo one elastic collision every few seconds. This collision rate can be increased by adiabatic compression [10,11] of the atomic cloud. First, we are able to achieve continuous quadrupole fields with a gradient G of 1 kGauss/cm. This compresses the cloud in the radial directions and increases the collision rate by a factor of 3. Additional compression can also be achieved by decreasing the value of the bias field. Since all the excitations are coupled into the ferromagnetic structure, this also reduces the longitudinal curvature (along Z), limiting the maximum increase of the collision rate to 6:1 with the present geometry. This would allow us to reach the runaway evaporation regime for a trap lifetime of a few 100 s [12] ($P \leq 10^{-11}$ hPa).

In conclusion, we have demonstrated the transfer of 95% of ^{87}Rb atoms from a MOT to a magnetic potential generated by an iron-core electromagnet. This design should already allow Bose-Einstein condensation with an improved MOT source (ten times more atoms initially could lead to a 2 s^{-1} collision rate) and straightforward improvements of the vaccuum system. In addition, the electromagnet can be improved for both shorter switching time and better compression. For instance, employing laminated materials will allow us to eliminate eddy currents. Preliminary tests show that a 1 ms switching time is possible. In addition, better compression can be achieved with a shorter gap between the tips. Calculations show that initial collision rate higher than 30 s^{-1} can be achieved with our new design, allowing faster Bose-Einstein condensation with high atom number. We therefore think that magnetic traps of this type can be useful tools for the production, study and application of Bose-Einstein condensates.

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