Lecture II
Manipulating and detecting atoms close o surfaces

Cool and tarp atoms on chips

Detecting Atoms

Absorption / Fluorescence imaging

Integrated, optical fiber based detectors

Atoms close to surfaces

Imperfections of the wires

Magnetic field microscope

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Atom Chip

how to cool and load atoms

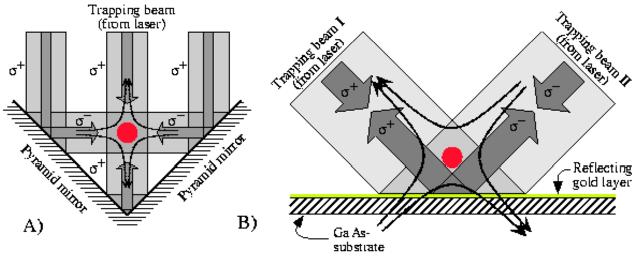
Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

EXPERIMENT

What We Need

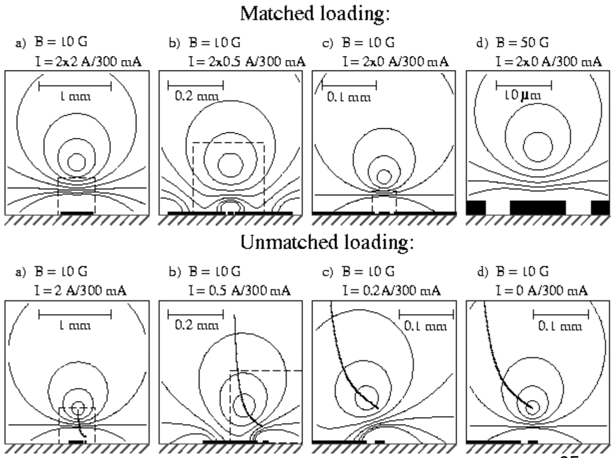
Cold atoms
MOT above surface
reflection MOT, Kim et al 1997



Reichel et al. PRL 83, 3398 (1999)
Folman et al. PRL 84, 4749 (2000)

Bring atoms to Chip
Magnetic Micro-Trap
U- Z-wire structures under the chip to assist with loading and cooling (evaporation)

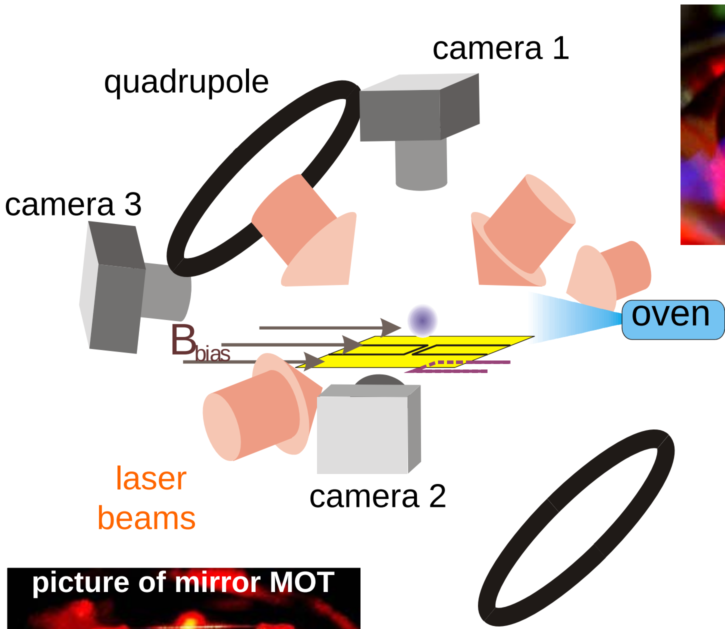
Load into successively smaller traps and guides
smooth switching of currents



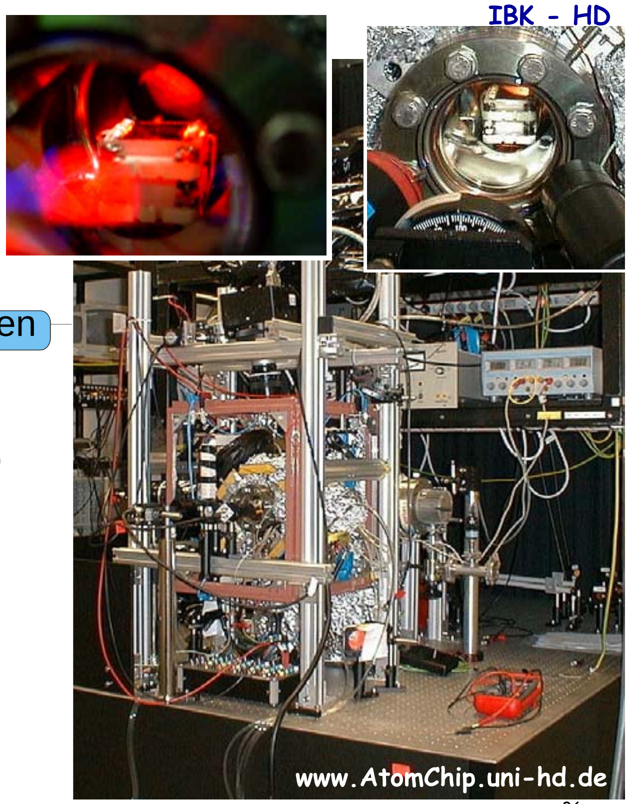
Observe atoms close to the surface
fluorescence imaging
absorption imaging
expand the tightest traps to see atoms

EXPERIMENTAL SETUP

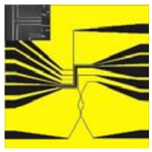
cooling close to surface



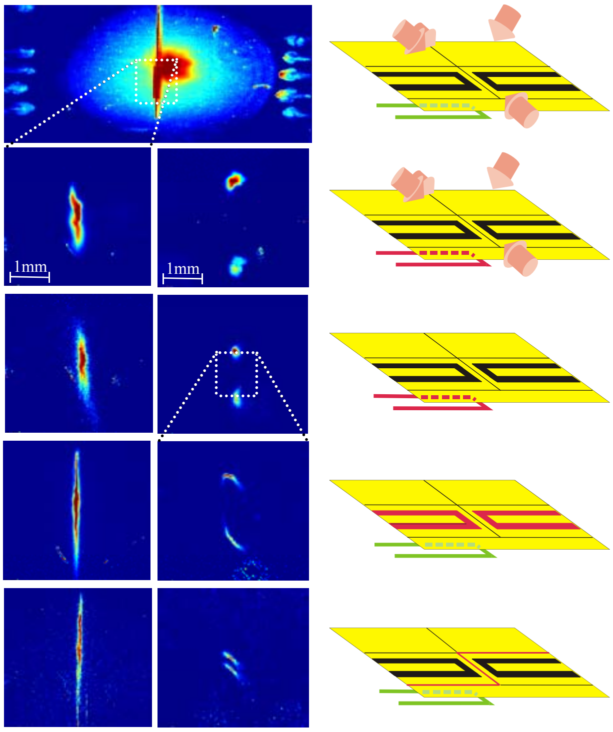
IBK - HD



LOADING THE ATOM CHIP



Folman et al. PRL 84, 4749 (2000)
D. Cassettari et al. Appl.Phys.B 70, 721 (2000)



Mirror MOT

Chip MOT

U-Magnetic Trap

Loading the Atom Chip

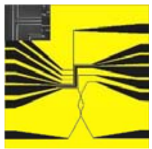
Trapping: 100kHz <100nm

camera 1
top view

camera 2
front view

see also: Reichel et al. PRL 83, 3398 (1999)
other experiments on structured surfaces:
Müller et al. PRL 83, 5194 (1999)
Dekker et al. PRL 81, 1124 (2000)

Compression of a Chip Trap
ramping up the bias field

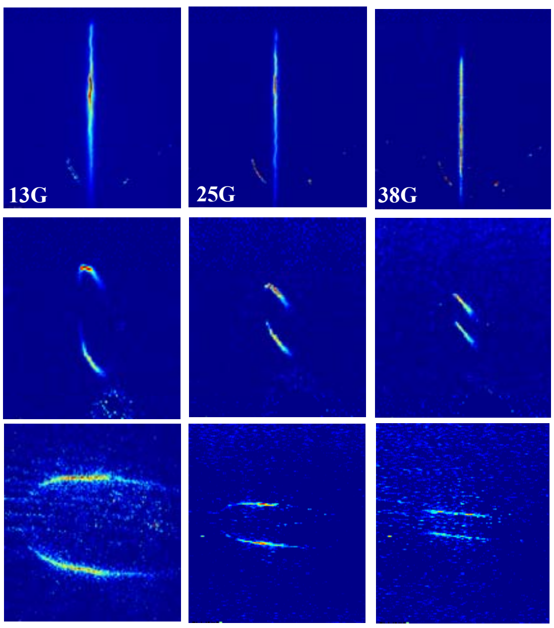


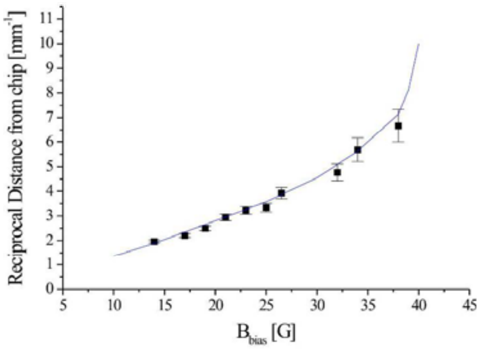
Folman et al. PRL 84, 4749 (2000)
D. Cassettari et al. Appl.Phys.B 70, 721 (2000)

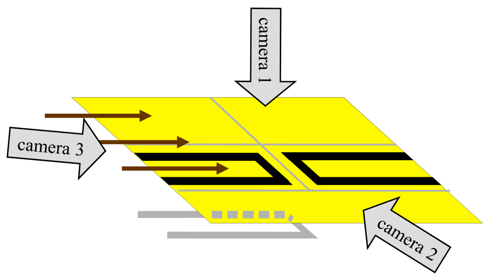
camera 1
top view

camera 2
front view

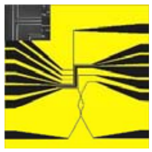
camera 3
side view







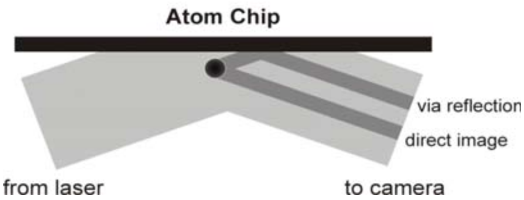
Atom Chip Mounting

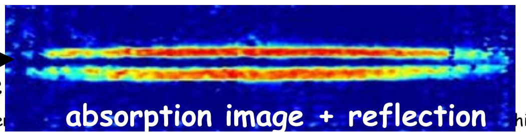


Heidelberg

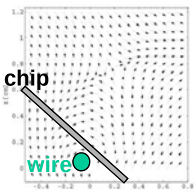
Big magnetic trap to give large BEC on-site independent from the chip

- Cu structure combining various U- and Z- traps;
  - Low resistance; large trapping volume; high gradients
  - >2 x 10^8 Atoms trapped
  - 200 μm away from chip
  - Vacuum < 1 x 10^{-11} mbar
- Connections to chip bonded: Enables absorption images down to chip surface

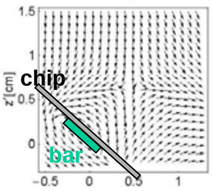




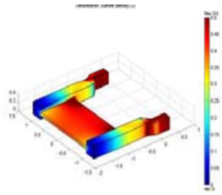
Large MOT without quadrupole coils



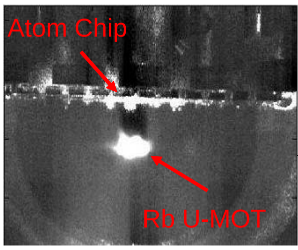
U-Wire trap

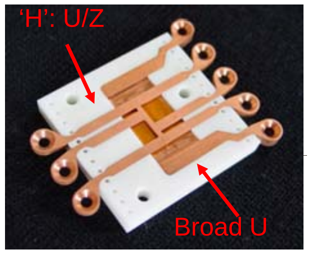


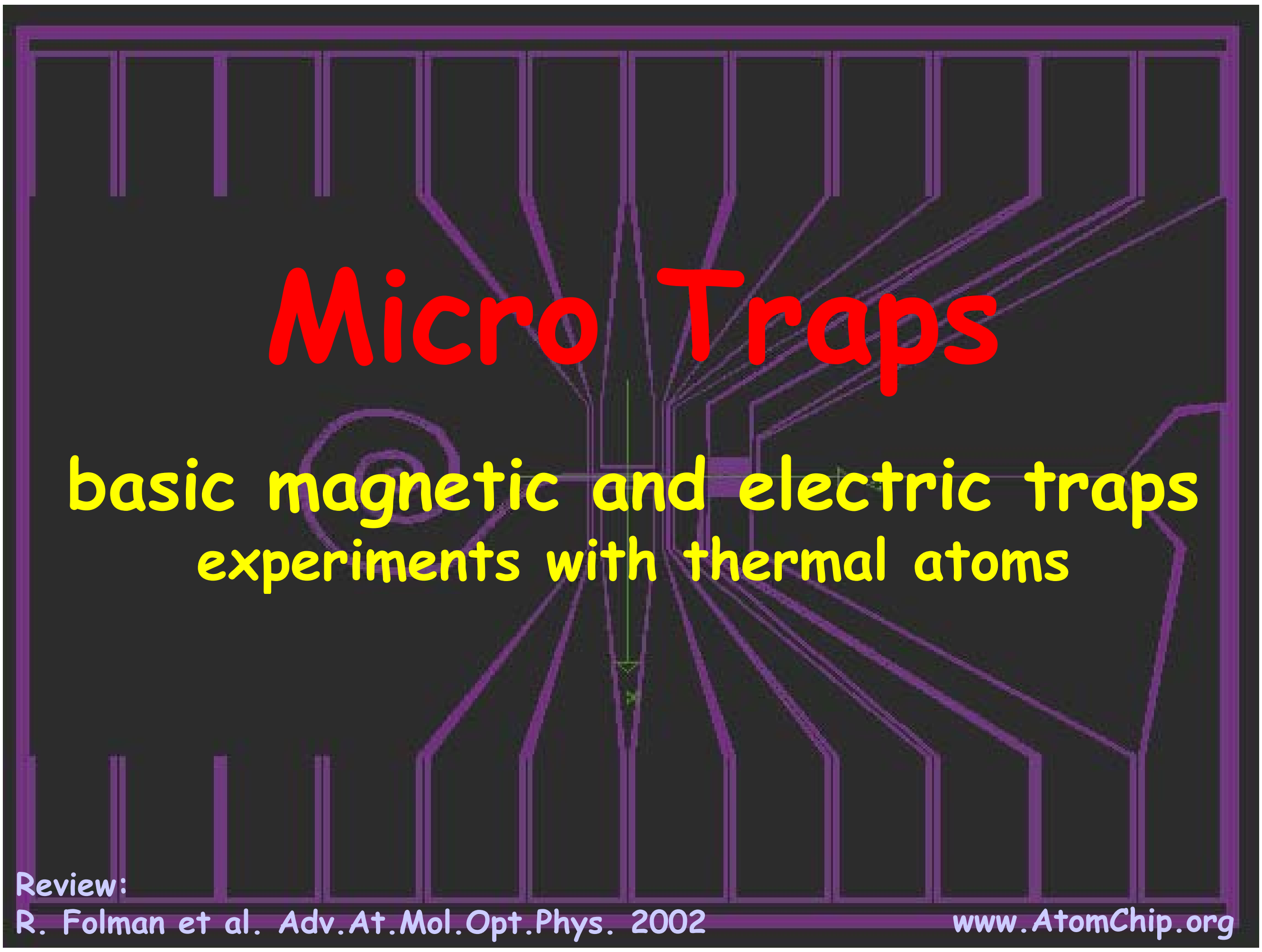
improved U-trap



current density

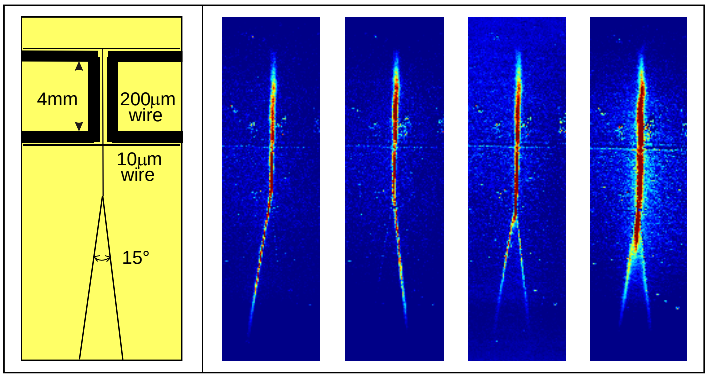


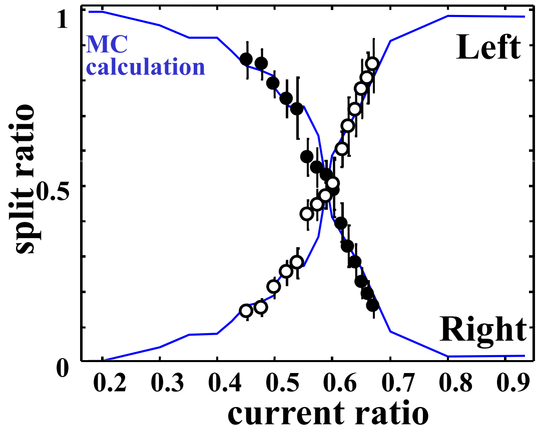


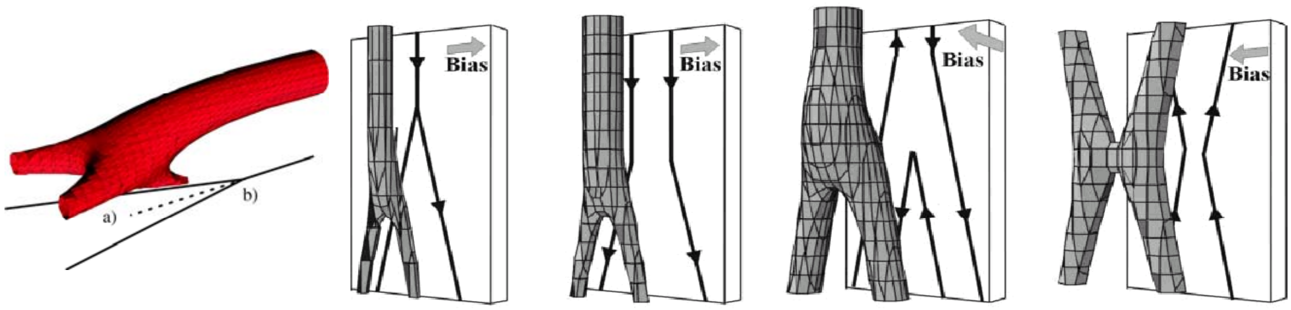


BEAM SPLITTER FOR GUIDED ATOMS

IBK





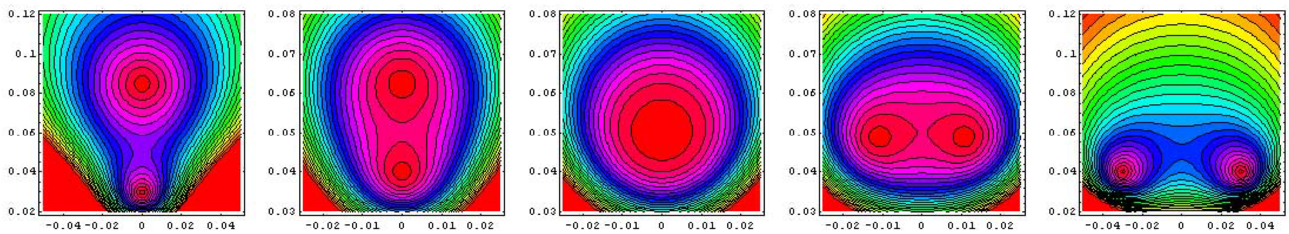


D. Cassettari et al. PRL 85, 5483 (2000)

Splitting and Recombining
Time Dependent Potentials

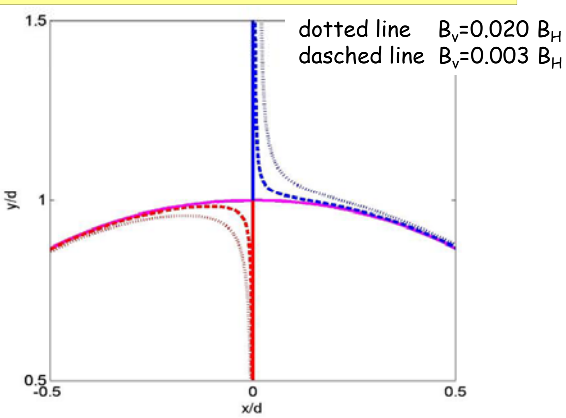
IBK-HD

2 wires + horizontal bias field



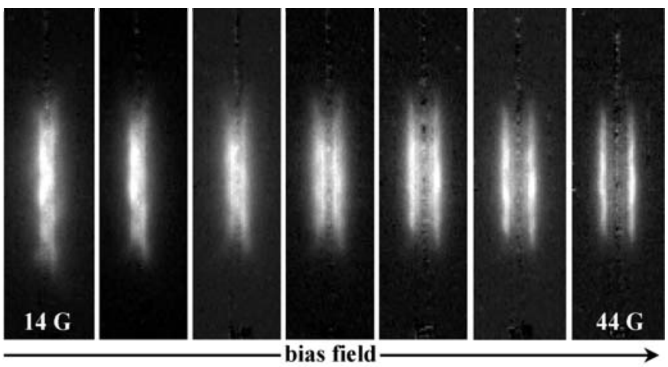
bias field

Crossing is highly sensitive to imperfections



experiment

double U-trap; 200 micron wires 2.0 A, 40 Gauss



Omni-Directional Guiding

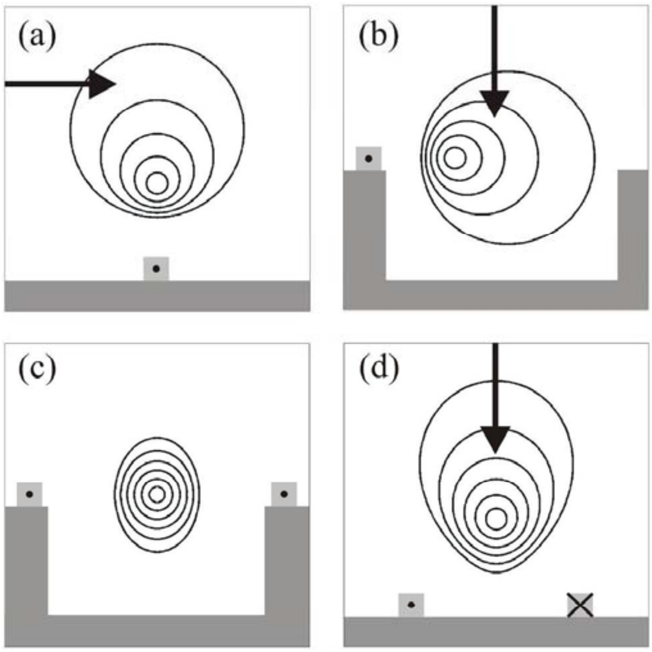
The direction of the bias field relative to the wire will determine the potential minimum in that plane:

For bent guides the bias field has always to have the same angle relative to the wire.

