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Cold Atoms close to surfaces: Measuring magnetic field roughness and disorder potentials

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Abstract.
Microscopic atom optical devices integrated on atom chips allow to precisely control and manipulate ultra-cold ($T < 1\mu K$) neutral atoms and Bose-Einstein condensates (BECs) close to surfaces. The relevant energy scale of a BEC is extremely small (down to $< 10^{-11}$ eV). Consequently, BECs can be utilized as a sensor for variations of the potential energy of the atoms close to the surface. Here we describe how to use trapped atoms as a measurement device and analyze the performance and flexibility of the field sensor. We demonstrate microscopic magnetic imaging with simultaneous high spatial resolution ($3\mu m$) and high field sensitivity ($4nT$). With one dimensional BECs, we probe the magnetic field variations close to the surface at distances down to a few microns. Measurements of the magnetic field of a 100 $\mu m$ wide current carrying wire imply that the magnetic field variations stem from residual variations of the current flow direction, resulting from local properties of the wire. These disorder potentials found near lithographically fabricated wires are two orders of magnitude smaller than those measured close to electroplated conductors.

1. Introduction
In recent years new tools for the precise control and manipulation of neutral atoms were developed, based on the adaptation of micro-fabrication techniques to atom optics and the implementation of the atom chip [1]. The atoms are held and manipulated microns above the surface using magnetic, electric and optical fields generated by micro fabricated structures on the chip. In a number of experiments various trapping, guiding and transporting potentials have been realized using current carrying wires [2, 3, 4, 5, 6, 7, 8, 9], atom manipulation with electric fields was integrated on an atom chip [10] and easy formation of Bose-Einstein condensates (BEC) was demonstrated [11, 12, 13, 14]. Atom chips combine the best of two worlds: The well established techniques of atomic physics and quantum optics and the capabilities of modern micro fabrication of electronic and optical devices are used to create a robust and simple toolbox for quantum manipulation of cold atoms and photons.

The full potential of the atom chip is only accessible if the potentials can be miniaturized to a scale of typically 1 $\mu m$ or below where appreciable tunneling rates between separated traps can be reached, and efficient atom-atom coupling between atoms in neighboring trap
sites [15, 16] can be achieved. While the fabrication of atom chips with structures < 1 µm is comparably simple [17], the atom surface interaction at these distances and energy scales is not well investigated. Magnetic noise potentials originating from thermal induced Johnson noise in the conducting surface layers limit the coherence and life time of the trapped atoms [18, 19]. In addition unintended potential roughness has been reported to severely alter the trapping at surface distances \(d\) below \(\sim 100\) µm, resulting in a longitudinal fragmentation of elongated clouds [20, 21, 22, 23]. The observed potential roughness can be attributed to an inhomogeneous magnetic field component \(\Delta B\) in the direction parallel to the current carrying wire creating the trapping field \(B\). It has been suggested that such field components could be derived from fabrication inhomogeneities, surface roughness [24, 25] and residual roughness of the wire borders [26]. The model of Wang et al. [26] provides a full quantitative explanation of the potentials found near electroplated gold wires [23].

In this paper we describe experiments using ultra cold atoms to investigate these potential landscapes close to a conducting surface of the atom chip. Using one dimensional (1d) BECs in exceptionally smooth potentials we design and demonstrate a new high resolution, high sensitivity magnetic field sensor [27], and use it to measure the potential roughness [28].

2. Atom chip experiments

Strongly confining trapping and guiding potentials on atom chips are formed by the subtraction of two magnetic fields: the field of a current carrying wire and a (homogeneous) bias field (side guide configuration [3]). The remaining field at the potential minimum is determined by the angle between wire field and bias field. A small change of the current direction may result in a significant change in the trapping potential. Inhomogeneous magnetic field components \(\Delta B\) in the direction parallel to the current carrying wire creating the trapping field \(B\) will result in a variation of the potential minimum along the guide. This fact is generally used to build traps for 3-dimensional confinement by bending the trapping wire. A U-shaped wire results in a quadrupole trapping field, a Z-shaped wire in an Ioffe-Pritchard type trap. Additional minute changes in the current direction will translate into potential modulations in the trap or guide.

