Quantum Information and Neutral Atoms and Hybrids

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Qubit Realization with Neutral Atoms

Traps for Neutral Atoms

Gates with Neutral Atoms

Architectures with Neutral Atoms

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Qubits Neutral Atoms

Gates with Neutral Atoms

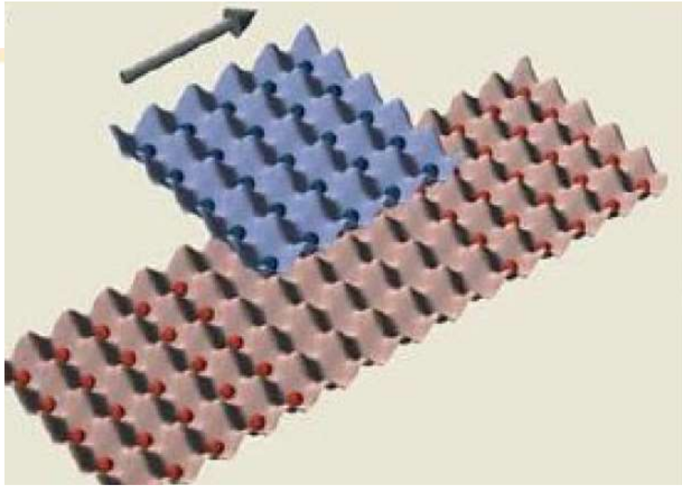
- Collisional Phase Gate

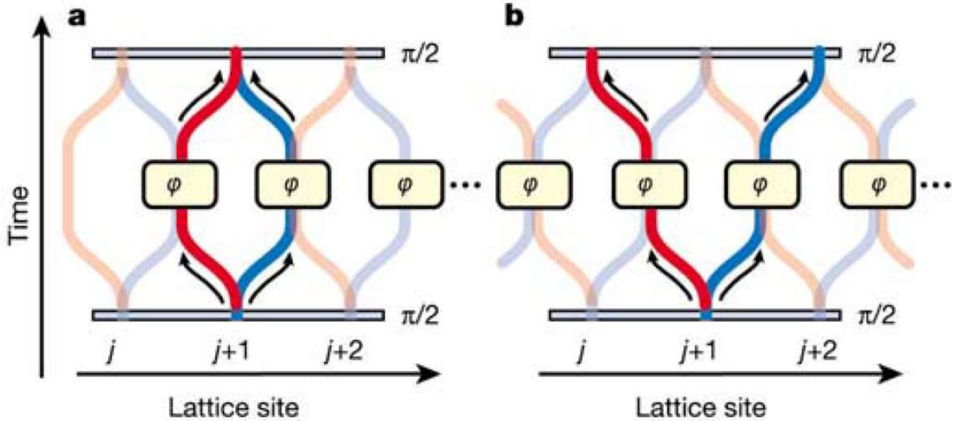
- Rydberg Gate

Collisional Phase Gate

Collisional Phase Gate

Entanglement is generated by
- coherently splitting the atomic wavefunction
- let neighbouring atoms collide by shifting the two state dependent lattices.





O. Mandel, M. Greiner, A. Widera, T. Rom, Th. W. Hänsch and I. Bloch; *Nature* **425**, 937-940 (2003)

Gates with Neutral Atoms

- Collisional Phase Gate

- Rydberg Gate

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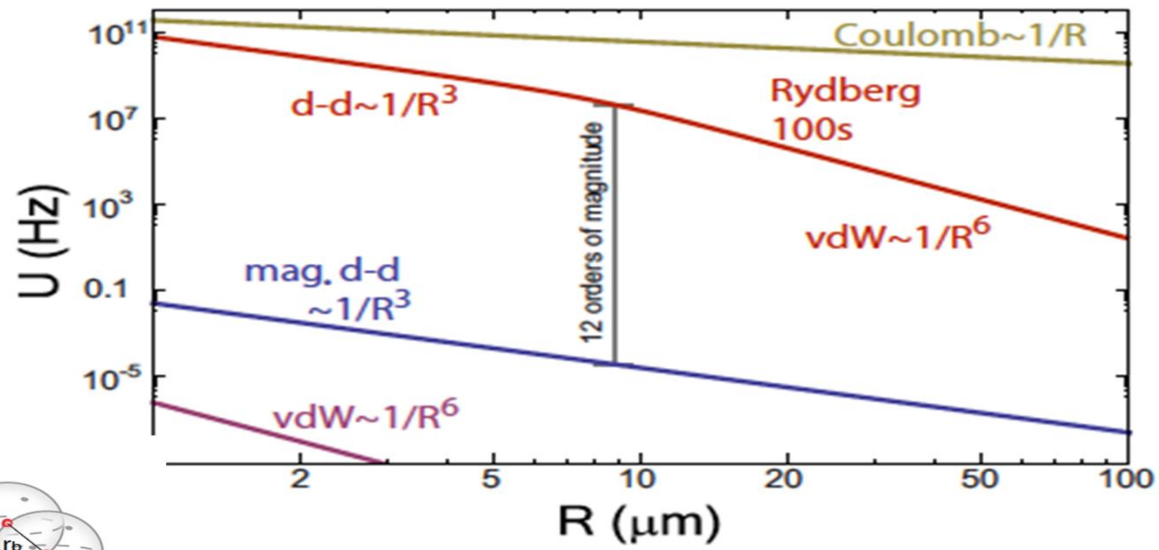
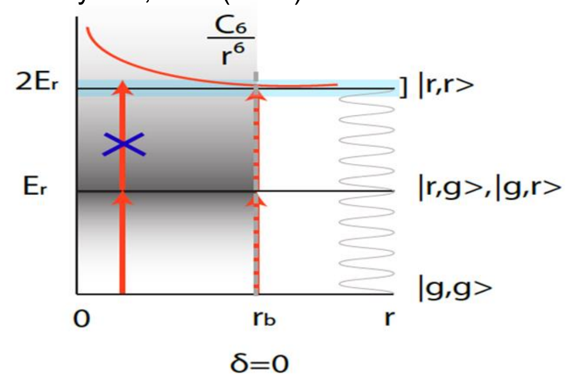
•Long range dipole-dipole interaction; **orders of magnitude larger than contact interaction in ultracold gases (up to GHz at micrometer distances)!**

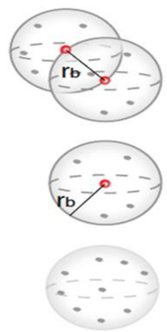
- Dipole-dipole interactions
  - •$C_3/r^3 \sim n^4$

- •Van-der-Waals interactions
  - •$C_6/r^6 \sim n^{11}$

Saffman *et al.* Rev. Mod. Phys **82**,2313 (2010)







Experimentally observed by:
Heidemann *et al.,* PRL, **99**, 163601 (2007)
Gaëtan *et al.,* Nat Phys **5**, 115 (2009)
Urban *et al.,* Nat Phys **5**, 110 (2009)
& many others

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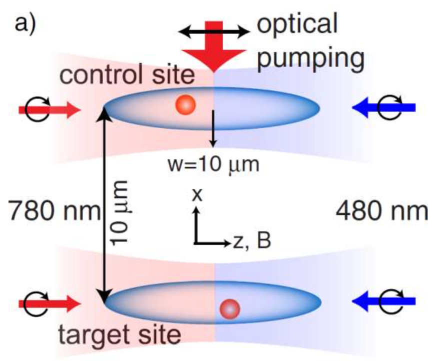
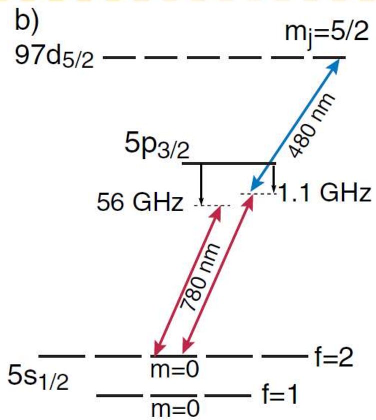
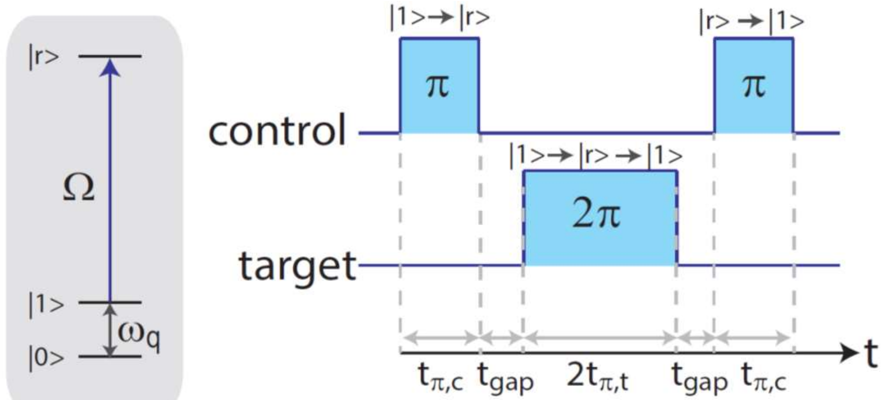
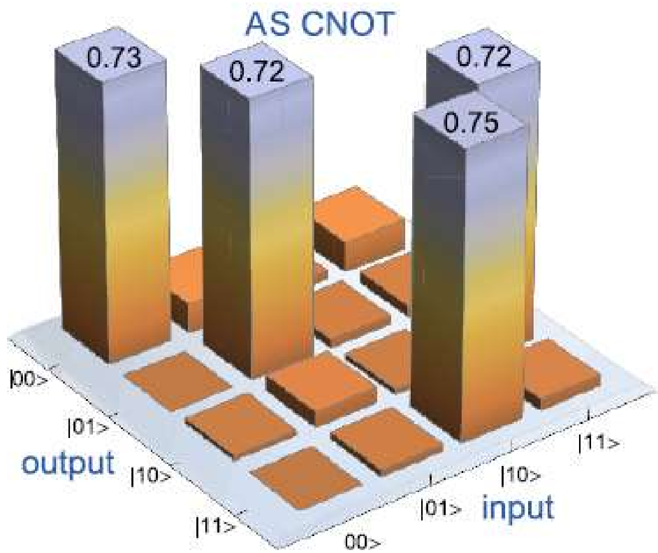
Gate Realization

D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin; Phys. Rev. Lett. 85, 2208 (2000)









L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman; Phys. Rev. Lett. 104, 010503 (2010)

T. Wilk, A. Gaetan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys; Phys. Rev. Lett. 104, 010502, (2010).

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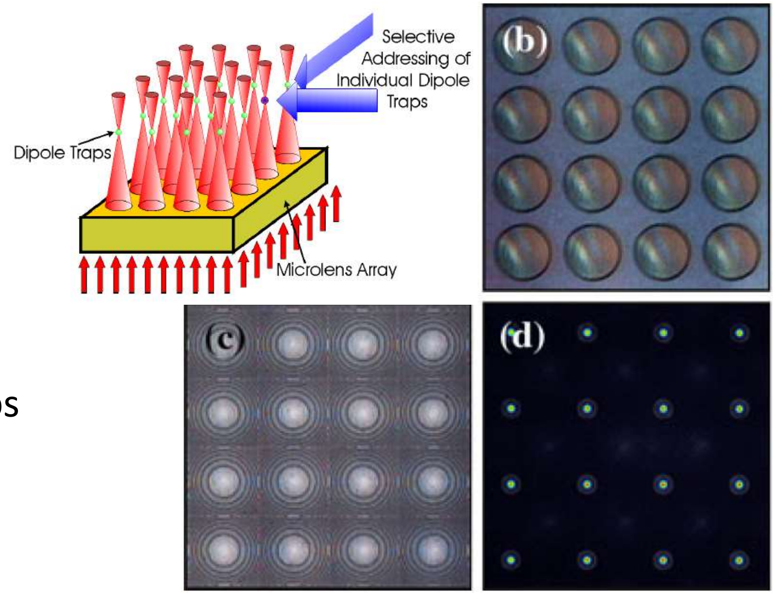
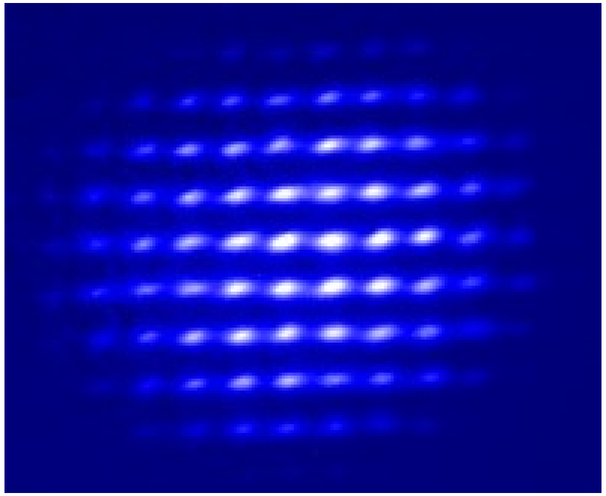
Trap Array

Dipole Trap Array

- System based on Microlenses
- Focal plane imaged onto atoms
- Square Lattice of optical dipole traps
- Side selective addressability
- Simple initialization





R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, G. Birkl, W. Ertmer, Phys. Rev. Lett. 89, 097903/1-4 (2002)