Remember:

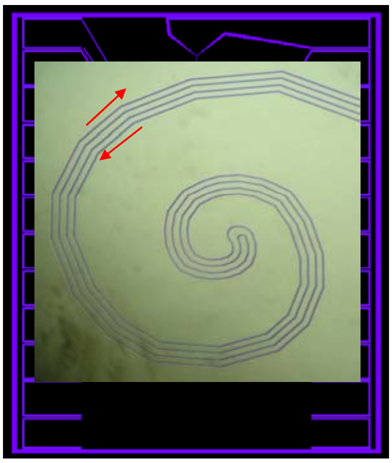
1mG ~ 67 nK

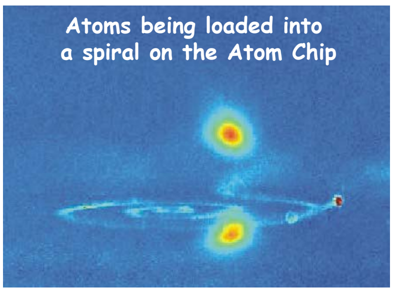
At 10G bias field this corresponds to an angle of 10^{-4} rad



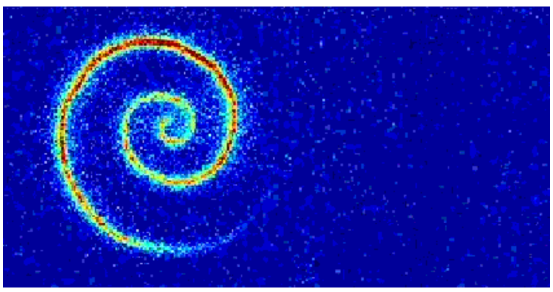
Omni-Directional Guiding
Experiment

Heidelberg

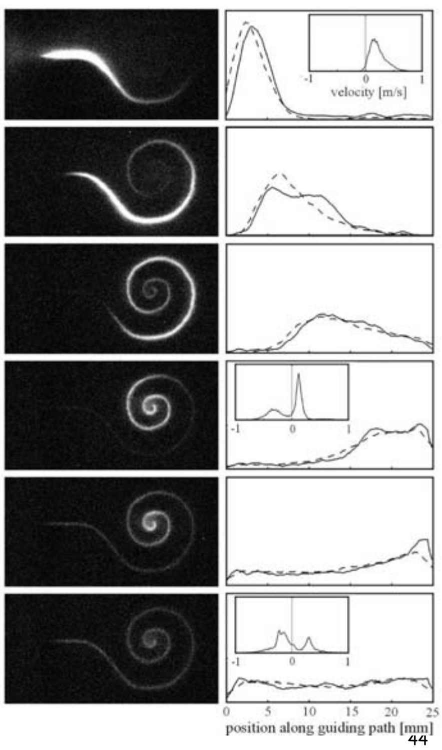




Wire size:	**5x45 μm**
Seperation:	**115 μm**
Length:	**~2 cm**



Experiment MC calculation



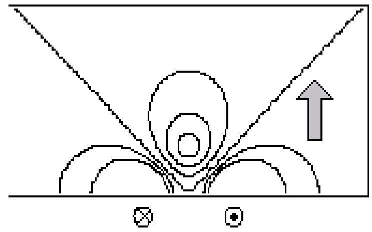
X. Luo et al. Optics.Lett **29**, 2145 (2004)

R. Brugger et al. PRA 72, 023607 (2005)

Guiding in any direction

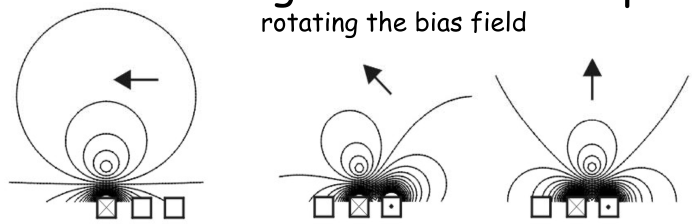
Bendable wire traps

bias field orthogonal to surface

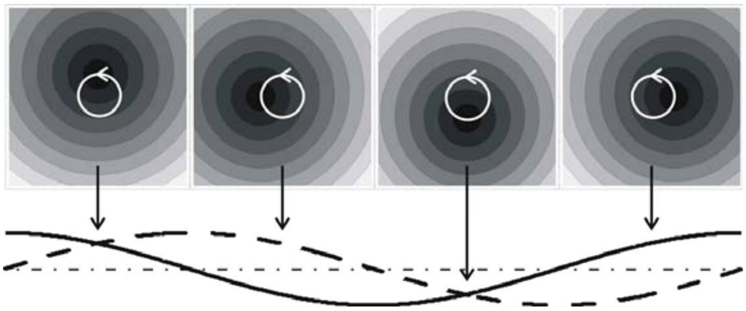


Loading from a side trap

rotating the bias field



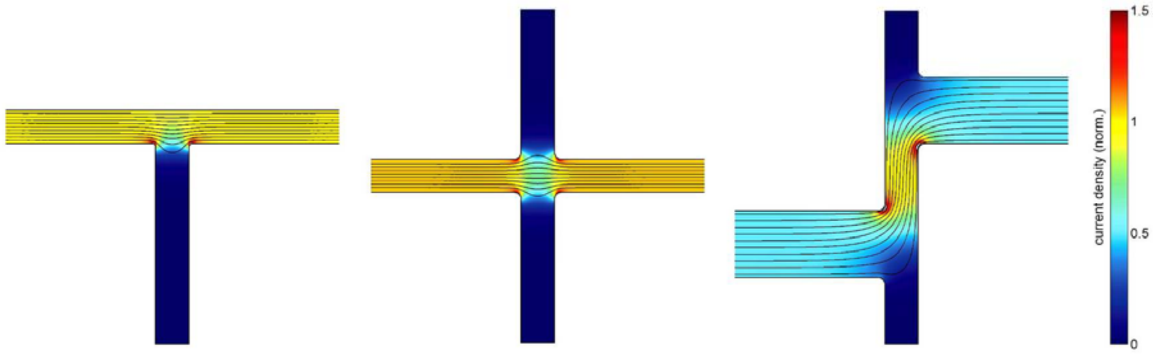
TOP trap guide to remove the zero of field



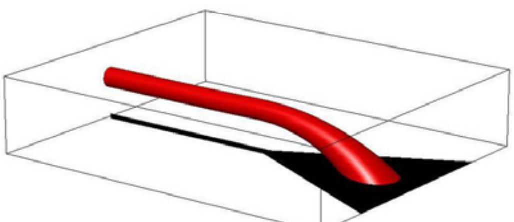
Influence of wire width

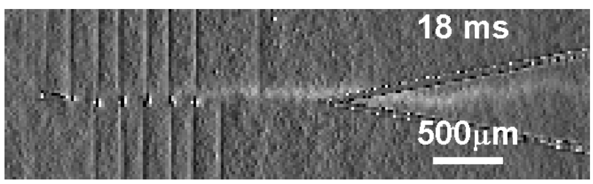
Heidelberg

Actual current density determines trap properties



– Can be used for beam dump



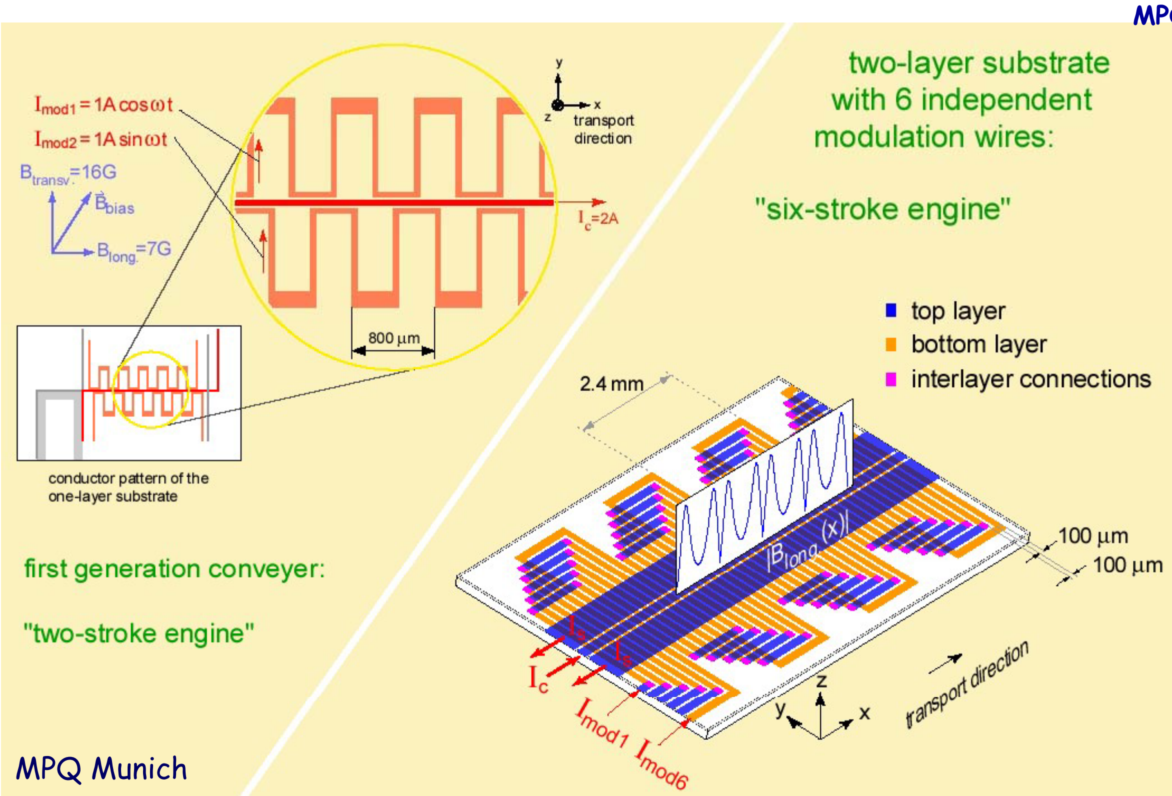


^{7}Li

Klein, Diploma Thesis 2003

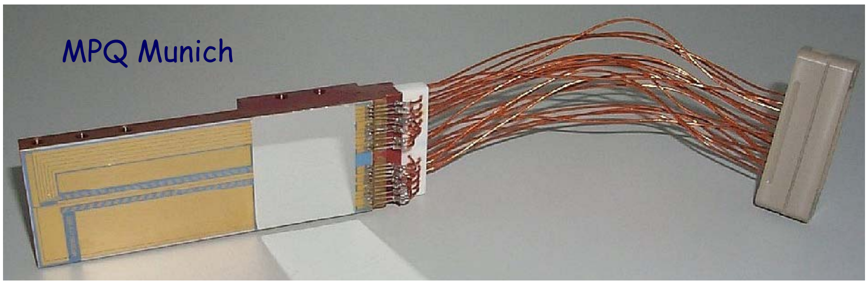
Atom Transport

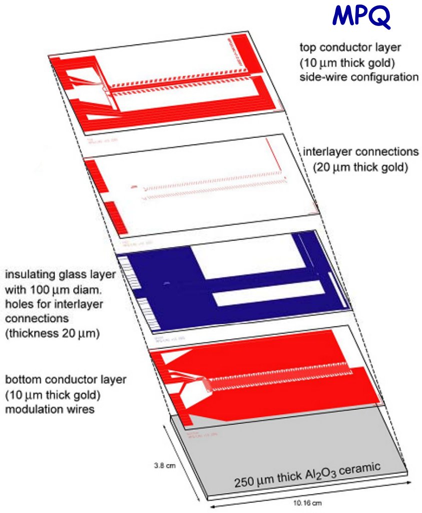
MPQ

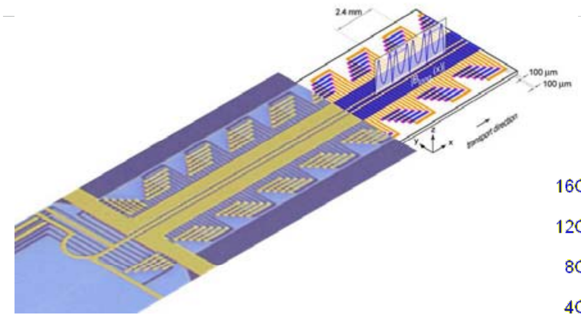


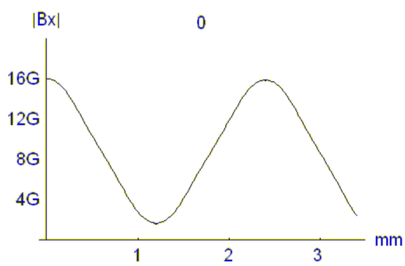
Multi Layer Conveyor Belt

MPQ

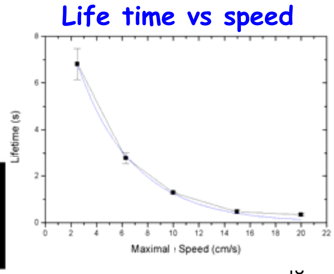




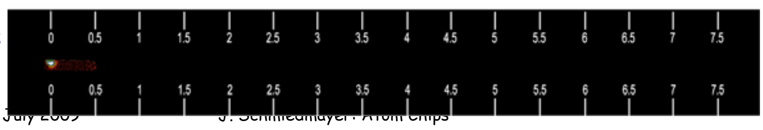




Life time vs speed



23,5 cm in 2.9s
v = 8 cm/s
v_{max} = 10 cm/s



Combining Electric Manipulaion with Magnetic Trapping

Heidelberg

The electric field leads to an interaction potetial: $U = -\frac{1}{2}\,\alpha\,E(r)^2$

It always attracts atoms towards higher field. No stable trap possible with static electric fields for ground state neutral atoms

Combine electric & magnetic interaction:

$$U(\mathbf{r}) = g_F\, m_F\, \mu_B\, B(\mathbf{r}) - \frac{1}{2}\,\alpha\, E(\mathbf{r})^2$$

Electrostatic interaction
- does not depend on m_F
- always attractive

Typical orders of magnitude (^{7}Li)
- $U_B\,[\mu K] \propto 67\, B \quad [G]$
- $U_E\,[\mu K] \propto 98\, E^2 \quad [V/\mu m]$

State dependent operation possible in a magnetic double well potential for qubit states with different $g_F m_F$

Magnetic + Electric Traps

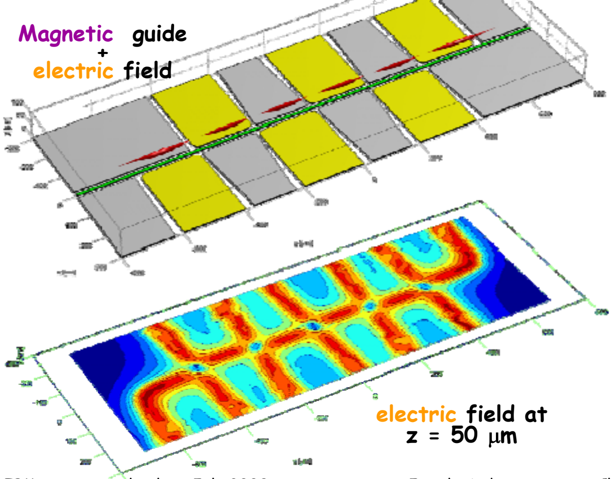
$$V = m_F\, g_F\, \mu_B\, B - \frac{1}{2}\,\alpha\, E^2$$

P.Krueger, et al. quant-ph/0306111, PRL in print

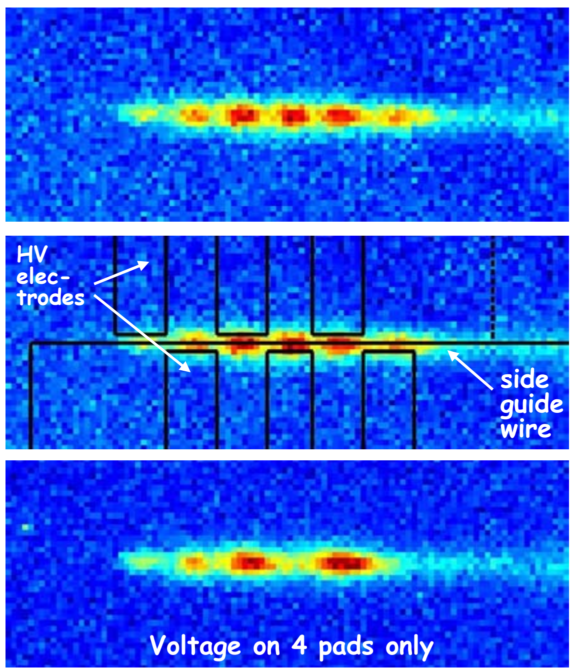
Heidelberg

- A current through wire + bias field create a magnetic trap.
- The electric field always attracts atoms towards higher field.

gray pads: ground
yellow pads: 400 V



Experiment
electric traps: 300 V
magnetic trap: 1.6 A, 44 G



Manipoulation with Electric Fields

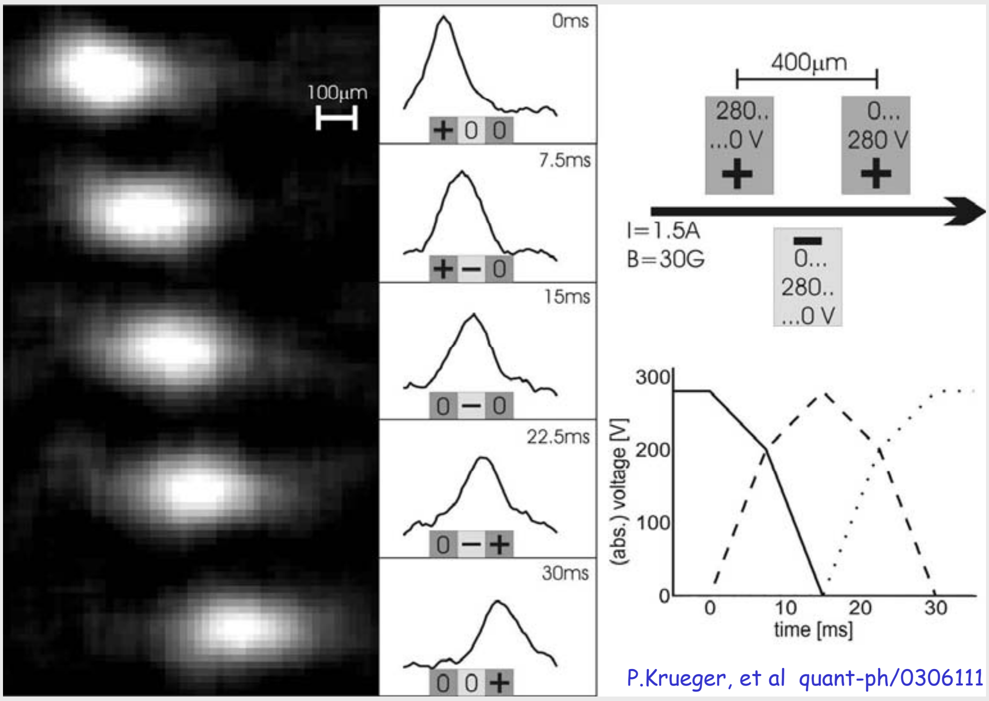
Heidelberg

Electric Motor

Dynamics

- Electric fields can be varied
- linearly summed

- Atomic transport 'motors'
- Splitting and recombining

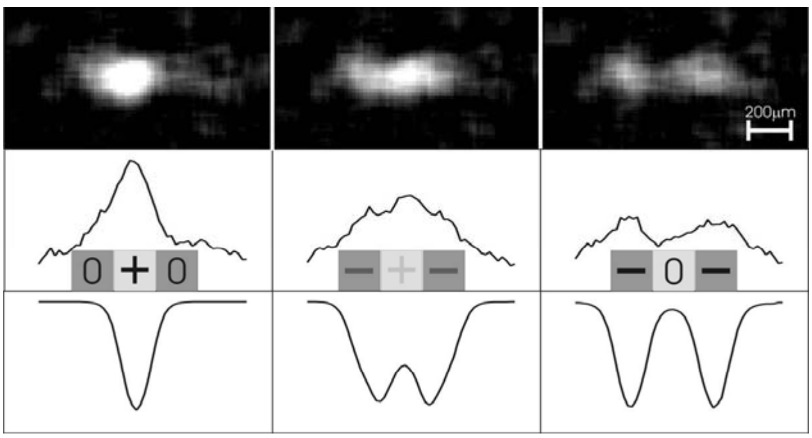


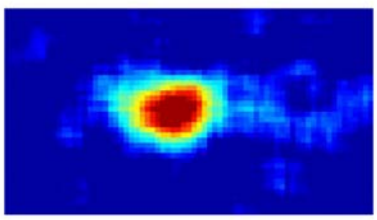
P.Krueger, et al quant-ph/0306111

B + E splitters

Heidelberg

dynamic splitting of a trapped cold atomic cloud with electric fields



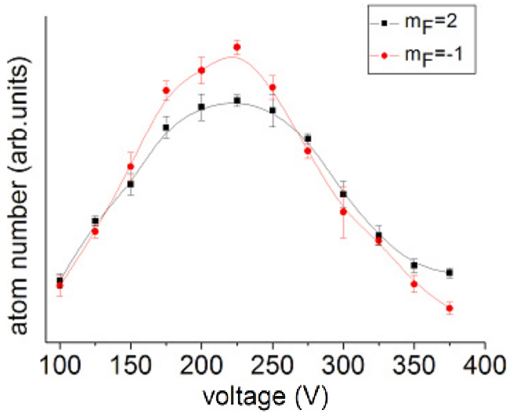


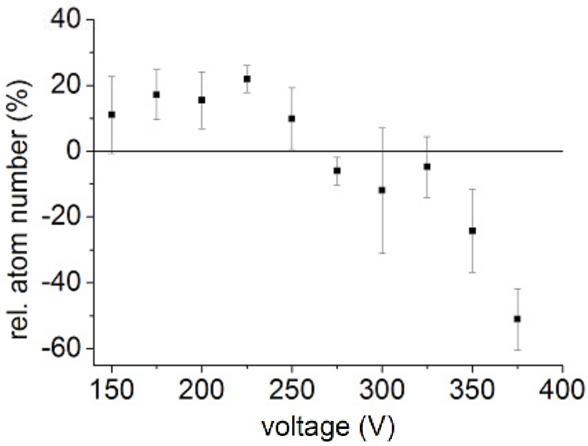
P.Krueger, et al quant-ph/0306111, PRL in print