In our experiment, more than \(10^8\) \(^{87}\)Rb atoms are accumulated a few mm from the chip surface which serves directly as a mirror for a reflection magneto-optical trap (MOT) [4]. These atoms are subsequently transferred to a purely magnetic trap and cooled to \(\sim 5\) µK by radio frequency (RF) evaporation. Both the MOT and the magnetic trap are based on copper wire structures mounted directly underneath the chip [29]. The resulting sample of \(> 10^6\) atoms is then loaded to the selected chip trap and location, where a second stage of RF evaporative cooling creates either a BEC or thermal cloud just above the critical condensation temperature. In our apparatus, we produce BECs in the one-dimensional Thomas-Fermi (1dTF) regime [28] in which the transverse ground state energy exceeds the chemical potential \(\mu\) while the longitudinal energy scale is dominated by \(\mu\) \((\hbar \omega_\parallel \ll \mu \ll \hbar \omega_\perp\)).

We image the atomic clouds near the surface in situ by resonant absorption imaging with \(\sim 3\) µm resolution. In order to determine the cloud's distance from the surface \(d\), we slightly incline the imaging light with respect to the chip mirror surface by \(\sim 25\) mrad. For sufficiently small \(d\) (< 100 µm) this leads to a duplicated absorption image [14] (Fig. 1). Using these duplicated images we can calibrate the trap parameters with measurements at sufficiently large \(d\). For distances smaller than the imaging resolution we use the calibrated values of the bias fields together with the measured wire currents to infer \(d\) with high precision.

3. Measuring small potential roughness

Cold atoms are well suited to serve as highly sensitive magnetic field sensors. At ultra-low temperatures the atoms accumulate at potential minima and are therefore very sensitive to changes of magnetic field landscapes, even in the presence of large homogeneous offset fields.
Figure 1. left Distance $d$ of the BEC from the chip surface as a function of wire current (100 $\mu$m$^2$ wide wire). Atoms produce a double image when illuminated by an inclined imaging beam (a,c). The reflection of the imaging beam from the chip surface produces a fringe pattern that makes measurements less reliable for certain surface distances (b). For clouds closer than $\sim 5$ $\mu$m from the surface, the two images merge (d). The solid line is a model taking the finite size of the wire into account.

right Longitudinal potential profiles measured with BECs at a constant distance of $d = 10$ $\mu$m from the surface of the 100 $\mu$m broad wire. The different traces were measured at different currents and are normalized to the respective trapping fields. The bias field (10 G, 20 G, 30 G; black dotted, solid green, dashed red lines, respectively) was adapted in order to keep $d$ constant. The insert shows a histogram of the deviations of the curves. The width of the distribution ($\sigma \sim 8 \times 10^{-6}$) is similar to the shot to shot variations of different realizations of the same experiment with equal wire currents.

For thermal atomic ensembles, the relevant energy scale and hence the sensitivity is given by the temperature $T$ of the trapped cloud. A temperature of 1 $\mu$K corresponds to $10^{-10}$ eV, the energy of the Bohr magneton ($\mu_B$) corresponds to a temperature of 67 $\mu$K. For thermal atoms, the local density in a 1d trap is then given by the Boltzmann distribution [23]:

$$n \sim \exp(-V/k_B T)$$

(1)

In a degenerate Bose quantum gas, the atoms accumulate in the Bose-Einstein condensed phase in the ground state of the potential. In this case, the relevant energy scale is given by the chemical potential, and that can be orders of magnitude smaller then the temperature ($\mu \ll k_B T$). Therefore BECs are a much more sensitive probe of the local potential than thermal atoms. The potential can be derived from the density distribution of the atoms using the Goss-Pitaevski equation. If the confinement is one dimensional (1d), i.e. the transverse single particle ground state energy exceeds the chemical potential $\mu$ of the BEC ($\mu < \hbar \omega_\perp$), the situation is much simpler. The actual potential experienced by the atoms can then be reconstructed according to

$$V(x) = -2\hbar \omega_\perp a_{\text{scat}} n_{1d}(x)$$

(2)

