

## Trapping and Manipulating Neutral Atoms with Electrostatic Fields

P. Krüger,<sup>1,\*</sup> X. Luo,<sup>1</sup> M.W. Klein,<sup>1</sup> K. Brugger,<sup>1</sup> A. Haase,<sup>1</sup> S. Wildermuth,<sup>1</sup> S. Groth,<sup>1</sup> I. Bar-Joseph,<sup>2</sup>  
R. Folman,<sup>1</sup> and J. Schmiedmayer<sup>1</sup>

<sup>1</sup>*Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany*

<sup>2</sup>*Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel*  
(Received 17 June 2003; published 2 December 2003)

We report on experiments with cold thermal <sup>7</sup>Li atoms confined in combined magnetic and electric potentials. A novel type of three-dimensional trap was formed by modulating a magnetic guide using electrostatic fields. We observed atoms trapped in a string of up to six individual such traps, a controlled transport of an atomic cloud over a distance of 400  $\mu\text{m}$ , and a dynamic splitting of a single trap into a double well potential. Applications for quantum information processing are discussed.

DOI: 10.1103/PhysRevLett.91.233201

PACS numbers: 39.90.+d, 03.75.Be

The controlled manipulation of cold neutral atoms in potentials created by substrate mounted microstructures has been progressing rapidly in recent years [1]. A variety of atom optical devices, e.g., tightly confining traps and guides [2,3], beam splitters [4], and mirrors [5] have been realized on such *atom chips*. Issues of current investigations include the behavior of Bose-Einstein condensates (BEC) in atom chip potentials [6], the coherent quantum dynamics and decoherence processes in traps and guides near surfaces [7,8], and the integration of new components for the preparation, manipulation, and detection of atomic quantum states [9].

In this Letter, we present the integration of charge carrying structures into atom chips. Utilizing electric fields in addition to the so far exclusively used magnetic fields enhances the functionality of atom chips by introducing an independent degree of freedom to the potentials. In our experiments, we have used electrostatic fields to form a novel type of combined electromagnetic trap where the confinement in two dimensions is magnetic while the movement in the third dimension is controlled by electric fields. In a string of up to six such traps we could arbitrarily switch the individual traps on and off, or split a single trap dynamically into two, thereby demonstrating a new type of atom chip beam splitter. We employed dynamic electric fields to transport a cloud of trapped atoms along a magnetic guide in a new type of atom “motor.”

The interaction of electrostatic fields and neutral but polarizable atoms (polarizability  $\alpha$ ) is given by the interaction energy  $U_{\text{el}}$  of the field  $E$  and the induced dipole:

$$U_{\text{el}} = -\frac{\alpha}{2}E^2. \quad (1)$$

Equation (1) shows that atoms in the ground state are drawn towards higher electric fields since the interaction of the induced dipole with the field is always attractive. As a consequence, the *minimum* of a purely electrostatic trapping potential will be located at a (local) *maximum* of  $E$ . According to the Earnshaw theorem, however, such a maximum cannot exist in free space. Any trap utilizing

electric fields therefore has to compensate for the attraction of the trapped atoms towards the charged objects creating the electric fields [10].

Stabilizing such a trap is possible either by adding (static) repulsive potentials, e.g., by introducing inhomogeneous magnetic fields or light fields, or by dynamically changing the electric fields [13]. For example, it has been suggested to realize the former by mounting charged structures onto magnetic or optical atom mirrors [5,14].