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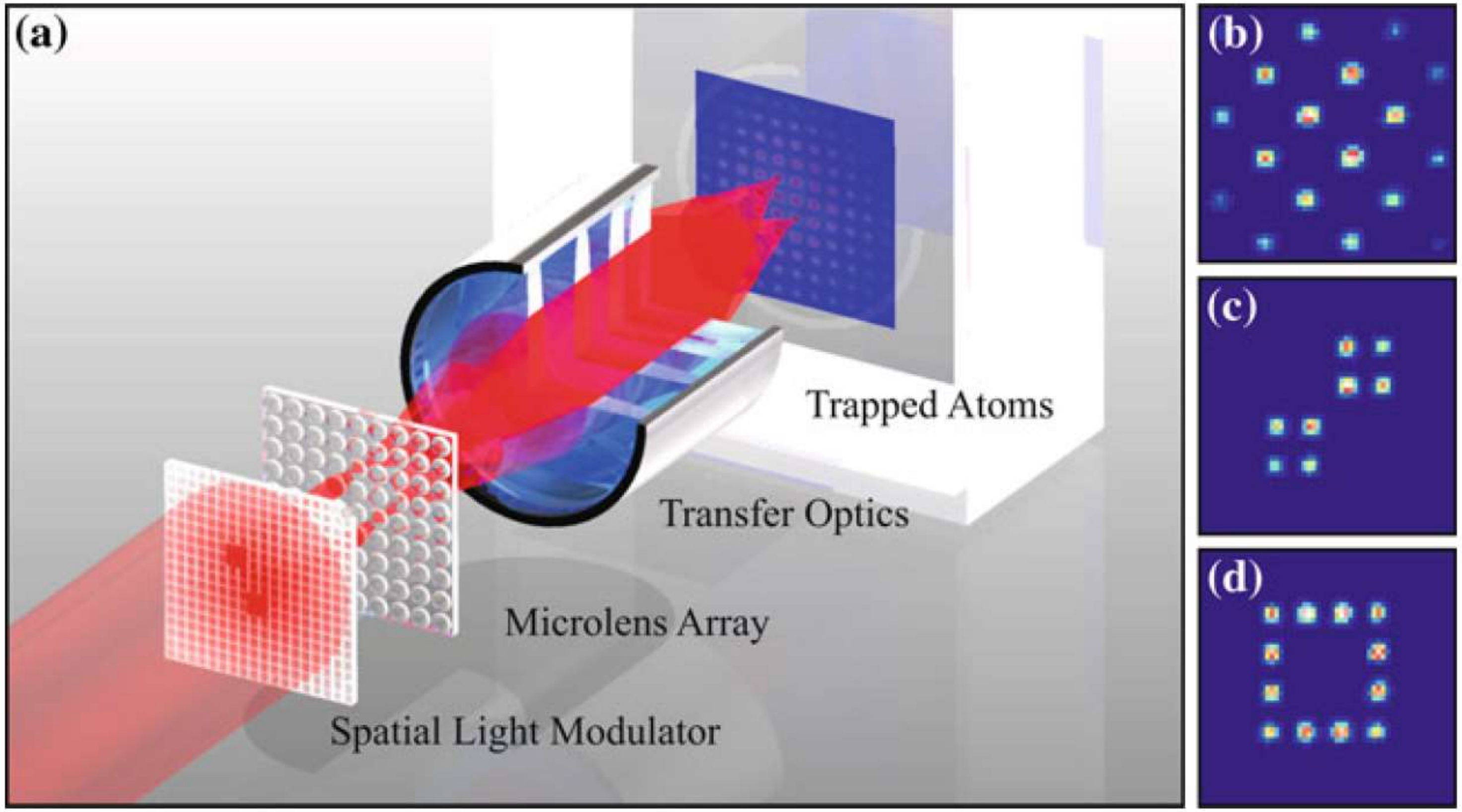
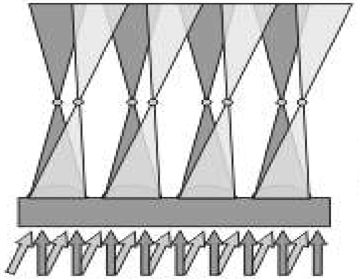
R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, W. Ertmer, and G. Birkl, ‘Quantum Information Processing’, G. Leuchs und T. Beth (eds.), Wiley-VCH, Berlin (2003).

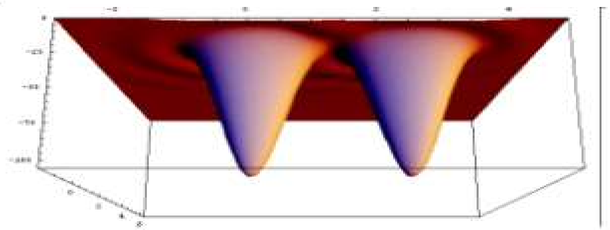
Addressable Trap Array

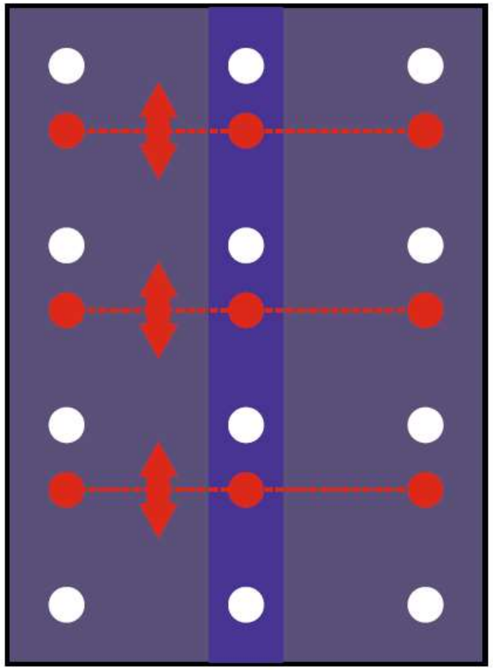


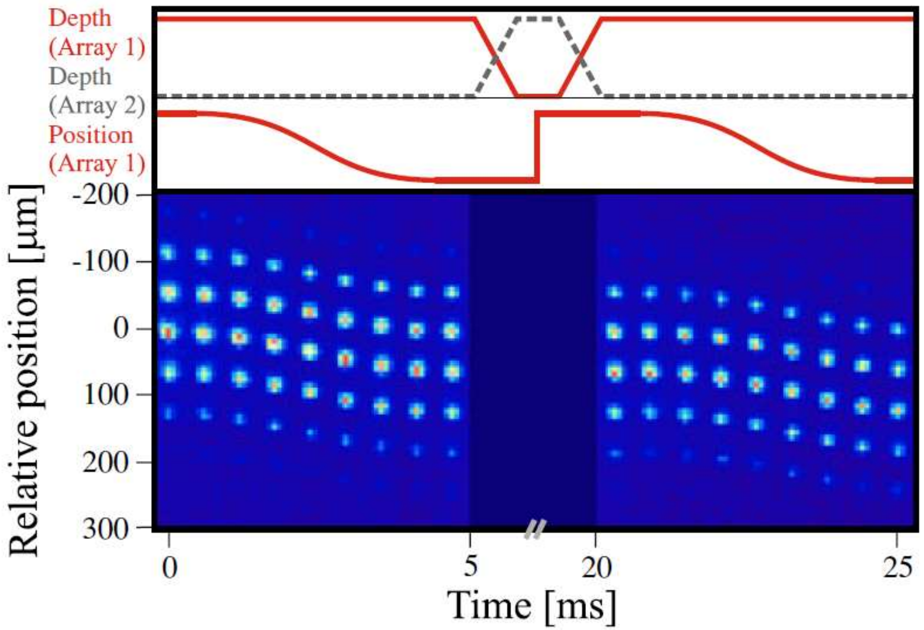
M Schlosser, J Kruse, C Gierl, S Teichmann, S Tichelmann, G Birkl
New J. Phys. 14, 123034 (2012)

Trap Transport



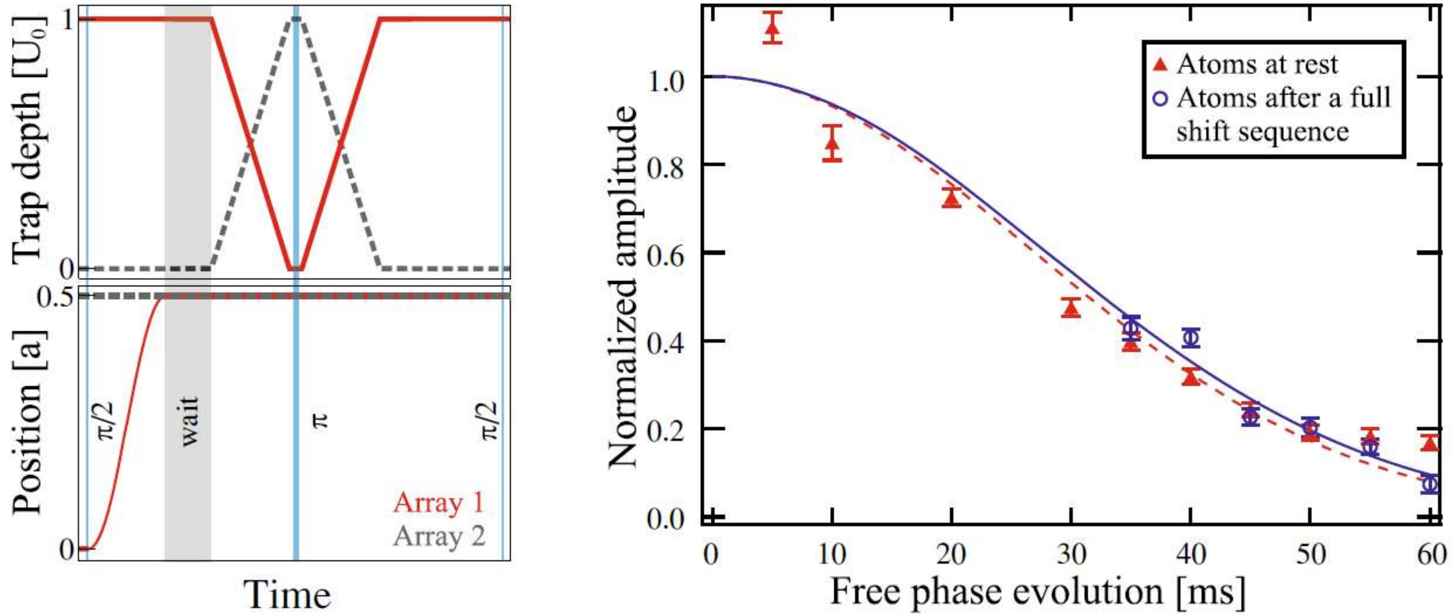






M. Schlosser, S. Tichelmann, J. Kruse, G. Birkl
Quantum Inf. Process. 10, 907-924 (2011)

Coherent Transport



M. Schlosser, S. Tichelmann, J. Kruse, G. Birkl
Quantum Inf. Process. 10, 907-924 (2011)

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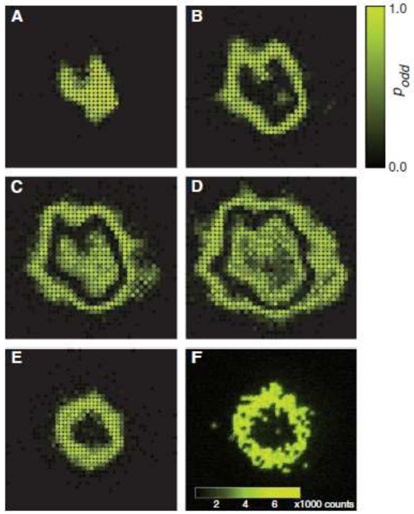
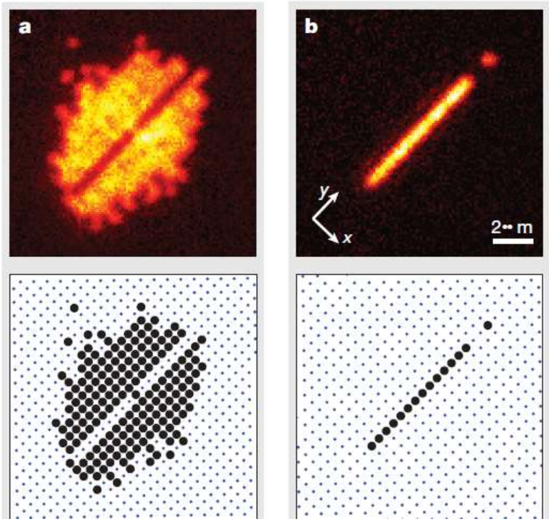
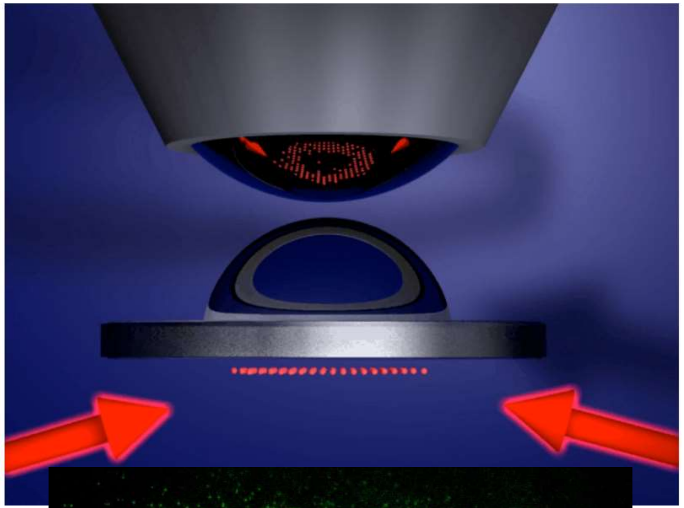
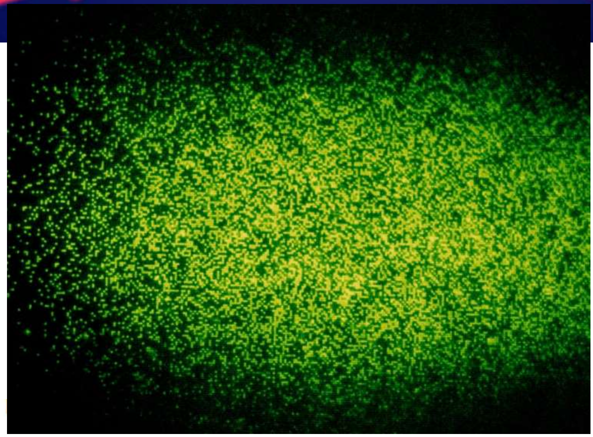
Quantum Microscope

Similar experiments in:
Greiner; Havard
Bloch; Munich
Thywissen; Toronto
Kuhr; Strathclyde
…









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Waseem S. Bakr, Jonathon I. Gillen, Amy Peng, Simon Fölling and Markus Greiner; Nature 462, 74-77 ((2009)

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Next….