State selective trapping

Combine electric & magnetic interaction:

$$U(\mathbf{r}) = g_F m_F \mu_B B(\mathbf{r}) - ½\, \alpha\, E(\mathbf{r})^2$$

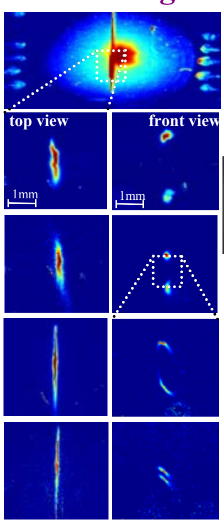




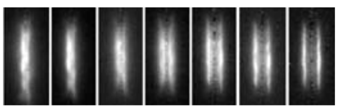
ATOM CHIP
experiments with thermal atoms

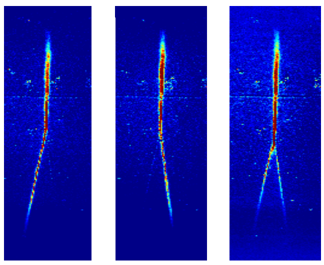
Innsbruck Heidelberg

Loading mesoscopic traps



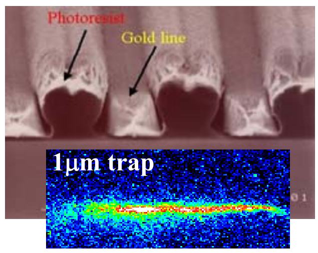
Dynamic Beam Splitter



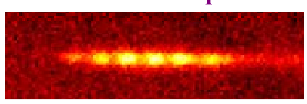


Beam Splitter

1µm structures

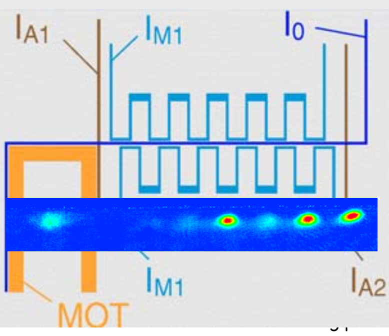


Electric traps

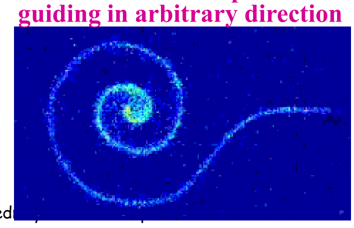


- trap frequencies > 100 kHz
- trap ground state < 30 nm
- trapping with on-board bias field
- structures down to 1 µm
- moving, splitting etc …

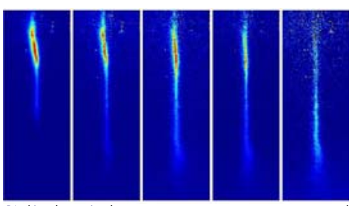
MPQ Munich
Moving atoms (conveyor belt)



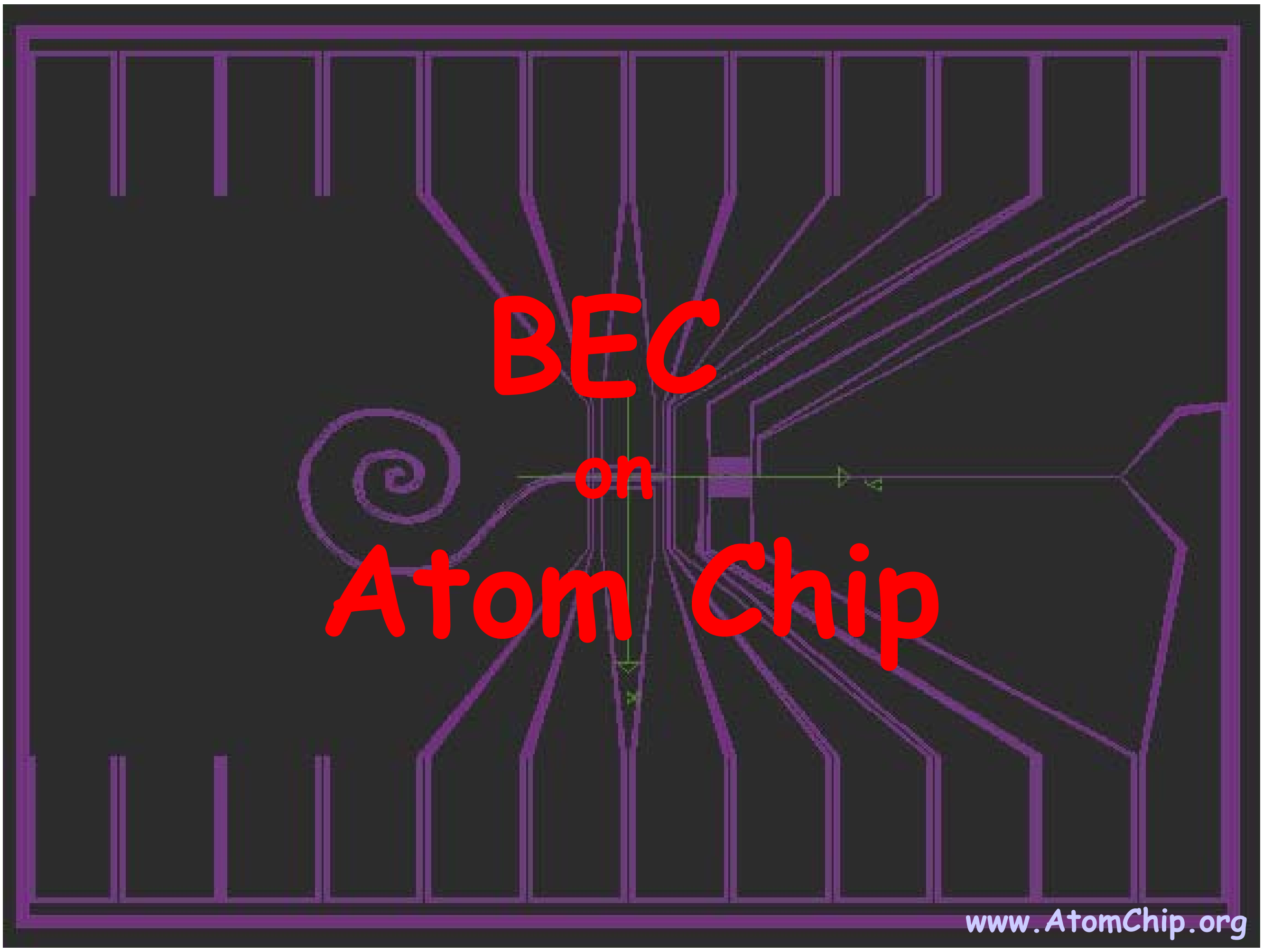
Vertical traps
guiding in arbitrary direction



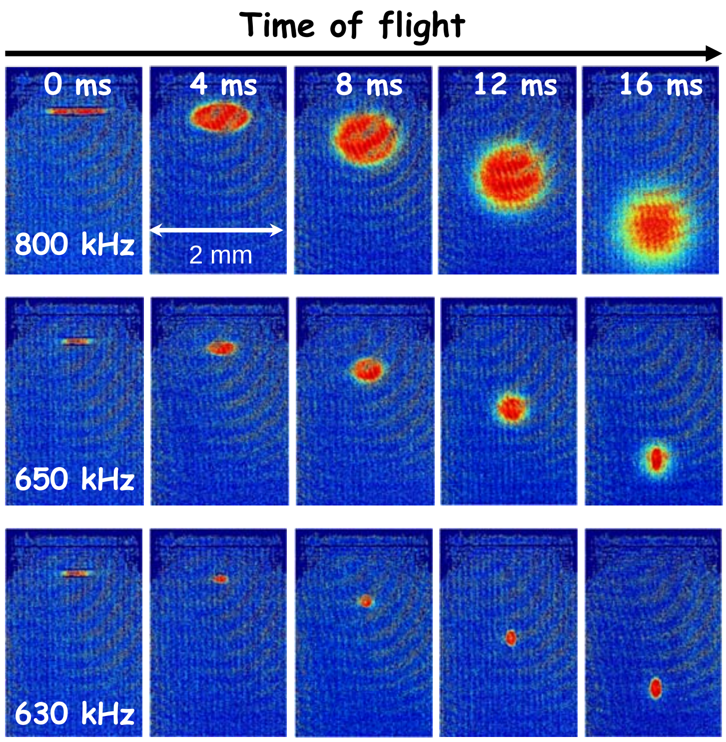
Continuous Loading



www.AtomChip.uni-hd.de



Atom Chip BEC



Quadrupole mirror MOT
- 10 sec loading, >10^8 At.

U-mirror MOT
- transfer without losses

Optical Molasses.
- 15 ms, <100 μK

Optical pumping -> |2,2>

Magnetic Z trap.
- > 10^8 atoms @ 250 μK

Compress
- trans.: ~500 Hz ~400 G/cm
- long.: ~ 50 Hz

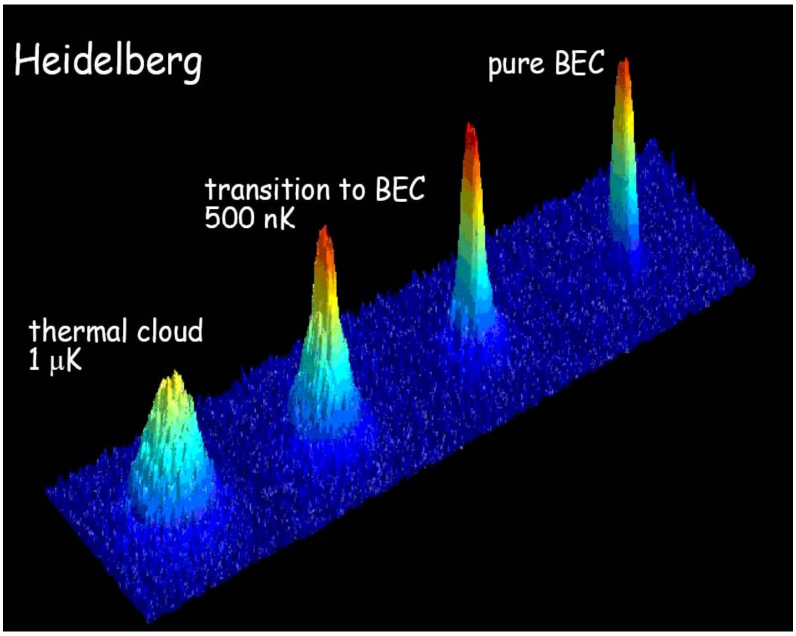
RF-Evaporation
- ~20 sec linear ramp
- **BEC** 3 10^5 atoms @ T_c < 1 μK

First chip-BECs: Ott et al. PRL **87,** 230401(2001); Hänsel et al. Nature **413**, 498 (2001)

Experiment setup ^{87}Rb

Apparatus:

- single chamber vacuum system operated with pulsed Rb-dispensers ($p<10^{-11}$ torr)
- optimized U-MOT, >3 10^8 atoms
- magnetic trap with ~10^8 atoms
- pre cooled thermal atoms (~10μK) transferred to various traps and guides
- BEC (up to >10^5 atoms) in different chip traps
- trapping and cooling in both $|F=2\ m_F=2\rangle$ and $|F=1\ m_F=-1\rangle$ states
- atom shot noise limited imaging with 3 μm resolution
- detection limit: n_{1d} ~ 1 atom/μm

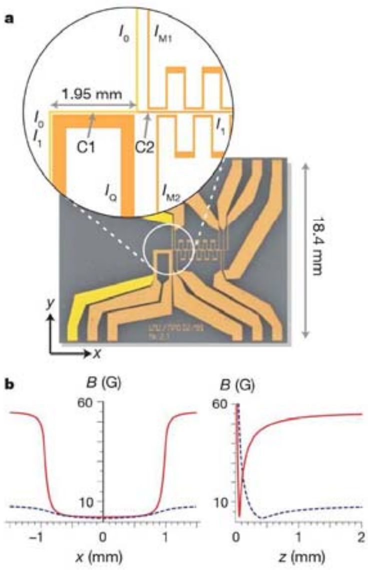


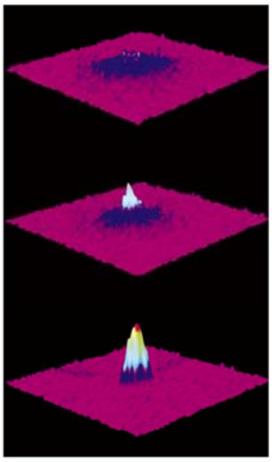
S. Wildermuth, et al, PRA 69, 030901(R) (2004)

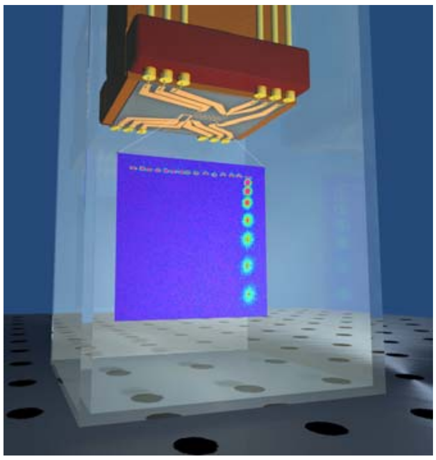
Transporting BEC on Chip

MPQ Munich

Hänsel et al Nature **413**, 498 (2001)

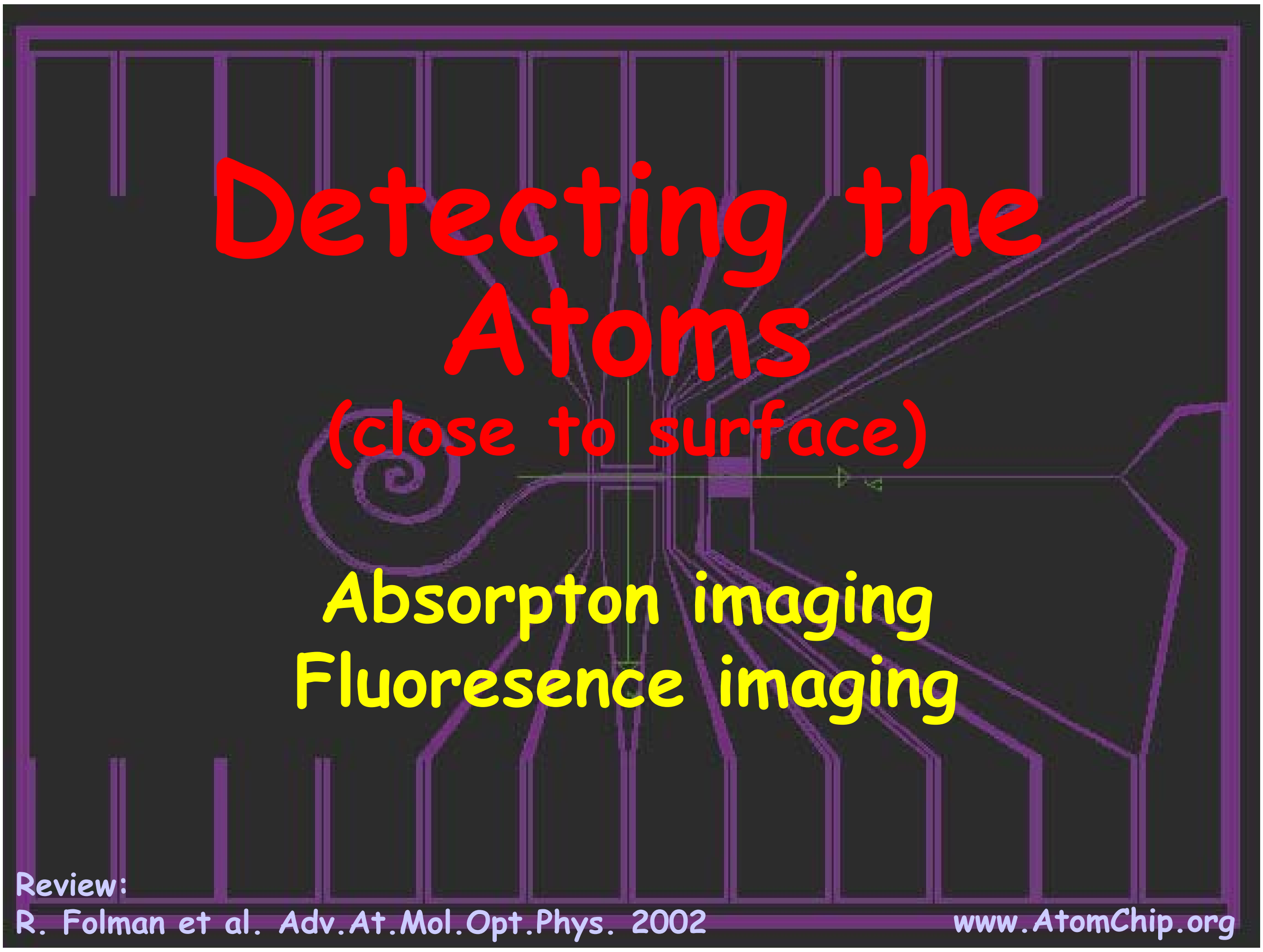






Transport of BEC along the chip

Evaporative cooling in a micro trap on an Atom Chip in < 1 sec.



Detecting the Atoms

(close to surface)

Absorpton imaging
Fluoresence imaging

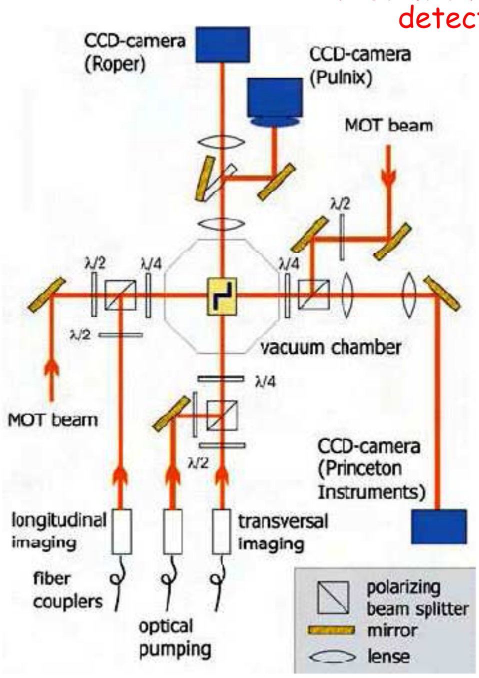
Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002 www.AtomChip.org

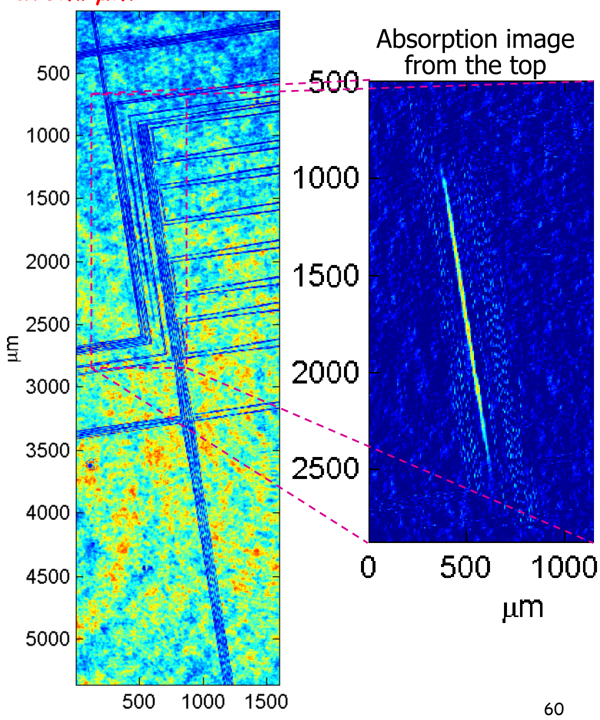
Imaging Atoms

ATOMINSTITUT

Diffraction and atom shot noise limited absorption imaging from 3 directions

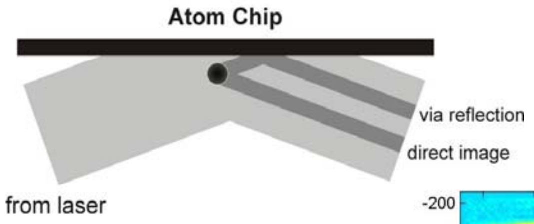
resolution ~3μm with simple lenses
detection limit 1 atom/μm



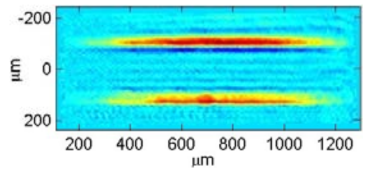


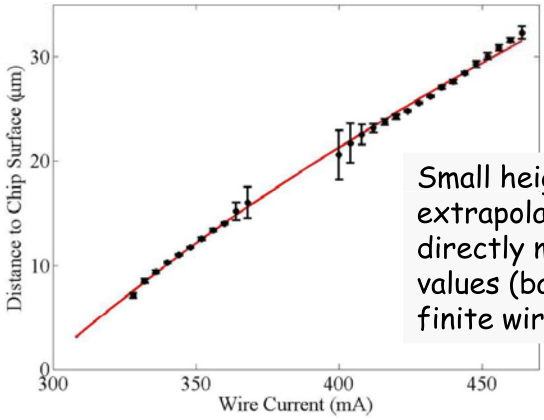
Imaging close to the surface
measure distance