In our experiment we combine the electric and magnetic interactions to realize stable trapping configurations on atom chips. We produce electric fields by charging a set of electrodes distributed along a current carrying wire (Fig. 1). The wire produces, together with a homogeneous external bias field, a two-dimensionally confining quadrupole potential above the chip (a so-called *side guide* [1]). Charging the electrodes results in an inhomogeneous electric field that is modulated in strength along the guide. Such a modulation can lead to a full three-dimensional confinement given by the potential

$$U_{\text{mag+el}} = \mu_B g_F m_F B - \frac{\alpha}{2}E^2 \quad (2)$$

with the magnetic field modulus  $B$ , the Bohr magneton  $\mu_B$ , the Landé factor  $g_F$ , and the magnetic quantum number  $m_F$  of the trapped atomic state. Figure 1 shows our design and typical equipotential surfaces of the magnetic side guide and a string of combined traps that is formed when a moderate voltage is applied to the six electrodes along the guiding wire. We have numerically investigated the parameter ranges needed to form combined electromagnetic traps with this geometry and found that a few hundred volts are needed in order to form potential wells that are deep enough to trap thermal <sup>7</sup>Li atoms of  $T \sim 100 \mu\text{K}$  at a height of 50  $\mu\text{m}$  above the chip surface. If the voltage is too low, the modulation of the guiding potential becomes weaker; if it is too high, the attractive electric interaction lowers the potential barrier to the chip, and the atoms can propagate onto the surface. However, the voltage range where traps are formed is large, and trap depths of up to  $k_B \times 500 \mu\text{K}$  are

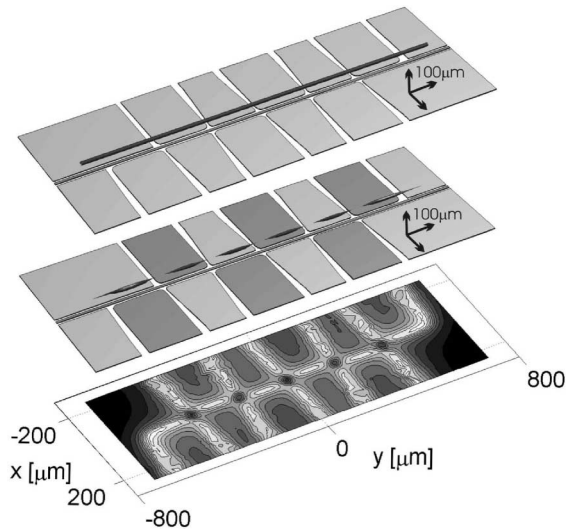


FIG. 1. Chip design: a magnetic side guide is modulated by applying voltages to the set of six electrodes (dark gray in center plot). Equipotential surfaces ( $E_{\text{pot}} = k_B \times 475 \mu\text{K}$ ) are shown for  ${}^7\text{Li}$  atoms in the  $|F = 2, m_F = 2\rangle$  ground state for the side guide (top) and a string of six combined electromagnetic traps (center). A contour plot of the electric field strength at the plane parallel to the chip at the height of the minimum ( $z = 50 \mu\text{m}$ ) is also depicted (bottom). The parameters chosen for these numerical calculations were  $I_{\text{wire,y}} = 1 \text{ A}$ ,  $B_{\text{bias,x}} = 40 \text{ G}$ , and  $V_{\text{elec}} = +475 \text{ V}$ .

possible. In this case, the barrier to the attractive potential near the electrodes is large enough to inhibit tunneling to the surface completely.

The two atom chips we have used in our experiments are based on silicon and sapphire substrates with a thickness of  $600 \mu\text{m}$ . A patterned gold layer (thickness  $\sim 4.5 \mu\text{m}$ ) was evaporated onto the substrates by standard lithographic and lift-off techniques. After the fabrication, a highly reflecting gold mirror is obtained with the current and charge carrying structures defined by  $10\text{--}50 \mu\text{m}$  wide grooves in the gold layer providing electrical isolation [15]. In our experiment, we accumulate typically  $10^8$   ${}^7\text{Li}$  atoms in a reflection magneto-optical trap (MOT) [16]. With the intermediate support of a U-shaped silver wire mounted directly underneath the chip, atoms in the weak field seeking states ( $|F, m_F\rangle = |2, 2\rangle; |2, 1\rangle; |1, -1\rangle$ ) are loaded into a Z-shaped wire trap on the chip. These magnetic traps and the loading procedure are described in [3,4]. Fluorescence images are taken by exposing the atoms to a light pulse of  $100 \mu\text{s}$  duration from two counterpropagating light beams that enter the vacuum chamber parallel to the chip surface. This configuration suppresses all artifacts on the images stemming from features on the chip surface. Even if electric fields are present at the time of the imaging light pulse, the resonance shift due to the differential Stark effect is much smaller than the linewidth of the atomic transition (at a typical field of  $10^6 \text{ V/m}$ ,  $\Delta\nu_{\text{Stark}} = 450 \text{ kHz} \ll \Gamma/2\pi = 5.8 \text{ MHz}$  [17]). Therefore, the