where $a_{\text{scat}}$ is the scattering length ($a_{\text{scat}} \approx 5.2$ nm for $^{87}$Rb). The above expression is derived under the assumption of a constant (global) $\mu$ in the 1dTF approximation [30]. By imaging its density profile, the potential energy and hence the local magnetic field is directly measured.
For the measurements the ultra cold atomic cloud or the BEC is trapped in an elongated magnetic micro trap with strong transverse and weak longitudinal confinement. In our atom chip experiments the traps can be designed in such a way that even a BEC with a low chemical potential $\mu$ stretches over a large length on the order of 1mm (trap aspect ratios of up to 5000). The position of the trap can be accurately controlled by adjusting the trapping wire current and both magnitude and direction of the bias field. For $n_{1d} < 100 \mu m^{-1} \left( ^{87}\text{Rb atoms} \right)$, the confinement of the BEC is one dimensional, and the simple relations described above can be used to extract the potential profile from the linear (1d) density. For a quantitative analysis of the potential landscape along the trapped atom cloud, we extract longitudinal density profiles $n_{1d}$ from the in situ absorption images and calibrate them with the absolute atom number derived from time-of-flight images taken under equal experimental conditions.

The 1dTF approximation is strictly valid only in an equilibrium state of the system. This may not be the case in our experiment over the entire length of the BEC ($\sim 1$ mm). Similar to the observations previously made in an optical dipole double well potential [31], a variation of $\mu$ on longitudinal length scales $> 200 \mu m$ is maintained longer than the life time of the BEC if strong potential barriers separate the different fragments of the condensate.

The sensitivity to potential variations in a single shot measurement is given by the detection noise which in principle is limited by atom shot noise. In our present measurements, we find a single shot sensitivity for a field measurement of $\Delta B = 4nT$ which corresponds to a potential energy change of $\Delta U \sim 10^{-13}eV$. This sensitivity is reached at an offset field of 10G, thus the relative detected inhomogeneities are $\Delta B/B = 4 \times 10^{-6}$.

We have probed the residual potential roughness for various trapping geometries based on a 100 $\mu m$ and several 10 $\mu m$ wide wires at atom-surface distances down to 3 $\mu m$. The global parameters of the atomic cloud like atom number and temperature are determined by the ballistic expansion of the cloud in time-of-flight measurements.

With thermal atoms we always observe smooth longitudinal absorption profiles inside the trap, independent of the wire used to form the trap and the position of the atomic cloud. For the closest approach of $d = 3 \mu m$, a cloud at $T = 1 \mu K$ remains unfragmented within our detection resolution, even when summing up many realizations of the experiment to reduce measurement noise. Assuming that the atomic density profile follows the Boltzmann distribution $n \sim \exp(-V/k_BT)$, we can set an upper limit to the residual magnetic field roughness $\Delta B/B < 2 \times 10^{-4}$ where $B$ is the field produced by the wire at the distance of the measurement site from the surface.

In order to measure the field roughness on a smaller scale, we use BECs. The inserts of Fig. 1 show absorption profiles of BECs at various heights $d$ above the 100 $\mu m$ wide wire. As the surface is approached, the longitudinal trapping potential becomes flatter, thus the BECs extend over a longer stretch of the wire. As $d$ is increased, the strength of the disorder potentials is reduced and the typical length scale of fragmentation increases. For $d > 30 \mu m$, virtually no fragmentation is detected, even with a BEC. Altering the longitudinal confinement by varying the current in an independent auxiliary wire leads only to an overall displacement of the cloud while the local disorder potential variations remain stable in their positions. Over many months of experiments no change was observed in the position of the fragments.

4. Magnetic field imaging

We now extend this concept and show how BECs can be used to probe magnetic field landscapes in general. The possibility of reaching high spatial resolution and field sensitivity in a single measurement makes this technique appealing for a variety of applications.

