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Optimized magneto-optical trap for experiments with ultracold atoms near surfaces

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We present an integrated wire-based magneto-optical trap for the simplified trapping and cooling of large numbers of neutral atoms near material surfaces. With a modified U-shaped current-carrying Cu structure we collect more than 3×10^8 ^{87}Rb atoms in a mirror magneto-optical trap without using quadrupole coils. These atoms are subsequently loaded to a Z-wire trap where they are evaporatively cooled to a Bose-Einstein condensate close to the surface.

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Recent progress in the field of trapping and manipulating atoms in micropotentials has significantly improved the possibilities of investigating the interaction of trapped atoms with material objects. Newly available techniques allow, for example, to bring cold neutral atoms close to surfaces and use them as highly sensitive local probes of electric and magnetic surface potentials. In this context, both the effects of thermally induced currents (Johnson noise) [1] and of disorder in surface structures [2] have been studied theoretically. The first indications of such disorder potentials have already been observed experimentally [3,4] and some effects attributed to Johnson noise have been measured in various materials [5].

Similarly, structuring surfaces allows one to tailor potentials for the atoms with a resolution of the order of the atom-surface distance. This distance can be in the micron range, possibly below. In this way, integrated devices for the controlled manipulation of matter waves, so called atom chips, can be built. Atom chips combine the potential of microfabrication technology, i.e., to create nearly arbitrary structures for detailed and robust atom manipulation, with the ability of a controlled quantum evolution developed in atomic physics and quantum optics. They pave the path to many applications ranging from fundamental physics of mesoscopic atomic systems and issues of low dimensionality to implementations of quantum information processing [6,7].

The starting point of many of these experiments is a cloud of ultracold atoms, ideally a Bose-Einstein condensate (BEC), close to the surface. The cloud has to be formed *in situ* or be transported to the experimental region. Here, we present an important simplification of this process that is particularly well suited for an efficient production of BEC samples near surfaces. We demonstrate that a large number ($>3\times10^8$) of ^{87}Rb atoms can be collected in a modified wire-based magneto-optical trap (MOT) located just millimeters above the reflecting surface in a simple dispenser loaded setup under ultrahigh vacuum (UHV) conditions ($<10^{-11}$ mbar). This allows one to subsequently transfer the atoms into a Z-shaped wire trap [8–10] that is used to cool atomic samples into the Bose-condensed phase [11].

A MOT requires laser light forces from all directions. Consequently, placing a MOT close to a surface implies that either the surface and the laser beam diameters have to be small enough relative to the height of the MOT above the surface or that the surface is transparent or reflecting. The problem of a material object (partially) obstructing the access of the six beams used in a conventional MOT has also been circumvented by producing the MOT [12] or even the condensate [13] elsewhere and transfer it to the chip by means of dynamic magnetic fields [12] or optical tweezers [13]. The alternative is to directly load a *mirror* MOT [9,14–16] only millimeters away from a reflecting surface that acts as a mirror. In this configuration, at least one of the MOT beams is reflected off the mirror. In the simple version used in many atom chip experiments [4,9,16], two of the regular six MOT beams are replaced by reflections of two beams impinging upon the mirror [18] at an angle of 45°. To ensure the correct quadrupole field orientation with respect to the helicities of the light beam pairs, the quadrupole field axis has to coincide with one of the 45° light beams. Up to now, this had to be considered a drawback since the coils usually employed to provide the field are bulky, dissipate a large amount of power, and deteriorate the optical access to the MOT itself and to the region where the experiments are carried out. As experimental setups are likely to grow more complex in the future, including quadrupole coils in the setup will present a major obstacle. Apparatus involving cryostats aiming at a significant reduction of thermal current noise in conducting surfaces [1] are just one example.

A known way of approximating a quadrupole field is to use a current carrying wire that is bent in a U shape together with a homogenous bias field parallel to the wire plane and perpendicular to the central bar of the U [6]. Figure 1(b) shows the field configuration obtained in comparison to a field created by external coils in the common anti-Helmholtz configuration [Fig. 1(a)]. But a MOT based on a simple U-shaped wire cannot be used for an efficient collection of a large number of atoms (for example, from the background Rb vapor). This is caused by the fact that the U-wire field is only a true quadrupole field near the field center (point of vanishing field). Further out there is a nonvanishing angle between the quadrupole axes and the field lines [Fig. 1(d)]. This angle increases at larger distances from the field zero,