modulation of the fluorescence signal can be attributed only to an actual modulation in the atomic density.

After loading, the atoms hover  $50\text{--}100 \mu\text{m}$  above the chip surface in an elongated trap of approximately  $1 \text{ mm}$  in length. In the next step, the trapping potential is opened on one side by switching the current so that it now runs along an L-shaped path. If no voltage is applied to the electrodes along the central piece of the Z-shaped wire, all atoms are lost within approximately  $50 \text{ ms}$  after they are released to the guide (Fig. 2 left). If, however, at the time of the opening of the guide the voltage on the electrodes is switched on nonadiabatically (within  $5 \mu\text{s}$ ) to  $250\text{--}350 \text{ V}$ , a sizable fraction of the cloud, i.e., those (sufficiently cold) atoms that are located above the electrodes where the potential minima appear, remains trapped (Fig. 2 right). A comparison of the two experiments described above clearly shows the trapping effect of the electric field introduced by the high voltage. All six electrodes could be switched separately so that an arbitrary subset of traps could be operated. The lifetime of the trapped clouds was consistent with lifetimes measured in purely magnetic traps [18].

The experimental results agree quantitatively with the numerical predictions presented above regarding size and position of the traps, while the exact voltages leading to a maximal number of trapped atoms differ by up to  $50\%$ . We attribute this deviation to the fact that the calculations were idealized; i.e., the dielectric properties of the involved materials were neglected and only the central

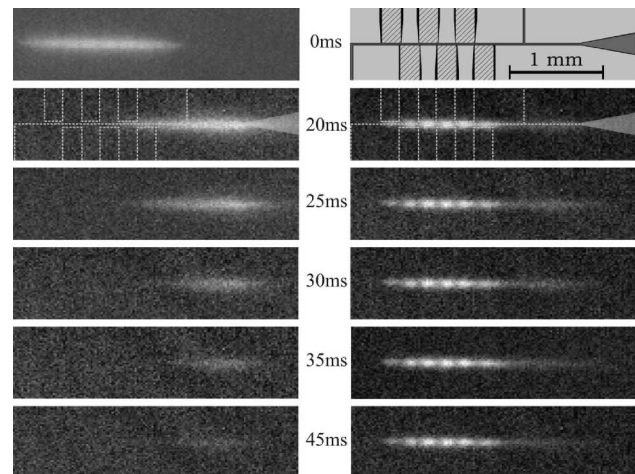


FIG. 2. Time series of fluorescence signals in experiments demonstrating the trapping of thermal  ${}^7\text{Li}$  atoms in combined electromagnetic traps: (left) At  $t = 0$ , a cloud of atoms is released from a magnetic Z trap into an open L-shaped guide where the guiding wire is broadened at the open end on the right-hand side, guiding the atoms towards the chip surface where they are lost. (right) If a voltage is applied to the electrodes along the guide, atoms remain in six individual trap sites. (top right) The actual chip design used in these experiments with the different current carrying and charged structures. The parameters used in this case were  $I_{\text{wire}} = 1.6 \text{ A}$ ,  $B_{\text{bias}} = 44 \text{ G}$ , and  $V_{\text{elec}} = +300 \text{ V}$ .

region of the chip was taken into account. The anticipated behavior of weaker modulation in the atom density for lower electric fields was observed as well as the loss of atoms to the chip surface at voltages that were too high.