Figure 2 illustrates the operation principle of a 1d BEC as a field sensor. The BEC is trapped at the measurement site in an elongated magnetic micro trap with strong transverse and weak longitudinal confinement. By imaging its density profile in situ, the potential energy and
Figure 2. right Experimental schema of the magnetic BEC microscope. (a) A BEC is trapped by a current-carrying wire mounted on a silicon surface and can be arbitrarily positioned above a sample to be probed. The position of the trap can be precisely controlled by tuning the current in the wire and the direction and magnitude of the external homogeneous offset field, e.g. directly above the trapping wire (i) or close to an independent sample (ii) (see insert). Irregular current flow in this sample or other local potentials (for example electric fields) lead to a modulation of the longitudinal trapping potential.

left Two-dimensional scan of the magnetic landscape above a 100µm wide and 3.1µm tall gold wire. (a) Z-component of the magnetic field (B_{IP}) 10µm above the current carrying wire from 28 equally spaced traces covering the full width of the wire. (20G bias field and I_{w}=340mA) (b) Reconstructed x-component (j_x) of the 2d current density as obtained by inverting Biot-Savard’s law. (c) Calculated magnetic field map from the reconstructed current density. The visible smoothing arises from filtering the experimental data in Fourier space.

hence the local magnetic field is directly measured. The position of the trap can be accurately controlled by adjusting the trapping wire current and both magnitude and direction of the bias field (inset figure 2left). Scanning the magnetic field landscape over large spatial volumes (~mm³) is possible simply by scanning the position of the BEC. The density distribution of the trapped BEC is imaged by high resolution (3µm) in situ absorption imaging. From the measured density profiles we reconstruct 1d magnetic field profiles according to the procedure outlined above.

As a demonstration of our magnetic imaging, we have extended the measurements described above and probed the field formed by the trapping wire over its full width. The image depicted in Figure 2right is obtained by scanning the position of the BEC over the entire width of the 100µm trapping wire in a plane parallel to the wire (chip) plane at a surface distance of 10µm. While the condensates extend over a large longitudinal stretch of the wire (~1mm), they can be transversely positioned to a high accuracy. In order to derive a full two-dimensional magnetic image, we have formed condensates at 28 equally spaced transverse positions above the wire covering a width that slightly exceeds that of the wire. The transverse positioning is achieved by adjusting the magnitude and direction of the homogeneous bias field orthogonal to the wire current. This affects only the position of the measurement but not its result since n_{1d}(z) is sensitive only to the longitudinal field B_{IP}(z). The fact that the nominal wire field is exactly compensated at the trap position makes our technique applicable for arbitrary wire currents. Additional images taken from a direction close to perpendicular to the chip (mirror) surface
allow to calibrate the transverse position relative to the wire edges with a precision exceeding our optical imaging resolution of $\sim 3\mu m$.

We have reconstructed traces of the magnetic potential variations at each of the transverse positions and combined them to obtain the complete two-dimensional magnetic landscape for the variations in the longitudinal magnetic field component shown in figure 2(a). As an application of our magnetic imaging close to a flat current carrying wire we have reconstructed the local current flow in the conductor. Its current profile is shown in figure 2 right together with the corresponding field image. It is obtained by a deconvolution method that allows to invert the problem of deriving magnetic fields from a known current flow. We find the angular deviations from the straight current path to be very small ($2 \times 10^{-4} \text{ rad rms}$).

This technique can not only be applied to study magnetic fields of slightly irregular currents through the wire forming the trapping potential itself but also to independently created fields. The smoothness of our trapping wires makes it possible to confine 1dTF condensates so that the residual field roughness is not visible and therefore negligible with respect to an arbitrary independent potential profile to be probed. We have investigated this by placing a condensate close (down to 5$\mu m$) to an independent wire structure. As long as this wire is grounded and carries no current, the atomic density profile is homogeneous within the detection sensitivity corresponding to an upper bound in potential roughness of $\Delta U \leq k_B \times 200pK \approx 10^{-14} \text{eV}$. As soon as a small current ($\sim 5\text{mA}$) is passed through the wire, a characteristic field profile is detected.

Besides magnetic potentials we have also imaged electric fields using an elongated BEC as sensor. The relevant interaction potential is $U = -\frac{1}{2}\alpha E^2$ in this case (polarizability $\alpha$). We have applied this technique to detect the small electric potential differences on a gold surface stemming from patch effects. It is hence possible to image local electric fields with high resolution. This last example shows that BECs in microtraps can be used as probes for small potential variations of an origin other than magnetic.

