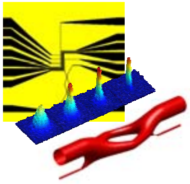
Micromanipulation of ultra-cold atoms close to conducting surfaces



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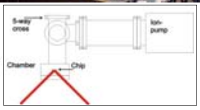
^{87}Rb-setup

Apparatus:

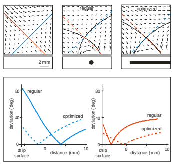
- single chamber vacuum system ($p<10^{-11}$ mbar), operated with pulsed Rb-dispensers
- optimized U-MOT, collects $>3\ 10^8$ atoms in 20s of loading
- magnetic trap with $\sim10^8$ atoms
- BEC in Cu-structure trap: $\sim10^5$ atoms
- precooled thermal atoms (~10μK) can be transferred to various traps and guides on the chip
- BEC in different chip wire traps
- trapping and cooling in both $|F=2\ m_F=2\rangle$ and $|F=1\ m_F=-1\rangle$ states



schematic drawing of single U-MOT setup

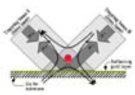

chip mounting and support structure

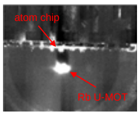
Main loading technique: Optimized mirror U-MOT



The quadrupole field originates from a specially designed U-shaped wire underneath the chip in combination with a homogenous bias field. The shape of the U is optimized to create a large volume quadrupole field (no bulky quadrupole coils necessary).

Field configurations for simple (thin) U and optimized broad U and angular deviations from ideal quadrupole field.

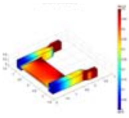


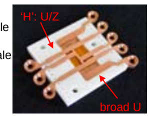


^{87}Rb mirror U-MOT

Multi-layer copper structure underneath the chip to be able to create a sizeable BEC:
- broad U-wire for large-scale MOT
- different Z-wires for evaporative cooling

Optimized U-MOT for experiments with ultracold atoms near surfaces, S. Wildermuth, P. Krüger, C. Becker, M. Brajdic, S. Haupt, A. Kasper, R. Folman, J. Schmiedmayer, PRA 69, 030901(R) (2004)

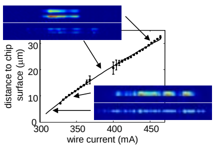

current density in broad U

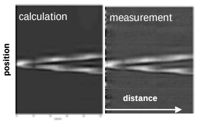


under the chip: multi-layer Cu structure

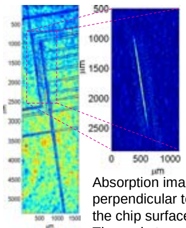
Imaging near surfaces

Horizontal absorption imaging with slightly tilted laser beam allows to measure distance to surface.





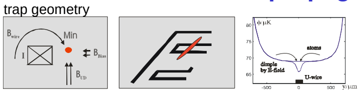
Two images of BEC overlap for d<7μm. Distance can be extrapolated taking the finite size of the wire into acount.



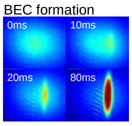
Absorption image perpendicular to the chip surface. Thermal atoms above 100 μm wide wire.

Condensate propagation in a 1d guide

trap geometry



BEC formation



- thermal atoms just above T_C in a 1d trap
- at 0ms electric dimple is suddenly created
- 1d BEC forms slowly
- BEC becomes larger and 3d
- equilibrium reached after ~80ms

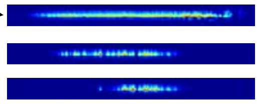
BEC propagating along 1d guide — ToF images (16ms)

- BEC is formed in 3d dimple
- off-center release to elongated (1d) trap by sudden (<1μs) switching off of dimple voltage
- background gas temperature $\sim T_C$
- movement of edge at ~5cm/s
- thermalization into equilibrium state (centered cloud at T_C) on slower time scale (~100ms)

Magnetic surface disorder potentials

Thermal clouds and BECs can be brought close (d~3μm) to the wire surface to probe surface disorder potentials.

Thermal clouds at T=1μK do not fragment down to distances of 3μm.



BECs are more sensitive probes for disorder potential.

Longitudinal displacement of BEC shows that disorder potential is stable in position.