HD

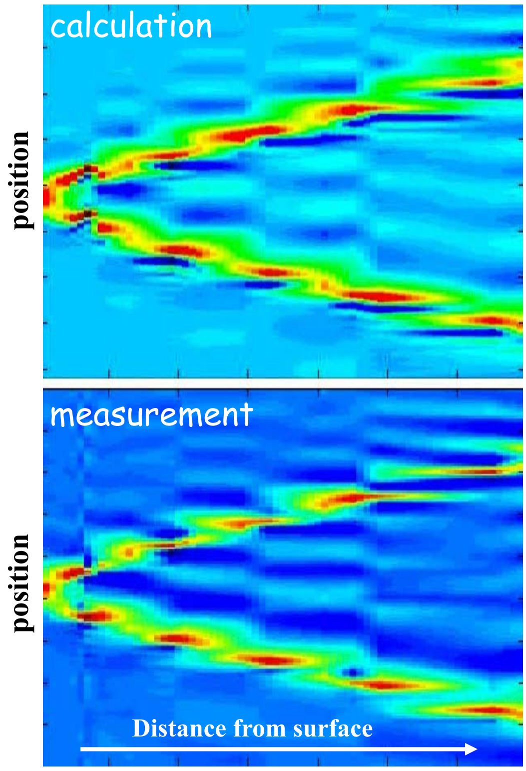


Need to consider the light wave close to the surface

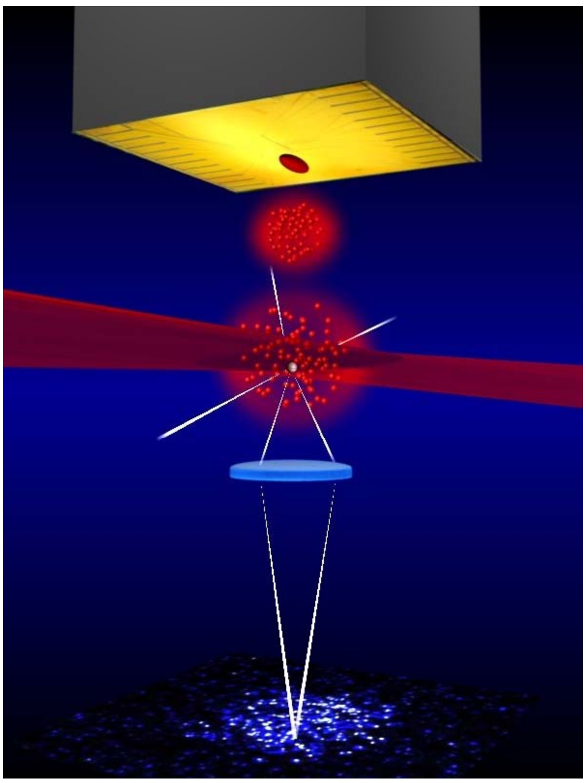




Small heights are extrapolated from directly measurable values (based on finite wire size)



A single-atom fluorescence camera



R. Bücker et al. arXiv:0907.0674

Experimental realization

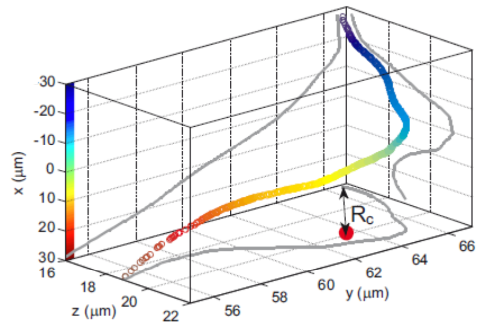
- Atom cloud is released from **chip trap**

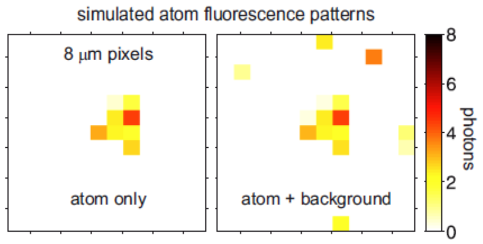
- After 4 – 8 mm fall it passes a thin **sheet of light**:
  - two counter-propagating lasers, 20 μm waist
  - resonant / detuned from $|5S_{1/2}, F=2\rangle \rightarrow |5P_{3/2}, F=3\rangle$
  - in light sheet, each atoms scatters ~ 900 photons

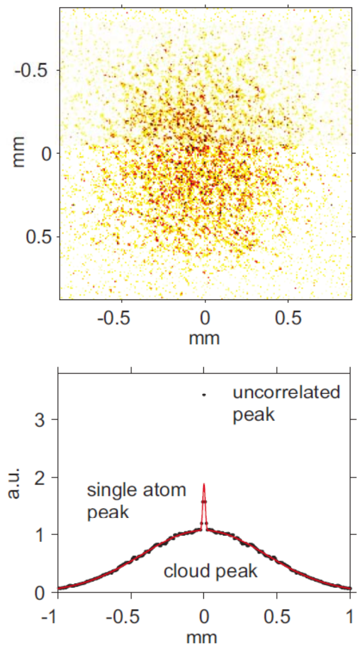
- a **high NA imaging system** captures 20 photons
  - numerical aperture 0.34
  - depht of field 40 μm (essentially zero background)
  - spatial resolution 8 μm over 4 mm diameter

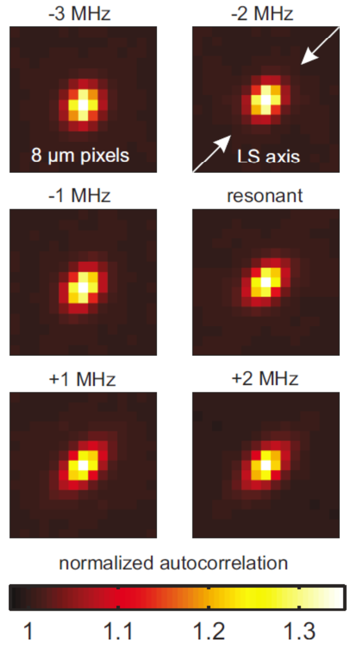
- **intensified (EMCCD) camera** records images
  - major noise source: clock induced charges $\cong$ 1 photon

Fluorescence Camera
Single Atom Detection



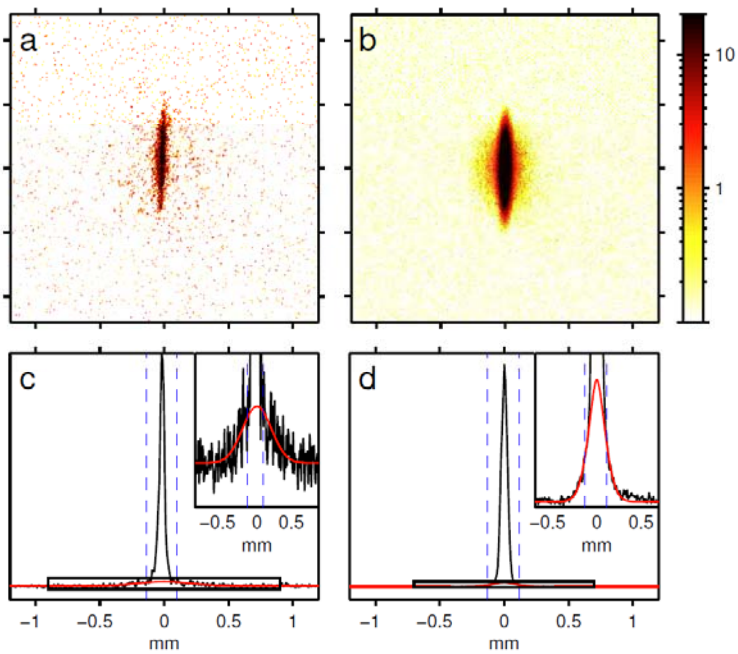




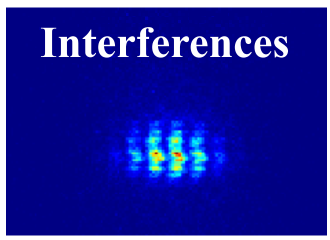


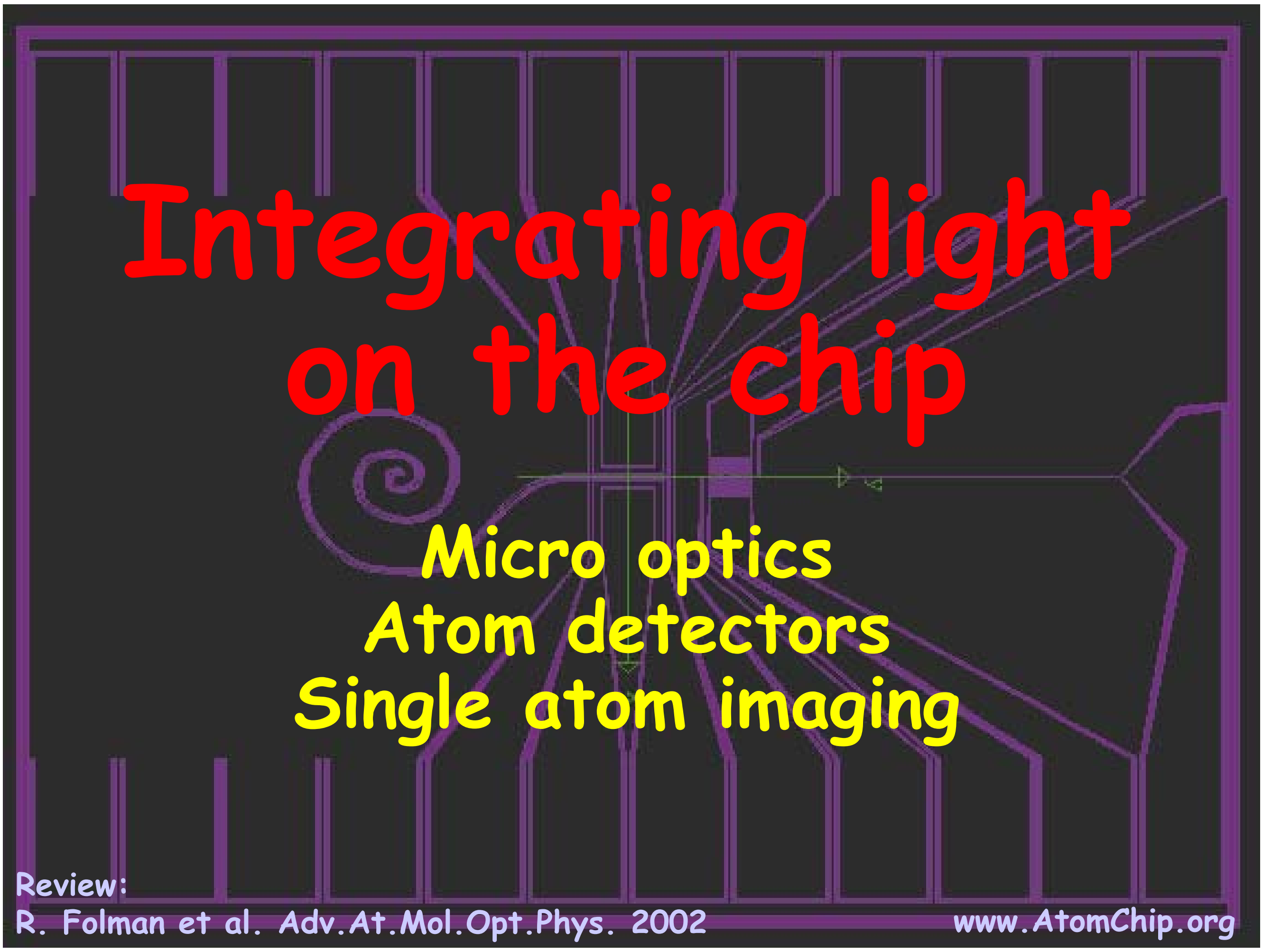
diffusion in the light field observed at single atom level

Fluorescence Camera
Large Dynamic Range



The large dynamic range of the single atom sensitive imaging allows to see very small thermal clouds besides the BEC, and measure very small temperatures $T \sim T_c/10$





Integrating light on the chip

Micro optics
Atom detectors
Single atom imaging

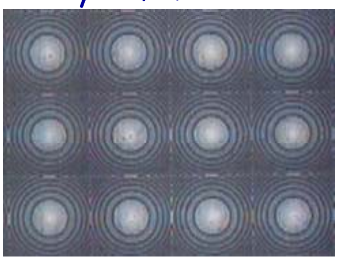
Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002 www.AtomChip.org

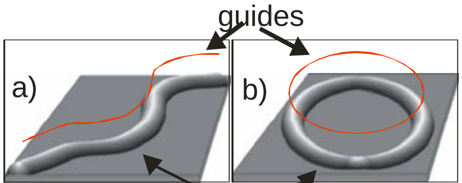
ATOMINSTITUT

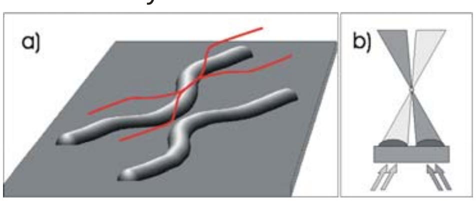
Dipole Traps using Micro Optics

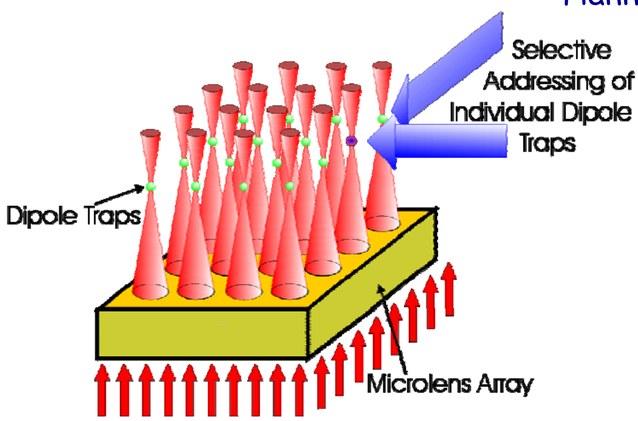
Hannover

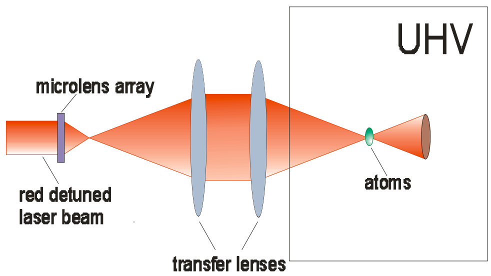
Arrays of micro lenses







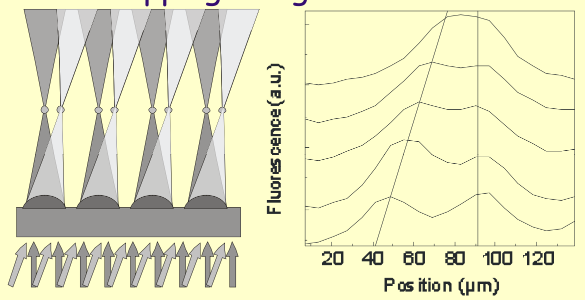


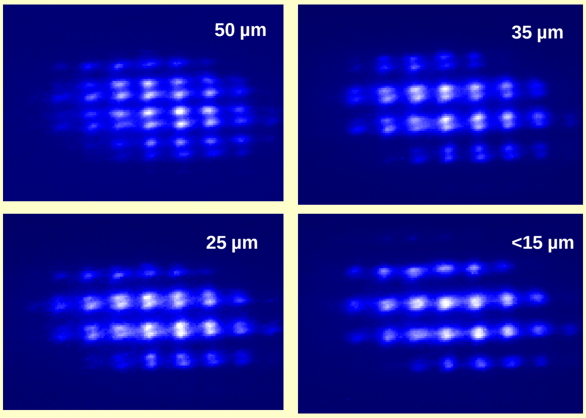


Micro optics for atom trapping

Hannover

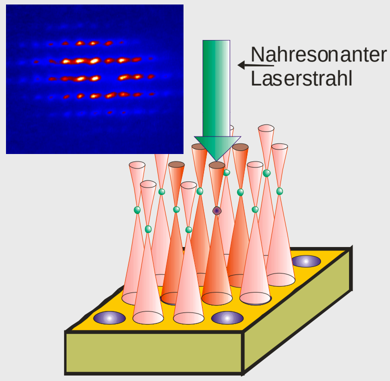
Trapping using microlenses



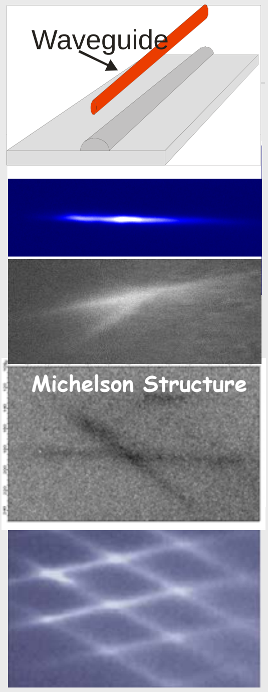


R. Dumke, et al., PRL **89**, 097903 (2002)

selective removal of one site

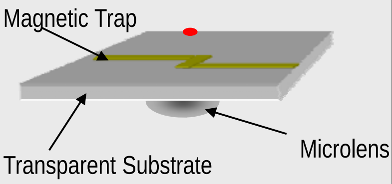


Guides, splitters networks



R. Dumke, et al., PRL **89**, 220402 (2002)

Next: Combining magnetic trapping and micro optics on the same chip

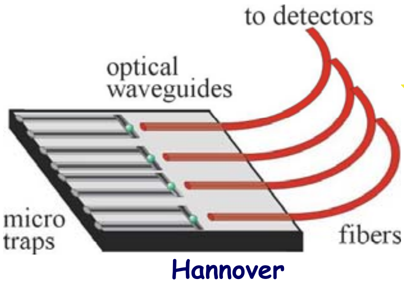


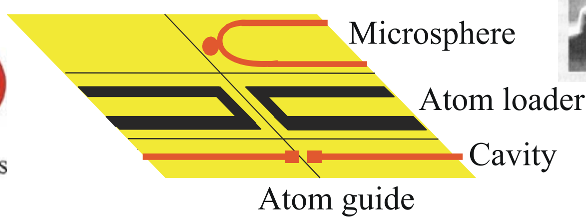
INTEGRATION OF LIGHT ON THE ATOM CHIP

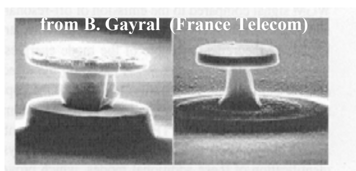
Goals: Preparation, Manipulation, Detection of atomic states on the Atom Chip

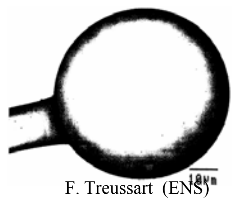
Tools: Micro optics: cavities, lenses, waveguides

Techniques of coupling to the atoms: Two mirror resonators, evanescent fields of micro spheres or micro discs, SNOM techniques, fiber cavities



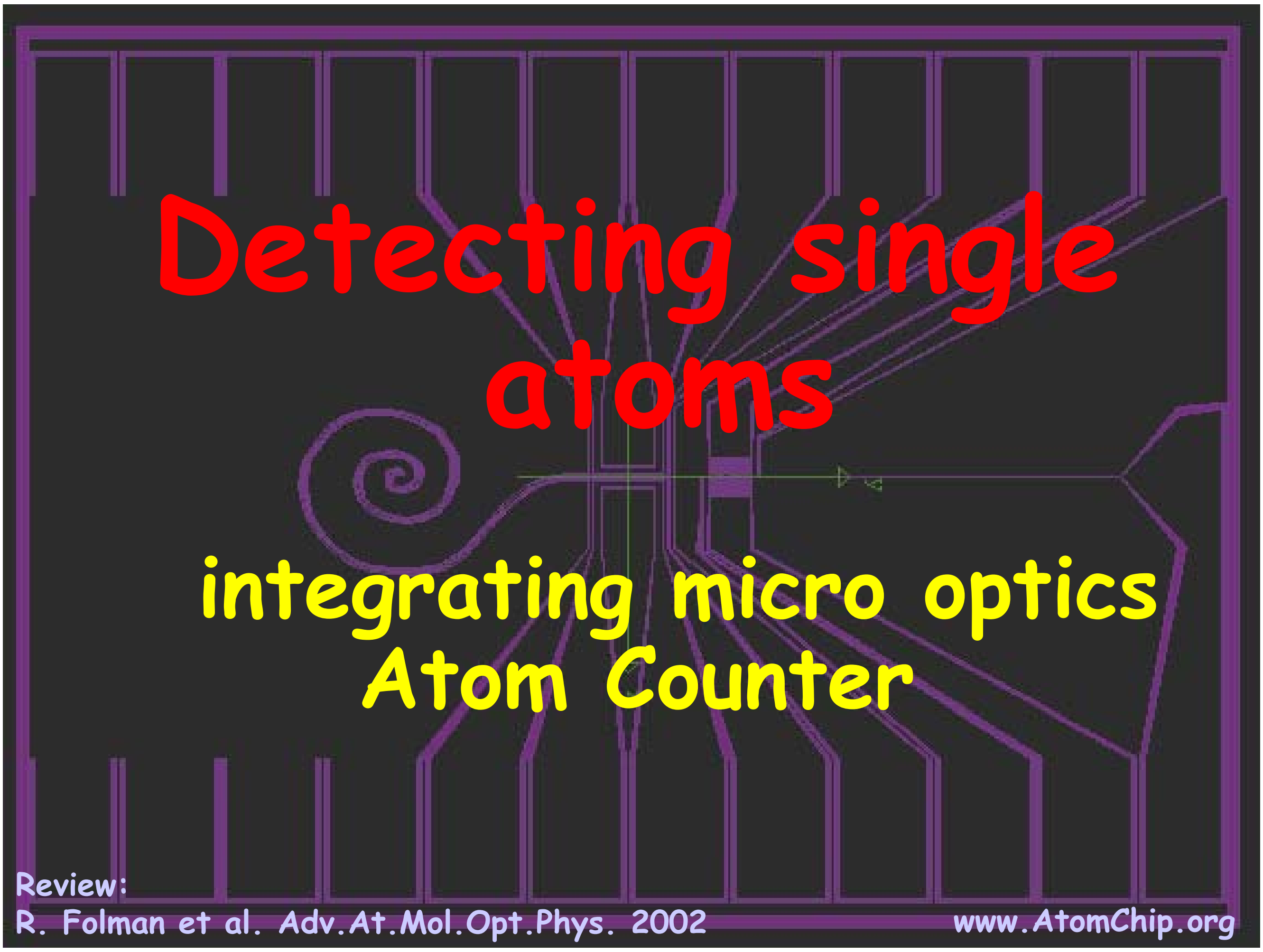






Longtime goals:

State selective, non-demolishing, single atom detection; Integration of all micro optical elements, including light sources, onto the Atom Chip



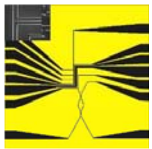
Detecting single atoms

integrating micro optics
Atom Counter

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

Detecting Atoms
Integrating Light on the Atom Chip



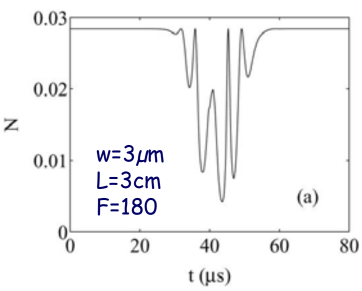
Goal:
Detect single atoms with an integrated detector on an Atom Chip

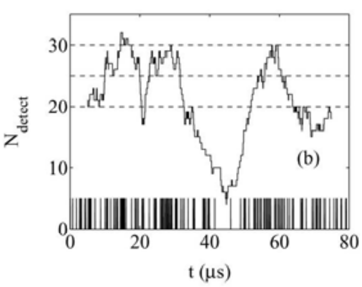
First approach:
- Fluorescence detection
- Detection by absorption of on resonant light
  $\eta_{abs} \sim \sigma_{atom} / \pi w^2$
- Enhance sensitivity with a cavity
  $\eta_{abs} \sim F\ \sigma_{atom} / \pi w^2$

Requirements for single atom detection
- small waist size (w~3μm)
- moderate finesse (F~100)
- state selectivity (line width << HF spac.)
- integration

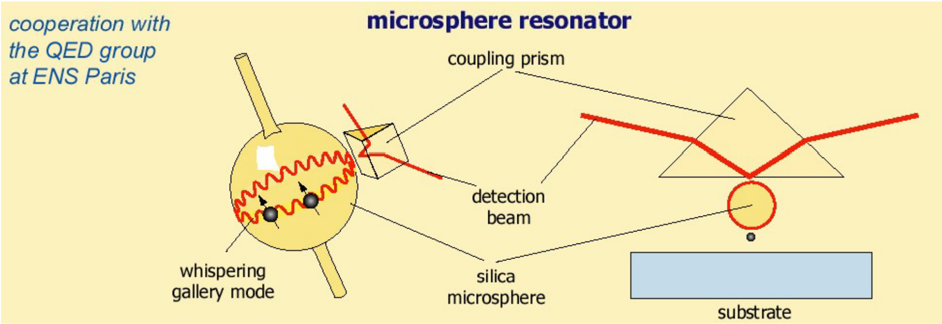
First experiment:
Detecting magnetically guided atoms with an optical cavity
A. Haase, et al. Opt. Lett. **31**, 268 (2006)

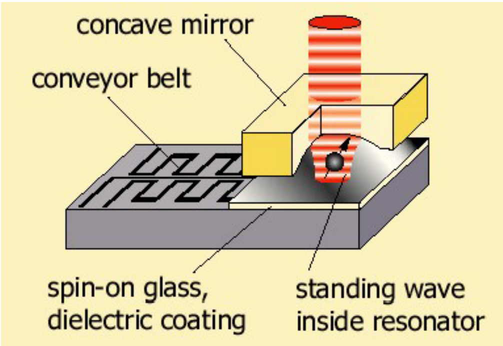
Theory proposal:
Possibility of single atom detection on a chip
P. Horak et al. Phys.Rev.A **67**, 043806

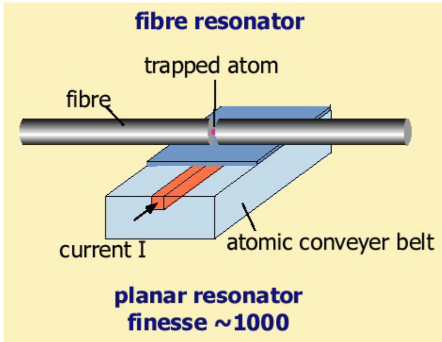




Arom Detection
basic designs





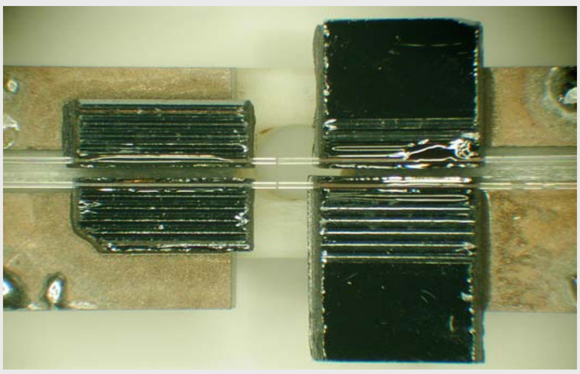


Heidelberg / Southampton, Munich, Sussex

Integrating Cavity QED on Atom Chip

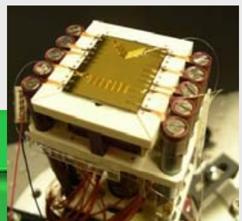
MPQ/ENS

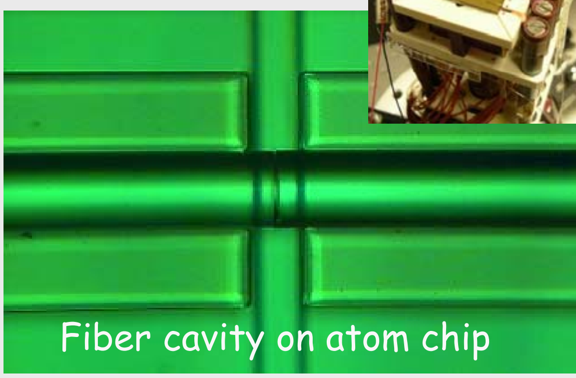
Cavity with curved front mirrors:
- 5 μm waist, ~25 μm gap.
- finesse >10000
- tuning using a macroscopic mounting
- active alignment
- On the limit to do cavity QED



HD

Fibre cavity formed by mirrors in the fiber + 5 μm gap for the atoms
- 2.5 μm waist, 5 μm gap.
- finesse >100
- tuning using a piezo stretcher
- no alignment needed
- >5σ detection of a single atom in 10 ms

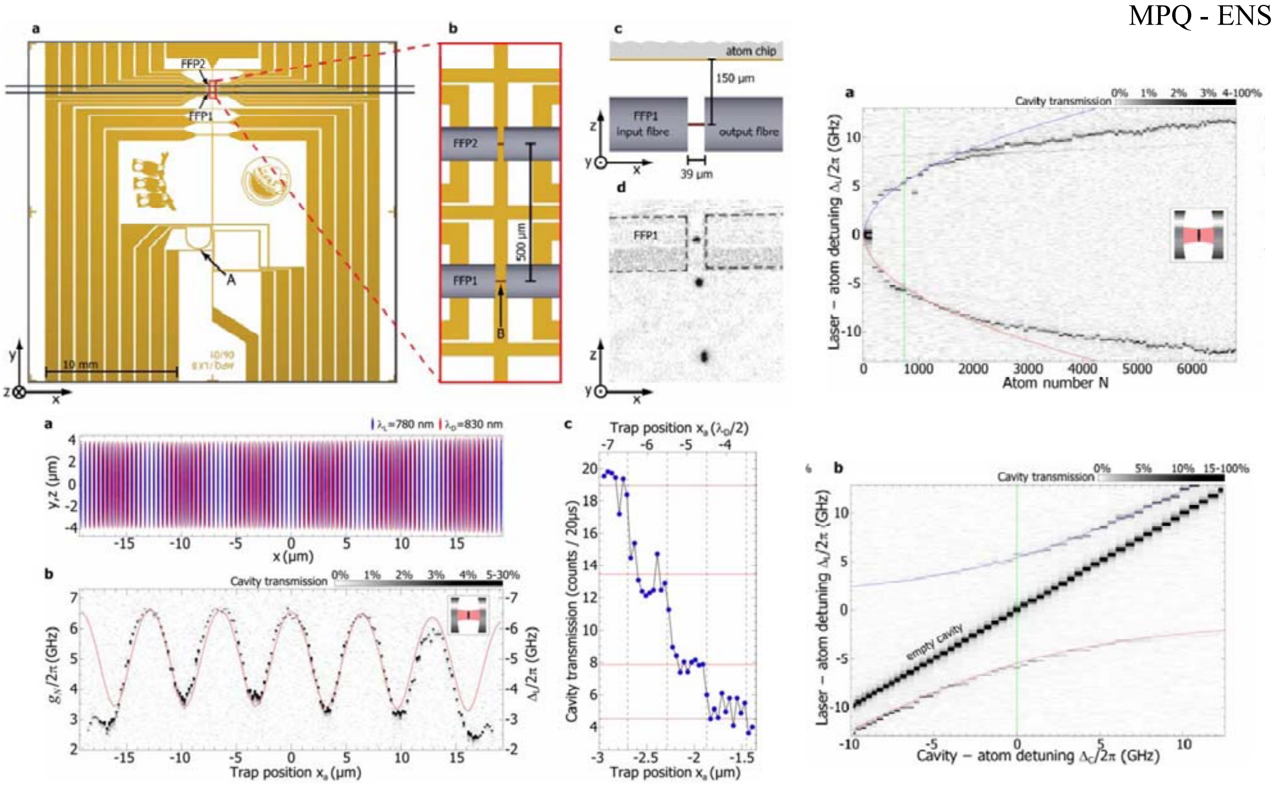




Mirror r=350 μm

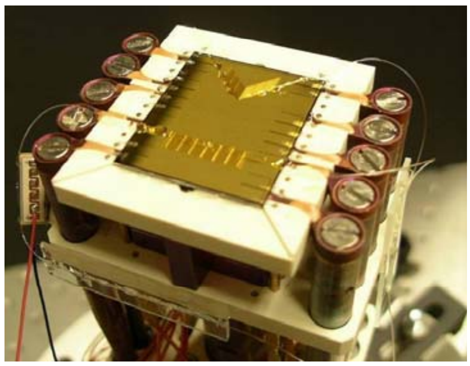
Cavity QED on a Chip

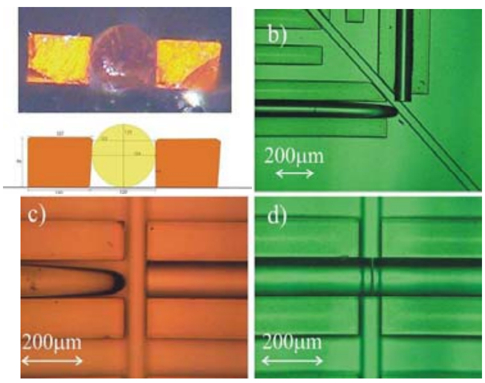
MPQ - ENS



Integrating Fiber Cavities on an Atom Chip

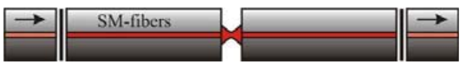
X. Liu, et al, Appl. Opt. 44, 6857 (2005)





Fibre cavity formed by (gluing) dielectric mirrors at the fibre ends + gap to introduce atoms connecting the cavity to two fiber ends

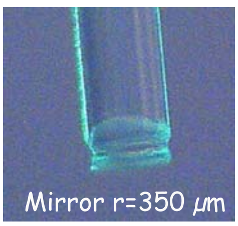
- 2.5 μm waist
- 5 μm gap
- finesse >100
- The cavity length is scanned using a piezo stretcher
- no alignment needed when mounted using SU8 structures
- >99% coupling through the gap



>5σ detection of a single atom in 10 μs

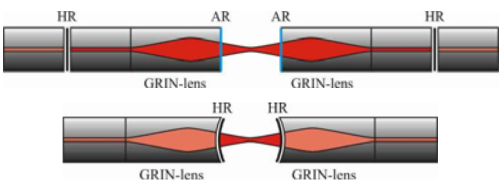
with curved mirrors

- Finesse > 1000,
- w~2.5 μm
- gap up to >50 μm

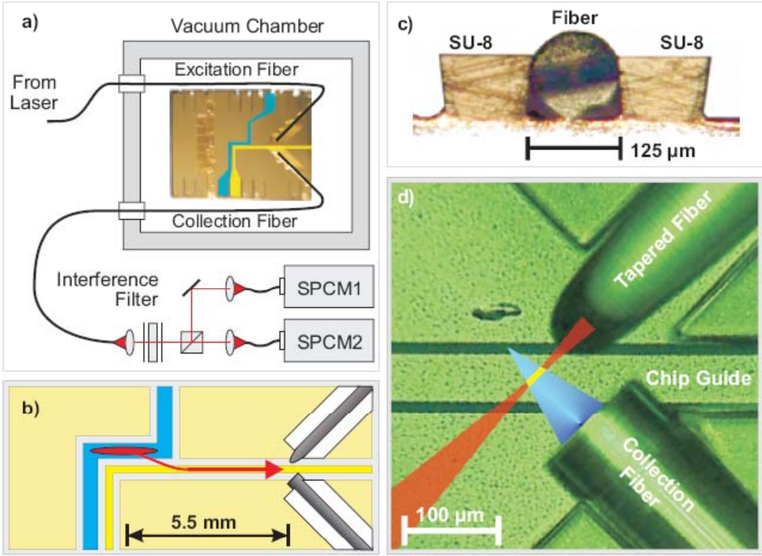


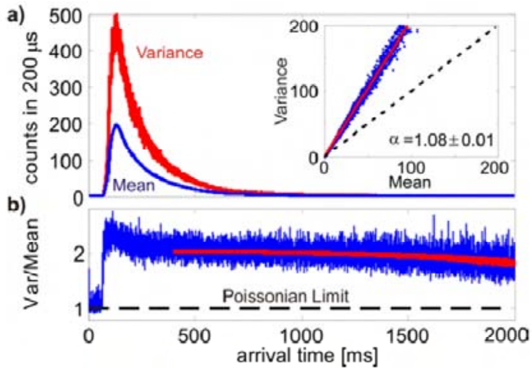
improved alignment free designs

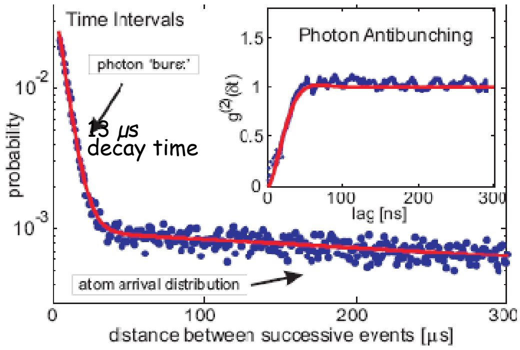
- Finesse up to ~10 000,
- w<2 μm
- **$g_0/k>1$**, $g_0/G>200$, C>100



Atom Detector
characterizing by photon statistics







$$\frac{\mathrm{var}[n]}{\langle n\rangle} = 1+\alpha$$

65% detection effitiency

Wizbach et al Opt.Lett. **34** 259 (2009)
Heine et al PRA **79** in print (2009)

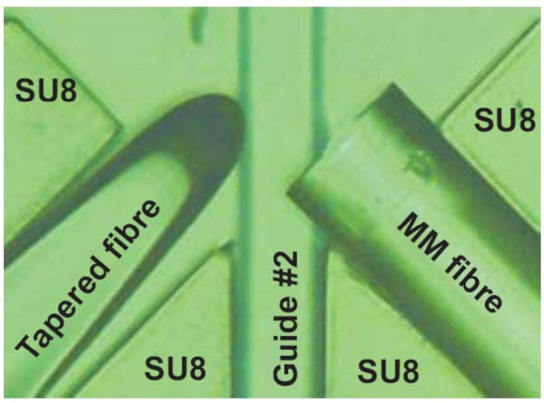
Atom Detector
outlook

•Integrated Fluorescence Detection

•very simple state selective atom counter with very low background

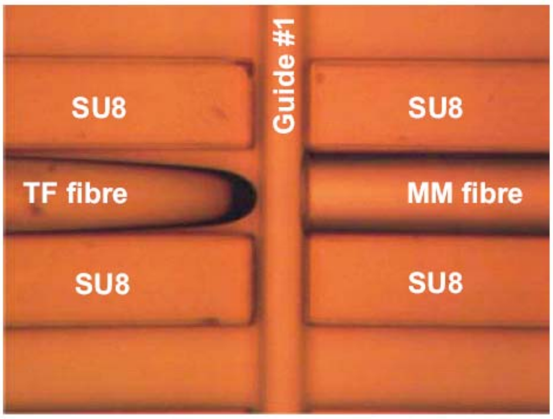
•detection efficiency (in< 40 µs):

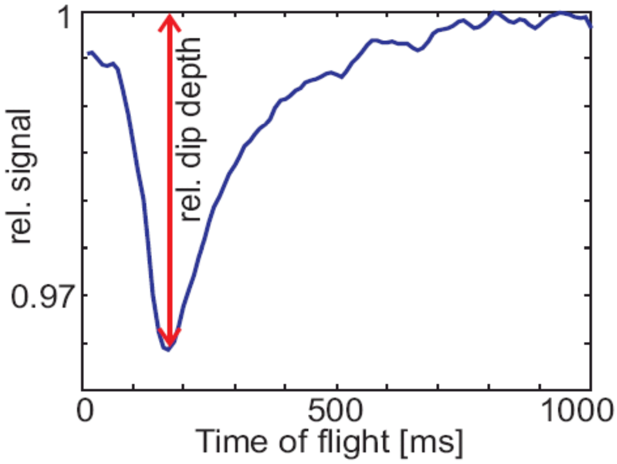
present	**η~70%**	**@ S/N > 100:1**
projected	**η>99.9%**	**@ S/N > 100:1**



Absorption Detection

preliminary





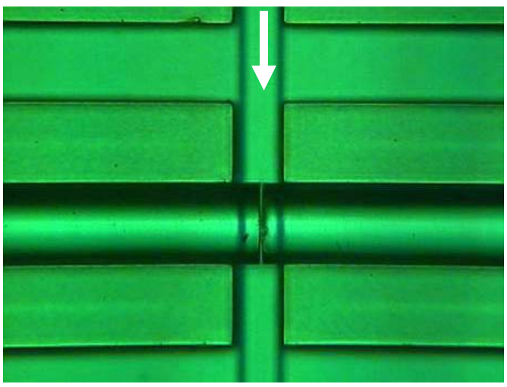
The atomic flux along the guide can also be monitored by measuring the absorption.
- Limited by photon shot noise.
- Low single atom absorption: σ_{abs}/A

Absorption can be enhanced by adding a cavity. $\frac{F}{2\pi}\frac{\sigma_{abs}}{A}$

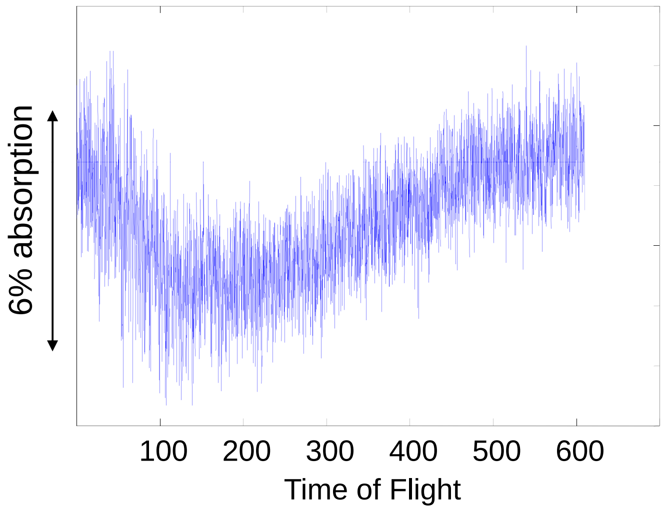
Detection with a Cavity

preliminary

Atom guide



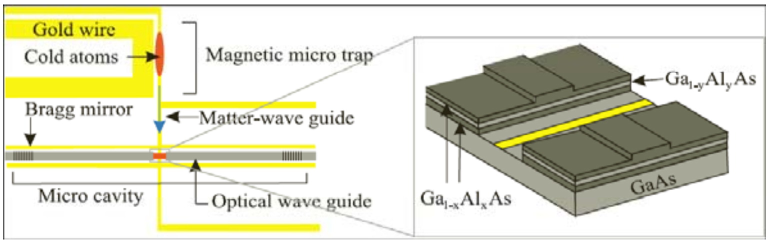
Gap 5µm
Finesse 40
L=10cm, w_0=3µm

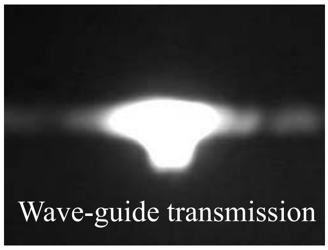


Future Integrated Detectors

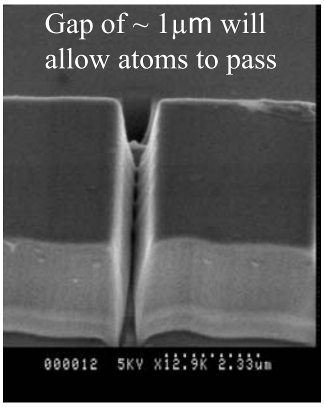
Single-atom detection with integrated semi-conductor high-finesse optical cavity

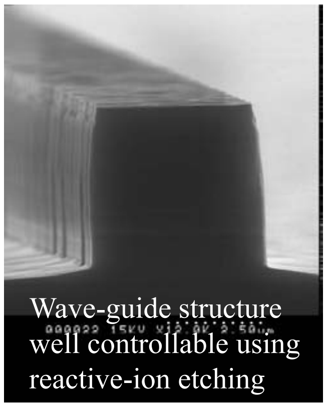
Institut d'Optique



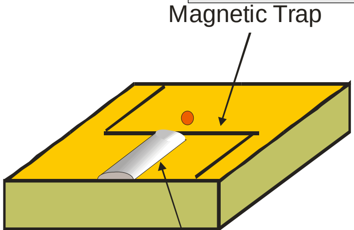


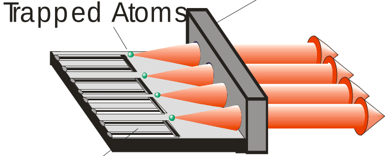
- Detect atoms by observing the cavity transmission
- Make use of well known techniques for production of laser diodes
- Scalable, reliable & reproducible