5. Sensitivity of the BEC potential sensor

The optimal potential single shot sensitivity $\Delta U$ of a BEC as field sensor is reached by detecting the density distribution atom shot noise limited. The detection sensitivity depends also on the desired spatial resolution that is not necessarily equal in the longitudinal ($z_0$) and transverse ($\rho_0$) directions. Ideally, the trap parameters are chosen such that the transverse ground state size is equal to $\rho_0$ and a section of length $z_0$ of the atom cloud is imaged onto one pixel. This optimal situation leads to a sensitivity of $\Delta B = \gamma \Delta N/(\rho_0^2 z_0)$ where $\Delta N$ is the minimal atom number variation that is resolved by the imaging system and contains the atomic properties ($\gamma = 8.63 \times 10^{-29} \text{Tm}^3$ for $^{87}\text{Rb}$ atoms in the $|F = 2, m_F = 2\rangle$ state). Currently commercially available CCD-cameras together with standard optics and laser systems allow to reach atom shot noise limited detection with at least $\Delta N \sim 10$ atoms/pixel in absorption imaging, so that even at high spatial resolution of $\rho_0 = z_0 = 1\mu m$ a sensitivity of $\Delta B = 1\text{nT}$ is possible. By changing to a different atom with higher mass and/or by tuning the scattering length $a_{\text{scat}}$ to close to zero using a Feshbach resonance, a significant increase in sensitivity can be achieved.

A comparison of different magnetic field measurement techniques (figure 3) shows that BECs as magnetic sensors potentially reach unprecedented sensitivity over a large spatial resolution range. Magnetic Force Microscopes (MFMs) and hall probes operate at a high spatial resolution whereas SQUIDs and thermal atom magnetometers offer high field sensitivity. The demonstrated BEC sensor allows mapping of magnetic fields in an intermediate parameter range. Even the example measurements performed at the current experimental parameter settings reach sensitivities orders of magnitude higher than those obtained with established techniques operating at the same spatial resolution. Using a shot noise limited atom detection of 100 atoms ($\Delta N = 10$) as achieved in our experiments we estimate a sub-nT field sensitivity at a spatial
resolution of 500nm. The optical resolution is limited to approximately this value if blue laser light is used. The best field sensitivity is estimated to be 1pT at a spatial resolution of 10µm (corresponding to 1Hz transversal oscillation frequency). For even higher field sensitivity (dashed line) and thus low oscillation frequencies, long trap lifetimes are required to reach equilibrium. To estimate the potential sensitivity of the BEC sensor (solid line in fig) a shot noise limited atom detection of 100 atoms (ΔN = 10) has been assumed.

6. Origin of disorder

For a quantitative analysis of the structure of the potential roughness, we first extract the longitudinal density profiles n_{1d} from the in situ absorption images as described above. Most importantly we then confirm the validity of the 1d TF-approach by monitoring the n_{1d}(x) profile over the entire lifetime of the condensate. We observe that the reconstructed potential fluctuations at wavelengths smaller than ~ 200 µm remain independent of the value of the chemical potential µ of the 1d BEC used. At larger length scales the chemical potential can vary with position and direct comparison at these length scales is difficult. We thus limit the further analysis to length scales shorter than 200 µm.

To assess whether the observed disorder potentials are magnetic in origin we have varied the wire current while adapting the bias field so that the BECs were trapped at fixed distances from the wire. We found the observed disorder potentials to scale linearly with the current in the wire I (figure 1). Comparing the shot to shot variations of ΔB/B with equal currents to those with different currents we conclude that within the statistical similarity of the distributions (ΔB/B ∝ 3 × 10^{-6}), one can exclude current independent sources of disorder potentials such as electrostatic patch effects [38] at the scale of 10^{-13} eV for d > 5 µm. Consequently the disorder potentials are created by an irregular current flow in the wire.