… what comes next?

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Next….

… what comes next?

Hybrids… as per schedule
Neutral Atoms and Superconductors

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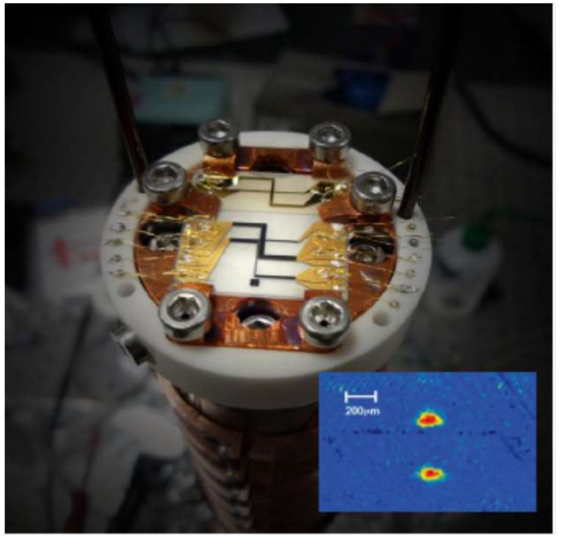
Content:

- **Overview**
  - Atomic / Superconducting Quantum Systems
  - Coupling
- **Superconducting Atom Chips**
  - Spin Flip Loss
  - Vortex Based Trap Geometries
- **Electrometry on Cryogenic Surfaces**
  - Chemisorption
  - Physisorption
- **Outlook**



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"Hybrid quantum circuits combine two or more physical systems, with the goal of harnessing the advantages and strengths of the different systems in order to better explore new phenomena and potentially bring about novel quantum technologies. " - Ze-Liang Xiang et al. Rev. Mod. Phys. **85**, 623 (2013)

	Neutral Atoms	Superconducting Circuit
Frequency Range	GHz and optical	1-20 GHz
Operating Temperature	nK - μK	approx. 10mK
Single Qubit Gates	kHz-MHz	GHz
Two Qubit Gate	kHz-MHz	10-100 MHz
Coherence Times	ms-s	10-100 μs

Z.L. Xiang, S. Ashhab, J. Q. You, and F. Nori
Rev. Mod. Phys. 85, 623 (2013)

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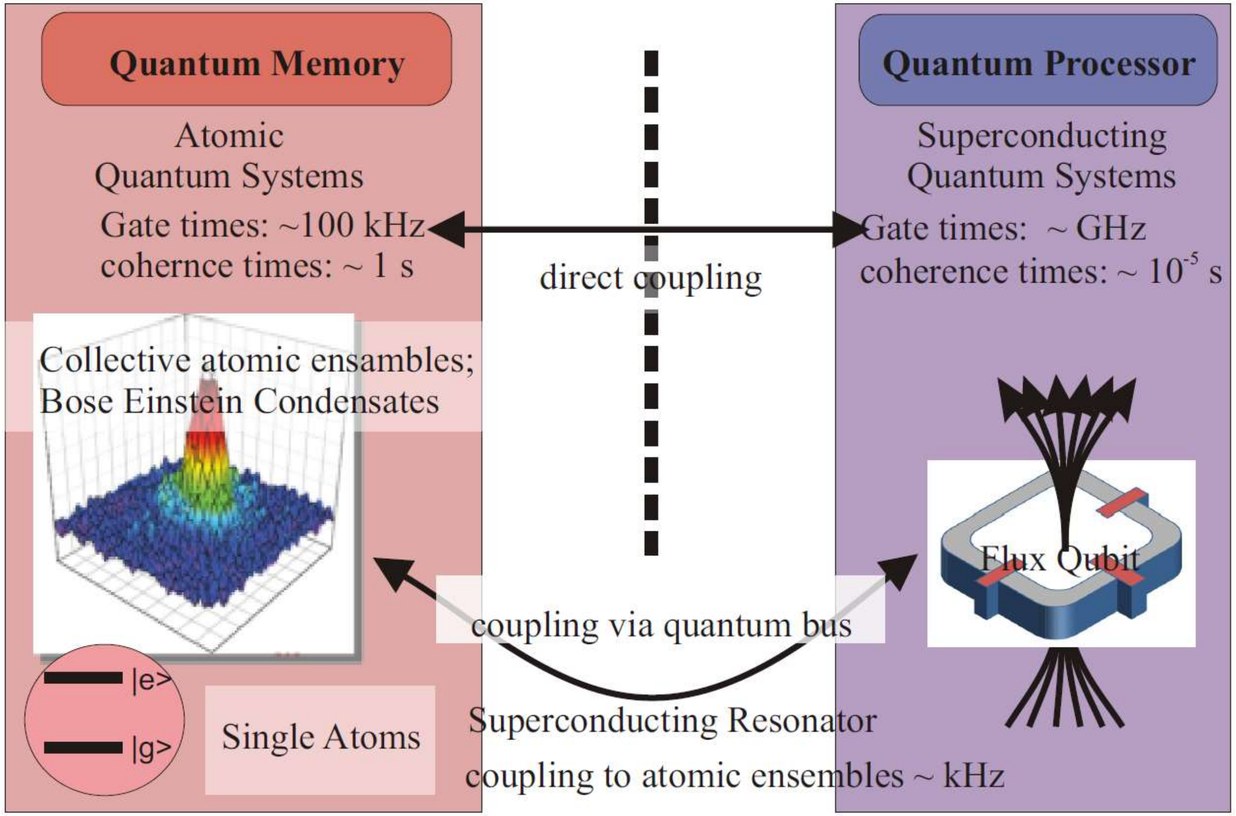
Hybrid Systems



Ch. Hufnagel, R Dumke, "Superconducting atom chips and hybrid quantum systems"; to be published in Journal of Optics

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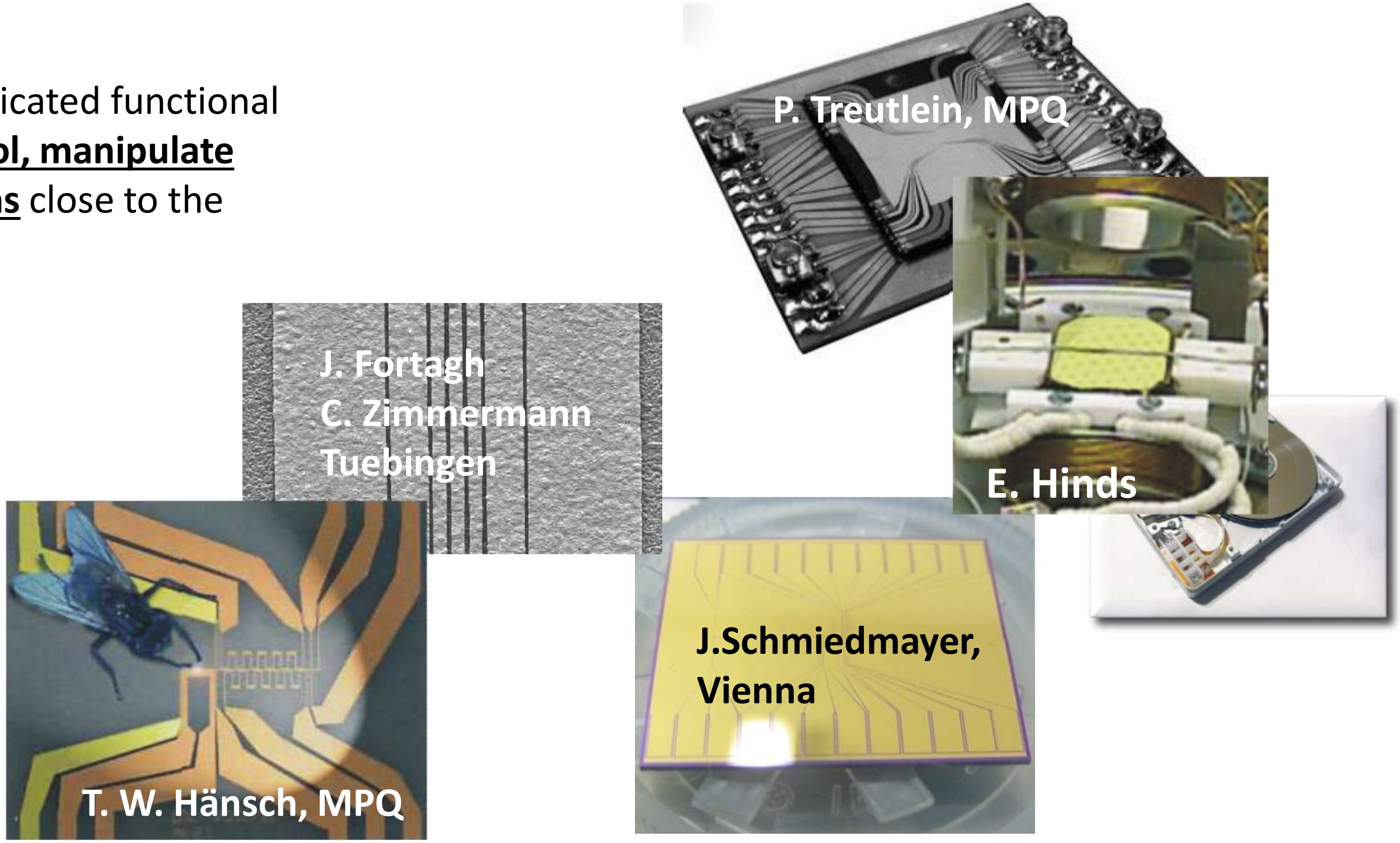
Atom Chips

Integrate microfabricated functional structures to **control, manipulate** and transport **atoms** close to the atomchip surface.



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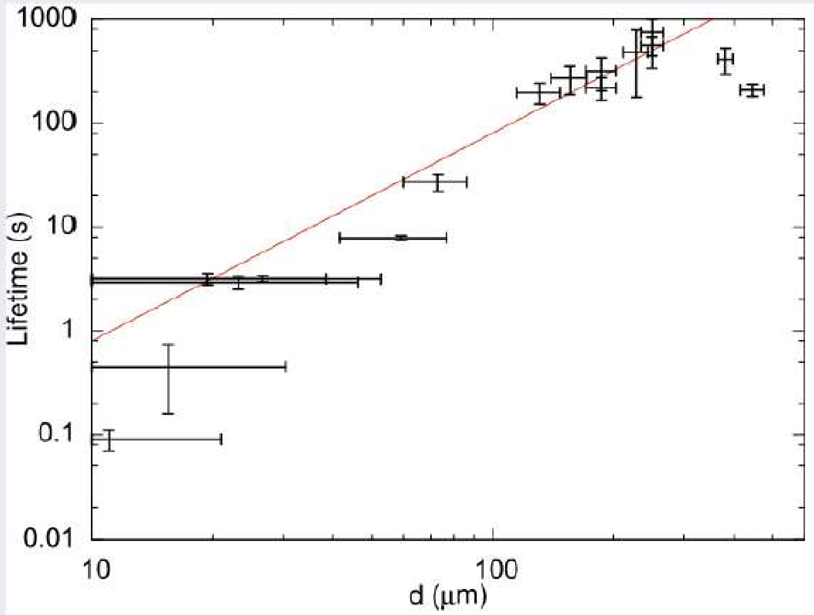
Spin Flip Lifetime

Large coupling strength in a hybrid architecture at small distances (μm-scale)

Coherence and trap life times in conventional chip traps are limited by:

- Technical noise due to "classical" current supplies
- Thermal noise due to finite resistance.