Boltzmann distribution

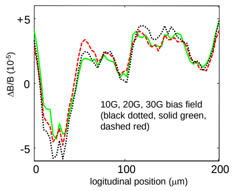
$$n \sim \exp(V / k_B T)$$

gives upper limit on potential roughness of $\Delta B/B < 2\mathrm{x}10^{-4}$.

Disorder potential can be reconstructed from density profiles of 1d BECs:

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

scaling of disorder potential with current in the wire

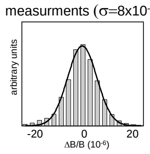


Measurement at same position and constant distance (10μm) to the wire but three different wire currents / bias fields.

we find a linear current scaling

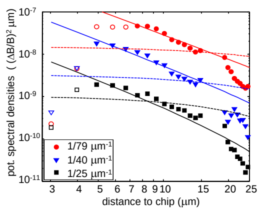
- → disorder potential stemming from irregular current flow in wire
- → excludes electric patch effects at a scale of 10^{-13}eV (d>5μm)

deviations between three measurments ($\sigma=8\mathrm{x}10^{-6}$)

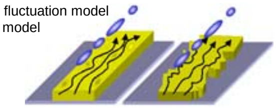


variation of disorder potential with distance to the wire

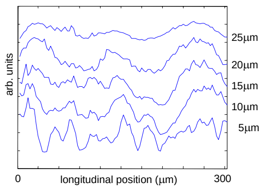
potential spectral densities (100μm wide wire)



dashed curves: wire edge fluctuation model
solid curves: local current model



In our case, disorder potential is dominated by local deviations from a straight current flow.
Sensitivity $\Delta B/B = 10^{-5}$ corresponds to a resolution of 10^{-5} rad.



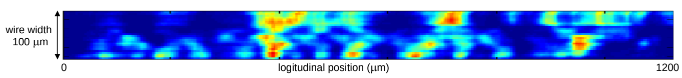
Disorder potential reconstructed from density profiles of 1d BECs.

Curves are shifted by equal amount from each other. Heights above the chip are indicated on the right.

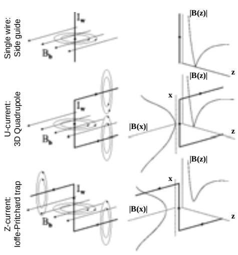
- at d=10μm we find rms $\Delta B/B=3\mathrm{x}10^{-5}$ ($k>1/200\ \mu m^{-1}$)
- fluctuation spectrum scales as $\sim 1/k^2$

variation of disorder potential with transverse position

2d potential landscape at constant height of 10μm above a 100μm wide wire.



Main building block: magnetic wire traps

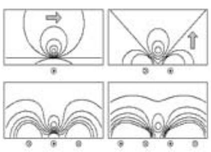


$V(r) = -\mu\cdot B(r) = g_F m_F \mu_B B(r)$; in adiabatic approximation: m_F is constant of motion; only important parameter is |B(r)|

Basic building block: wire traps, derived from combining the magnetic field from current carrying wire(-structures) with homogeneous bias fields.
Single wire + bias field: 2D quadrupole along the wire: side guide
U-shaped wire + bias field: 3D quadrupole trap
Z-shaped wire + bias field: 3D Ioffe-Pritchard trap

The bias fields need not be applied from the outside; extra wires can suffice. This allows even more freedom when designing a device.

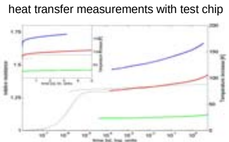
Magnetic traps on atom chips can be combined with:
- electric fields
- dipole traps
- other quantum-optics techniques like cavities, etc.

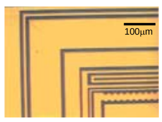


Chip fabrication

- semiconductor (Si, GaAs) and sapphire substrates
- lithographicly patterned gold layer (5μm thickness, resolution <1μm)
- current densities up to 10^7 A/cm^2 possible
- voltages of more than 300V (10μm gaps)

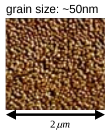
heat transfer measurements with test chip





chip design detail (light microscope)

grain size: ~50nm



AFM image

Atom Chips: Fabrication and Thermal Properties, S. Groth, P. Krüger, S. Wildermuth, R. Folman, T. Fernholz, D. Mahalu, I. Bar-Joseph, J. Schmiedmayer, APL in press, cond-mat/0404141