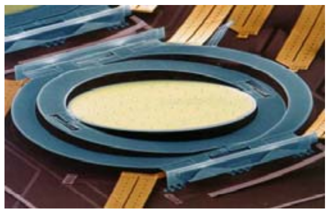


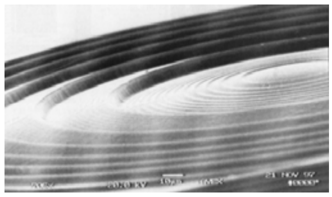


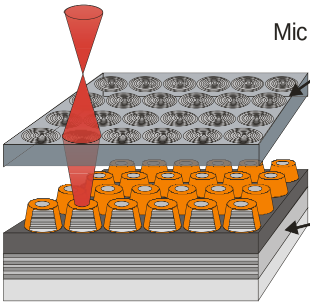
More advanced integration whish list

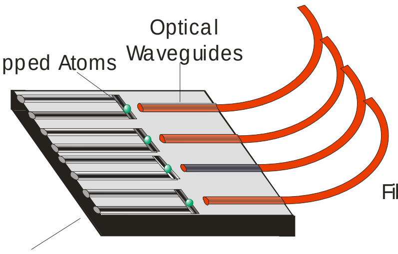


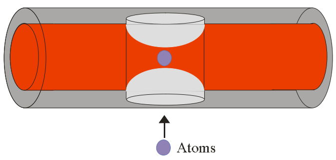


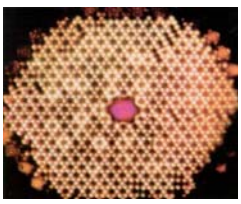


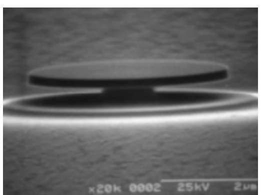


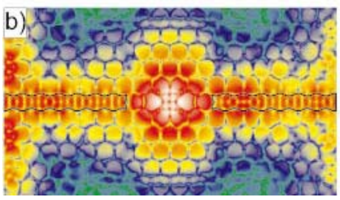


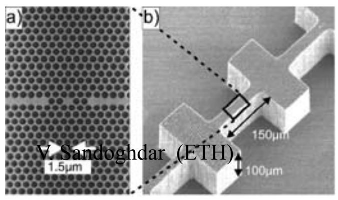


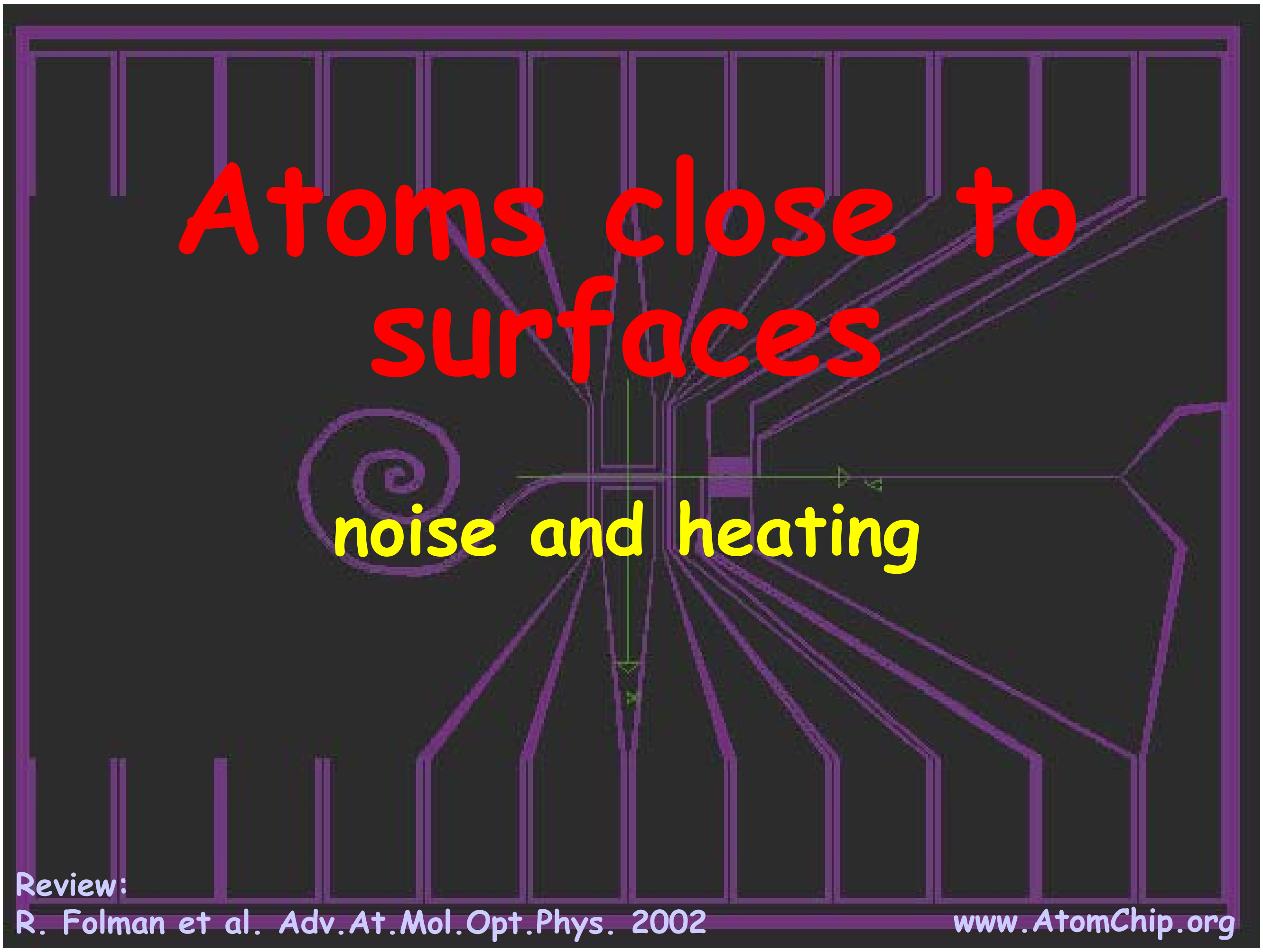












Atoms close to surfaces

noise and heating

Review:
R. Folman et al. Adv.At.Mol.Opt.Phys. 2002

www.AtomChip.org

ATOMINSTITUT

NOISE: the bad guy

life time, heating, decoherence

Heidelberg / Potsdam

Decoherence in magnetic micro traps close to surface

internal states:

Decoherence rate is the same order of magnitude as spin flip rate

external states: transverse, longitudinal

Separation larger than correlation length l_c:
-> decoherence is similar to spin flip rate

For thermal currents l_c is in order of the height above the chip

Johnson noise magnetic fields

$$\gamma \simeq 75\mathrm{s}^{-1}\frac{(\mu/\mu_\mathrm{B})^2(T_s/300\mathrm{K})}{(\varrho/\varrho_\mathrm{Cu})}(\mathrm{Tr}Y_{ij}\times 1\mu\mathrm{m})$$

Geometry	Tr Y_{ij}
Half-space	π/h
Layer	$\pi d/h^2$
Wire	$\pi^2 a^2/(2h^3)$

Technical current noise

$$\gamma \simeq \frac{\mu^2}{2\hbar^2}\left(\frac{\mu_0}{2\pi h}\right)^2 S_I(\omega_L)$$

$$\simeq 2.6\mathrm{s}^{-1}\frac{(\mu/\mu_B)^2}{(h/1\mu\mathrm{m})^2}\frac{S_I(\omega_L)}{S_\mathrm{SN}}$$

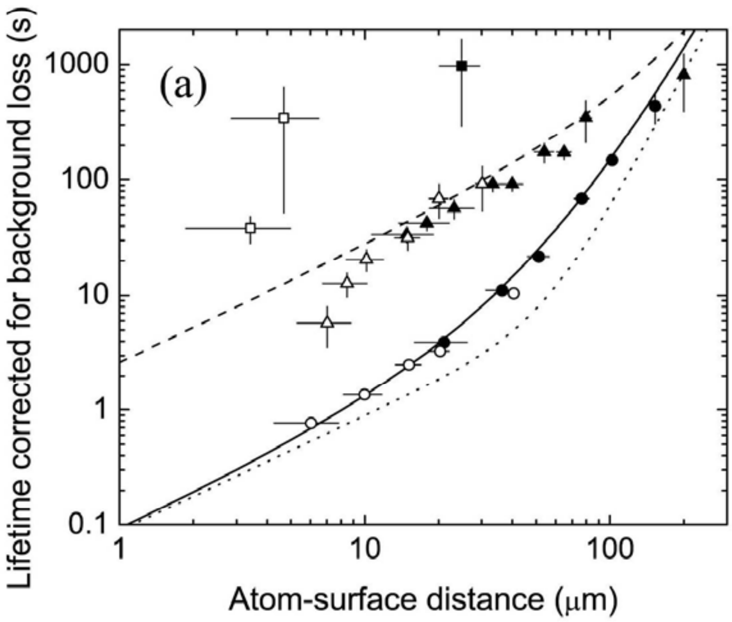
S_{SN}=6.4 10^{-19} A^2/Hz

Other mechanisms: Majorana transitions in a harmonic trap

C. Henkel

Lifetime as the atoms approach the surface

Potsdam



JILA data

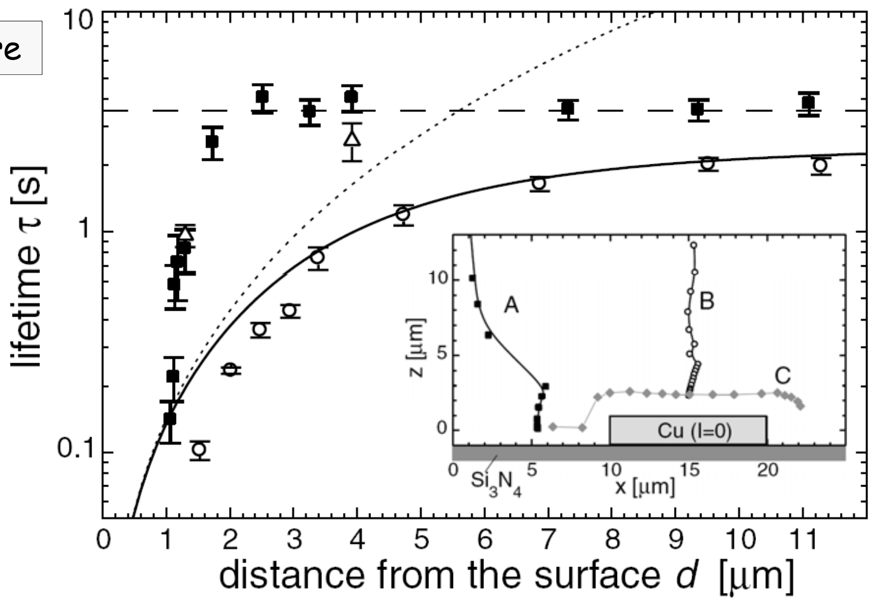
Harber et al (2003)

In good agreement with calculations of Carsten Henkel

Atoms close to surface
lifetime of trap

Stanford

2 μm Cu wire

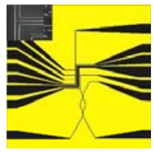


- Long life time close to a dielectric surface
- Loss at a metal surface.
- Observe Casimir Polder intertaction between the atom and the surface

PRL 92, 050404 (2004)

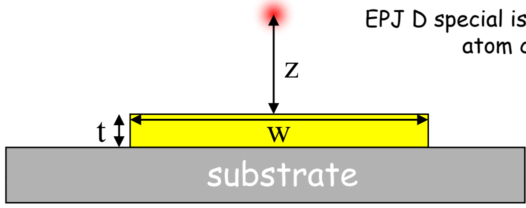
How long lifetime is possible ?

Rectangular wire, specified confinement



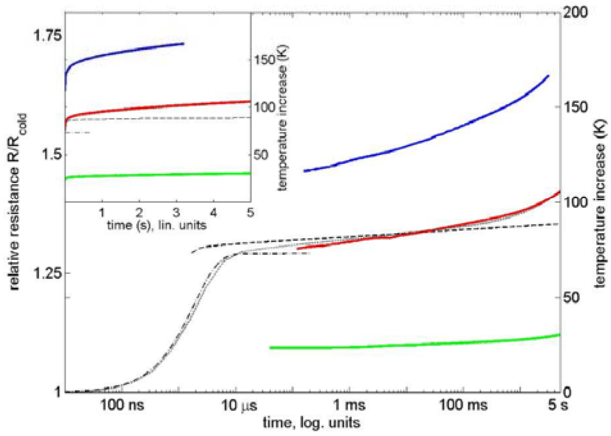
HD - Potsdam
EPJ D special issue
atom chip

Spin-flip rate from C. Henkels theory



$$\gamma \approx A \frac{T_w}{\varrho(T_w)} \frac{3\pi t}{8z^2\left(1+(2z/w)^2\right)^{1/2}}$$

- scaling from the magnetic field gradient calculation
- Heating of the wire
  - thermal conductivity
  - resulting maximum current

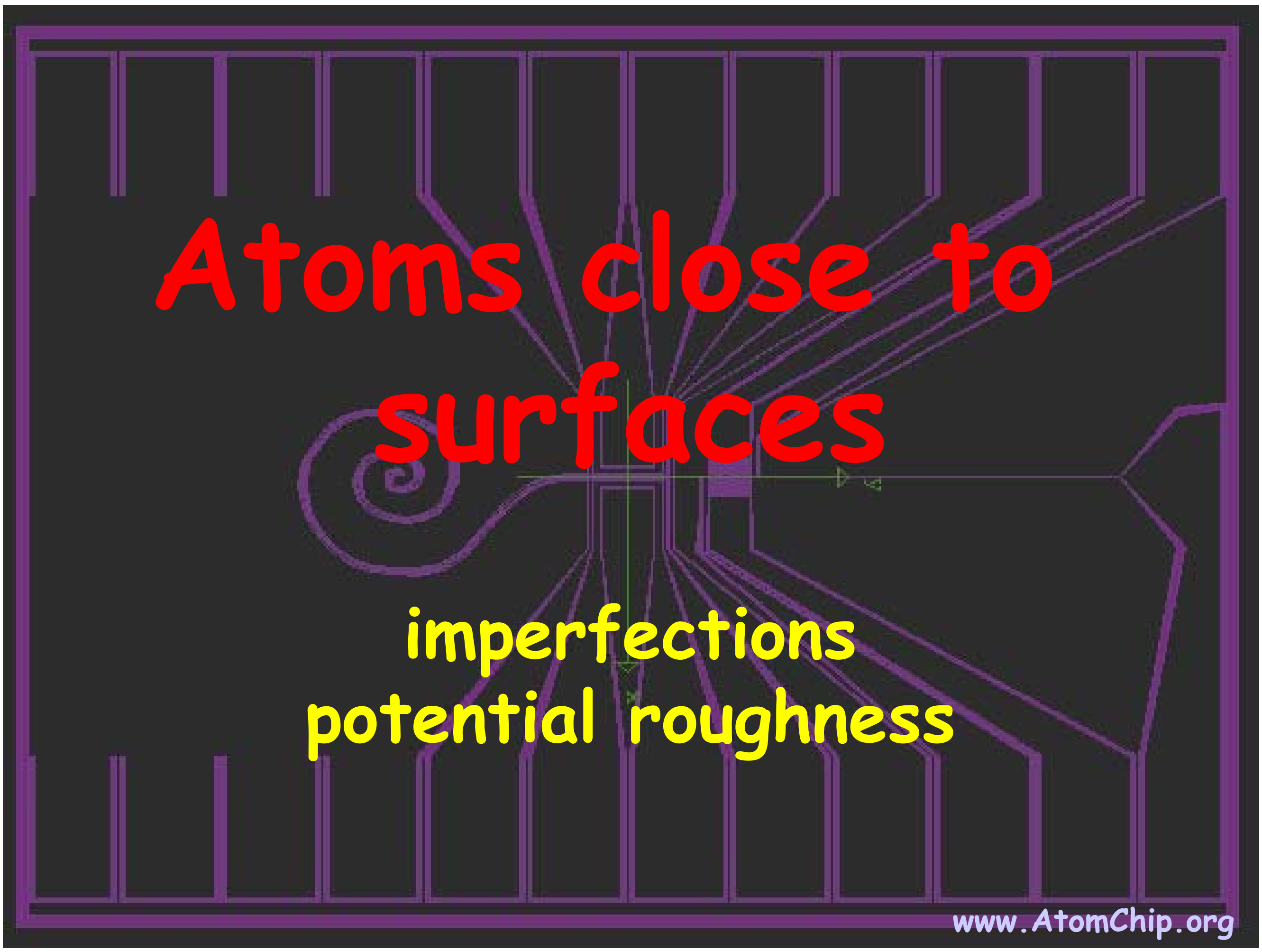


Typical numbers for dB/dz = 10^5 G/cm
(100kHz trapping frequency for Rb):

$$\boxed{\gamma \approx 4\times 10^{-4}\left(\frac{T}{\Delta T}+1\right)\ s^{-1}}$$

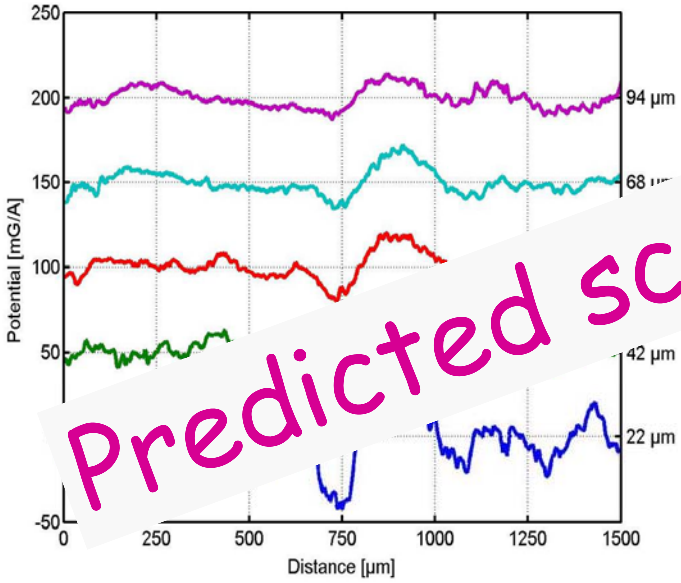
Material properties

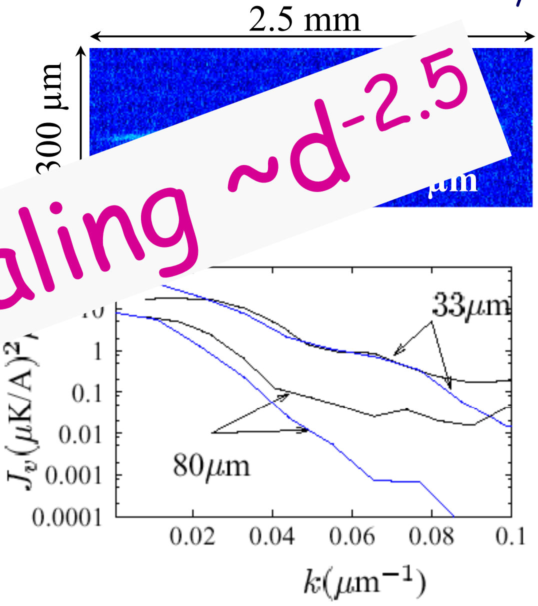
$$\frac{T}{\Delta T}+1=\frac{d\varrho}{dT}\frac{T}{\varrho}\frac{j_{\max}^2-j^2}{j^2}+1$$



Roughness of the magnetic potential
electro-plated Atom Chips

Orsey





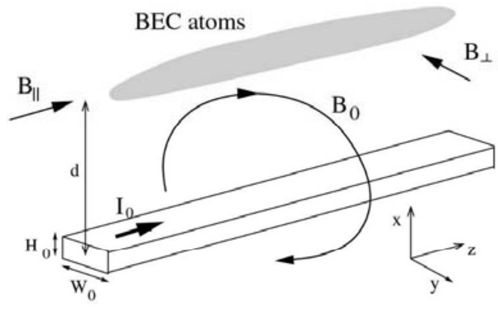
Predicted scaling ~$d^{-2.5}$

Observed potential at different heights

Power spectrum of roughness in terms of potential energy (1 µK = 15 mG)

From where do the dissorder potentials come from

- Atoms are trapped in the minima of potentials created by the subtraction of two large fields.
- Minimum in that plane depends on the angle between these two fields.
- Sensitivity to changes in the current direction which are **not** orthogonal to the bias field.
- Sensitivity: thermal atoms: 1G ~ 67 µK
  BEC: chem. potential (~1-10 mG) sensitivity < 10^{-5} rad



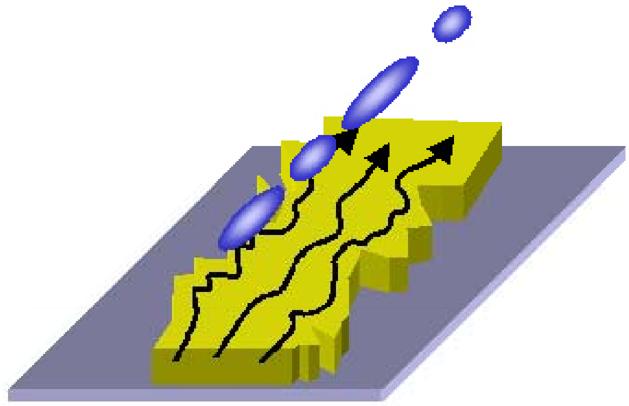
Proposal:

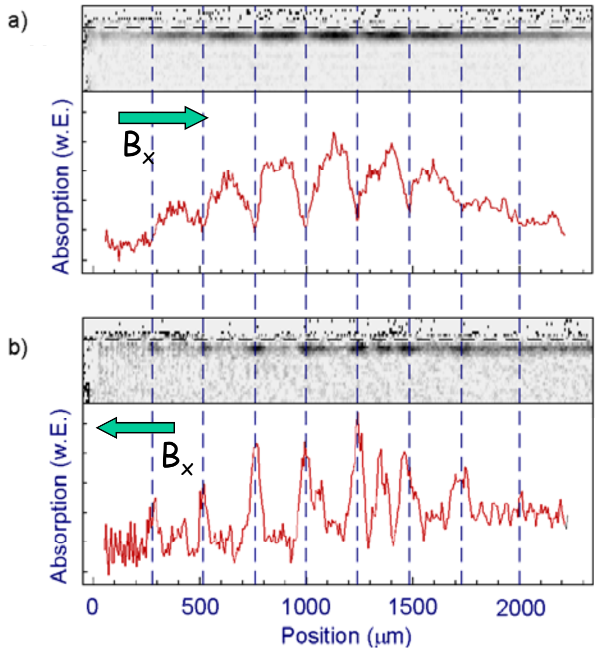
- Roughness of the wire edge causes the current to deviate from a straight flow (we choose evap. gold and nanofab.) for theory see: Daw-Wie Wang et al. PRL 92, 076802 (04).
- Imperfections in the surface of substrate (we chose Si and GaAs).
- Disordered current flow due to grain size in the wire.