Measurement of the trapping lifetime close to a cold metallic surface on a cryogenic atom-chip, Emmert et. al., Eur. Phys. J. D **51** , 173177 (2009)

"Spatial decoherence near metallic surfaces", R. Fermani, S. Scheel, and P. L. Knight, Phys. Rev. A **73**, 032902 – Published 8 March 2006

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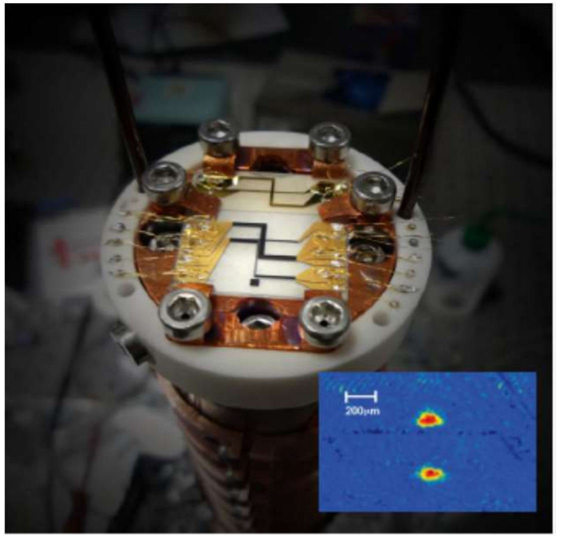


Superconducting atom chip

- long coherence times due to suppression absorptive noise
  U. Hohenester, A. Eiguren, S. Scheel, E.A. Hinds, Phys. Rev. A 76, 03316
  S. Scheel · R. Fermani · P. K. Rekdal · P. L .Knight · E. A. Hinds, Journal of Physics Conference Series 04/2006; 36(1)

- novel trapping/guiding geometries
  T. Müller, X. Wu, A. Mohan, A. Eyvazov, Y. Wu, and R. Dumke, New. J. Phys. 10, 073006 (2008)

- investigating superconducting properties with ultra cold atoms

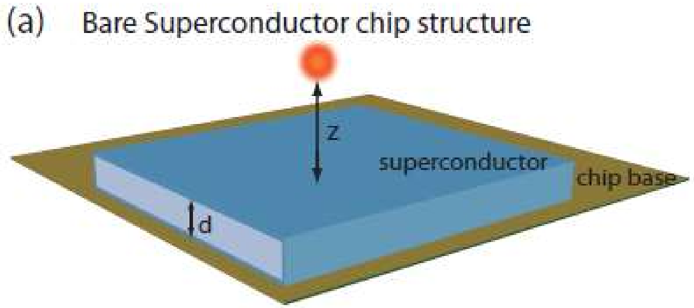
- ………

- pairing superconducting quantum circuits with ultra cold atoms/molecules

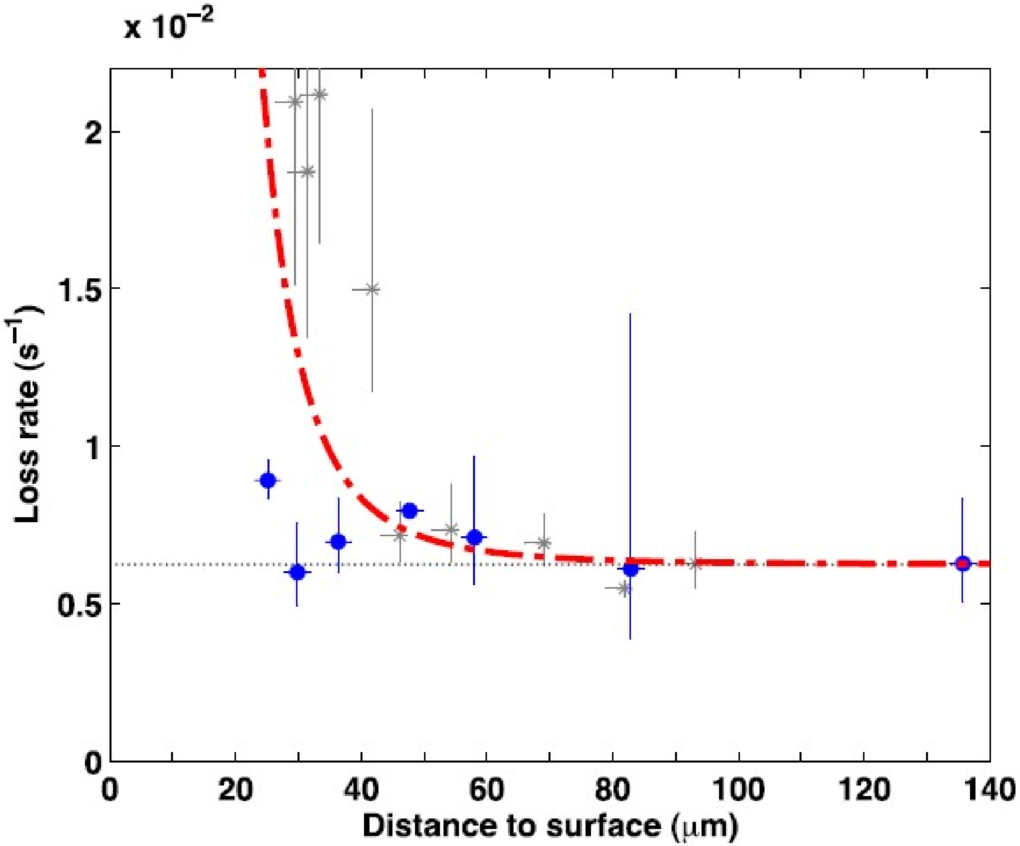
-Thermal fluctuations and resistivity of absorbing materials (e.g. metals result in noisy currents)

-The Fluctuation-Dissipation theorem leads to fluctuating electromagnetic fields at the materials surface.

- The atom interacts with those fields and a spin flip may occur leading to atomic loss or the atoms can be heated by fluctuations in the trapping potential.



Thermal Fluctuations



B. Kasch, H. Hattermann, D. Cano, T. E. Judd, S. Scheel, C. Zimmermann, R. Kleiner, D. Koelle, and J. Fortágh, New J. Phys. 12, 065024 (2010).

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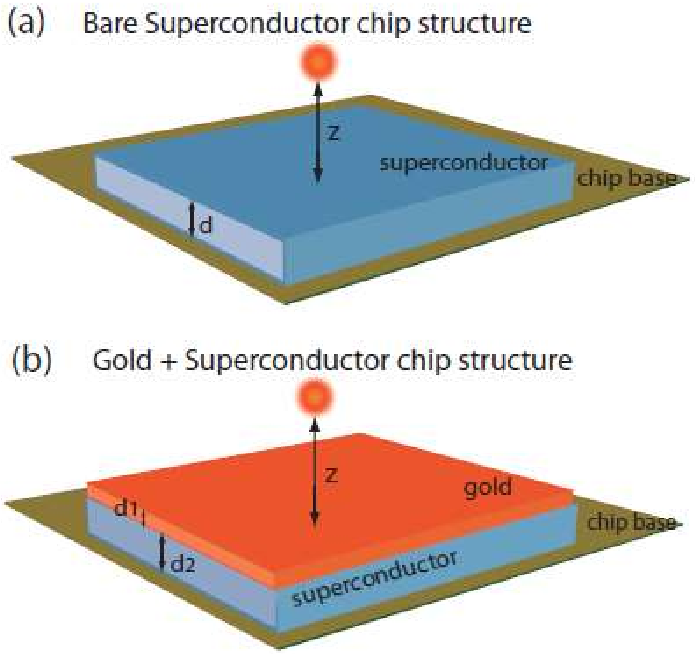

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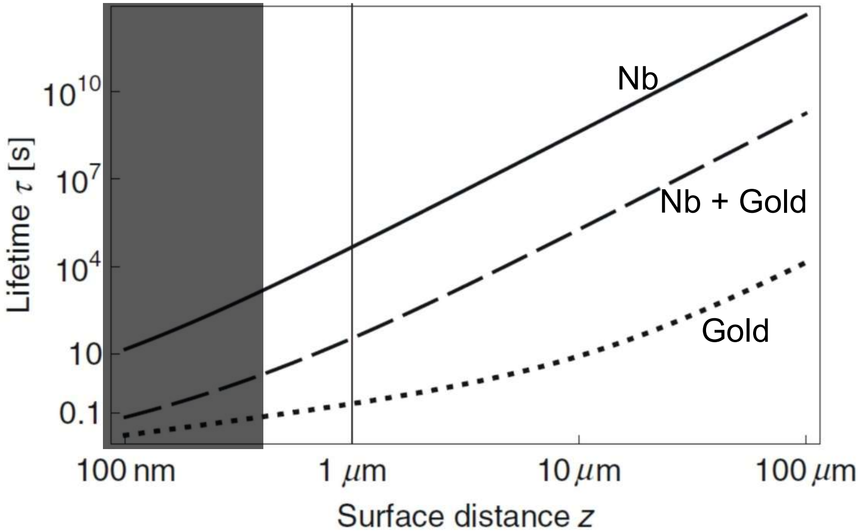
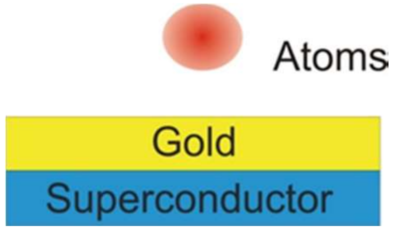




Adding gold layer:
- Protection / reflection of light
- Current safeguard

Spin flip lifetime for a niobium-based chip at 4.2 K,
- thickness of the Nb layer: 1 μm.
- Distinct difference in lifetime for the various structures.
  bare niobium chip (solid)
  niobium+gold chip with gold thickness of 50 nm (dashed)
  infinitely thick gold (dotted).

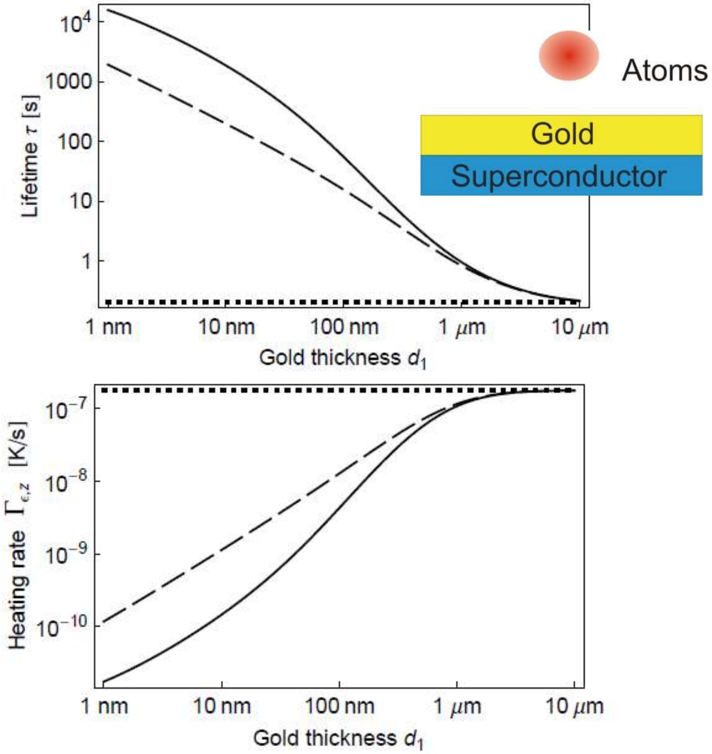
Lifetime / Heating

- Heating rate and spin flip lifetime of an atom 1 µm above a superconducting chip with a top gold layer.

- **Niobium+gold chip (solid curve).**
- **YBCO+gold chip (dashed curve)**
- **Gold substrate (dotted line).**

- Both chips have a temperature of 4.2 K and the thickness of the superconducting layer is 1 µm.

- The deposition of the gold layer can have a significant impact on the heating rate and spin flip lifetime.

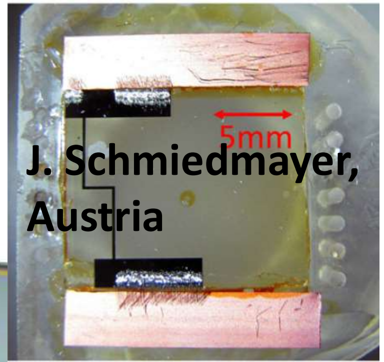


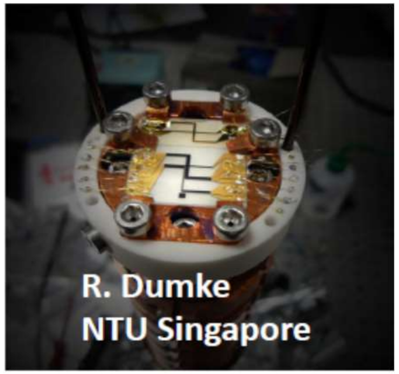
R. Fermani, T. Müller, B. Zhang, M. J. Lim, and R. Dumke, J. Phys. B: At. Mol. Opt. Phys. 43, 095002 (2010).

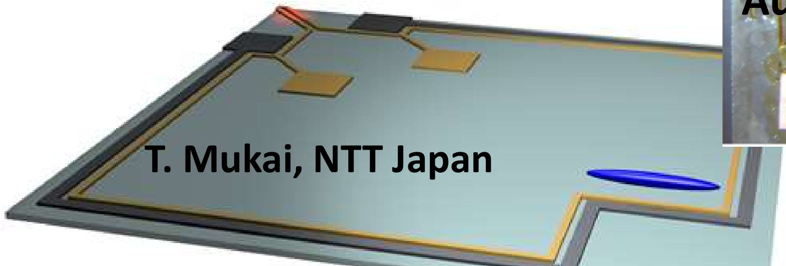
Superconducting Atom Chips

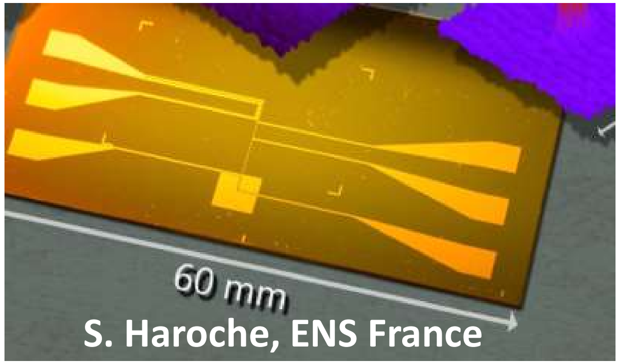
Advantages:

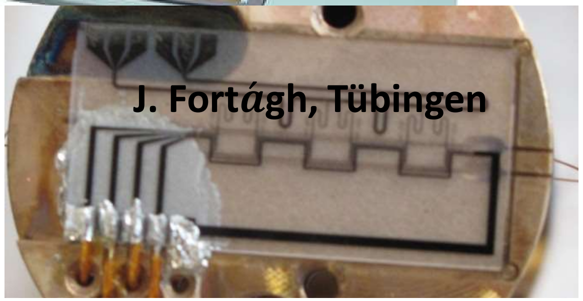
- Suppression of thermal noise
- Eliminate heating
- Longer coherence time
- Compatibility with hybrid system