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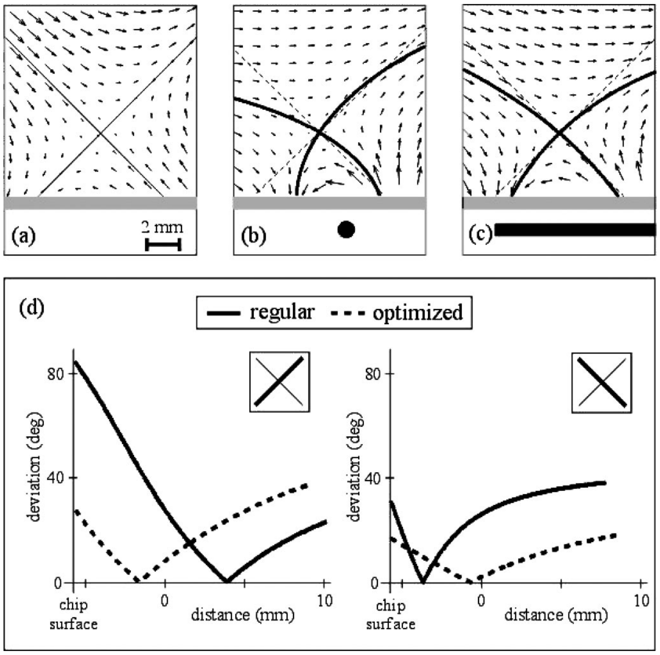

FIG. 1. Vector plots of different field configurations. The solid (dashed) lines indicate the axes of the approximated (ideal) quadrupole fields. (a) Ideal quadrupole field, (b) regular U-wire quadrupole field with untilted bias field, (c) optimized U-wire quadrupole field. The bottom parts of (a)–(c) show a cross section of the wire (black), the substrate, and the surface above it (gray). (d) Angular deviations from the ideal quadrupole axes are plotted as a function of the distance from the reflecting surface along the two 45° light beam paths [dashed lines in (b) and (c)]. The solid (dashed) lines correspond to the regular (optimized) U-wire configuration. The zero point of the position axes is chosen to be the center of the quadrupole field (field zero). The broad wire U clearly approximates the ideal quadrupole field better throughout a larger spatial region than the thin wire U. The parameters chosen in these examples were $I_{U-wire}=55$ A, $B_{\|}=14.5$ G (12.8 G) in the plane parallel to the wire and $B_{\perp}=0$ G (3.0 G) perpendicular to the wire for the regular (optimized) U.

i.e., the MOT center, and eventually the direction of the field vectors is even reversed. As the operation principle of a MOT relies on the correct orientation of the fields with respect to the polarization of the laser light in each beam, the effective capture region of the trap and thus the loading rate and the maximum number of atoms in the MOT are limited. Consequently, the U-MOT [19] has to be loaded from a regular quadrupole coil MOT in order to collect a large number of atoms.

However, by altering the geometry of the U-shaped wire, a much better approximation of a quadrupole field can be obtained: The bent field lines in the case of a simple U wire can be attributed to the fact that a thin wire produces a field whose field lines are circles. Consequently, the simplest way to overcome this is to fan out the current flow through the central part of the U by replacing the thin wire by a broadened plate. Inclining the bias field with respect to the plane formed by the outer leads of the U improves the field configuration further. If the plate is inclined and if the shape of the current flow through the plate is adjusted properly, the resulting field will approximate an ideal quadrupole field even more closely.

We chose to set the last two possibilities aside in our experiment, mainly because they lead to only marginal improvement compared to the wide U, and they are more difficult to implement. Figure 1(c) shows the field vectors of the quadrupole field obtained with a modified planar U-shaped wire. The various parameters (geometry, wire current, and bias field) were optimized numerically to achieve typical field gradients (10–20 G/cm) of a MOT at a height of 6–8 mm above the wire center (4–6 mm above the chip surface) while maintaining small angular deviations of the field from an ideal quadrupole field throughout the maximal capture region given by a typical light beam diameter of 2 cm. A comparison of the field configurations of the U-wire quadrupole field with the ideal field shows no significant differences in the planes not shown in Fig. 1. Only the field gradients deviate from those obtained in a conventional quadrupole configuration: In the direction parallel to the central bar of the U-shaped wires, the gradients are weak while those in the transverse directions are of approximately equal magnitude. The gradient ratios for the regular (optimized) U wire are $\sim 1:4:5 (\sim 1:3:4)$, for the ideal quadrupole field, $1:1:2$. Gradient ratios, however, are not critical for a MOT operation. In fact, this can even be an advantage because the aspect ratio of the MOT cloud is better matched to the magnetic microtraps. With our configuration, it turns out that moderate wire currents of 50–70 A at small power consumptions (<1 W) and small bias fields of 7–13 G [20] are sufficient to create a near to ideal quadrupole field at a variable height above the chip surface. The residual angles of the field vectors are small enough to lie within the tolerance of a MOT, as was tested by rotating the light polarizations in an external MOT experiment. The MOT remained unimpaired for elliptical polarizations corresponding to deviations of the field line direction of up to 40° from the ideal situation.