Fragmentation

~250 μm (quasi) periodic break up of a cold cloud observed above (3-500 μm thick) copper wires.
Tübingen, MIT, Sussex, JILA … etc.

Fragmentation due to corrugations in mag. potential.





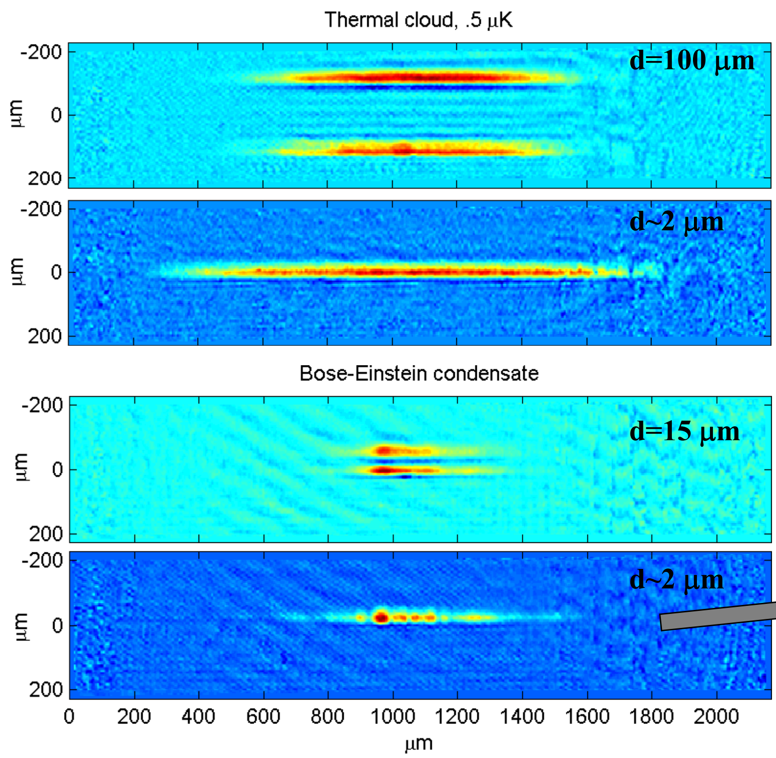
Solution: fabrication method

Tübingen: change the direction of longitudinal bias field B_x.

Roughness of the magnetic potential

evaporated gold Atom Chips

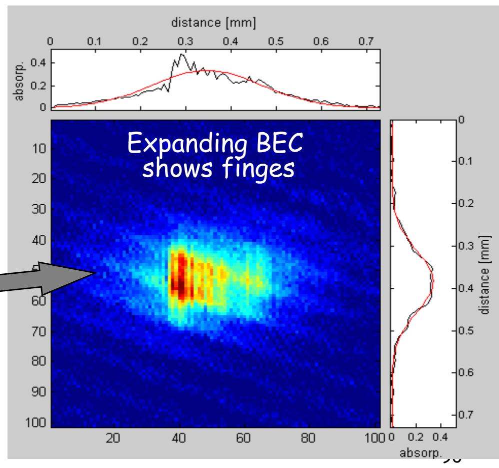
Heidelberg/WIS



No fragmentation for a thermal cloud even at T~500nK

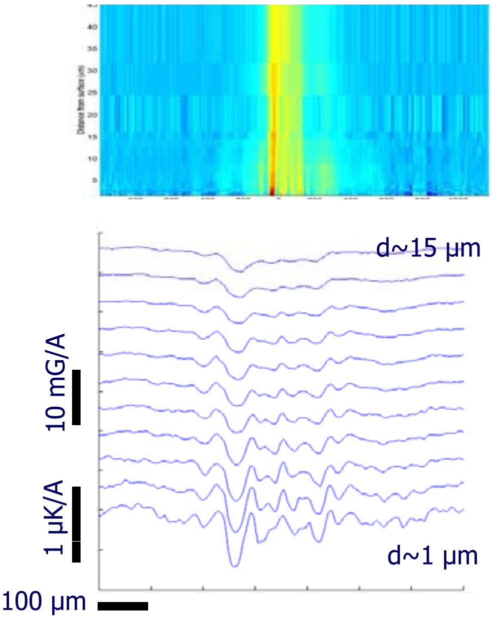
Some fragmentation for a BEC below 10 μm from surface

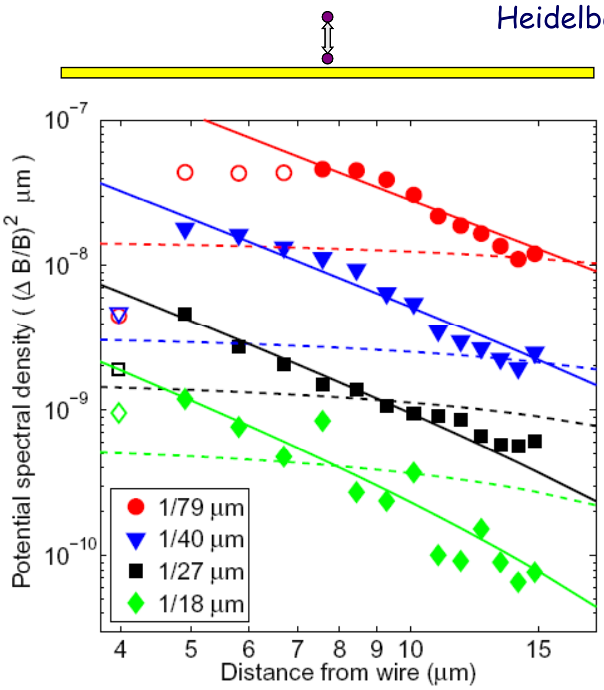
Disorder potentials ~ 10nK or smaller



Edge or local effect?

Heidelberg



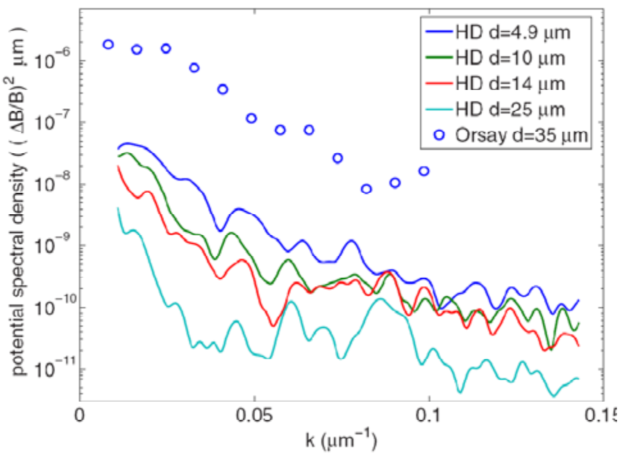


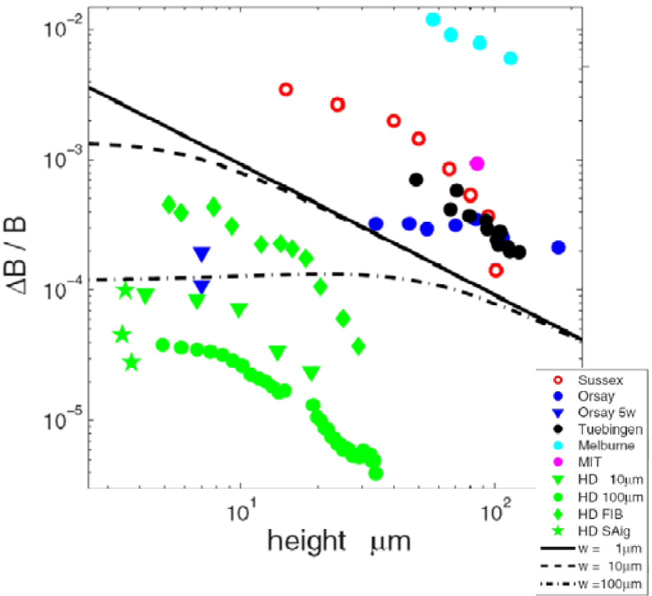
Roughness is dominated by large scale fluctuations,
very smooth potentials at short length scale

IBK-Summer School July 2009 J. Schmiedma La Tuille meeting march 2004; Kruerger at al. arXiv:cond-mat/0504686

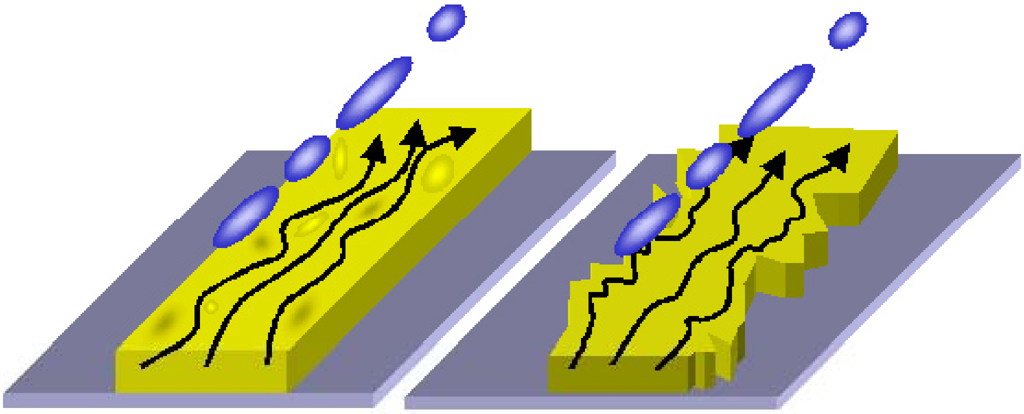
Comparison

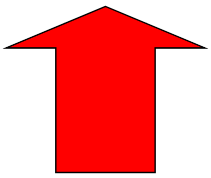
P. Krüger et al. Phys. Rev. A **76**, 063621 (2007)





What causes the disorder potentials?



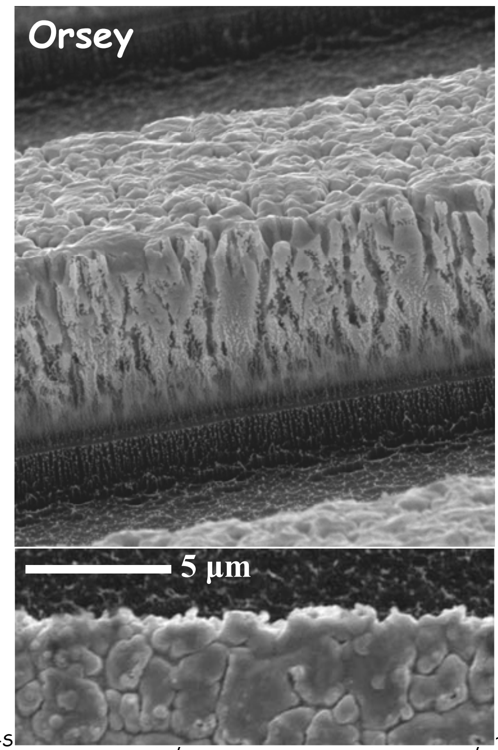


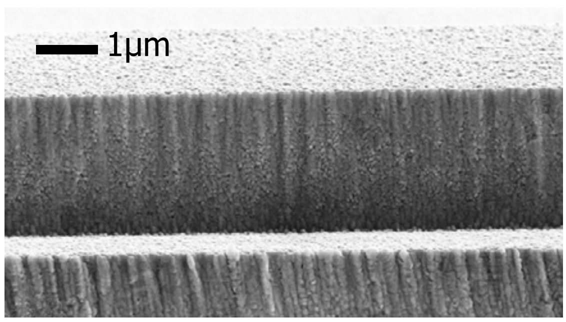
Important contribution
from the local properties

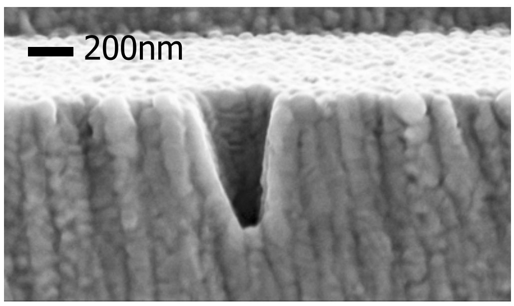
Roughness of the micro wire

microscope images of the surface quality of the wire

HD/WIS/ATI







How smooth are the potentials

Heidelberg

Measured roughness corresponds to <1 cm in 1000 m (pretty boring ski slope)
We can see < 1 mm in 1000 m

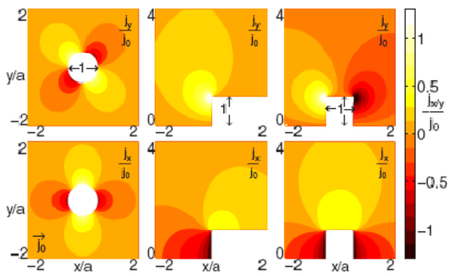
Present experiments can measure changes in

- Changes in magnetic field direction of < 10^{-6} rad
- electric fields, patch charges of small impurities <10 mV at μm distance
- Resolution <4μm (or better)

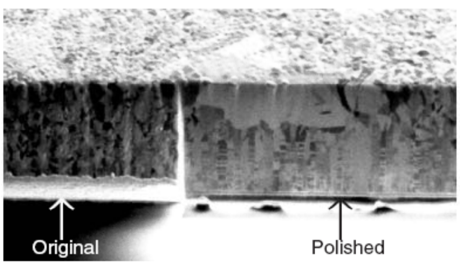
Designing Potential by Sculpturing the Wire

L. Della Pietra et al. Phys Rev A **75**, 063604 2007

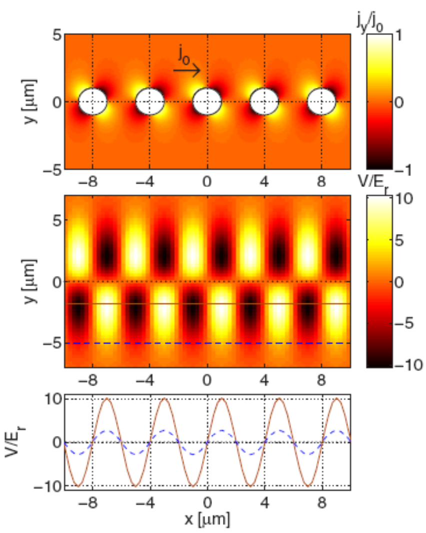
current flow around a defect



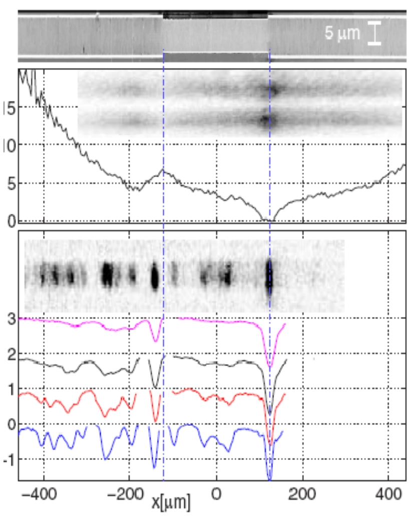
polishing with a FIB



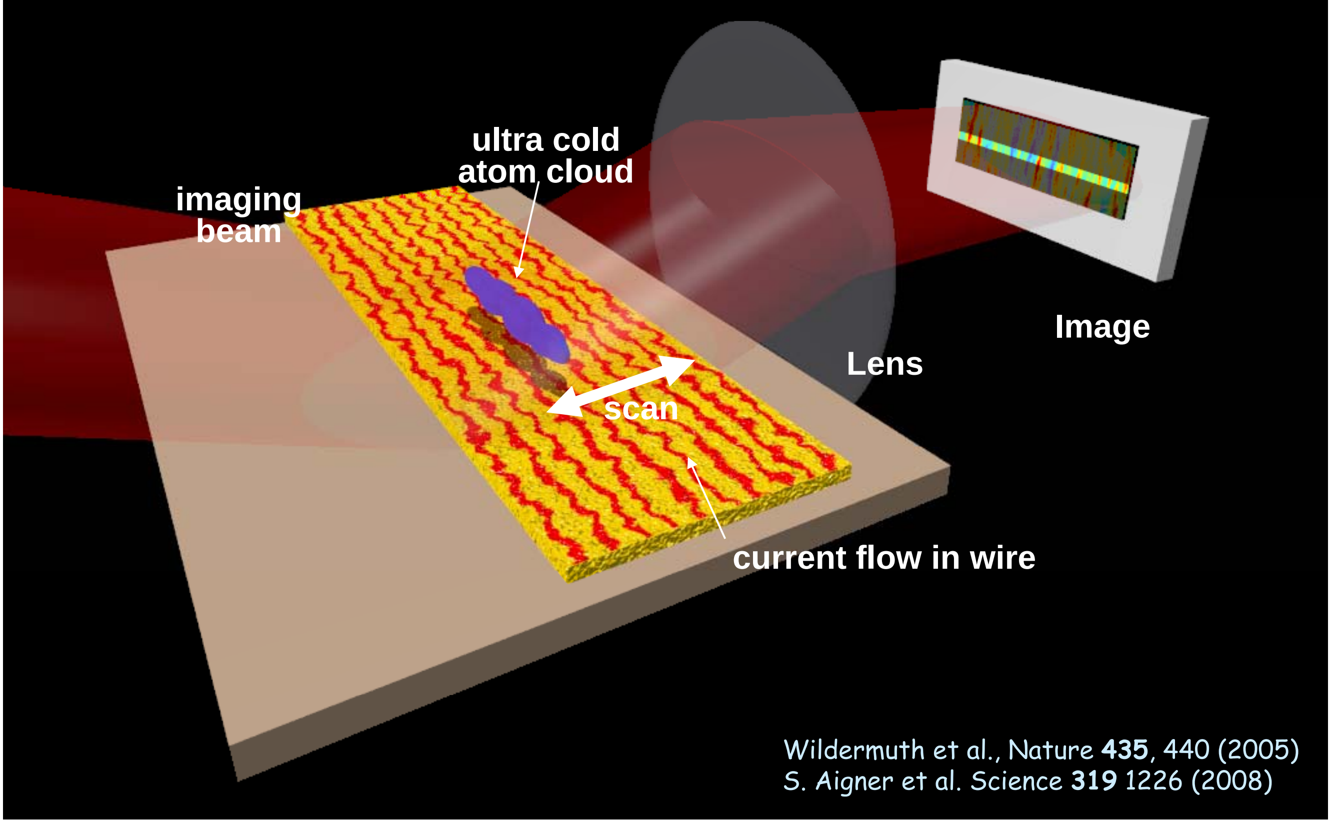
array of holes -> magnetic lattice



modified wire



Magnetic Field Microscope



Wildermuth et al., Nature **435**, 440 (2005)
S. Aigner et al. Science **319** 1226 (2008)

ATOMINSTITUT

How to measure potentials with ultra cold atoms

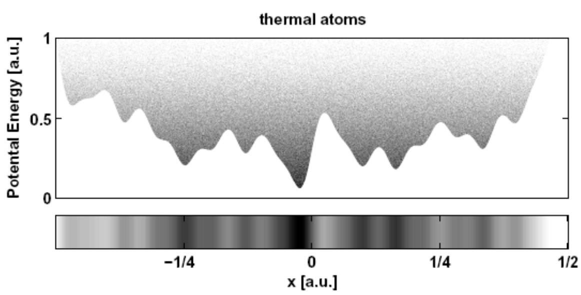
Basic idea:
Cold atoms accumulate in a trap according to their energy

Thermal Atoms:

the energy scale: temperature:

$$\Delta V(x) = -k_B T \ \log \frac{n_{1d}(x)}{< n_{1d} >},$$

100µT (1 G) ~ 67 µK

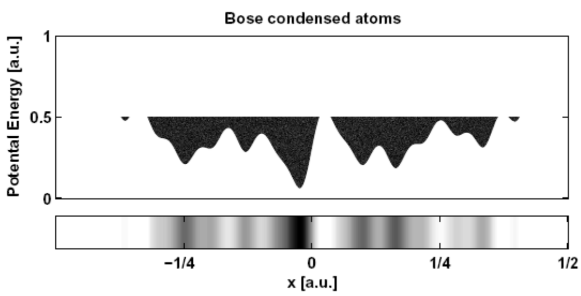


Bose Condensed Atoms:

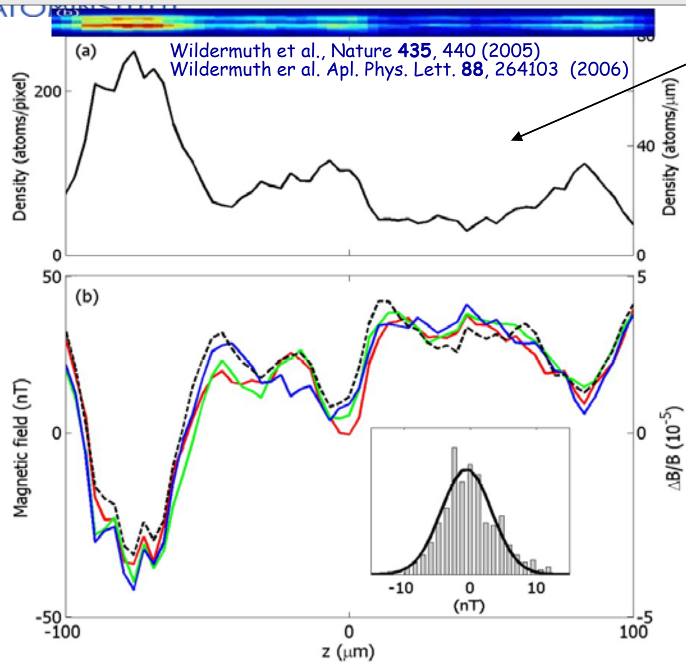
energy scale: transverse grounds of trap (chemical potential = constant):

$$\Delta V(x) = -\hbar\omega_\perp \sqrt{1 + 4a_{\rm scat} n_{1d}(x)},$$

1 kHz ~ 70 nT (0.7 mG)



