Traitement intégré d’ondes de matière

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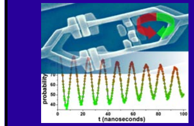
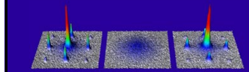
Increasing interaction of Quantum Optics and Solid-State physics

Quantum optical concepts + condensed-matter systems:



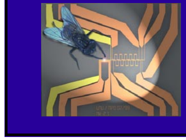
SQUIDS, Cooper-pair boxes, quantum dots:
“artificial atoms”,
Rabi oscillations, controlled coupling, …
e.g. cond-mat/0402216: cavity QED
with superconducting stripline resonator + Cooper pair box

Condensed-matter concepts + cold atomic systems:



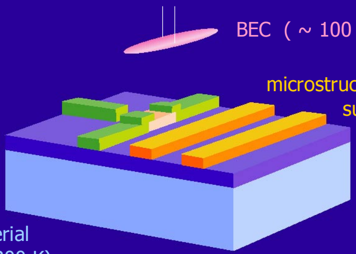
Bloch oscillations, Mott insulator, …
Kondo effect, Bose glass…
general quantum simulation

Cold atomic systems + condensed-matter systems:

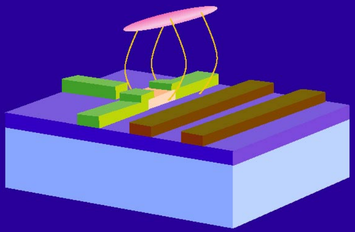


Atom chips

Atom chips: BEC meets the nanoworld



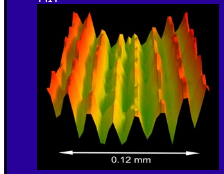
Atom chips: BEC meets the nanoworld



1. BEC on a chip
2. Coherent atom manipulation
3. Controlling atom-surface interactions

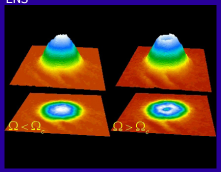
An atomic Bose-Einstein condensate is…

MIT



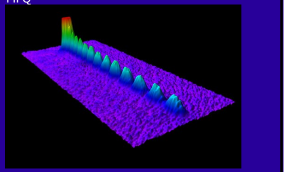
a matter wave…

ENS



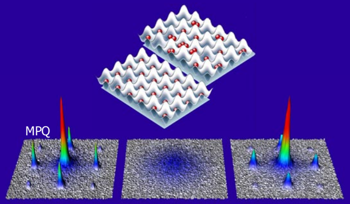
a superfluid…

MPQ



an atom laser…

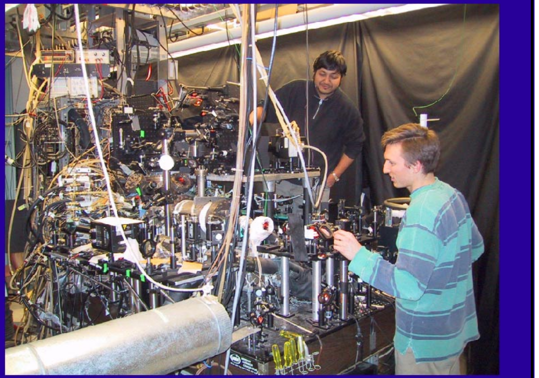
MPQ



…a many-body quantum system

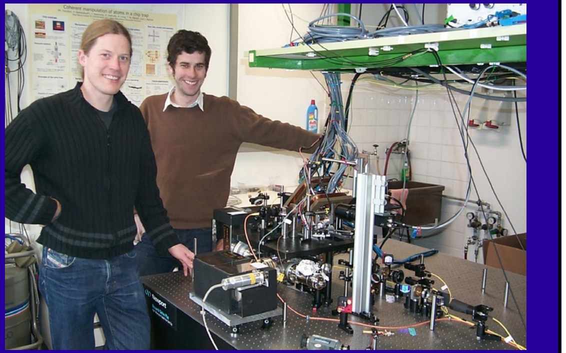
BEC was hard work…

1995	JILA	Rb
	MIT	Na
1995/97	Rice	Li
.		
.	---	
.		
1997 first follow-ups		

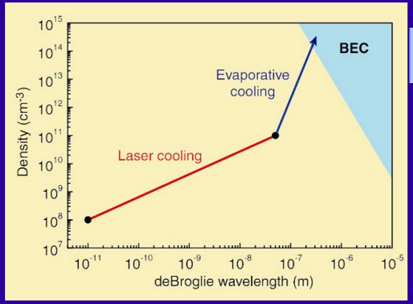


MIT BEC apparatus

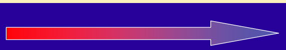
… it has become much easier



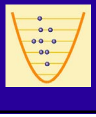
The route to BEC



$$n\lambda_{dB}^{3} \approx 1$$

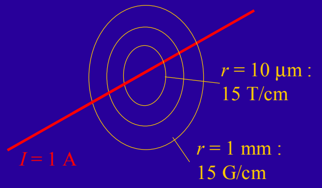


300 K 10 µK 500 nK

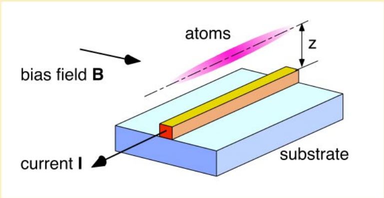


Magnetic Chip Traps
("Atom Chips")

$$\nabla B = \frac{\mu_0}{2\pi}\frac{I}{r^2}$$



Magnetic Microchip Traps

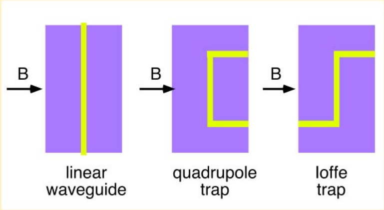


related:

superconducting
microtrap (theoretical):
J. D. Weinstein, K. G. Libbrecht,
PRA 52, 4004 (1995)

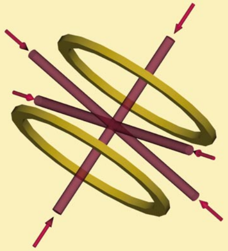
wire traps:
Schmiedmayer group,
Zimmermann and Hänsch grps.

waveguides:
Prentiss and Westervelt grps.,
Anderson and Cornell grps.

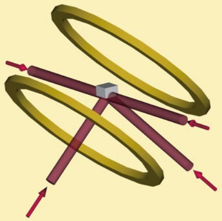


J. Reichel, W. Hänsel,
and T. W. Hänsch,
PRL **83**, 3398 (1999).

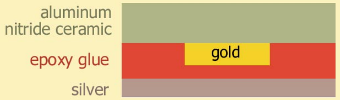
Solving the Loading Problem



standard MOT

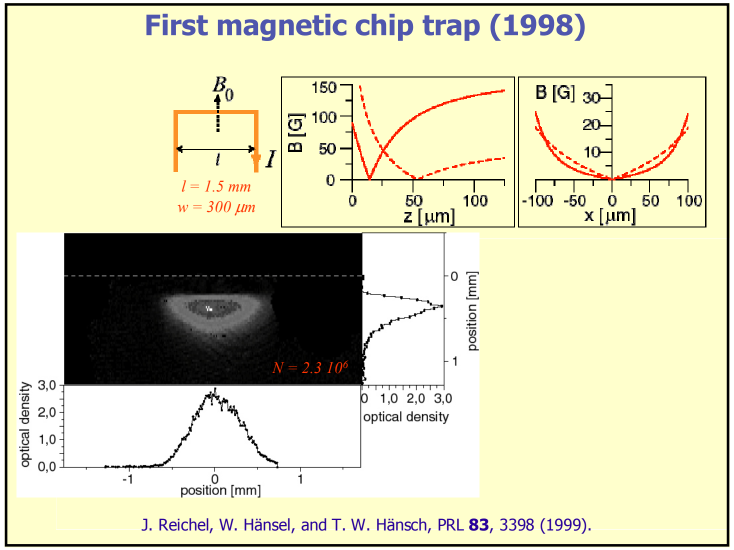


mirror MOT



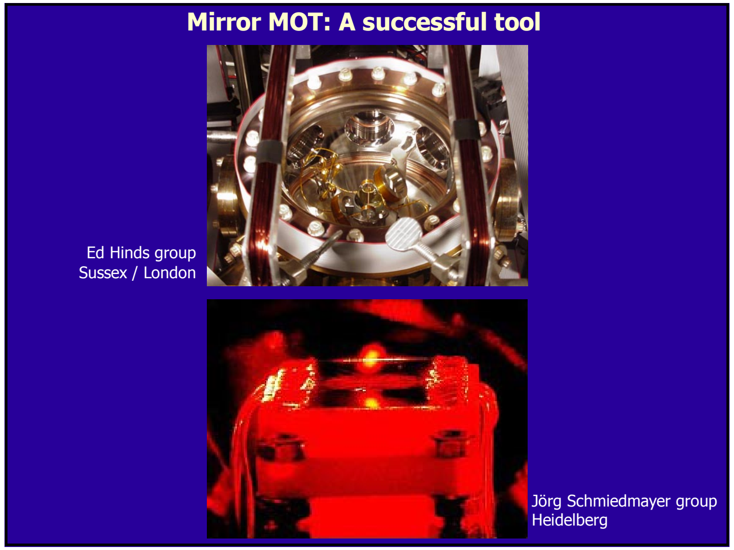
J. Reichel, W. Hänsel, and T. W. Hänsch, PRL **83**, 3398 (1999).
Details: J. Reichel, Appl. Phys. B **74**, 469 (2002).