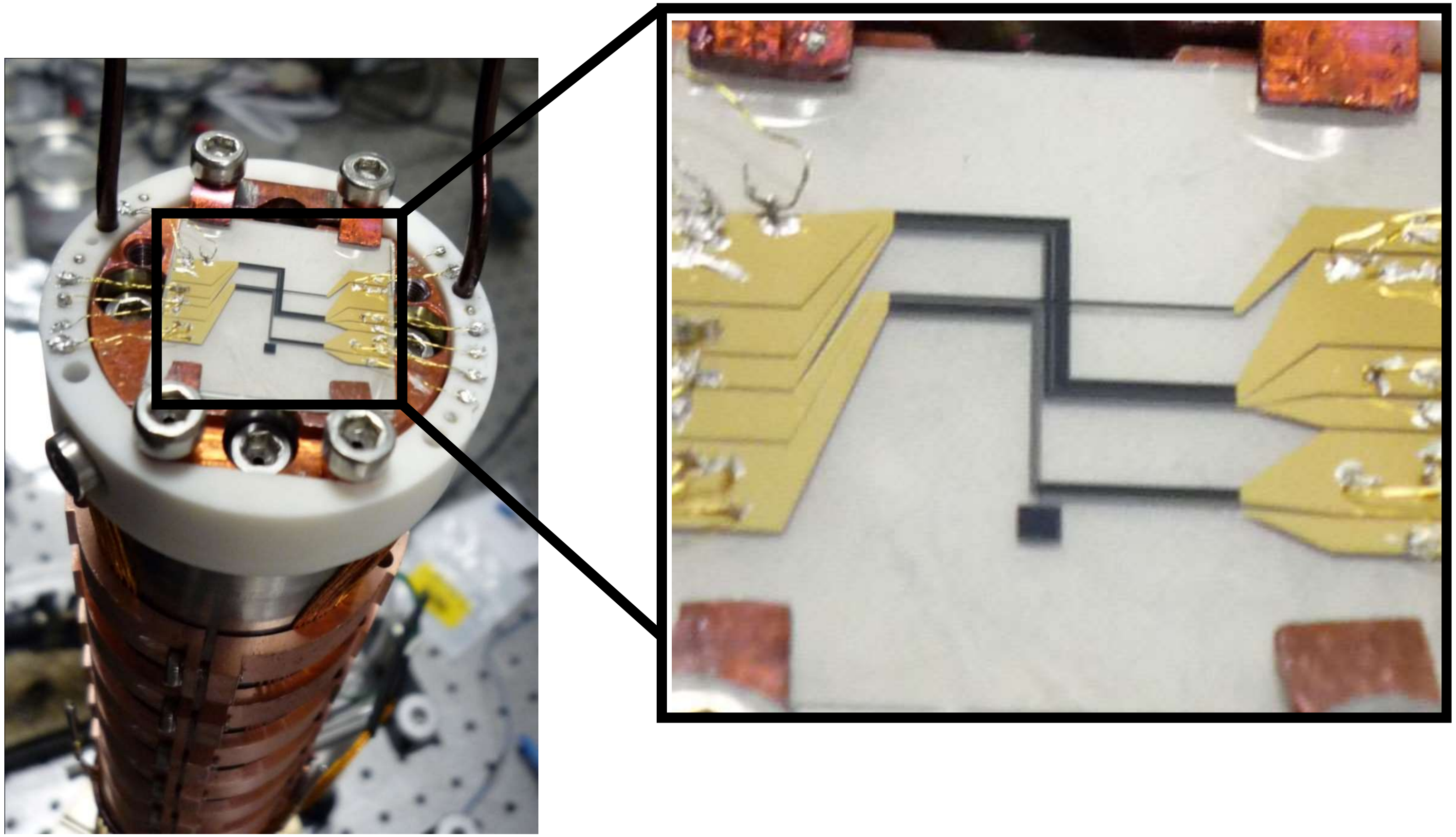








HTS Atom Chip



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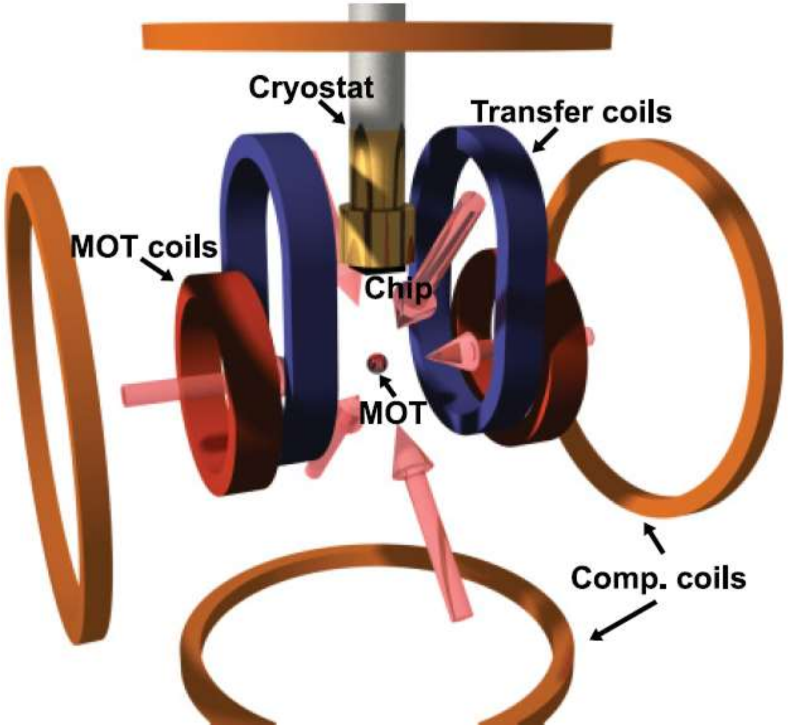
- Load atoms from a MOT into a quadrupole magnetic trap produced by external MOT coils.

- Transport atoms to chip using transfer coils and offset fields.

- Turn off transport coil field to capture atoms in SC vortex field



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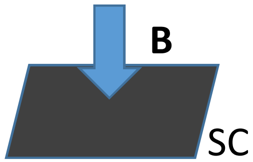
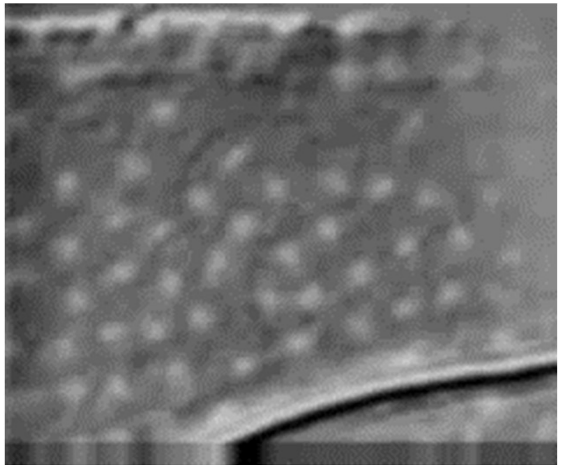
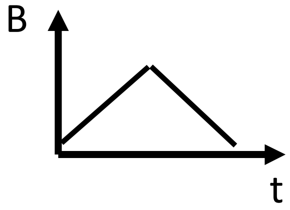
Vortex Dynamics on Type II SC

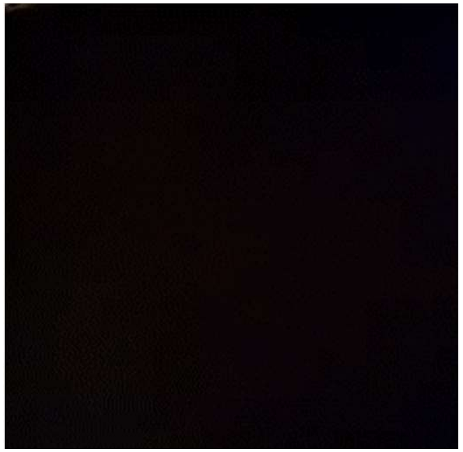
Vorticies Entering Superconductor

Vortex Distribution









Courtesy: Advanced materials and complex systems Group, Department of Physics / Oslo University

Bean's model

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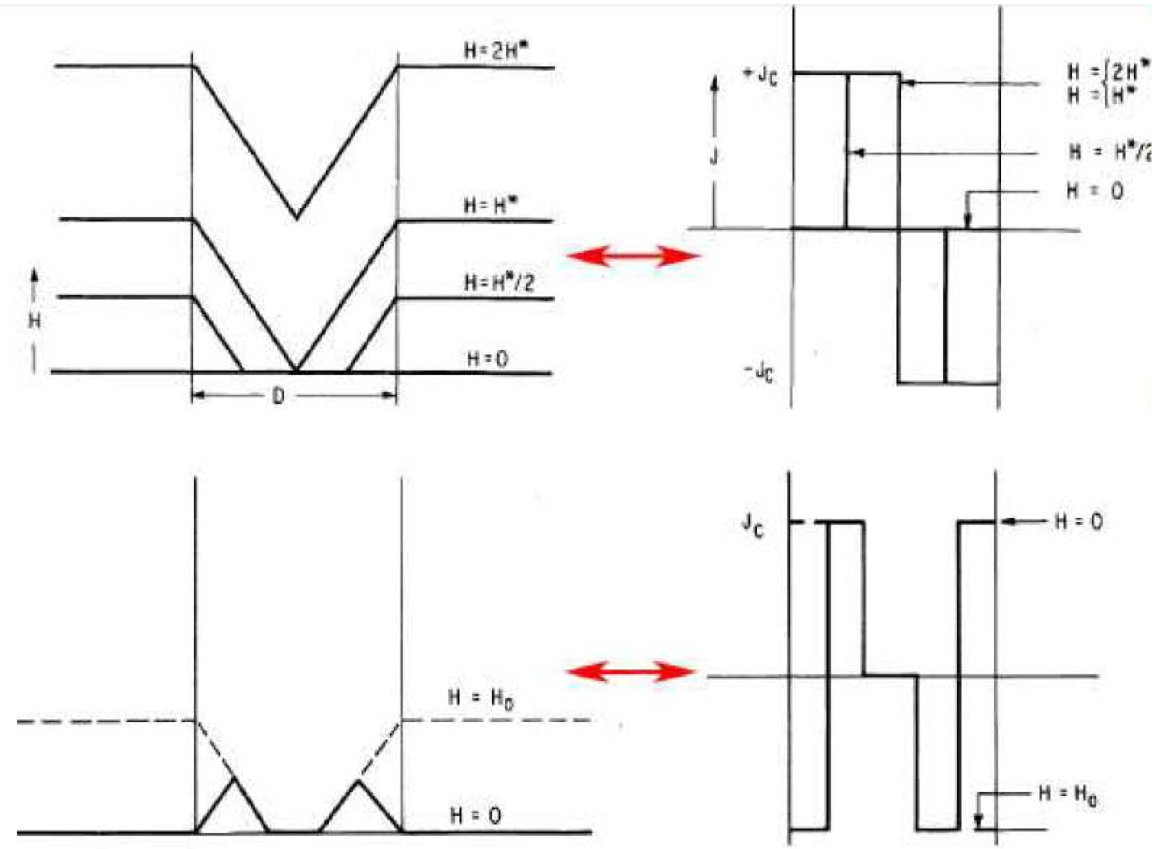
The simple picture

Superconductors will resist any change in magnetic field by producing a countering magnetic field (Lenz's Law)

- Assume the current in the SC takes a maximum value J_c.
- 0 resistivity means any small induced voltage gives maximum current
- Current values of J_c, 0 or $-J_c$ possible



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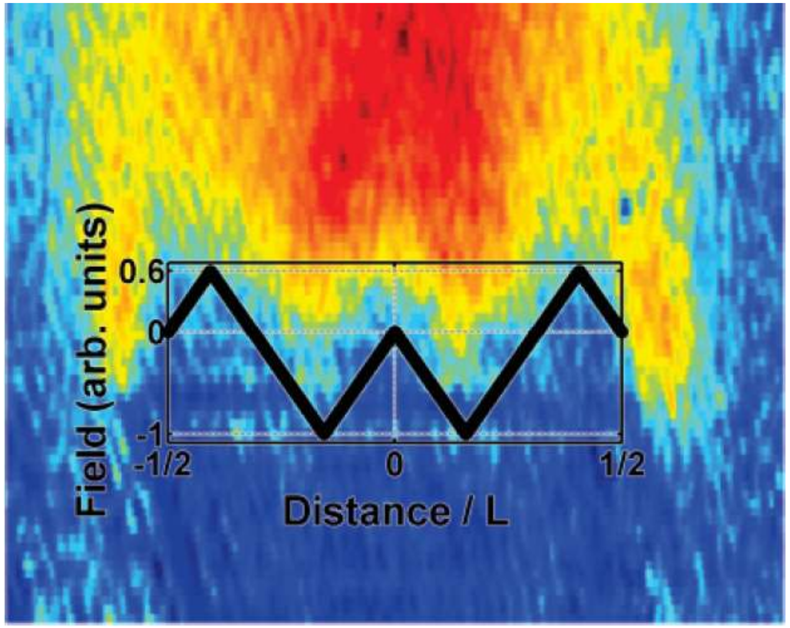
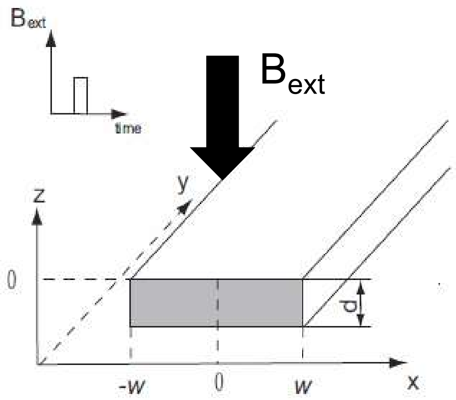
Mapping Vortex Distribution

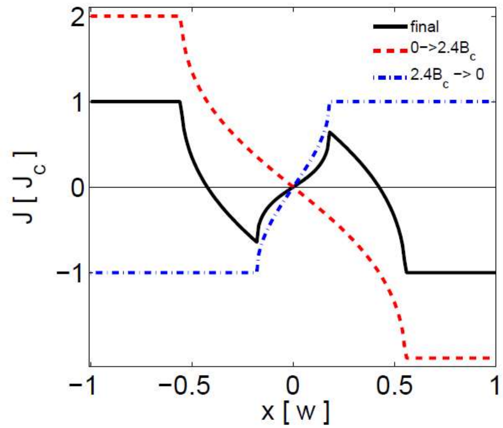
Probing vortex induced current distribution with atoms.