In order to demonstrate some of the new capabilities of the atom chip introduced by the integration of electric fields, we carried out two further experiments. In the first experiment we showed the controlled transfer of an atom cloud along a magnetic guide by means of electric fields (see [2] for a purely magnetic transfer). The geometry of the chip structures necessary for this motor experiment and the timing sequence is illustrated in Fig. 3. A single trap was initially loaded by repeating the above described procedure, but only switching on the voltage on one of the electrodes. After a short trapping time, a voltage of reversed polarity was ramped up on a neighboring electrode on the opposite side of the guiding wire while the voltage on the first electrode was ramped down to zero. At the intermediate stage where the voltages on both electrodes are on, the electric field strength along the guide is maximal in the middle between the two electrode centers. The different polarity is essential for a smooth, barrier-free transfer of the cloud. To maintain a nearly constant trap depth throughout the transfer, the voltage ramps were run in two steps: During the first 7.5 ms the voltage on the first electrode was ramped from +280 to +200 V, while the voltage on the second electrode was ramped from 0 to -200 V. Within the following 7.5 ms, the first voltage was ramped down to 0, while the second voltage was ramped up completely to -280 V. This process was subsequently replicated between the second electrode and a

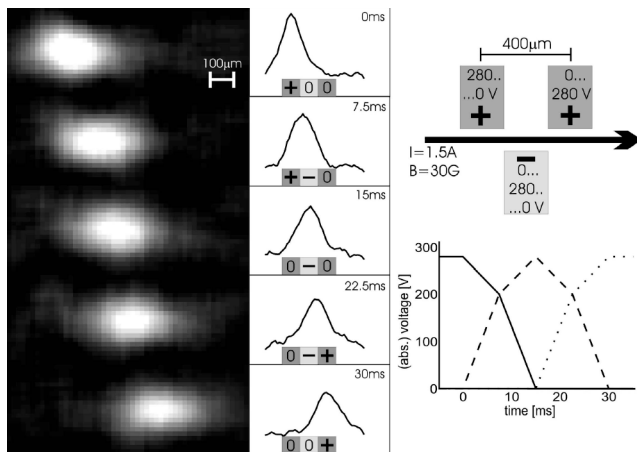


FIG. 3. (left) An atom cloud confined in a single combined electromagnetic trap ( $I_{\text{wire}} = 1.5$  A,  $B_{\text{bias}} = 30$  G, and  $V_{\text{elec}} = 280$  V) is smoothly transported along the magnetic side guide. (center) Longitudinal profile of the atom distribution as the cloud is transferred over a distance of  $400 \mu\text{m}$  during 30 ms. The voltages on the different electrodes at the different phases of the transfer are depicted schematically. (right) The timing of the voltage ramps was chosen to allow a smooth transfer from one trapping site to another while maintaining a nearly constant trap depth of  $50\text{--}60 \mu\text{K} \times k_B$ .

233201-3

third electrode, again located on the opposite side of the guiding wire. After the complete sequence of 30 ms duration, the whole atomic cloud had been transported over a distance of  $400 \mu\text{m}$ . Adiabaticity conditions limit the speed of the transport. When colder atoms, ideally BEC are used, the traps can be made much smaller, and trap frequencies of up to 1 MHz are possible. This will allow an adiabatic transport on a time scale ( $\mu\text{s}$ ) that is much faster than predicted coherence times [7]. The measured loss of atoms during the transfer is equal to that observed in a static trap which proves that losses induced by the transfer process are negligible with respect to the trap lifetime.

In the second experiment we observed a dynamic splitting and recombination of an atom cloud into two separate clouds. Again, the experiment was initiated by loading a single trap. While the voltage on the first electrode is ramped down to 0, voltages of equal magnitude but different polarity ( $-200$  V) are gradually (within 15 ms) ramped up on the two neighboring electrodes on the opposite side of the guiding wire in a fashion similar to the one used for the motor. The results of this experiment and the calculated potentials during the different stages of the experiment are shown in Fig. 4. For the recombination of the two clouds, the process is reversed. In these experiments, again no additional loss with respect to the lifetimes in the static traps could be detected.