Example: Magnetic Conveyor chip



First magnetic chip trap (1998)

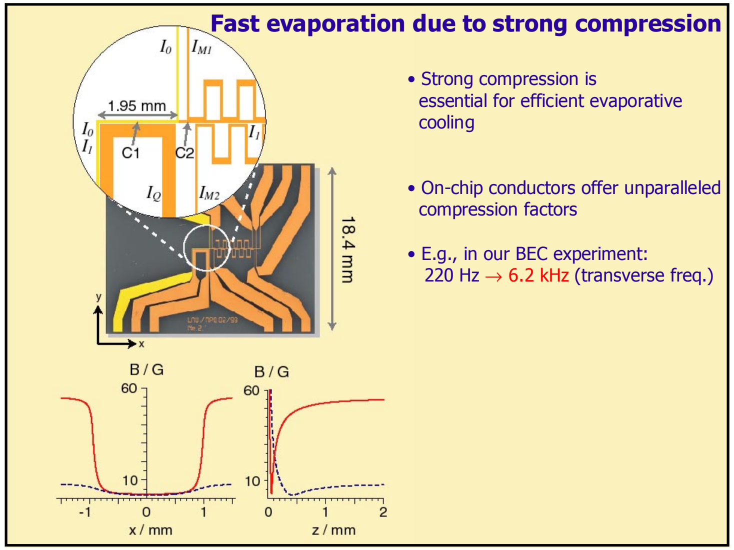
J. Reichel, W. Hänsel, and T. W. Hänsch, PRL **83**, 3398 (1999).



Mirror MOT: A successful tool

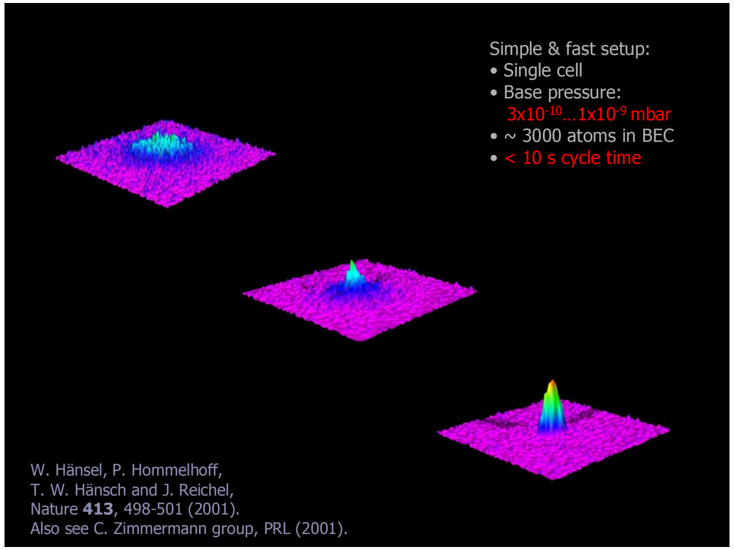
Ed Hinds group
Sussex / London

Jörg Schmiedmayer group
Heidelberg



Fast evaporation due to strong compression

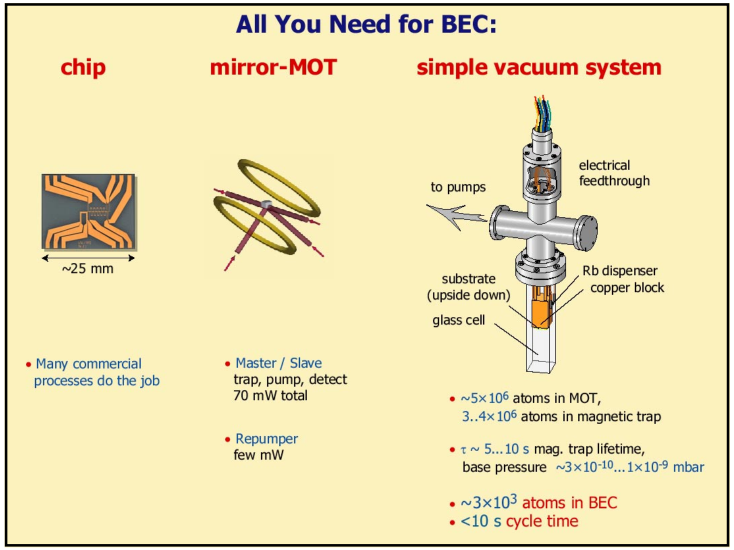
- Strong compression is essential for efficient evaporative cooling
- On-chip conductors offer unparalleled compression factors
- E.g., in our BEC experiment: 220 Hz → 6.2 kHz (transverse freq.)



Simple & fast setup:

- Single cell
- Base pressure: $3\text{x}10^{-10}...1\text{x}10^{-9}$ mbar
- ~ 3000 atoms in BEC
- < 10 s cycle time

W. Hänsel, P. Hommelhoff,
T. W. Hänsch and J. Reichel,
Nature **413**, 498-501 (2001).
Also see C. Zimmermann group, PRL (2001).



All You Need for BEC:

chip

mirror-MOT

simple vacuum system

- Many commercial processes do the job

- Master / Slave trap, pump, detect 70 mW total
- Repumper few mW

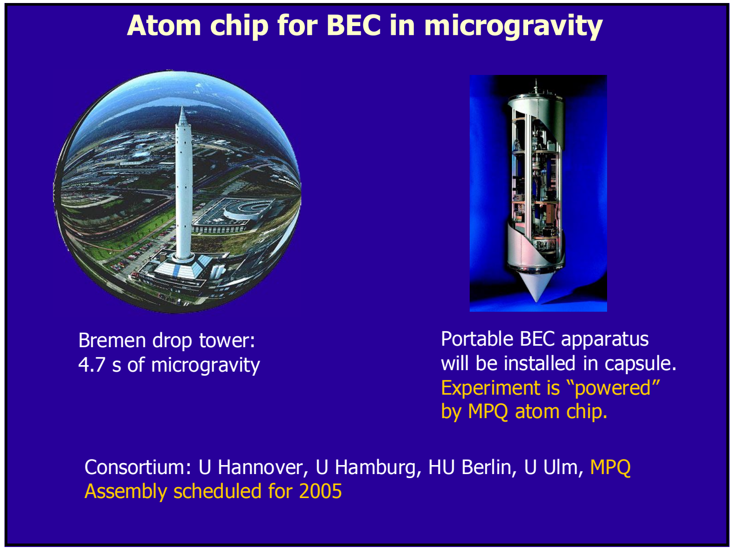
- $\sim 5\times10^6$ atoms in MOT, $3..4\times10^6$ atoms in magnetic trap
- $\tau \sim 5...10$ s mag. trap lifetime, base pressure $\sim 3\times10^{-10}...1\times10^{-9}$ mbar
- $\sim 3\times10^3$ atoms in BEC
- <10 s cycle time

Chip BEC

- Atom chips: Easy & fast way to create BECs.
- Exceptionally strong confinement – 1 MHz trapping freq. is possible.
- The method is rapidly spreading in the community:

  2001: First 2 chip BECs (our group & independent, simultaneous work in C. Zimmermann's group, Tübingen)

  2003: ≥8 chip BECs worldwide, >10 more coming
- With atom chips, BEC is ready for applications – can even be portable.

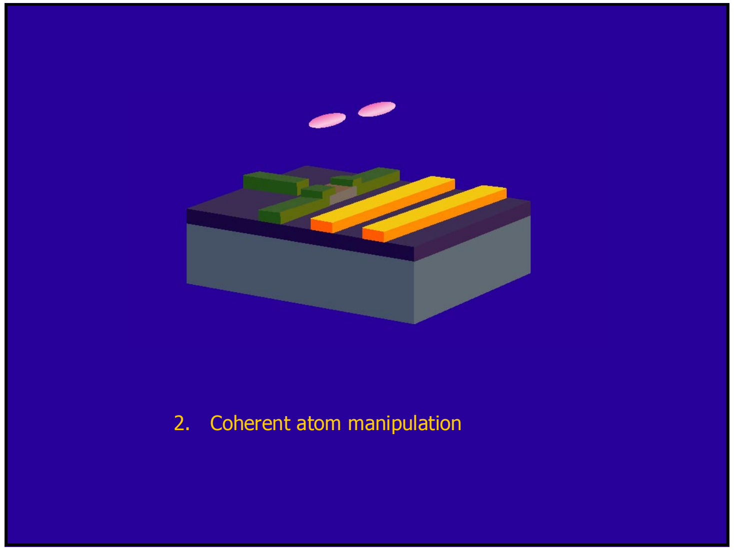


Atom chip for BEC in microgravity

Bremen drop tower:
4.7 s of microgravity

Portable BEC apparatus will be installed in capsule. Experiment is "powered" by MPQ atom chip.