In our experimental implementation we use a U-wire structure that has been machined out of a single copper piece. This structure is incorporated in a MACOR ceramics block holding an atom chip. Between chip and central part of the U, a small space was left to allow the placement of another copper structure that contains several Z-shaped wires for magnetic trapping for BEC production [Fig. 2(b)]. In order to keep ohmic heat dissipation as low as possible while allowing currents of up to 100 A, a wire cross section of at least 7 mm^2 is maintained all over the U-wire structure. The 3×3 mm^2 leads are thicker than the plate (thickness $\times$ width $\times$ length $=0.7\times 10\times 18$ mm^2) to ensure a homogenous current density in the plate [Fig. 2(c)]. Isolated by a thin (100 μm) Kapton foil, the 1 mm thick additional structure for purely magnetic trapping is positioned on top of the plate. The geometry of this structure resembles an H with two extra leads connected to the central bar. This allows to run currents through a variety of Z-shaped wires with a (center to center) length of the central bar ranging from 4 mm to 10 mm by choosing the proper connectors. The U- and the H-shaped structures were designed in such a way that their surfaces lie in a common plane so that an atom chip can be mounted directly on top of both structures. The copper struc-

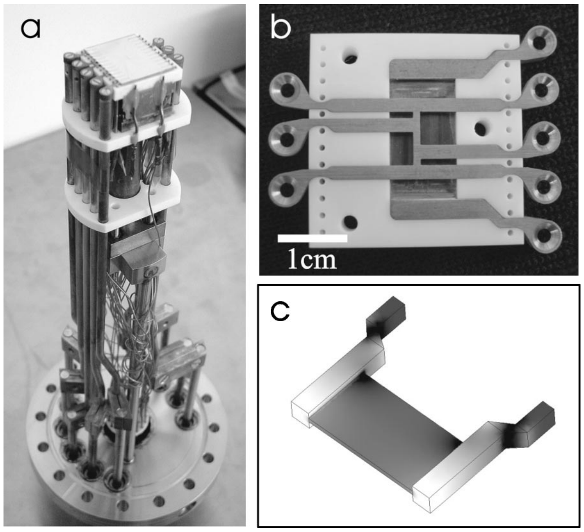

FIG. 2. (a) Atom chip assembly: The U-wire structure for the MOT and an additional structure containing Z-shaped wires in several sizes are connected to high-current vacuum feedthroughs. The atom chip is mounted directly on top of these wire structures. (b) Photograph of the wire structures fitted into a MACOR ceramics holder. (c) Results of a numerical calculation of the current-density distribution in the U wire. Dark (light) shades correspond to high (low) current densities. The thick connecting leads ensure a homogenous fanning out of the current through the central plate as it is needed to improve the quadrupole field for the MOT.

tures are connected to high current vacuum feedthroughs by simple screw contacts, the chip wires are attached to pin connectors by a bonding technique.

The complete assembly with the current connections, the wire structures for the MOT and magnetic traps, and the atom chip [Fig. 2(a)] is built into a UHV chamber [21] that was constructed to allow good optical access to the experimental region directly above the surface of the chip. This was realized by including optical quality quartz windows in an octagonally shaped stainless steel body. The distance from the outer surfaces to the experimental region is 4 cm and 10 cm for the directions perpendicular and parallel to the chip surface, respectively. As a source for rubidium atoms we use three dispensers that are connected in parallel. A high pumping speed in combination with a pulsed operation mode of the dispensers facilitates sufficient loading rates of the MOT of typically 3×10^7 atoms/s while the rubidium background vapor is quickly reduced in the purely magnetic trapping phase of the experiment.

Typically, we operate the MOT at a U-wire current of 60 A and a bias field of 13 G, i.e., at magnetic-field gradients of 5 G/cm (20 G/cm) along the axis of weakest (strongest) confinement. In order to confirm the effect of the improved quadrupole field on the MOT, we have compared a MOT formed by a thin U-shaped wire with the broad wire U-MOT. The change in geometry yielded an improvement factor of 10 in atom number in the MOT in our experiment. Inclining the bias field further enhances this number by a factor of 2–3. Figure 3 shows the measured atom number in the MOT as a function of the angle between the bias field and the plane of the modified U-shaped wire. The corresponding quadrupole fields for specific angles are shown. The dependence of the number of atoms on the quality of the approximation of a true wide range quadrupole field is clearly visible: The MOT contained the highest number of atoms (3×10^8) for the optimal quadrupole field that is obtained at a 13° inclination of the bias field. To compare the results of the U-MOT, we carried out test experiments with a conventional six-beam MOT before introducing the atom chip assembly in the apparatus. Neither the loading rates nor the maximum number of trapped atoms exceeded those measured with the U-MOT under similar UHV conditions. Thus we conclude that a modified U-MOT can replace a conventional MOT completely.