- Induced magnetic field along x at the surface of the square according to Bean's model.
- The square carries super currents loaded by two mag. field pulses.
- The atoms display a triangular structure closely resembling the magnetic field produced by the vortices.



Absorption image of ultracold atoms in vicinity of superconducting square.

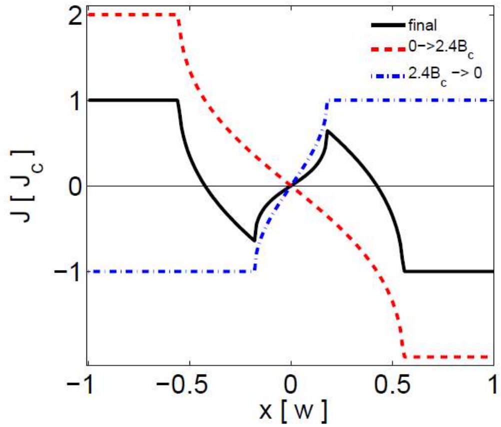




Beyond Bean's model -> more sophisticated **Brandt's model**.

- Numerical model for sheet current density distribution and magnetic field for single loading pulse.

Beyond Bean's model



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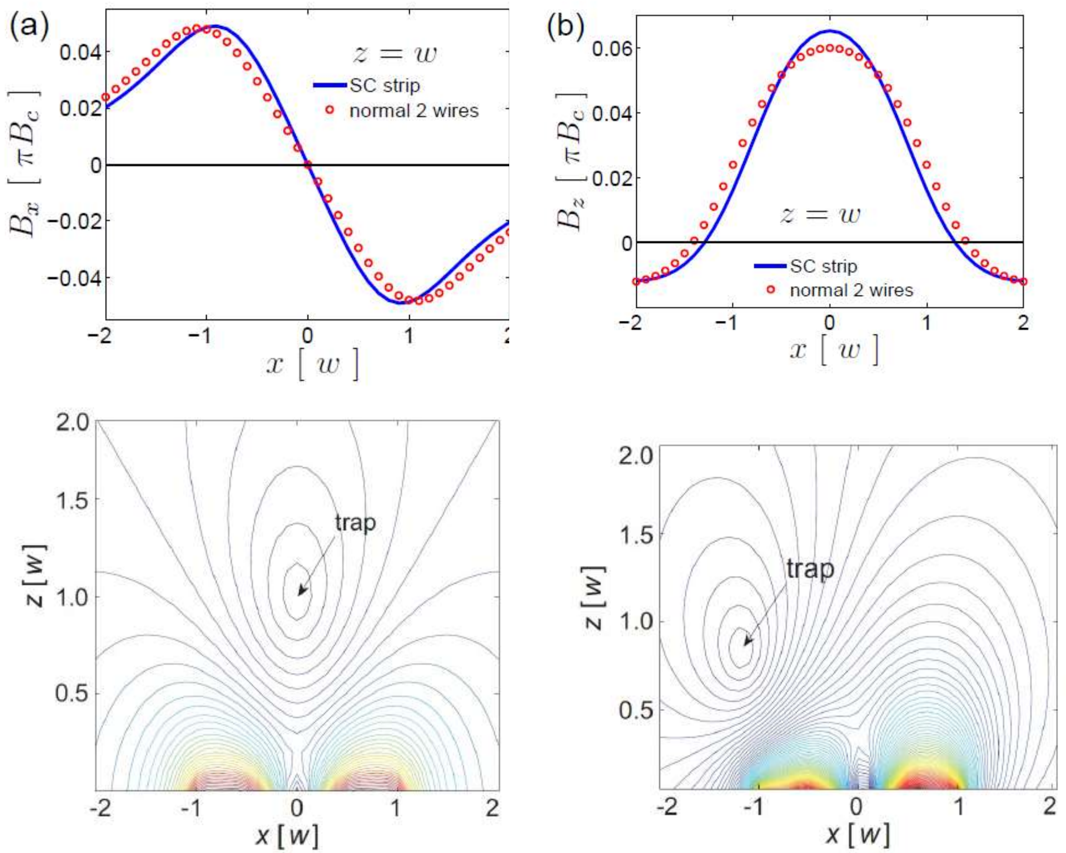
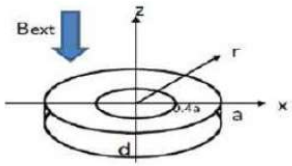
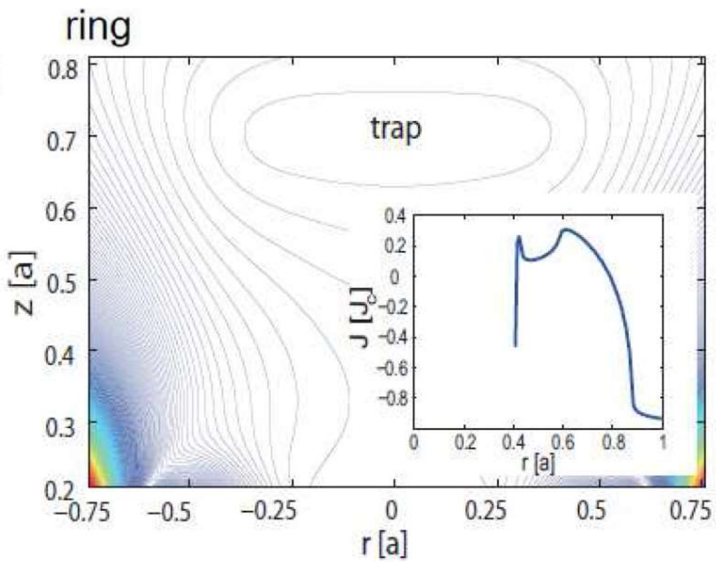


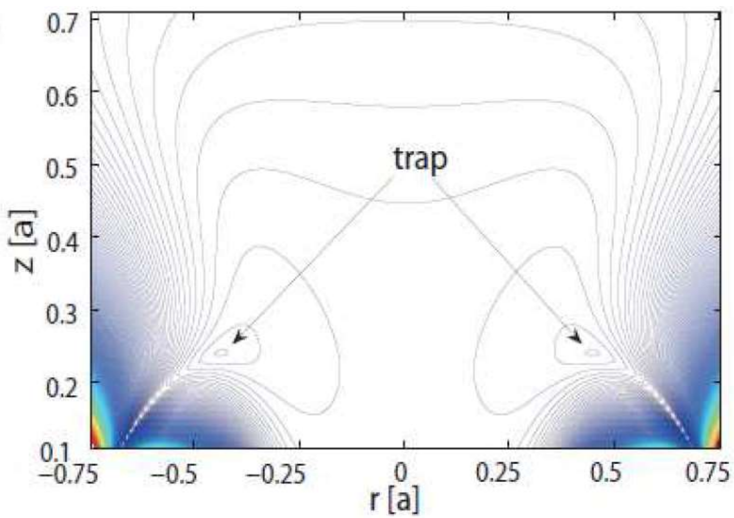
B. Zhang, R. Fermani, T. Müller, M. J. Lim, and R. Dumke Phys. Rev. A 81, 063408 (2010)

2D Geometries

Employing superconducting rings:
- Rings can produce large radius and strong confinement by using a two magnetic field pulse sequence.







B. Zhang, M. Siercke, K. S. Chan, M. Beian, M. J. Lim, and R. Dumke, Phys. Rev. A 85, 013404 (2012)

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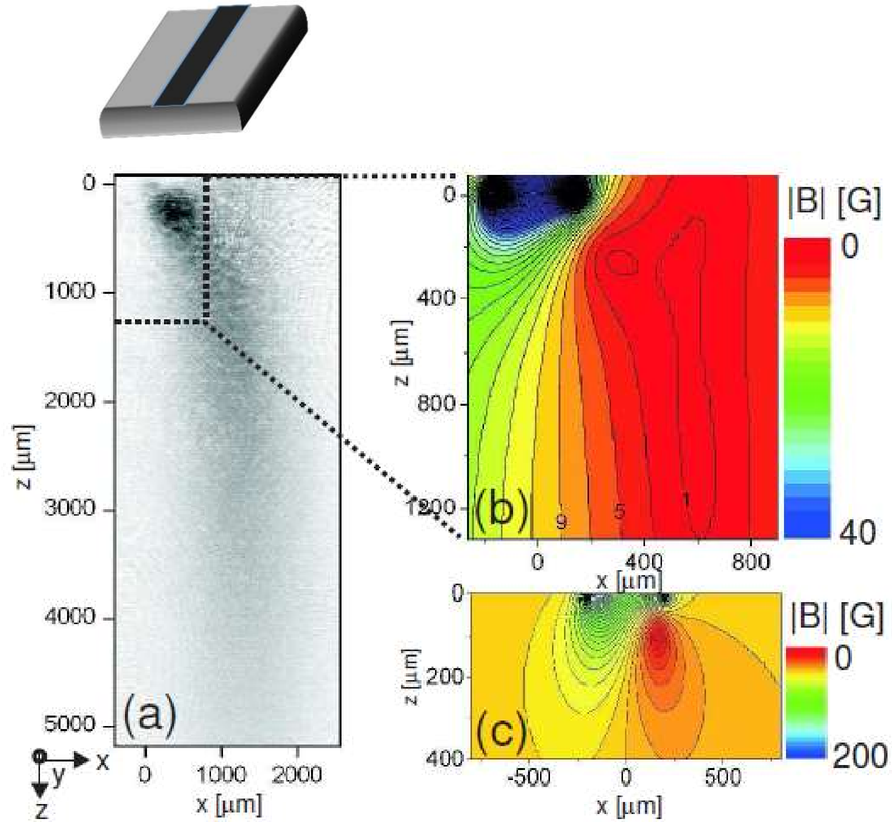
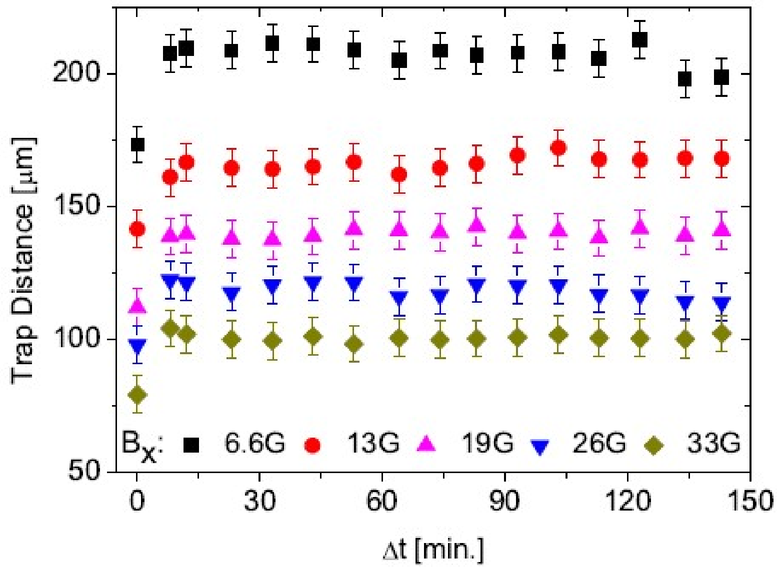
Characterization





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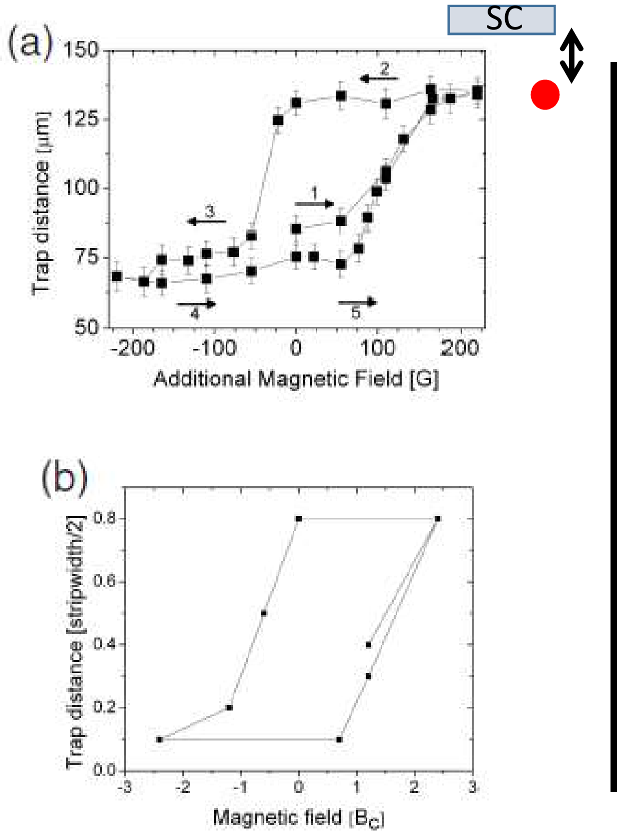
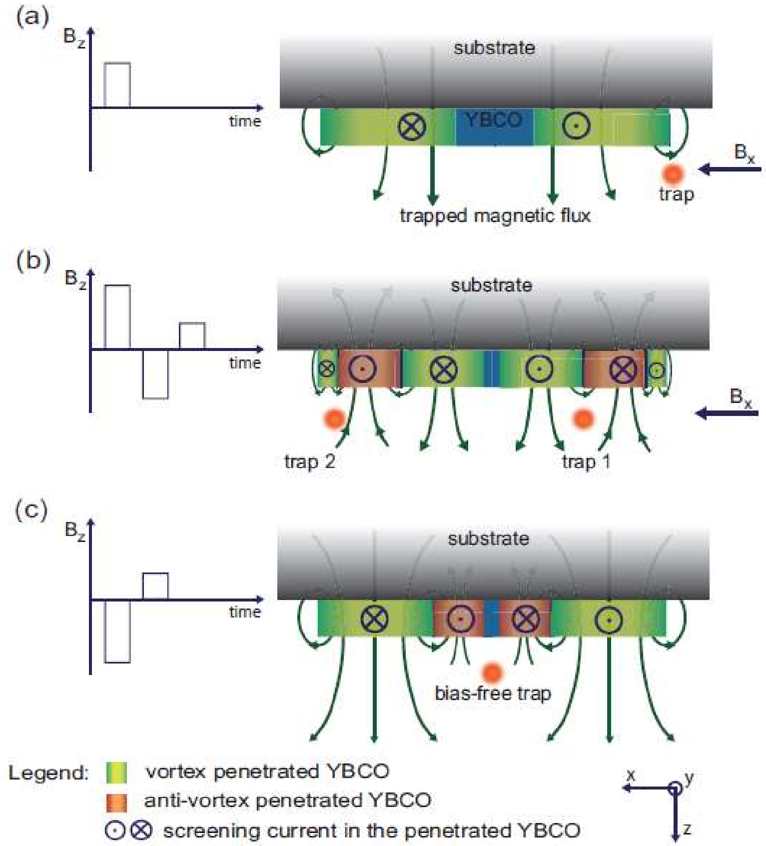
T. Müller , B. Zhang , R. Fermani , K. S. Chan , Z. W. Wang , C. B. Zhang , M. J. Lim and R. Dumke New J. Phys. 12 043016, (2010).