Consortium: U Hannover, U Hamburg, HU Berlin, U Ulm, MPQ
Assembly scheduled for 2005



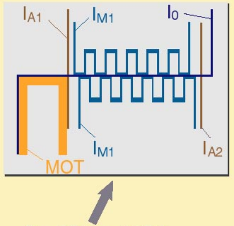
2. Coherent atom manipulation

Atomic Conveyor Belt

wire layout

potential

absorption images

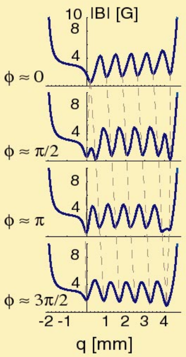


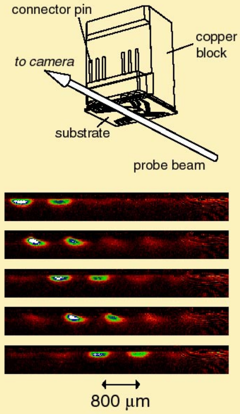
$B_0 = 3G\ \mathbf{e}_x + 16G\ \mathbf{e}_y$

$I_0\ = 1.5\,A$

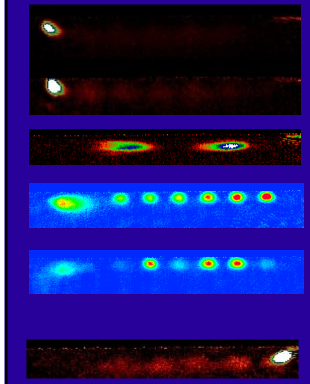
$I_{M1} = 0.8\,A \cos\phi$

$I_{M2} = 0.8\,A \sin\phi$





Atomic Conveyor: Theme and Variations



conveyor belt (sinusoidal modulation)

optimized conveyor belt
(faster transport with less heating)

“linear collider”

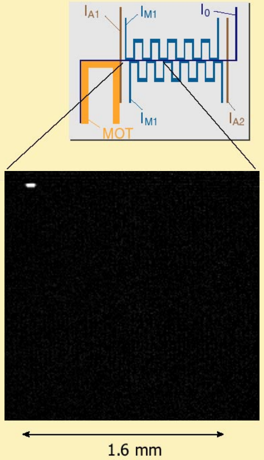
integrated cold atom source

...with switchable output

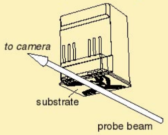
adiabatic splitting and merging

see also: splitting and merging in waveguides
Anderson / Cornell groups (Boulder)
Schmiedmayer group (Heidelberg)

Transporting a BEC



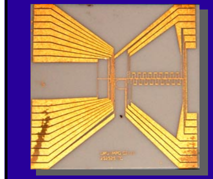
absorption images



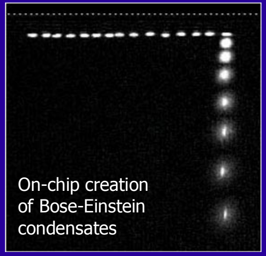
A ~ 500 nK object,
~100µm from a
room temperature surface!

W. Hänsel, P. Hommelhoff,
T. W. Hänsch and J. Reichel,
Nature **413**, 498-501 (2001).

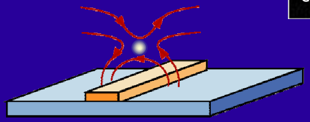
Atom chips: from first experiments...



Complex conductor
pattern on chip

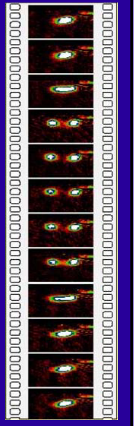


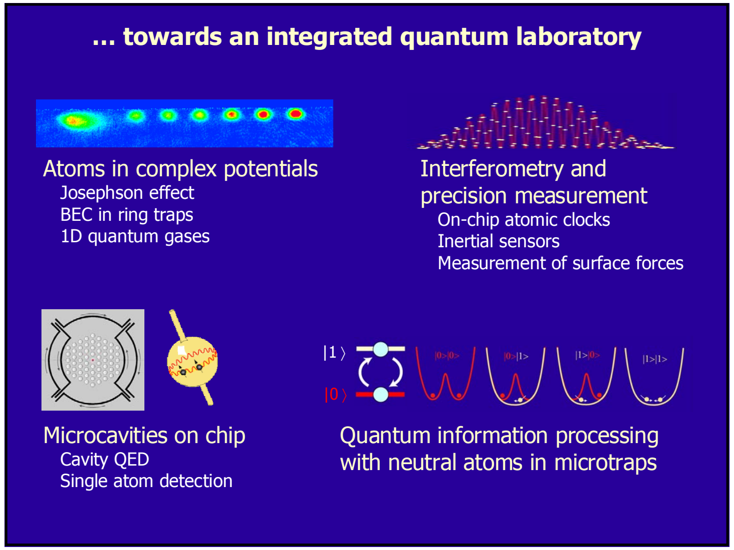
On-chip creation
of Bose-Einstein
condensates



wire current I (~ 1A)
+ external bias field B_0 (~ 10-100 G)
⇒ trapping freq. ~100 kHz

Manipulation of
atomic ensembles in
complex potentials





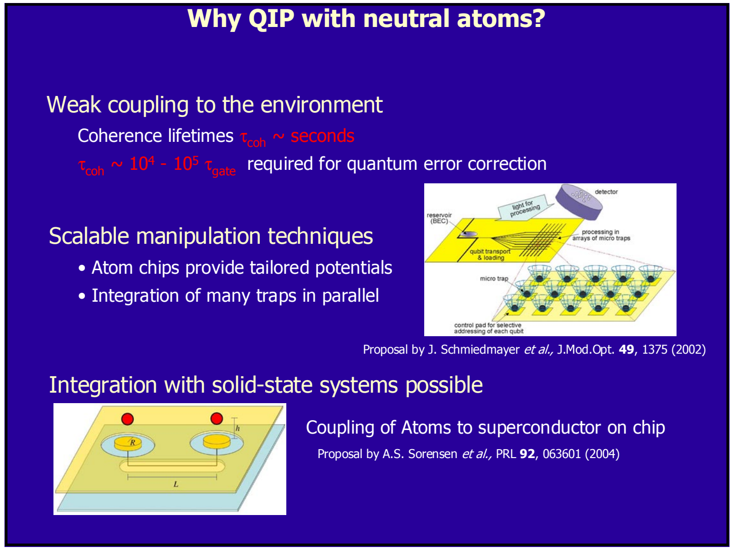
… towards an integrated quantum laboratory

Atoms in complex potentials
- Josephson effect
- BEC in ring traps
- 1D quantum gases

Interferometry and precision measurement
- On-chip atomic clocks
- Inertial sensors
- Measurement of surface forces

Microcavities on chip
- Cavity QED
- Single atom detection

Quantum information processing with neutral atoms in microtraps



Why QIP with neutral atoms?

Weak coupling to the environment

Coherence lifetimes τ_{coh} ~ seconds

$\tau_{coh} \sim 10^4 - 10^5\ \tau_{gate}$ required for quantum error correction

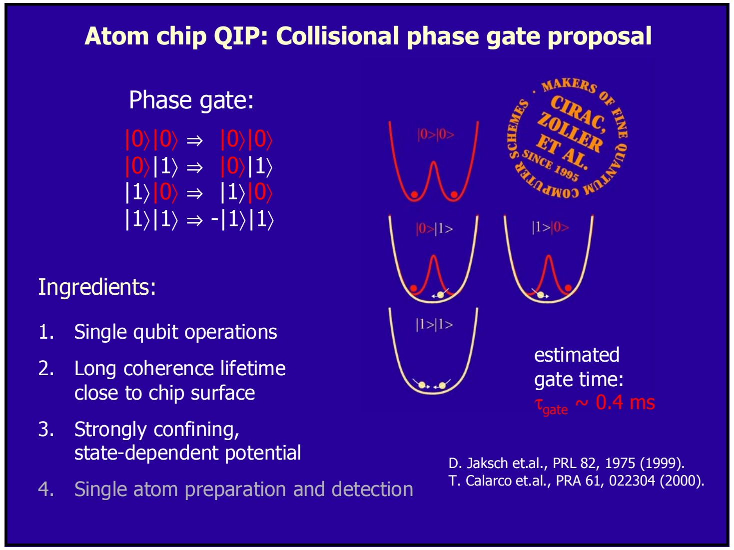
Scalable manipulation techniques
- Atom chips provide tailored potentials
- Integration of many traps in parallel

Proposal by J. Schmiedmayer *et al.,* J.Mod.Opt. **49**, 1375 (2002)

Integration with solid-state systems possible

Coupling of Atoms to superconductor on chip

Proposal by A.S. Sorensen *et al.,* PRL **92**, 063601 (2004)



Atom chip QIP: Collisional phase gate proposal

Phase gate:

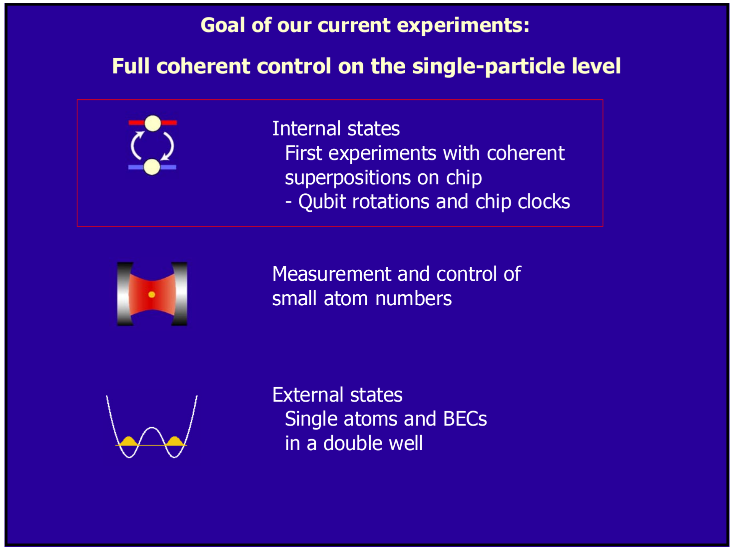
$|0\rangle|0\rangle \Rightarrow |0\rangle|0\rangle$
$|0\rangle|1\rangle \Rightarrow |0\rangle|1\rangle$
$|1\rangle|0\rangle \Rightarrow |1\rangle|0\rangle$
$|1\rangle|1\rangle \Rightarrow -|1\rangle|1\rangle$

estimated gate time: τ_{gate} ~ 0.4 ms

Ingredients:

1. Single qubit operations
2. Long coherence lifetime close to chip surface
3. Strongly confining, state-dependent potential
4. Single atom preparation and detection

D. Jaksch et.al., PRL 82, 1975 (1999).
T. Calarco et.al., PRA 61, 022304 (2000).



Goal of our current experiments:

Full coherent control on the single-particle level

Internal states
- First experiments with coherent superpositions on chip
- \- Qubit rotations and chip clocks

Measurement and control of small atom numbers

External states
- Single atoms and BECs in a double well

Coherence of internal states

…is essential in in QIPC with internal-state qubits,
but also in atomic clocks

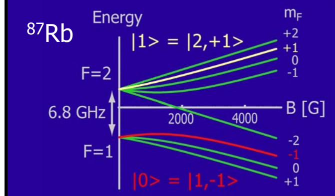
…is more delicate to handle in traps
than for untrapped atoms

Good choice for magnetic trapping:
|1,-1>, |2,1> (^{87}Rb)

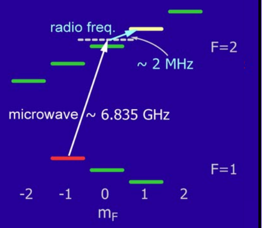
2 s coherence time has been demonstrated
D.M.Harber, H.J.Lewandowski, J.M.McGuirk, and E.A.Cornell, PRA **66**, 053616 (2002)

Decoherence induced by the surface?

Single qubit rotations



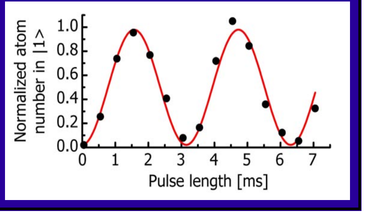
Two-photon
microwave-RF
transition



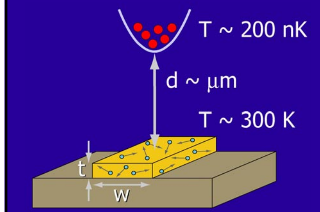
States with equal magnetic moment
- experience same trapping potential
- robust against decoherence

Rabi oscillation (qubit rotation):

20,000 atoms in F = 1, m_F = -1
15 W microwave power
~ 1 W RF power
1.2 MHz intermediate state detuning
Ω_{Rabi} ~ 0.2 – 1 kHz: eff. two-photon Rabi frequency



Surface decoherence and loss?



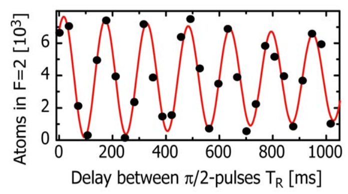
Loss and decoherence due to magnetic near-field noise

(Theory by C. Henkel et al., 1999-2003)

↓

In our experiment at d = 9 µm:
Γ_{dec} ~ 10^{-6} Hz (states with equal magn. moment)
Γ_{loss} ~ 0.2 Hz (thin conductors)

Coherence measurements:
Ramsey spectroscopy

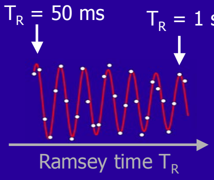


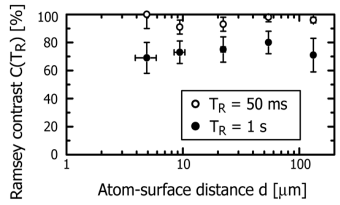
coherence lifetime (d = 9 µm):

τ_{coh} = 2.8 s ~ 10^4 τ_{gate}

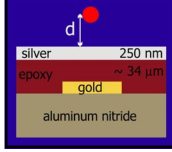
similar to experiments in macroscopic magnetic traps (Cornell group, Boulder)

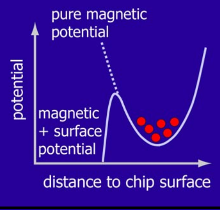
Surface decoherence and loss?

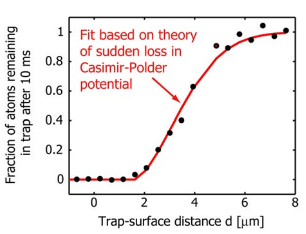


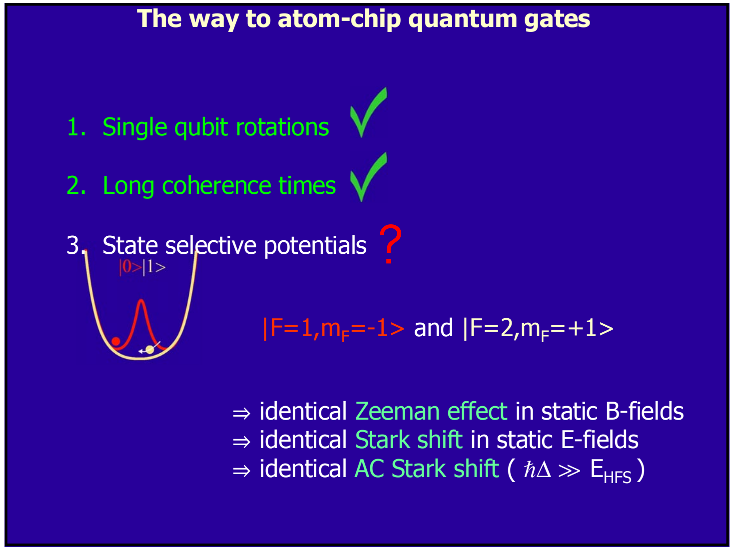


Casimir-Polder surface potential modifies the trap:







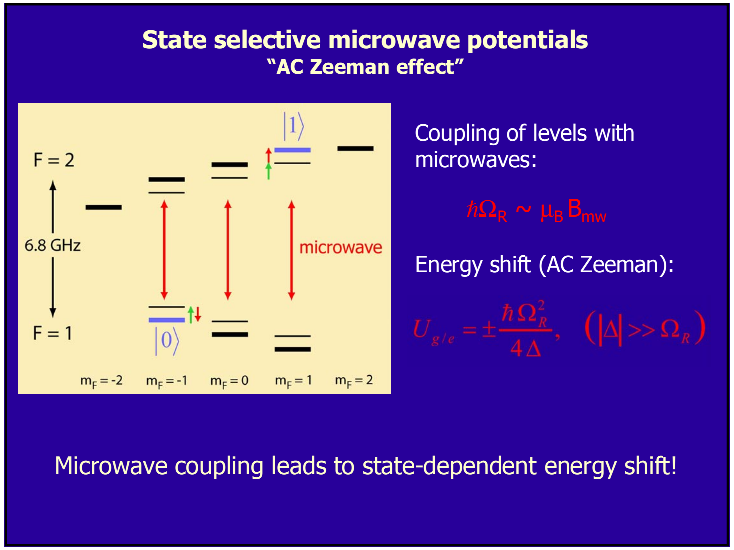


The way to atom-chip quantum gates

1. Single qubit rotations ✓
2. Long coherence times ✓
3. State selective potentials ?

$|F=1, m_F=-1\rangle$ and $|F=2, m_F=+1\rangle$

⇒ identical Zeeman effect in static B-fields
⇒ identical Stark shift in static E-fields
⇒ identical AC Stark shift ($\hbar\Delta \gg E_{HFS}$)



State selective microwave potentials
"AC Zeeman effect"

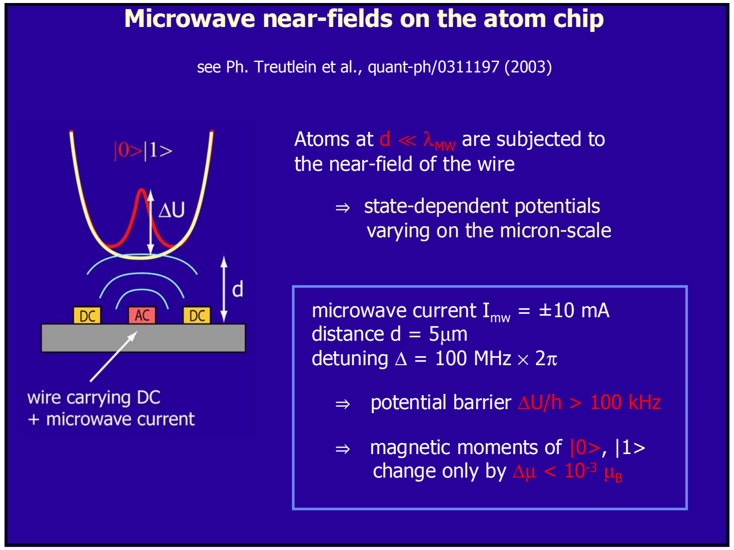
Coupling of levels with microwaves:

$$\hbar\Omega_R \sim \mu_B B_{mw}$$

Energy shift (AC Zeeman):

$$U_{g/e} = \pm\frac{\hbar\Omega_R^2}{4\Delta}, \quad \left(|\Delta| >> \Omega_R\right)$$

Microwave coupling leads to state-dependent energy shift!