Measuring Potentials with 1d BEC



Wildermuth et al., Nature **435**, 440 (2005)
Wildermuth er al. Apl. Phys. Lett. **88**, 264103 (2006)

one-dimensional BEC in Thomas-Fermi regime ($\mu < \hbar\omega$)

On AtomChip:
BEC ~1mm long <200nm wide

Atom density is a measure of the potential

Sensitivity

trap transverse size: r~200nm
long. resolution: l~3 μm
volume ~ 0.4 μm³

single shot gives >300 points
each 30s a measurement
=> 10 measurements / second
single shot: ΔB ~ 4nT
ΔB ~ 1.3nT $Hz^{-1/2}$

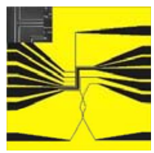
Sensitivity with a relaxed trap

r~700nm l~3 μm
volume ~ 5 μm³

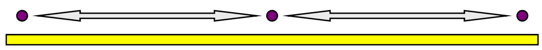
single shot: ΔB ~ 0.3 nT
ΔB ~ 0.1 nT $Hz^{-1/2}$

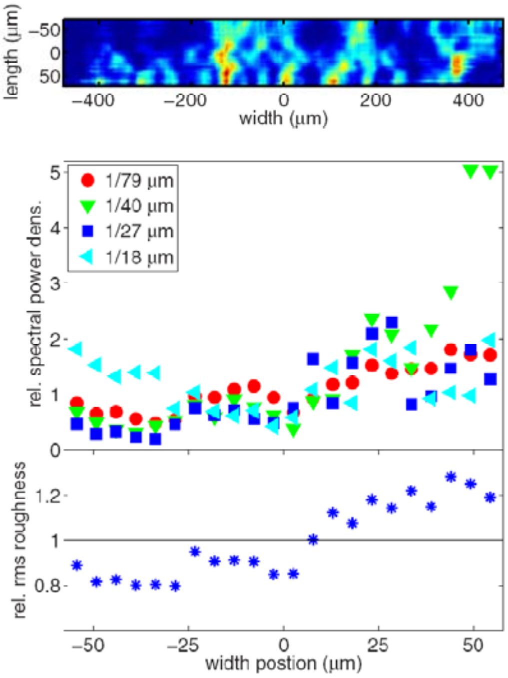
measurement cycle time can easily improved to 1s
longitudinal imaging resolution can be improves to 1 μm
→ measurement volume decreases by factor 3
→ ΔB increases by sqrt(3) (atom shot noise in)
→ effective time per measurement point decreases by factor 30
→ overall sensitivity improves by sqrt(10)

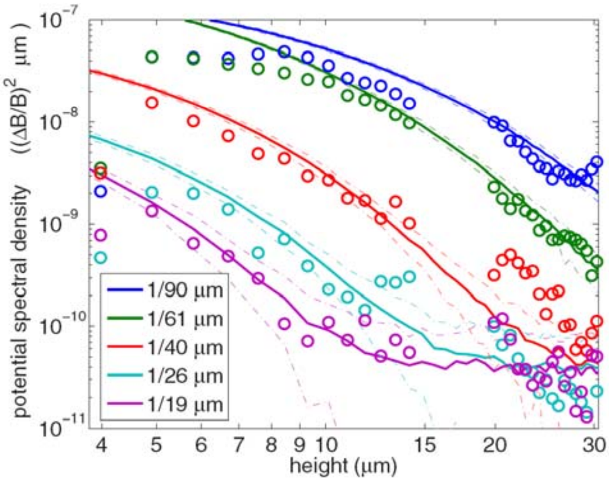
Magnetic field map of the wire



P. Krüger et al. Phys. Rev. A **76**, 063621 (2007)





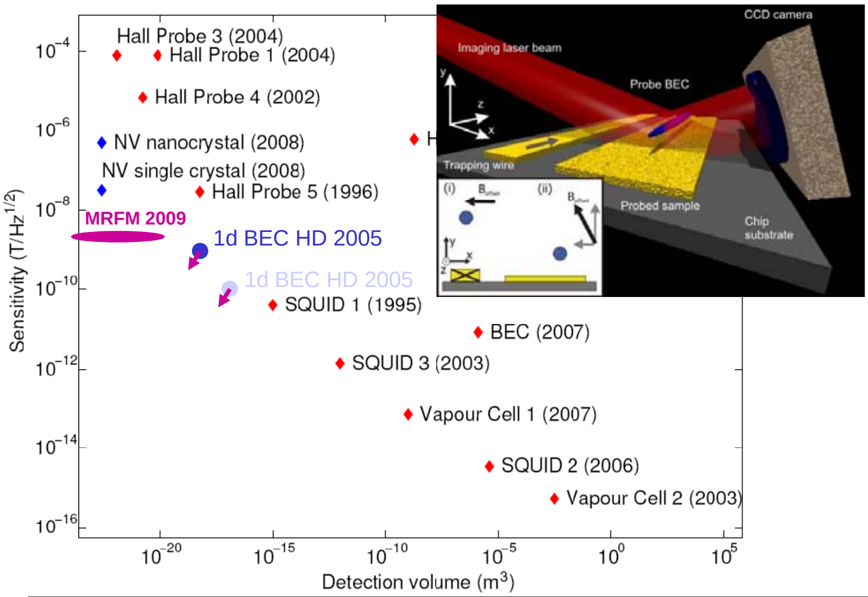


Sensitivity
Compare to other methods

Wildermuth et al., Nature **435**, 440 (2005)

Magnetic Field sensitivity: $\Delta B = \gamma \, \Delta N / (\rho_0^2 z_0)$ $\quad \gamma = 2\hbar^2 a_{scat} / (g_F m_F \mu_B m)$

$\gamma = 9.29 \cdot 10^{-29}$ Tm^3 For ^{87}Rb atoms in the $|F=2, m_F=2\rangle$ state

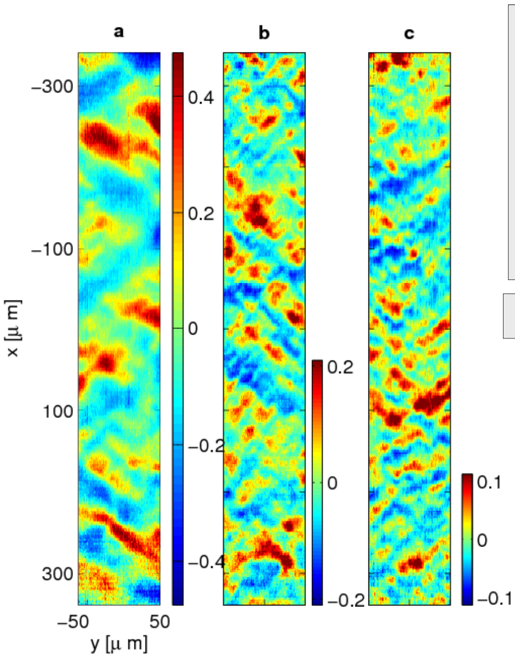


$\rho_0 = z_0 = 1\mu$m a sensitivity of ΔB = 1nT is possible.

By changing to a different atom with higher mass and/or by tuning the scattering length a_{scat} to close to zero using a Feshbach resonance a significant increase in sensitivity can be achieved.

Application in Solid State Physics:
Long-Range Order in Electronic Transport through Disordered Metal Films: Science **319**, 1226 (2008)

current flow in gold wires

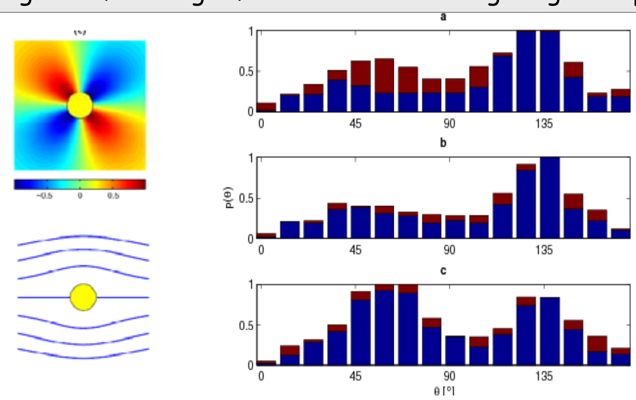


Magnetic field angle fluctuations $\sigma(\theta)$ at a height of z ~ 3.5μm above the three wires with different thickness (h) and grain size (S_G).

Wire a:	h = 2 μm	S_G = 35 nm	$\sigma(\theta_a)$ = 0.16 mrad
Wire b:	h = 250 nm	S_G = 35 nm	$\sigma(\theta_b)$ = 0.07 mrad
Wire c:	h = 250 nm	S_G = 120 nm	$\sigma(\theta_c)$ = 0.035 mrad

the thinnest wire with the largest grains shows the smoothest current nearly an order of magnitude smaller then pedicted from surface roughness

Magnetic field angle fluctuations show long range 45° pattern

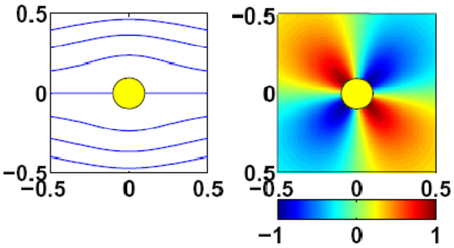


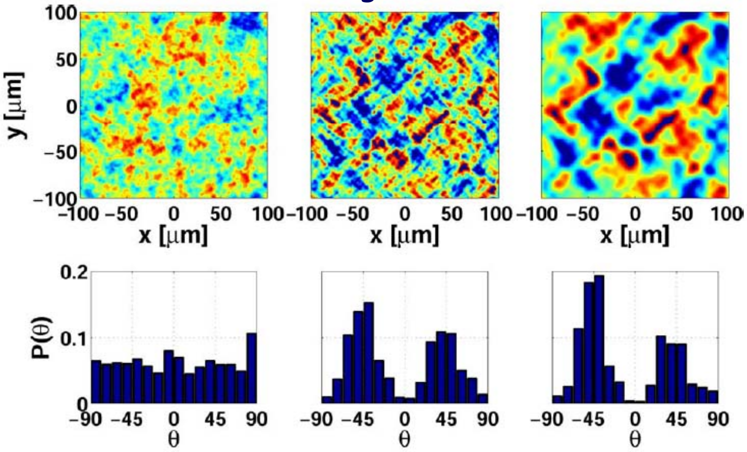
Long-Range Order in Electronic Transport through Disordered Metal Films
S. Aigner, et al. Science **319** 1226 (2008)

Current flow around a defect

emergence of the 45° pattern from a random arrangement of defects

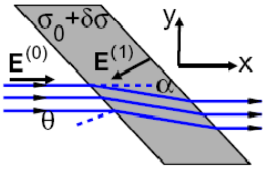
Current flow around a defect





$$E_y^{(1)} \propto \sin 2\theta$$

Conductivity edge



$$\delta \mathbf{J} = J_0 \frac{\delta\sigma}{\sigma_0}(\sin^2\theta\hat{x} - \cos\theta\sin\theta\hat{y}).$$

damping with distance

$$\hat{B}_x = f(k_x,k_y,z,d)\hat{j}_y(k_x,k_y), \qquad f(k_x,k_y,z,d) = \frac{\mu_0}{2}d\left(\frac{1-e^{-kd}}{kd}\right)e^{-kz},$$

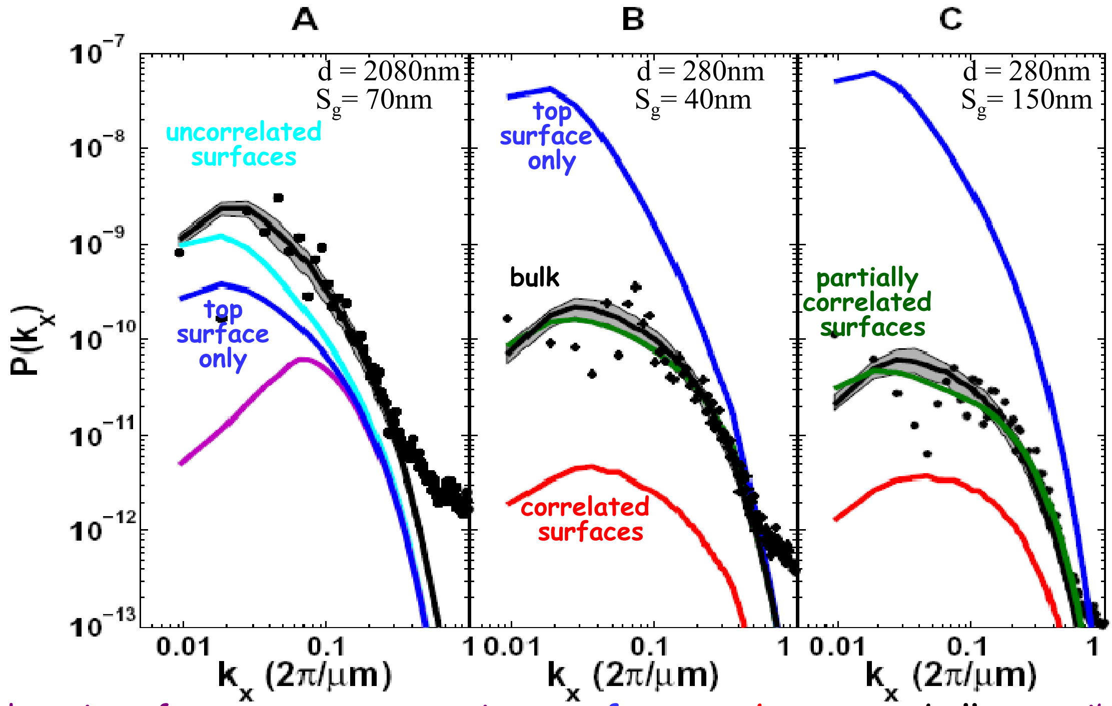
reconstructing the current from the magnetic field

$$J_y(x,y) = \frac{2}{\mu_0 d}\,\mathcal{F}^{-1}\{\bar{B}_x(k_x,k_y)\,e^{k|z|}\}(x,y),$$

$$\bar{B}_x(k_x,k_y) = \mathcal{F}\{B_x(x,y)\}(k_x,k_y)$$

S. Aigner, et al. Science **319** 1226 (2008)

Current direction fluctoations



explanation of measurements requires surface + substrate + bulk contribution
bulk contributions are different for the different wires

S. Aigner, et al. Science **319** 1226 (2008)

Reduction of Potential Roughness

HD / IOTA

Heidelberg

- Subtract the Ioffe field to 0
- Adding a circular polarized RF field creates a TOP trap

$$V = <\mu\sqrt{(\delta b_x + b_{\rm rf}\cos\omega t)^2 + (\delta b_y + b_{\rm rf}\sin\omega t)^2 + \delta b_z^2}>_t$$
$$= \mu(b_{\rm rf} + O(\frac{\delta b^2}{b_{\rm rf}}))$$

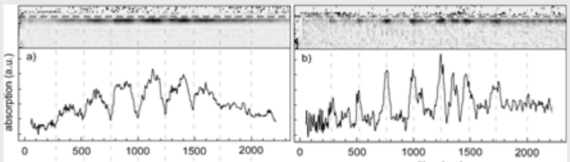
- The RF field is orthogonal to the potential roughness
- reductiion of the potential roughness by a factor

$$\frac{\delta B_z}{B_{RF}}$$

typical reduction by 10^3 or more

IOTA

- the signe of the roughnes δB_Z depends on the direction of the current

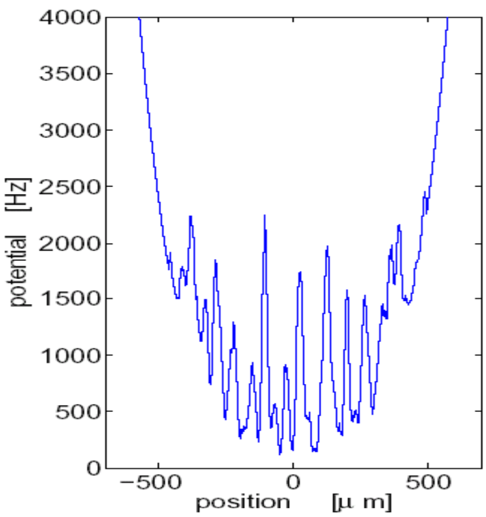


Thübingen (Zimmermann)

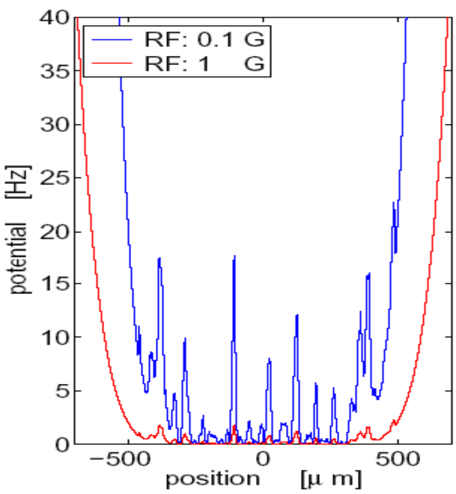
- use alternating current modulatin to average out the longitudinal potential roughness.
- this requires fast switching of all the fierlds including the bias field.

Reduction of Potential Roughness

HD/ATI

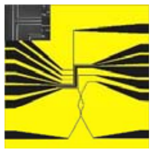


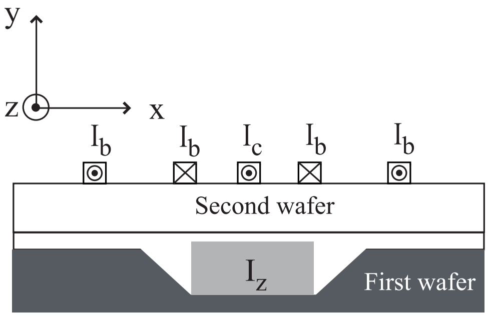
Measured potential roughness

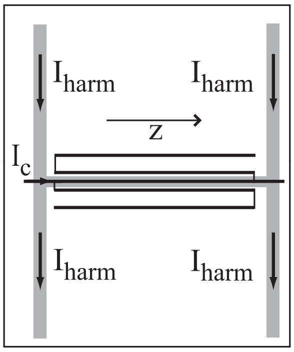


Potential roughness reduced by adding a circular polarized RF field to create a TOP trap

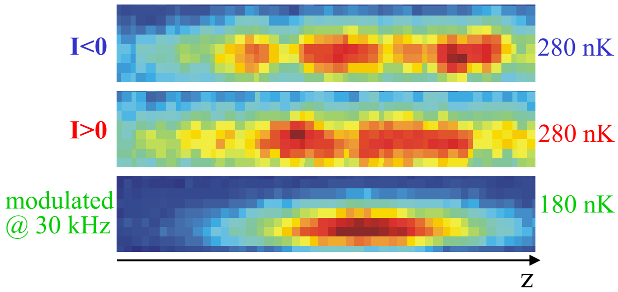
Reducing the Roughness
pilot experiment

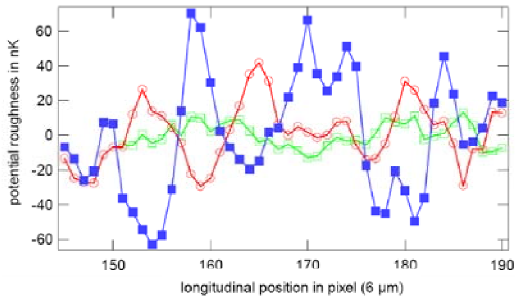

IOTA





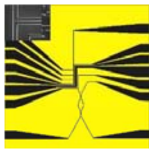
simple 5 wire setup allows fast oscillation of the trap potential (30 kHz)





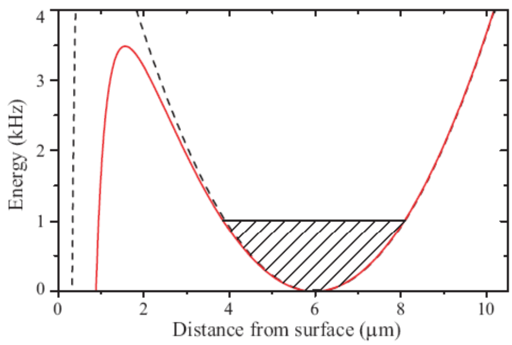
a factor of 3 rms roughness reduction limited by quality of imaging system

Measuring Surface Charges with BEC

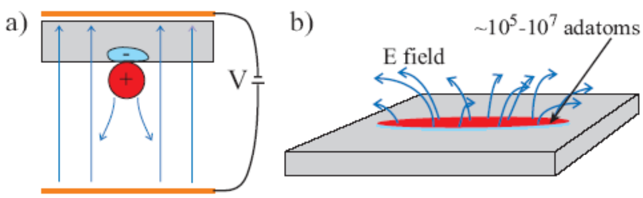

JILA

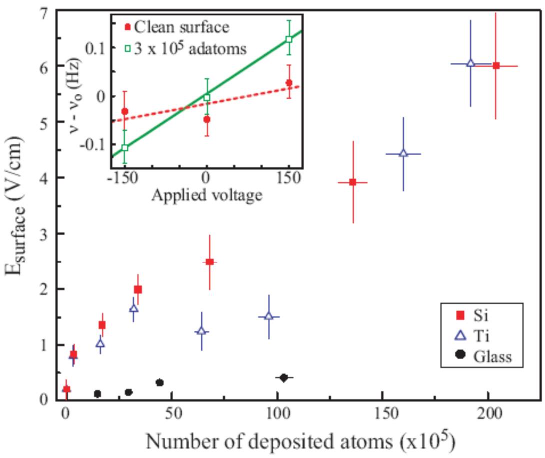
- Trapping potential (radial trap frequency ω_{trap}) depends on the surface patch charges.
- Measuring the dipole excitation allows very precise measurement of ω_{trap}

trapping potential with and without patch charges



Changing the potential by applying an additional field





J. M. McGuirk et al. cond-mat/0403254