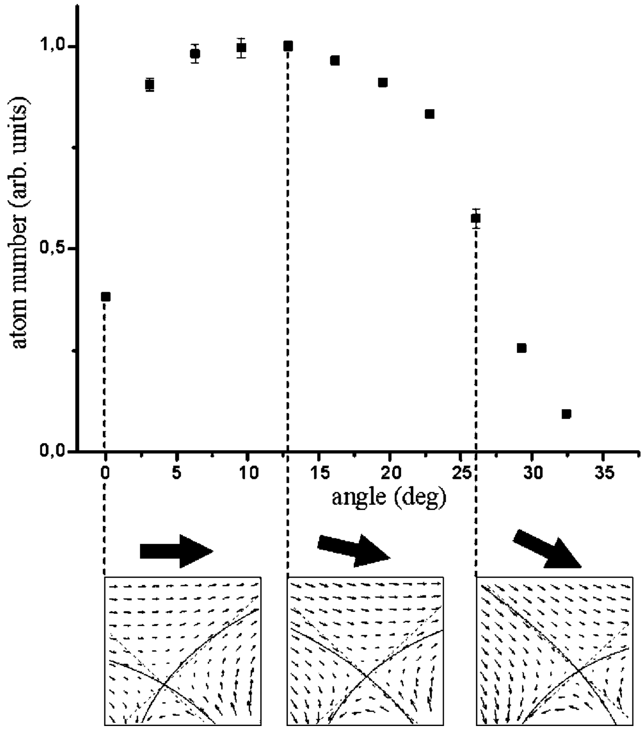

FIG. 3. Top: The number of atoms is plotted vs the tilting angle between the bias field and the plane of the broad U-shaped wire. For these measurements the U current was 55 A, the bias field strength 13 G. Bottom: corresponding vector field plots for three different angles (0°, 13°, and 26°) as indicated by the arrows. The maximum number of atoms is trapped at a bias field angle of 13° where the shape of the field is closest to an ideal quadrupole field. Note that this optimal trap position is not centered above the wire center.

After loading the U-MOT from the Rb background pressure, we turn off the dispensers while leaving both light and magnetic fields of the MOT on for 5 s. During this period, the dispensers are cooled efficiently through their Cu rod connectors (6 mm diameter) while the pressure in the chamber is quickly reduced by the pumps. In the next step, the atoms are molasses cooled to $\sim30\ \mu$K and optically pumped to the $|F=2,m_F=2\rangle$ state. This allows to transfer up to 2×10^8 atoms to a magnetic trap (lifetime >30 s) that is formed by the H-shaped integrated Cu structure. In the configuration used, the current runs through the innermost possible Z-shaped path where the length of the central bar of the

Z has a length of 4 mm. This trap is operated with a current of 60 A through the wire and a bias field of initially 41 G. The bias field is rotated within the plane parallel to the Z wire by approximately 42° in order to compensate the strong longitudinal field of the two leads of the Z wire such that only a small Ioffe field remains at the trap minimum position. The trap is compressed by increasing the bias field to 60 G while forced evaporative cooling through a linear radio frequency sweep is applied. The trap frequencies are $\omega_{tr} = 2\pi \times 150$ Hz ($\omega_{tr} = 2\pi \times 1.5$ kHz) and $\omega_{lo} = 2\pi \times 35$ Hz ($\omega_{lo} = 2\pi \times 50$ Hz) for the uncompressed (compressed) trap along the transverse and longitudinal axes, respectively. During the compression, the transverse trap gradient is increased from 190 G/cm to 450 G/cm. After 15 s of evaporative cooling, a Bose-Einstein condensate of approximately 10^5 atoms forms at a distance of 400 μm from the chip surface. The details of this process are very similar to the ones presented in Refs. [11,17].

To conclude, we have introduced an important simplification of experiments with ultracold atoms near surfaces. The loading and cooling of atoms all the way to a BEC can be achieved by exclusively using integrated structures and small external homogeneous bias fields. To demonstrate this, we have designed and tested a simple Cu structure that can be fitted underneath any reflecting thin (up to several millimeter thickness are tolerable) planar surface.

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[18] In our experiments with atom chips, the microstructures creating the potentials manipulating the atoms are directly fabricated into the reflecting gold surface used as the mirror.
[19] This simple type of U-MOT is typically used as an intermediate experimental stage because it can be aligned to surface patterns by construction and it allows a simple compression of the atomic cloud as it is lowered towards the surface by increasing the homogenous bias field.
[20] To produce homogenous fields of this strength, currents of a few amperes in Helmholtz coils outside of the vacuum chamber are sufficient. These coils can even be replaced by integrating a current sheet into the ceramics block.
[21] The vacuum system reaches a base pressure of below 7×10^{-12} mbar and is pumped by a combination of a Ti sublimation pump and a 300 l/s ion pump.