Microwave near-fields on the atom chip

see Ph. Treutlein et al., quant-ph/0311197 (2003)

wire carrying DC
+ microwave current

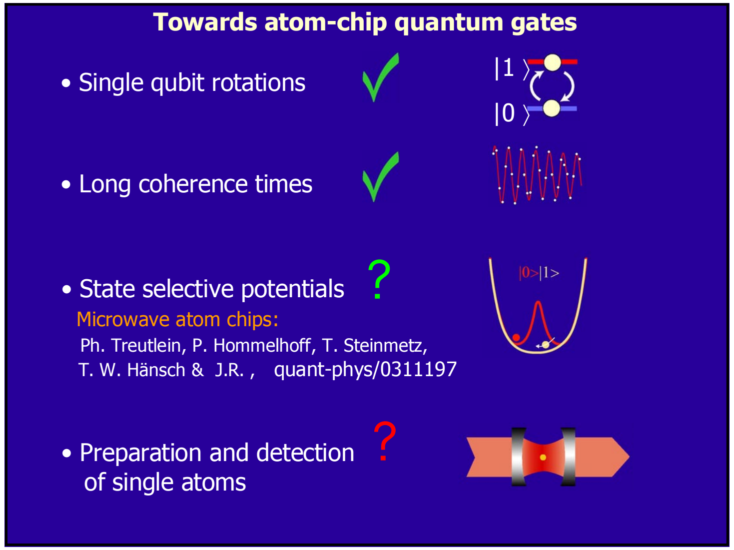
Atoms at $d \ll \lambda_{MW}$ are subjected to the near-field of the wire

⇒ state-dependent potentials varying on the micron-scale

microwave current $I_{mw} = \pm 10$ mA
distance d = 5μm
detuning $\Delta = 100$ MHz × 2π

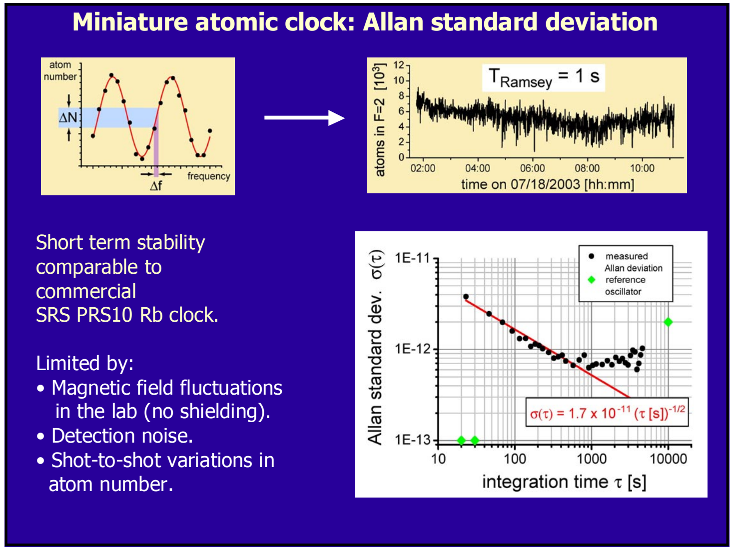
⇒ potential barrier $\Delta U/h > 100$ kHz

⇒ magnetic moments of |0>, |1> change only by $\Delta\mu < 10^{-3}\ \mu_B$



Towards atom-chip quantum gates

- Single qubit rotations ✓
- Long coherence times ✓
- State selective potentials ?
  Microwave atom chips:
  Ph. Treutlein, P. Hommelhoff, T. Steinmetz, T. W. Hänsch & J.R., quant-phys/0311197
- Preparation and detection of single atoms ?

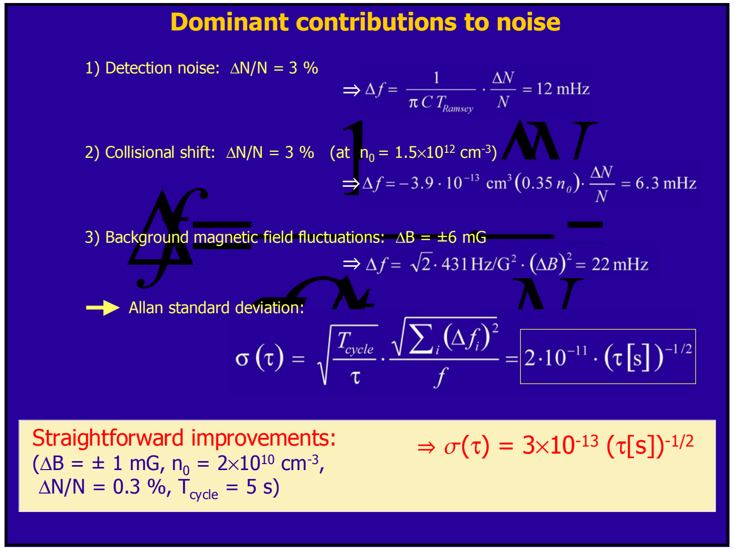


Miniature atomic clock: Allan standard deviation

Short term stability comparable to commercial SRS PRS10 Rb clock.

Limited by:

- Magnetic field fluctuations in the lab (no shielding).
- Detection noise.
- Shot-to-shot variations in atom number.



Dominant contributions to noise

1) Detection noise: $\Delta N/N = 3\ \%$

$$\Rightarrow \Delta f = \frac{1}{\pi C\, T_{Ramsey}} \cdot \frac{\Delta N}{N} = 12\ \mathrm{mHz}$$

2) Collisional shift: $\Delta N/N = 3\ \%$ (at $n_0 = 1.5\times10^{12}\ \mathrm{cm}^{-3}$)

$$\Rightarrow \Delta f = -3.9\cdot10^{-13}\ \mathrm{cm}^3\left(0.35\, n_0\right)\cdot\frac{\Delta N}{N} = 6.3\ \mathrm{mHz}$$

3) Background magnetic field fluctuations: $\Delta B = \pm 6\ \mathrm{mG}$

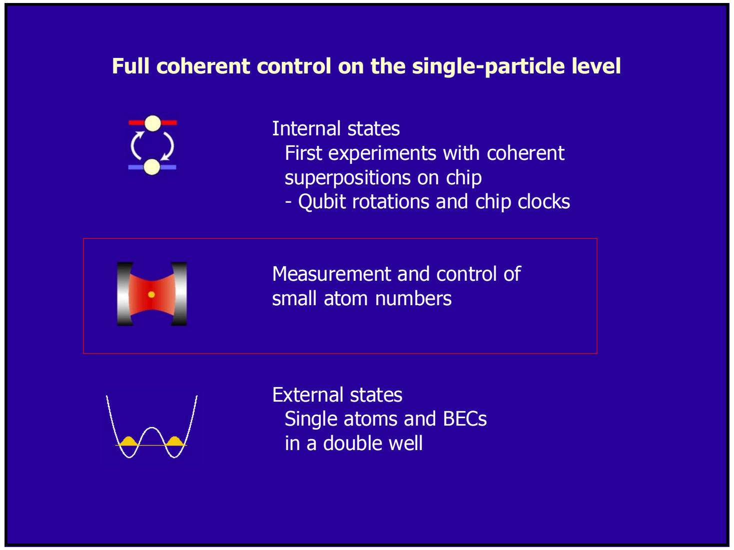
$$\Rightarrow \Delta f = \sqrt{2}\cdot 431\ \mathrm{Hz/G}^2\cdot(\Delta B)^2 = 22\ \mathrm{mHz}$$

→ Allan standard deviation:

$$\sigma(\tau) = \sqrt{\frac{T_{cycle}}{\tau}}\cdot\frac{\sqrt{\sum_i (\Delta f_i)^2}}{f} = \boxed{2\cdot10^{-11}\cdot(\tau[\mathrm{s}])^{-1/2}}$$

Straightforward improvements: $\Rightarrow \sigma(\tau) = 3\times10^{-13}\ (\tau[\mathrm{s}])^{-1/2}$

($\Delta B = \pm 1\ \mathrm{mG}$, $n_0 = 2\times10^{10}\ \mathrm{cm}^{-3}$, $\Delta N/N = 0.3\ \%$, $T_{cycle} = 5\ \mathrm{s}$)

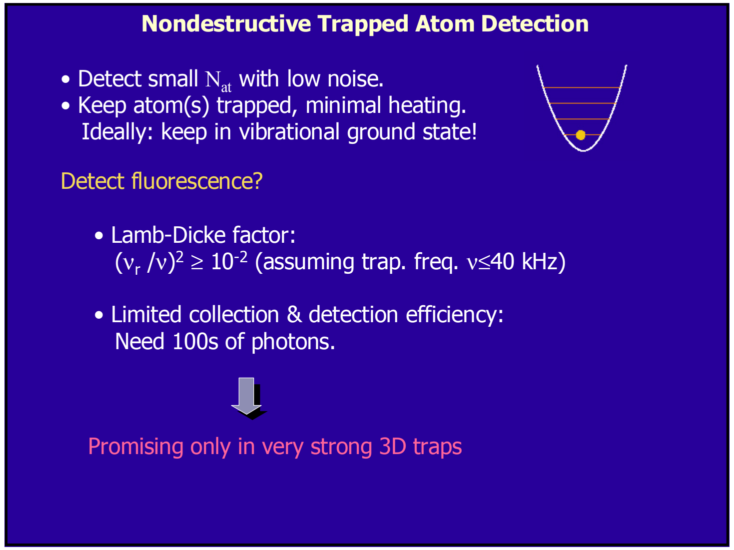


Full coherent control on the single-particle level

Internal states
First experiments with coherent superpositions on chip
- Qubit rotations and chip clocks

Measurement and control of small atom numbers

External states
Single atoms and BECs in a double well



Nondestructive Trapped Atom Detection

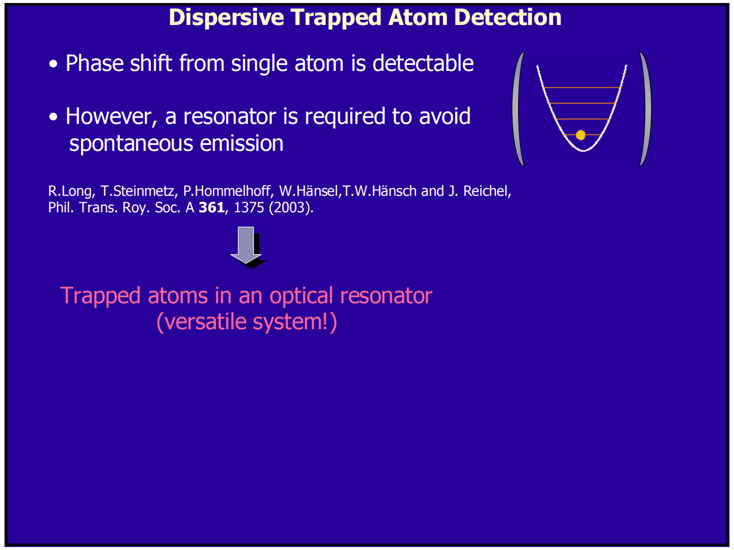
- Detect small N_{at} with low noise.
- Keep atom(s) trapped, minimal heating.
  Ideally: keep in vibrational ground state!