The atom chip potentials can be made tight enough to control and localize single atoms to the extent necessary to implement quantum information processing (QIP) proposals [3,19,20]. The integration of electric fields on atom chips are thereby of particular interest.

Electric fields can be used to tune the phase evolution of atoms (qubits) in magnetic traps and guides in a

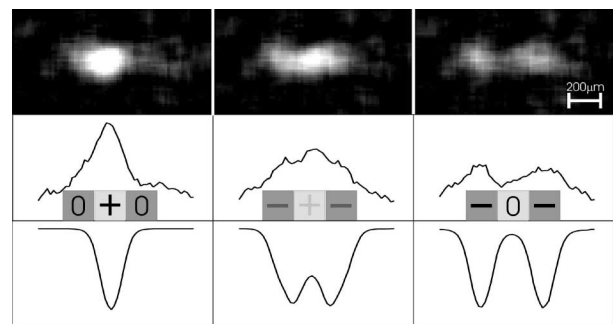


FIG. 4. Dynamic splitting of an atom cloud. A single trap is gradually (within 15 ms) turned into a double well potential by ramping the voltage on one electrode down while two neighboring electrodes are slowly charged. (top) Fluorescence images of the atoms during different stages of the experiment. (center) The density profile clearly shows the gradual splitting of a single cloud into two. The insets schematically show the polarities and voltages (darker shading corresponds to higher voltage) during the different phases of the experiment. (bottom) The corresponding potentials along the axis of free motion in the magnetic guide.

233201-3

controlled way. This is also relevant for various types of atom chip based interferometers [1].

Another application exploits the differential Stark effect which does not play a role in the current experiments: Atom chips offer the possibility to design trapping structures with a submicron spatial resolution. An array of traps with intertrap distances of the same order will be desirable in scaled QIP experiments. However, individual addressability of the trapping sites by laser light beams would be limited by the achievable beam waist. This problem could be overcome by introducing switchable electric fields at each trap site that would be used to shift the atoms in and out of resonance with the light frequency. In contrast to the current experiments where the goal was to trap atoms which requires large *gradients* in  $U_{\text{el}}$  at relatively low field strengths, the charged structures used here should produce strong (for sufficiently large detuning) and locally (more) homogeneous fields in order to keep the potential shape unaltered. This is possible when the confinement of the atoms is much tighter than the intertrap spacing and the atom-surface distance is equal to or smaller than the trap separation.

Finally, electric fields can be used for state-selective operations. This is based on the fact that the magnetic part of the combined electromagnetic potential [Eq. (2)] depends on the magnetic quantum number  $m_F$  while the electric part does not. In [19] it has been shown that a two-qubit phase gate based on controlled collisions can be realized by storing two atoms in the two minima of a double well potential in which the separating barrier can be conditionally removed for one qubit state but not for the other. If the qubit is encoded in atomic hyperfine states with different  $m_F$ , a combination of electric and magnetic potentials will allow such a configuration: The central barrier in a magnetic double well potential is of different height for the different  $m_F$  and can therefore be removed state selectively by an electric field since the electric potential does not depend on  $m_F$  [Eq. (1)].

To conclude, we have demonstrated for the first time that electrostatic fields can be used to trap and manipulate atoms. This adds a new degree of freedom to quantum optics on atom chips and paves the way to a variety of novel experiments and applications.

This work was supported by the European Union, Contracts No. IST-2001-38863 (ACQP) and No. HPRI-CT-1999-00069 (LSF) and by the Deutsche Forschungsgemeinschaft, Contract No. SCHM 1599/1-1.

---

\*Corresponding author.