Programmable trap geometries





Programmable trap geometries

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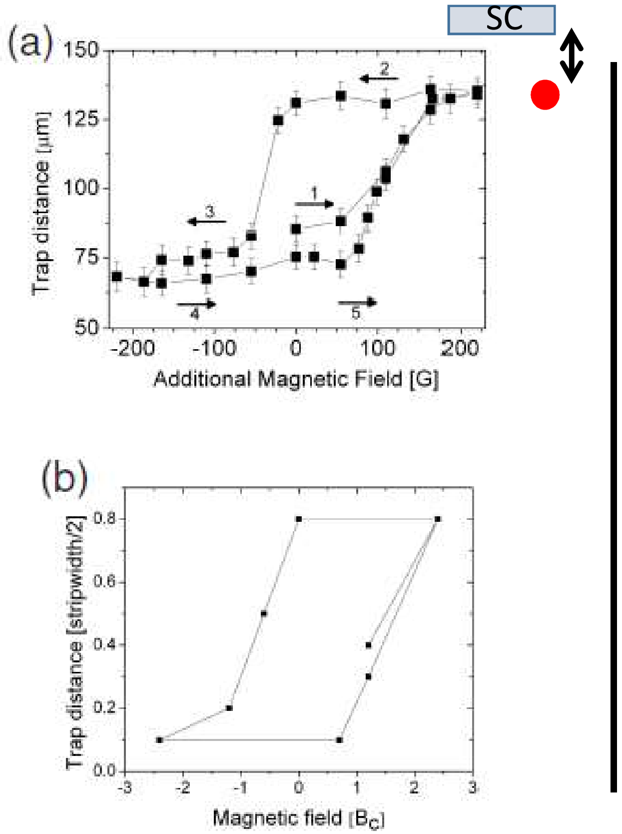

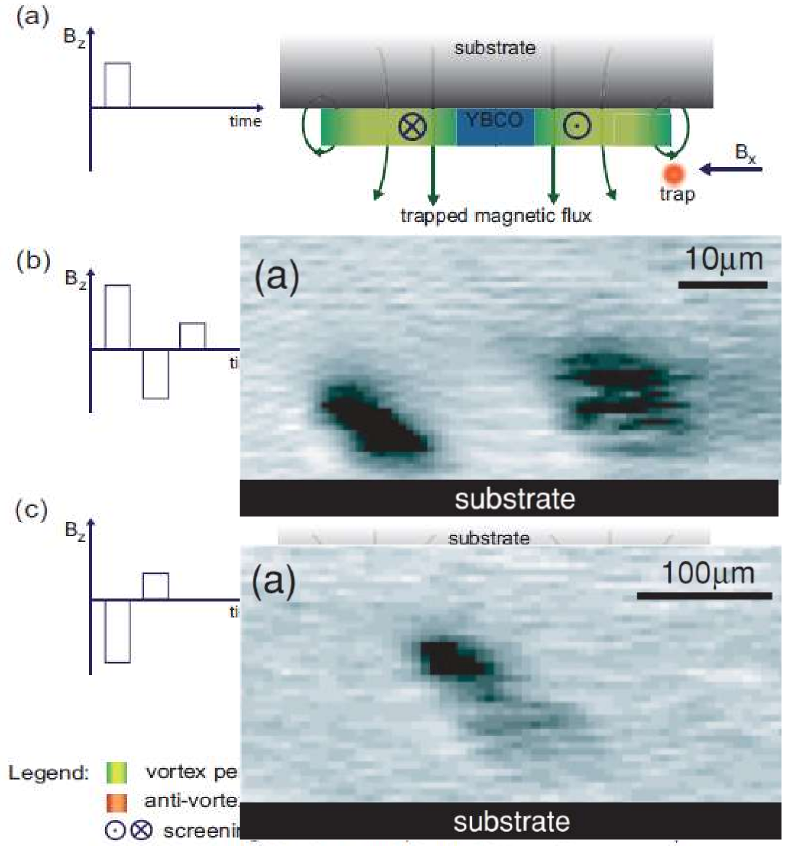

T. Mueller, B. Zhang, R. Fermani, K.S. Chan,
M.J. Lim, R. Dumke, Rev. A 81, 053624 (2010),

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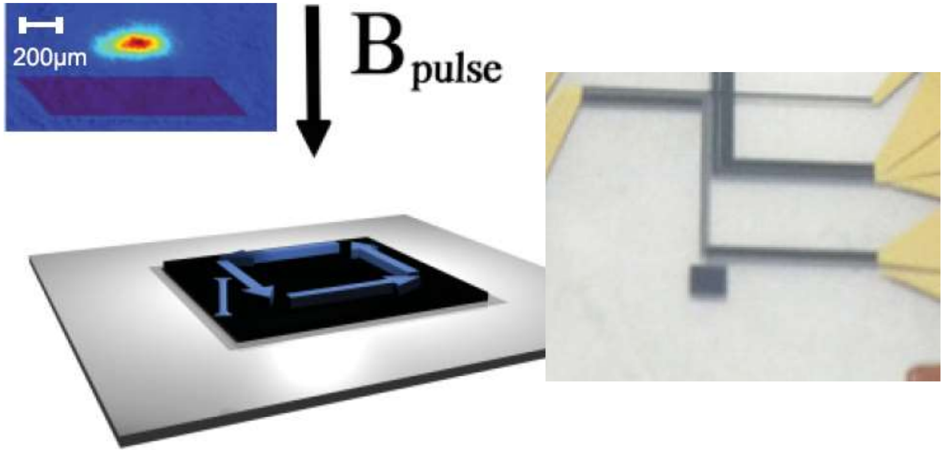
SC Square

Square Structure

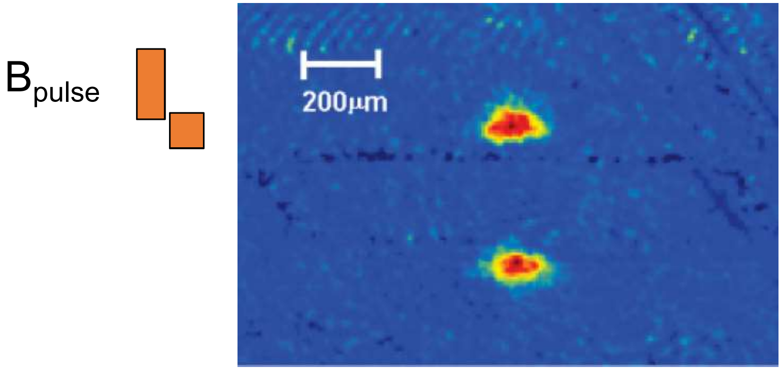
- Applying magnetic field pulse generates persistent sheet current.

-> Quadrupole trap with bias field



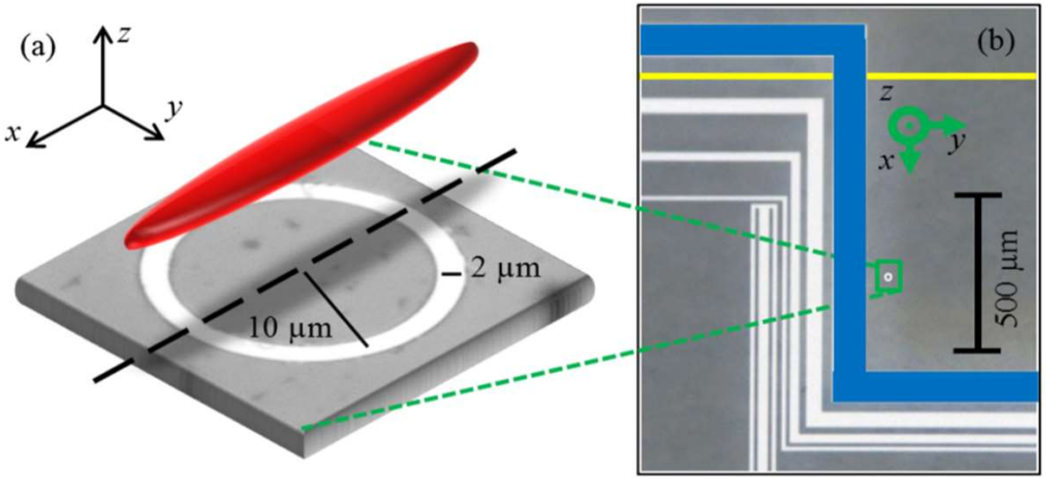
Self-sustaining trap on a square

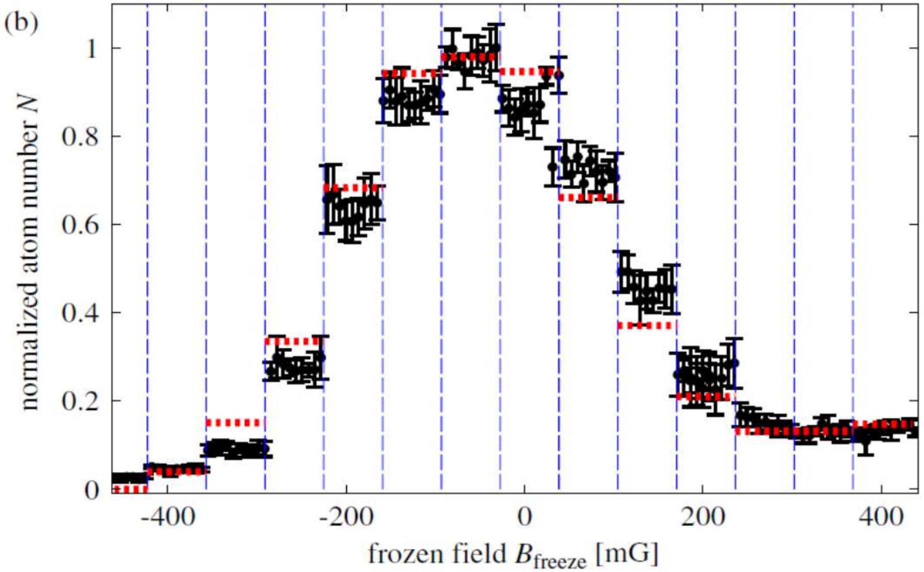
- >10μK trap depth
- Trap height governed by difference in pulse strength between the 2 loading pulses



M. Siercke, K. S. Chan, B. Zhang, M. Beian, M. J. Lim, and R. Dumke, Phys. Rev. A 85, 041403 (2012)

SC Square





P. Weiss, M. Knufinke, S. Bernon, D. Bothner, L. Sárkány, C. Zimmermann, R. Kleiner, D. Koelle, J. Fortágh, and H. Hattermann; PRL 114, 113003 (2015)

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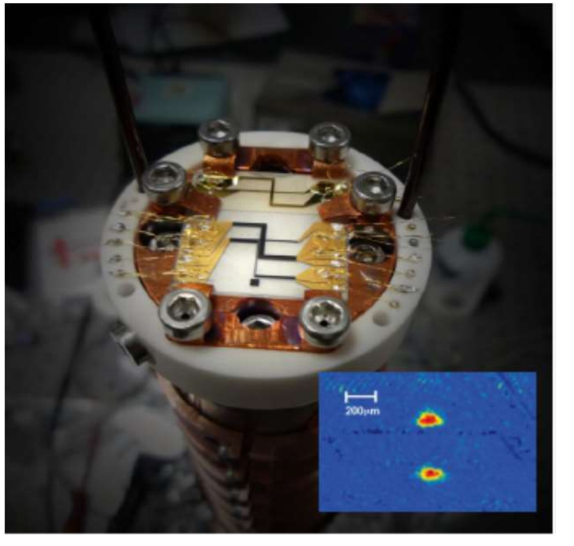
Content:

- Overview
  - Atomic Quantum Systems
  - Superconducting Quantum Systems
  - Coupling
- Superconducting Atom Chips
  - Spin Flip Loss
  - Vortex Based Trap Geometries
- **Electrometry on Cryogenic Surfaces**
  - Chemisorption
  - Physisorption
- **Outlook**