Detect fluorescence?

- Lamb-Dicke factor:
  $(\nu_r/\nu)^2 \geq 10^{-2}$ (assuming trap. freq. $\nu \leq 40$ kHz)
- Limited collection & detection efficiency:
  Need 100s of photons.

⇩

Promising only in very strong 3D traps

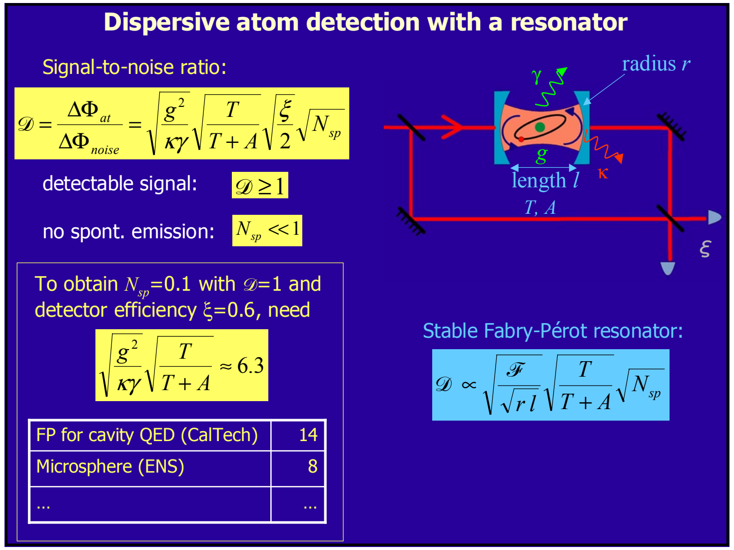


Dispersive Trapped Atom Detection

- Phase shift from single atom is detectable
- However, a resonator is required to avoid spontaneous emission

R.Long, T.Steinmetz, P.Hommelhoff, W.Hänsel,T.W.Hänsch and J. Reichel, Phil. Trans. Roy. Soc. A **361**, 1375 (2003).

Trapped atoms in an optical resonator
(versatile system!)



Dispersive atom detection with a resonator

Signal-to-noise ratio:

$$\mathscr{D} = \frac{\Delta\Phi_{at}}{\Delta\Phi_{noise}} = \sqrt{\frac{g^2}{\kappa\gamma}}\sqrt{\frac{T}{T+A}}\sqrt{\frac{\xi}{2}}\sqrt{N_{sp}}$$

detectable signal: $\mathscr{D} \geq 1$

no spont. emission: $N_{sp} \ll 1$

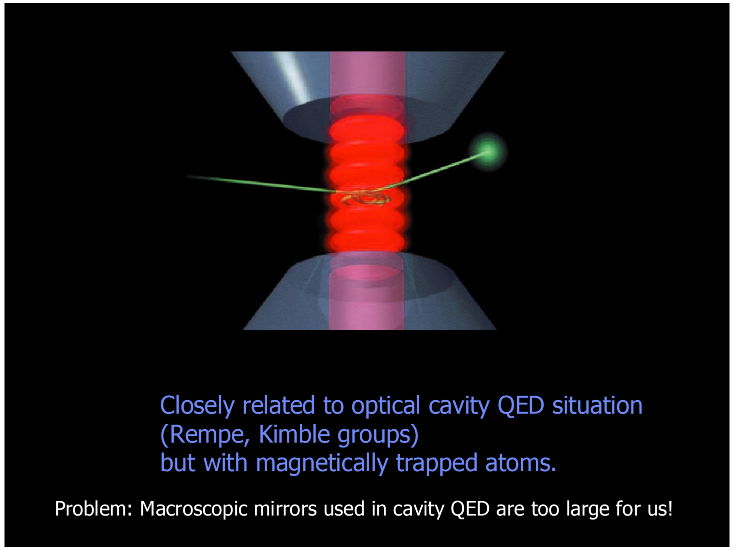
To obtain N_{sp}=0.1 with $\mathscr{D}$=1 and detector efficiency ξ=0.6, need

$$\sqrt{\frac{g^2}{\kappa\gamma}}\sqrt{\frac{T}{T+A}} \approx 6.3$$

FP for cavity QED (CalTech)	14
Microsphere (ENS)	8
…	…

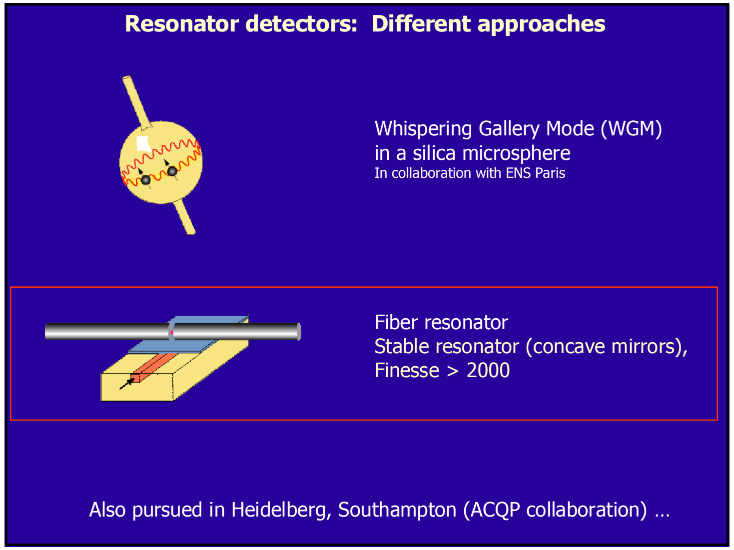
Stable Fabry-Pérot resonator:

$$\mathscr{D} \propto \sqrt{\frac{\mathscr{F}}{\sqrt{r\,l}}}\sqrt{\frac{T}{T+A}}\sqrt{N_{sp}}$$



Closely related to optical cavity QED situation
(Rempe, Kimble groups)
but with magnetically trapped atoms.

Problem: Macroscopic mirrors used in cavity QED are too large for us!

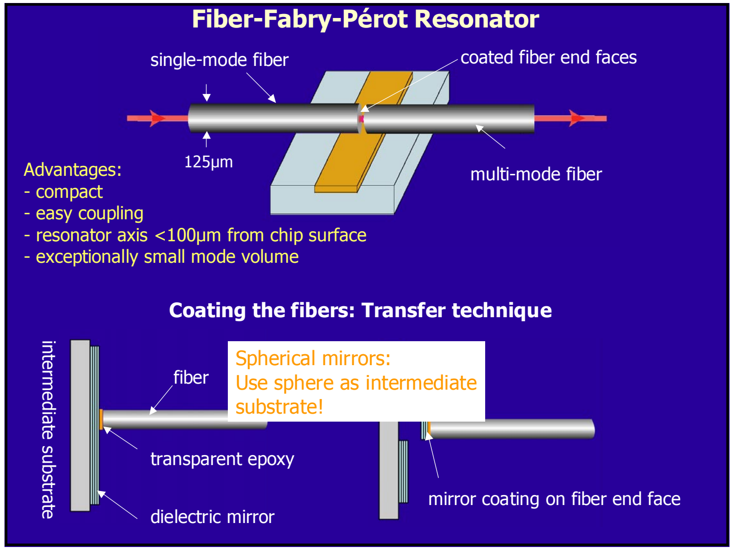


Resonator detectors: Different approaches

Whispering Gallery Mode (WGM)
in a silica microsphere
In collaboration with ENS Paris

Fiber resonator
Stable resonator (concave mirrors),
Finesse > 2000

Also pursued in Heidelberg, Southampton (ACQP collaboration) …

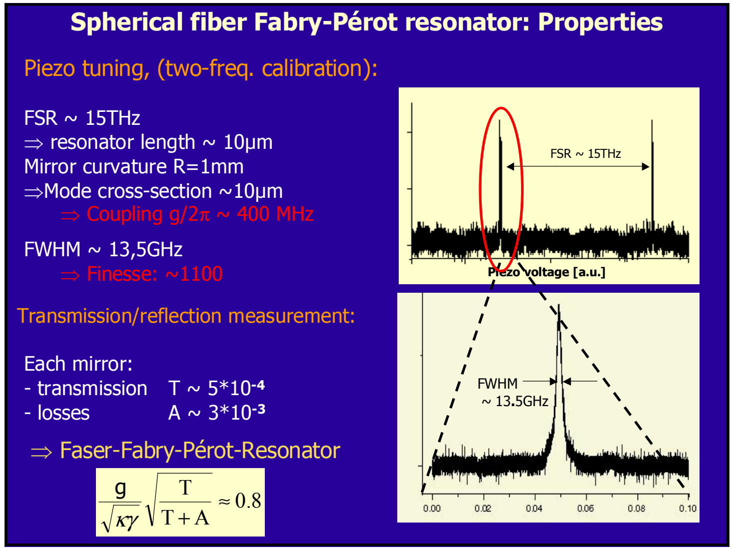


Fiber-Fabry-Pérot Resonator

Advantages:
- compact
- easy coupling
- resonator axis <100µm from chip surface
- exceptionally small mode volume

Coating the fibers: Transfer technique

Spherical mirrors:
Use sphere as intermediate substrate!