Electronic addresses: krueger@physi.uni-heidelberg.de;  
http://www.atomchip.net

- [1] R. Folman, P. Krüger, J. Schmiedmayer, J. Denschlag, and C. Henkel, *Adv. At. Mol. Opt. Phys.* **48**, 263 (2002).
- [2] J. Reichel, W. Hänsel, and T.W. Hänsch, *Phys. Rev. Lett.* **83**, 3398 (1999); W. Hänsel *et al.*, *Phys. Rev. Lett.* **86**, 608 (2001).
- [3] R. Folman, P. Krüger, D. Cassettari, B. Hessmo, T. Maier, and J. Schmiedmayer, *Phys. Rev. Lett.* **84**, 4749 (2000).
- [4] D. Cassettari, B. Hessmo, R. Folman, T. Maier, and J. Schmiedmayer, *Phys. Rev. Lett.* **85**, 5483 (2000).
- [5] E. A. Hinds and I.G. Hughes, *J. Phys. D* **32**, R119 (1999).
- [6] H. Ott *et al.*, *Phys. Rev. Lett.* **87**, 230401 (2001); W. Hänsel *et al.*, *Nature (London)* **413**, 498 (2001); A. E. Leanhardt *et al.*, *Phys. Rev. Lett.* **89**, 040401 (2002); S. Schneider *et al.*, *Phys. Rev. A* **67**, 023612 (2003).
- [7] C. Henkel, P. Krüger, R. Folman, and J. Schmiedmayer, *Appl. Phys. B* **76**, 173 (2003), and references therein.
- [8] A. E. Leanhardt *et al.*, *Phys. Rev. Lett.* **90**, 100404 (2003); M. P. A. Jones *et al.*, *Phys. Rev. Lett.* **91**, 080401 (2003).
- [9] P. Horak *et al.*, *Phys. Rev. A* **67**, 043806 (2003).
- [10] The motion of atoms near an attractive  $1/r^2$  singularity has been studied both theoretically [11] and experimentally [12]. It has been shown that there are no stable orbits for the atoms in such a potential.
- [11] J. Denschlag and J. Schmiedmayer, *Europhys. Lett.* **38**, 405 (1997).
- [12] J. Denschlag, G. Umshaus, and J. Schmiedmayer, *Phys. Rev. Lett.* **81**, 737 (1998).
- [13] L. Hau, M. Burns, and J. Golovchenko, *Phys. Rev. A* **45**, 6468 (1992).
- [14] J. Schmiedmayer, *Eur. Phys. J. D* **4**, 57 (1998).
- [15] Both types of substrates tolerated voltage differences of a few hundred volts over spatial separations of 10  $\mu\text{m}$ . The Si substrate, however, exhibited a slow degradation at  $V_{\text{elec}} > 300$  V which was not encountered on the sapphire substrate at all tested voltages, i.e., up to 400 V.
- [16] The chip serves as a mirror for the MOT and is mounted inside a standard single vacuum chamber with a typical rest gas pressure of  $\sim 10^{-9}$  mbar. We use a dye laser to drive the  $F = 2 \rightarrow 3$  transition of the D2 line at 671 nm for cooling and imaging. An electro-optic modulator introduces a sideband at the repumping transition ( $F = 1 \rightarrow 2$ ) to the beam.
- [17] L. Windholz *et al.*, *Phys. Rev. A* **46**, 5812 (1992).
- [18] In our case, the lifetimes are limited by background gas collisions to 1 s, with better vacuum, lifetimes  $> 100$  s have been obtained [6]. Losses induced by Majorana transitions do not play a role here, due to the relatively high temperatures of the atoms. For colder atoms, they can be avoided by adding a small longitudinal magnetic bias field component.
- [19] T. Calarco *et al.*, *Phys. Rev. A* **61**, 022304 (2000).
- [20] Possible ways of loading and selecting individual atoms to these traps include the Mott-insulator transition [21] and optical tweezers [22].
- [21] M. Greiner *et al.*, *Nature (London)* **415**, 39 (2002).
- [22] R. B. Diener *et al.*, *Phys. Rev. Lett.* **89**, 070401 (2002).