In order to study the source of the irregular current flow we have additionally measured the variation of the disorder potentials with height d over a large range. Wires of two different widths, 10 µm and 100 µm, were used. The main observation is that even for small heights (d ≪ 50µm) the scaling of the amplitude and the frequency spectrum of the disorder potentials for the two wires are very similar.

For the 100 µm wide wire, Fig. 4 shows potential spectral densities (PSD) of the disorder potential at three different spatial frequencies k. In the examined d-range, the potentials scale more strongly with d than they would for dominating edge fluctuations [26] for all frequency components. We interpret the clear difference in slope of the experimental data and the wire edge model as an indication that local current path deviations are important. Such deviations
Figure 4. Spectral power density of the disorder potentials near the 100 µm wide wire for three spatial frequencies. The solid lines are best fits according to a local fluctuating current path model, the dashed lines show best fits to the model outlined in [26]. For both models the only fitting parameter is the strength of current path fluctuation at the respective spatial frequency $k$. Data where the complete depth of the potential depth could not be measured (open symbols) were omitted in the analysis.

can occur due to in homogeneous conductivity or top surface roughness [24, 25].

The simplest model taking local sources of current path deviations into account is a current flowing along a narrow irregular path below the atoms\(^1\). Such a model gives reasonable agreement in the slope of the PSD as $d$ is increased as can be expected as long as $d$ is small compared to the relevant period $1/k$. Applying this method over the full spectrum ($k > 1/200 \mu m^{-1}$), we obtain a local current flow fluctuation spectrum that scales as $\sim 1/k^2$. Microscopically well characterized wires will have to be fabricated and tested to develop a more refined model explaining the disorder potentials caused by local current deviations.

From our data and the simple local model we can estimate the rms strength of the relative disorder potential and scale it to different heights. At a surface distance of $d = 10 \mu m$ we find the rms $\Delta B/B = 3 \times 10^{-5}$ ($< 10^{-5}$) for spatial frequencies $k > 1/200 \mu m^{-1}$ ($k > 1/50 \mu m^{-1}$). At $d > 30 \mu m$, where disorder potentials near electroplated wires have been measured, $\Delta B/B$ is significantly smaller than the measurement sensitivity in our case ($5 \times 10^{-6}$). This corresponds to a reduction by about two orders of magnitude.

7. Conclusion

Atom chips provide an environment with ample flexibility for the design and implementation of tailored potentials for complex matter wave manipulation. We have shown that this flexibility allows to utilize Bose-Einstein condensates as sensitive high resolution sensor of magnetic field and other potential landscapes. In demonstration experiments we have measured fields with a sensitivity ($\sim 4$ nT) that cannot be reached at the same spatial resolution ($\sim 3\mu m$) by conventionally used methods. We are able to position the condensates at a wide range of transverse positions at various distances from surfaces (down to single microns) and image the atomic density profile inside the trap. From these profiles, the field profile can be directly derived. Optimal parameter settings are shown to provide means to measure magnetic fields and other field variations (for example electric fields) with a magnetic field sensitivity that is more than two orders of magnitude higher than previously demonstrated with alternative methods operating at high spatial resolution.

We have applied this technique to investigated magnetic disorder potentials near lithographically fabricated current carrying wires using quasi 1d BECs. The measured potentials are orders of magnitude smaller than previously observed in other atom chip experiments, which we attribute to our different chip fabrication method resulting in much smoother and much more homogeneous wires. We have characterized the residual extremely small modulations in the manipulating potentials in detail. The analysis shows that their origin are deviations of

\(^1\) This is equivalent to using the wire edge model mentioned above but with a very small wire width and equal current.
the current flow in the microwires from its nominal path. The irregularities cannot only be attributed to wire edge roughness, so that local effects are shown to contribute significantly. A strong scaling of the magnetic field fluctuations with spatial frequency indicates a dominance of large scale inhomogeneities which can be dealt with by improving the fabrication. The smallness of high frequency fluctuations opens up the way to μm scale quantum manipulation on atom chips.

We are convinced that BECs as magnetic field imaging sensors can be used as a technologically and scientifically relevant tool, for example to obtain a deeper understanding of the local current flow in superconductors and two-dimensional electron gases.

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