Spherical fiber Fabry-Pérot resonator: Properties

Piezo tuning, (two-freq. calibration):

FSR ~ 15THz
⇒ resonator length ~ 10µm
Mirror curvature R=1mm
⇒Mode cross-section ~10µm
⇒ Coupling $g/2\pi$ ~ 400 MHz

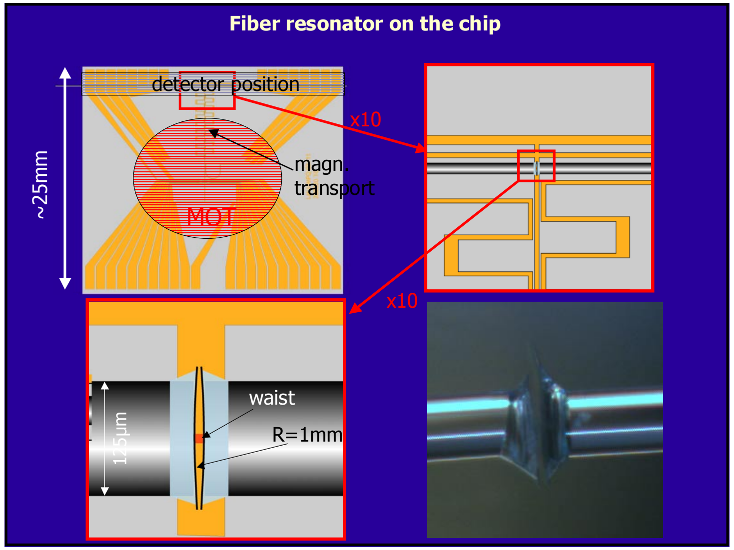
FWHM ~ 13,5GHz
⇒ Finesse: ~1100

Transmission/reflection measurement:

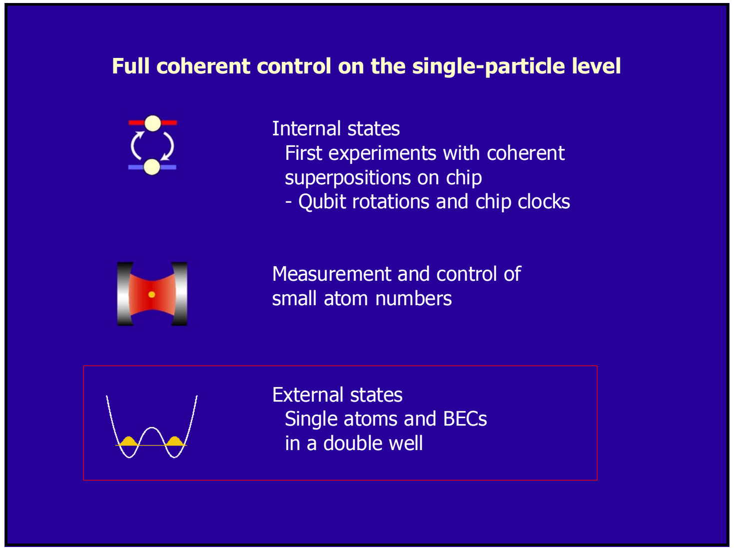
Each mirror:
- transmission T ~ $5*10^{-4}$
- losses A ~ $3*10^{-3}$

⇒ Faser-Fabry-Pérot-Resonator

$$\frac{g}{\sqrt{\kappa\gamma}}\sqrt{\frac{T}{T+A}} \approx 0.8$$



Fiber resonator on the chip



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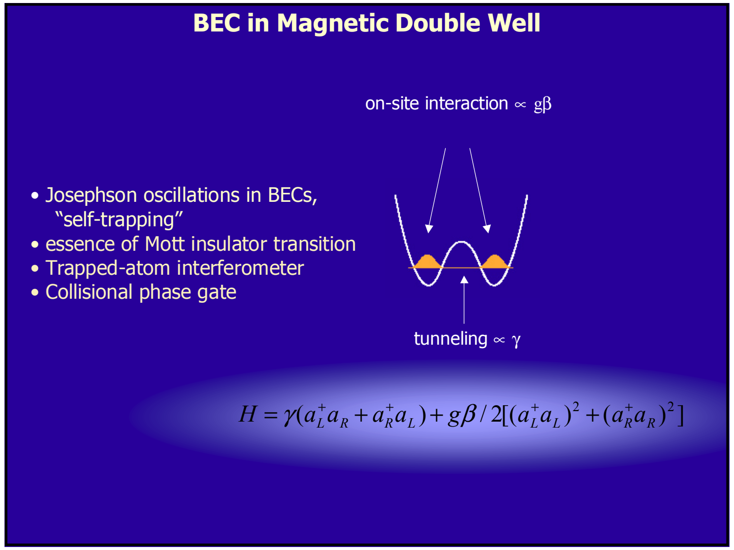
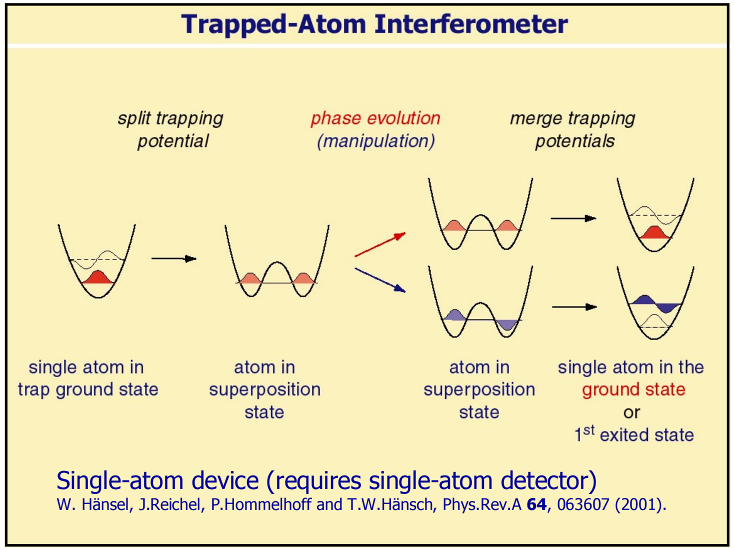


BEC in Magnetic Double Well

- Josephson oscillations in BECs, "self-trapping"
- essence of Mott insulator transition
- Trapped-atom interferometer
- Collisional phase gate

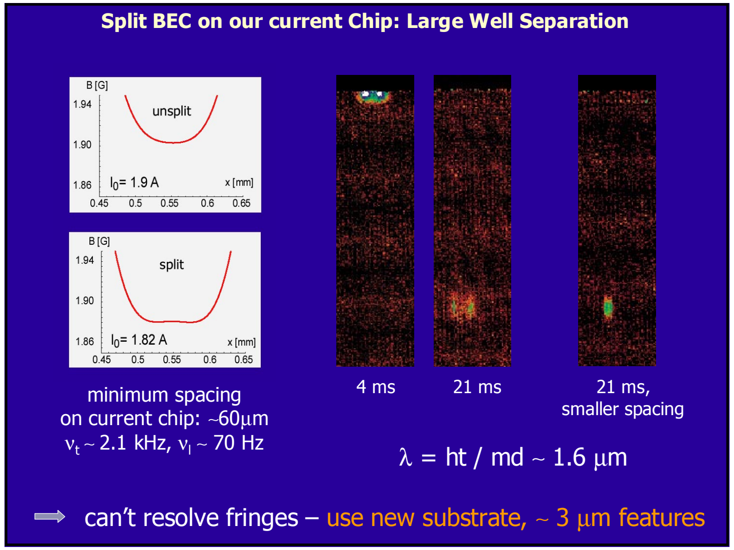
$$H=\gamma(a_L^+a_R+a_R^+a_L)+g\beta/2[(a_L^+a_L)^2+(a_R^+a_R)^2]$$



Trapped-Atom Interferometer

Single-atom device (requires single-atom detector)

W. Hänsel, J.Reichel, P.Hommelhoff and T.W.Hänsch, Phys.Rev.A **64**, 063607 (2001).



Split BEC on our current Chip: Large Well Separation

minimum spacing
on current chip: ~60µm
$\nu_t \sim 2.1$ kHz, $\nu_l \sim 70$ Hz

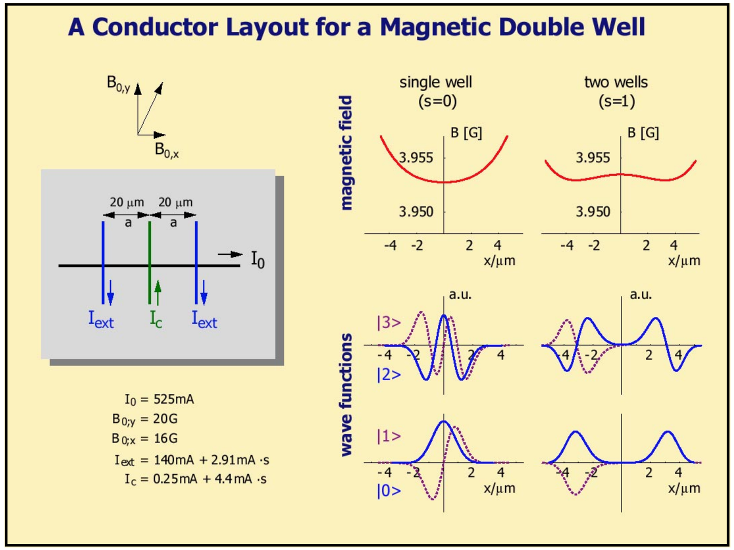
4 ms

21 ms

21 ms, smaller spacing

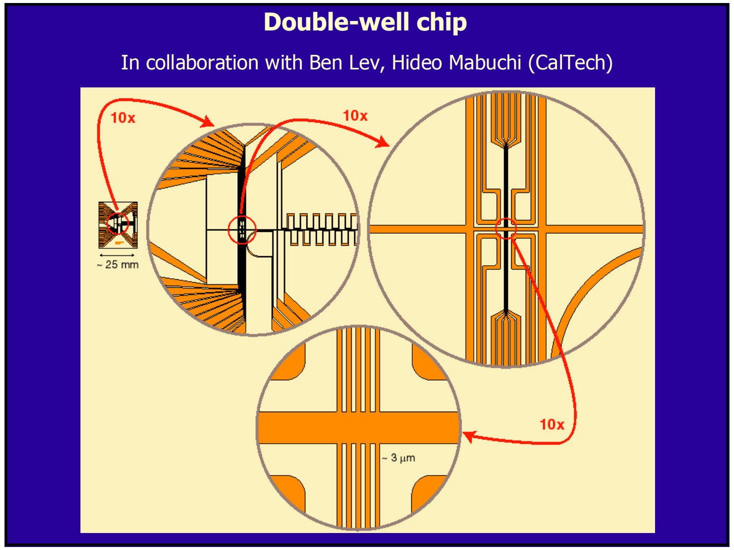
$\lambda = ht / md \sim 1.6\ \mu m$

⟹ can't resolve fringes – use new substrate, ~ 3 µm features



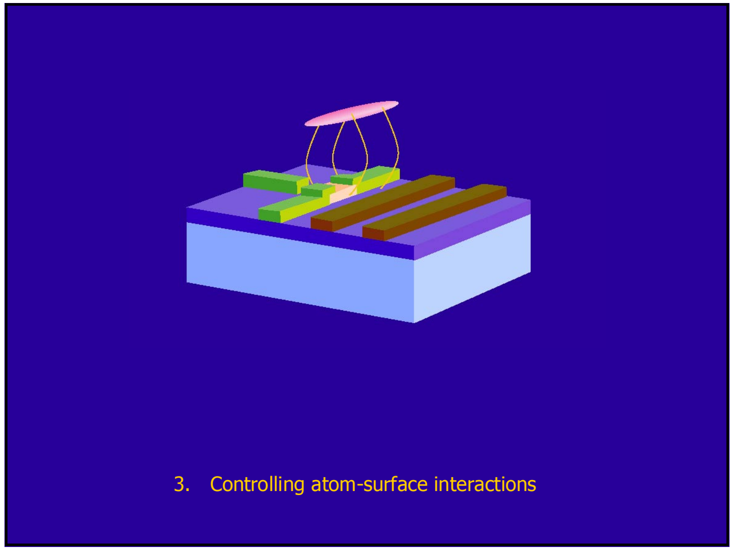
A Conductor Layout for a Magnetic Double Well

I_0 = 525mA
$B_{0;y}$ = 20G
$B_{0;x}$ = 16G
I_{ext} = 140mA + 2.91mA ·s
I_c = 0.25mA + 4.4mA ·s

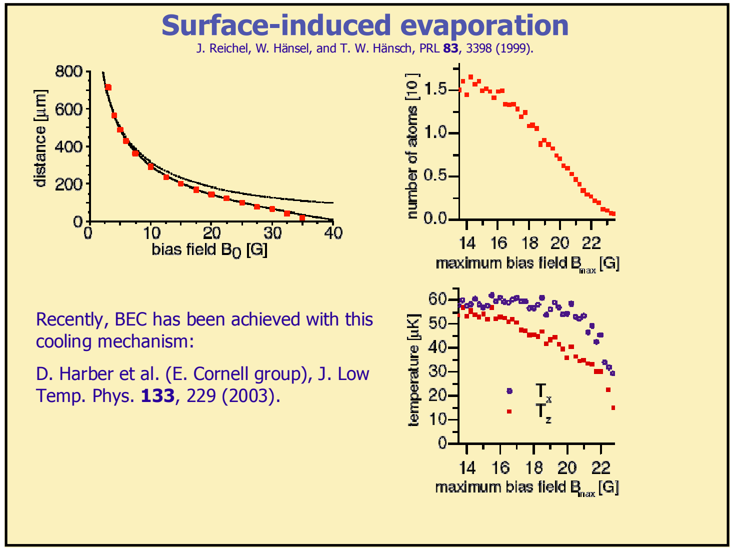


Double-well chip

In collaboration with Ben Lev, Hideo Mabuchi (CalTech)



3. Controlling atom-surface interactions

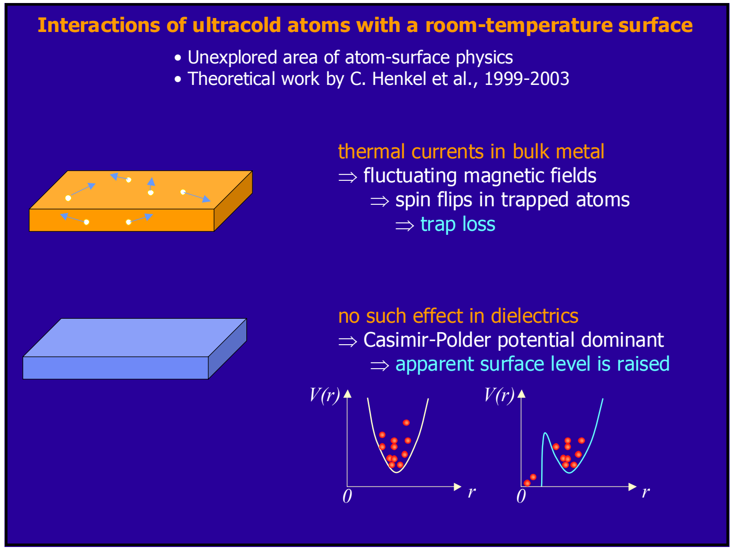


Surface-induced evaporation

J. Reichel, W. Hänsel, and T. W. Hänsch, PRL **83**, 3398 (1999).

Recently, BEC has been achieved with this cooling mechanism:

D. Harber et al. (E. Cornell group), J. Low Temp. Phys. **133**, 229 (2003).



Interactions of ultracold atoms with a room-temperature surface

- Unexplored area of atom-surface physics
- Theoretical work by C. Henkel et al., 1999-2003

thermal currents in bulk metal
⇒ fluctuating magnetic fields
⇒ spin flips in trapped atoms
⇒ trap loss

no such effect in dielectrics
⇒ Casimir-Polder potential dominant
⇒ apparent surface level is raised

How close can the cold atoms be brought to the surface?

- Metal surfaces: Fluctuating, thermally excited currents in the surface cause trap loss.
- Dielectric surfaces: No such effect. Casimir-Polder potential can be observed.

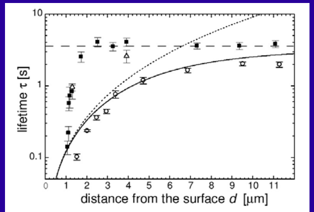
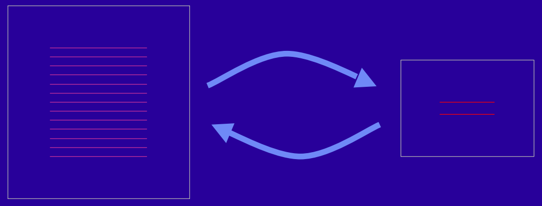


FIG. 4: Trap lifetime as a function of distance from a dielectric (solid squares) and metal (open circles) surface, for T=1.0 μK and B_0=0.57 G. The dotted line is the calculated lifetime above the metal due to thermal B fields only, the solid line includes the one-body lifetime of 3.5 s (dashed line). The open triangles are measurements for a pure condensate above the dielectric.

V. Vuletic group,
Stanford (now MIT)

Coherent atom-surface interactions?



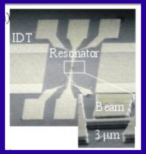
nanostructured
surface

atom

Vision: Coherent interaction with mesoscopic solid-state system

BEC on chip could be used as
- quantum actuator
- quantum probe

(“quantum”=all degrees of freedom are controlled on the quantum level).



Nanomechanical resonator
J. Kotthaus group, CENS/LMU

Couple atoms to
mesoscopic solid-state systems:
- Spin detection
- Fundamentals of detection and decoherence:
  A coherent two-level system coupled to
  an engineered, mesoscopic, solid-state system

The Microtrap Team

Tilo Steinmetz
Philipp Treutlein

Rémi Delhuille
Romain Long

Theodor W. Hänsch
JR

Frequent guest:
Benjamin Lev
(Mabuchi group, CalTech)

Former members:
Peter Hommelhoff
(now Stanford)
Wolfgang Hänsel
(now Innsbruck)

Diploma students
Christian Sartena
Chiara Chiffi
Tim Rom
Astrid Richter

PhD and postdoc positions available!