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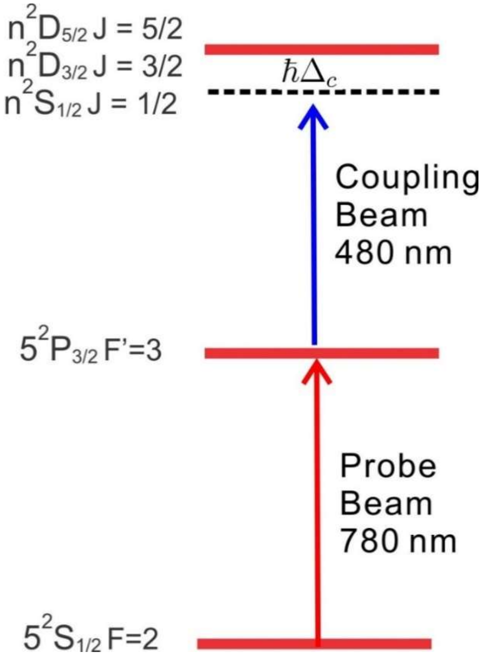
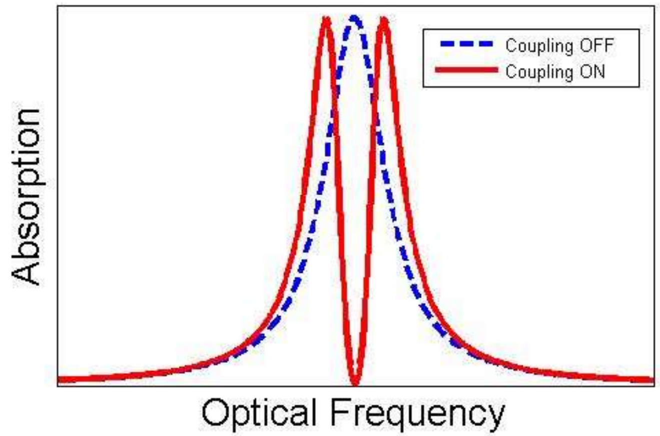
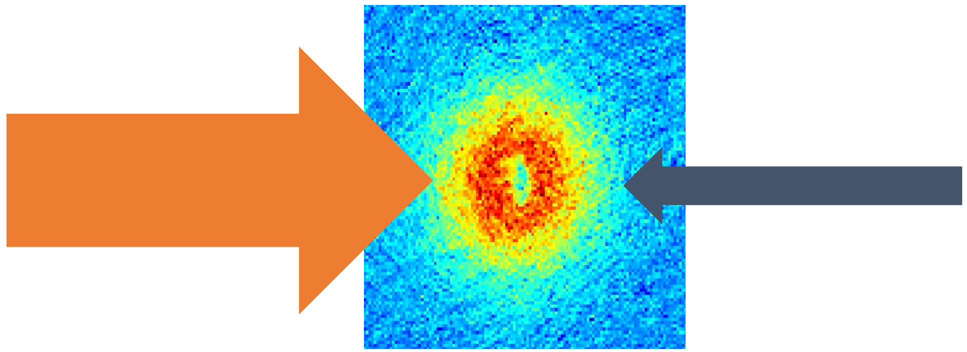
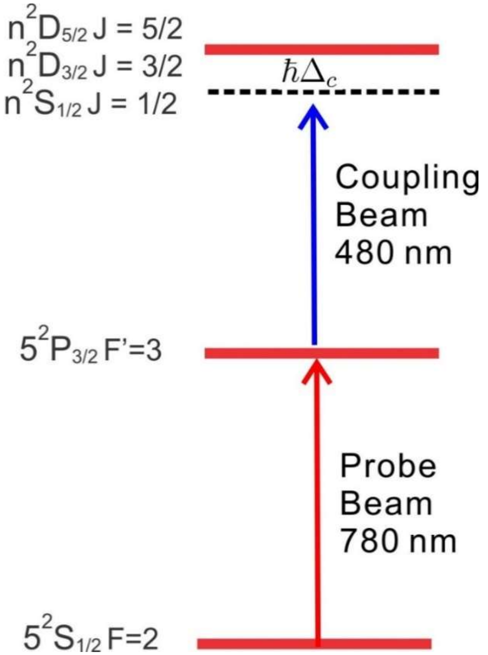
Rydberg Electrometry

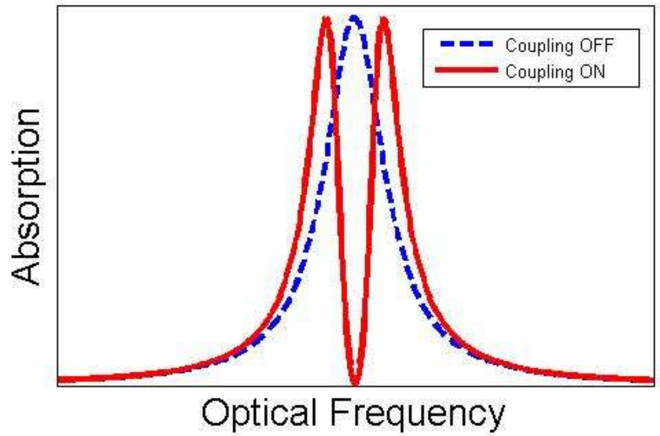


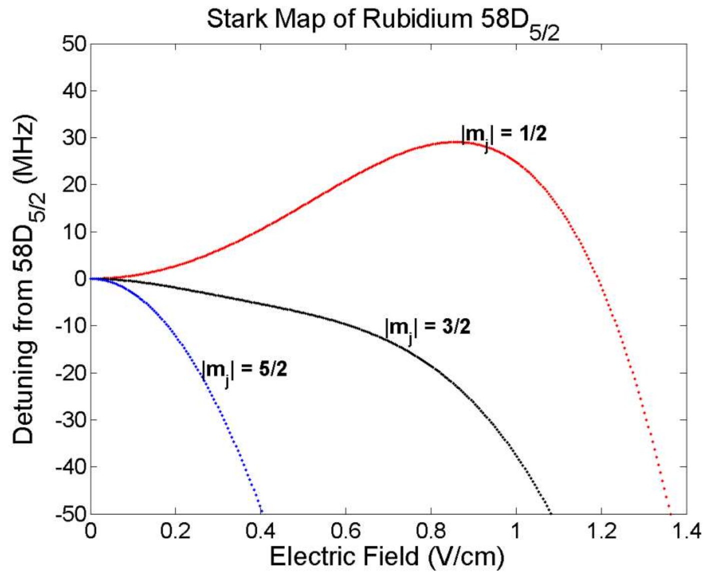




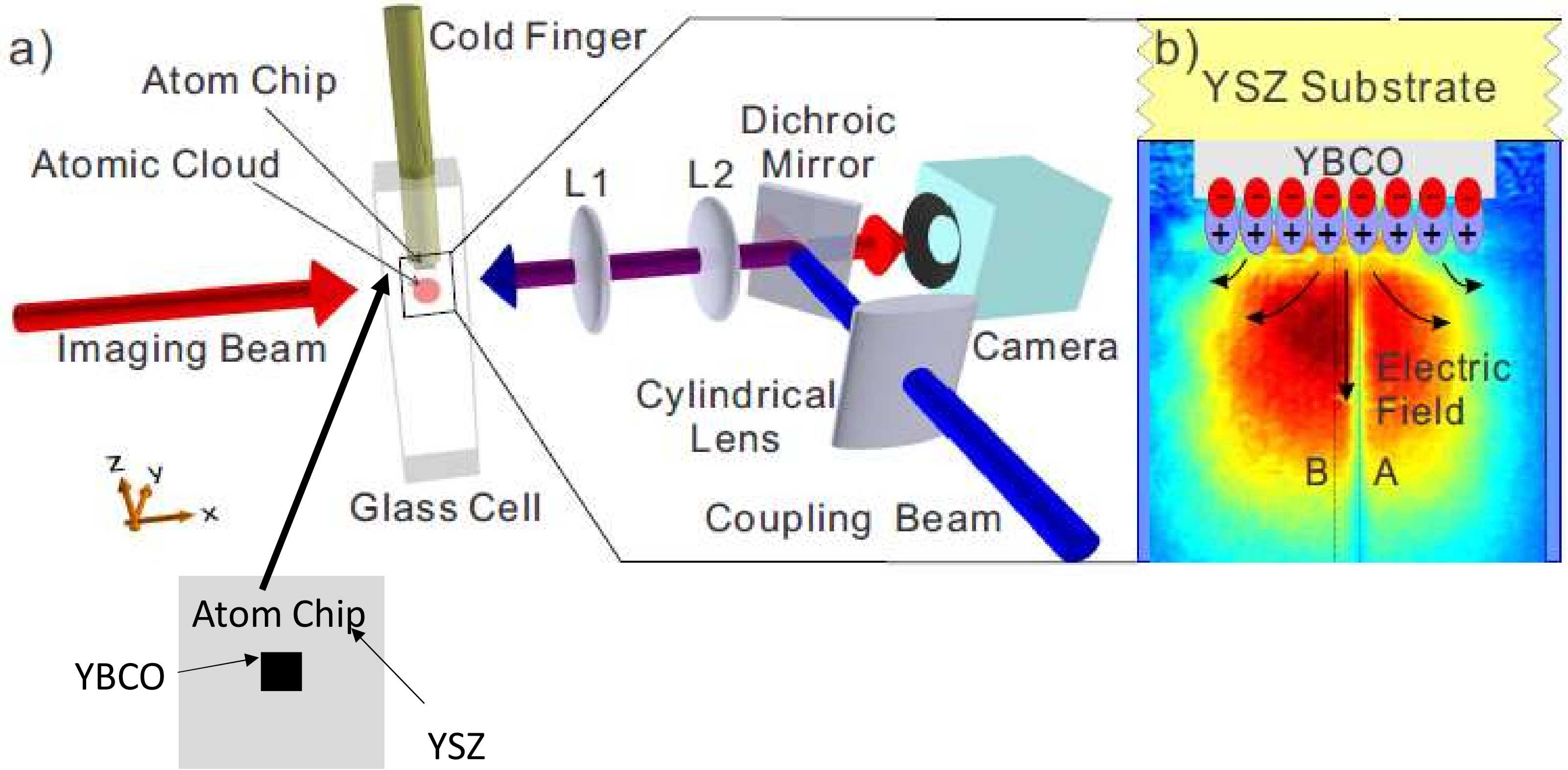
Rydberg Electrometry



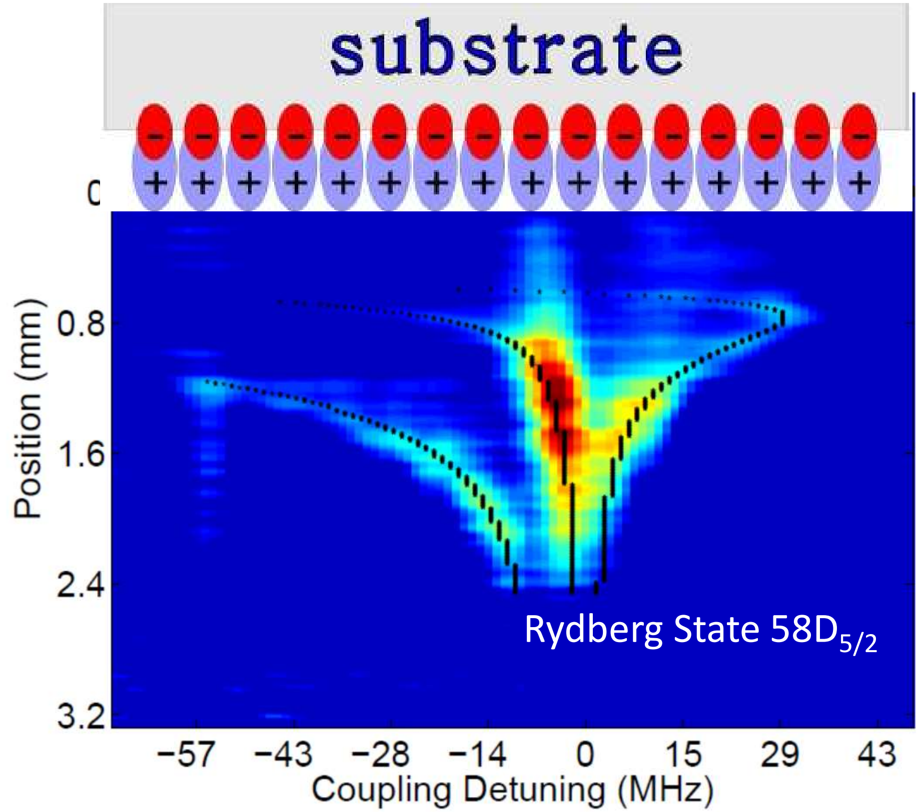


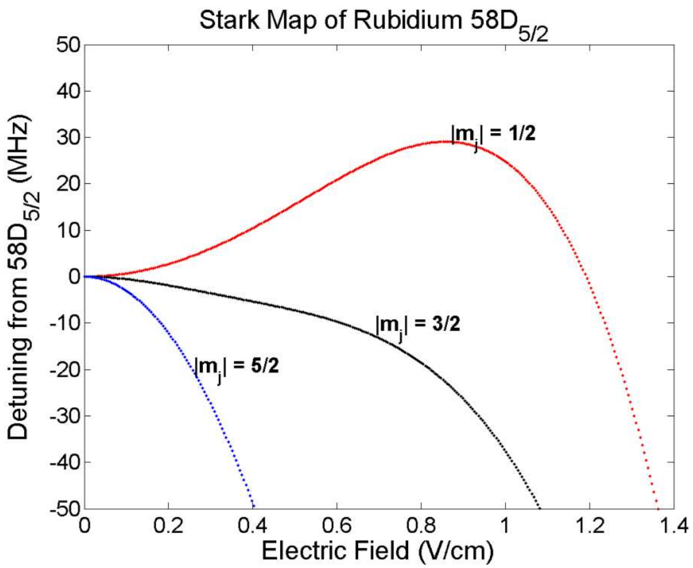


Atomic Electrometry

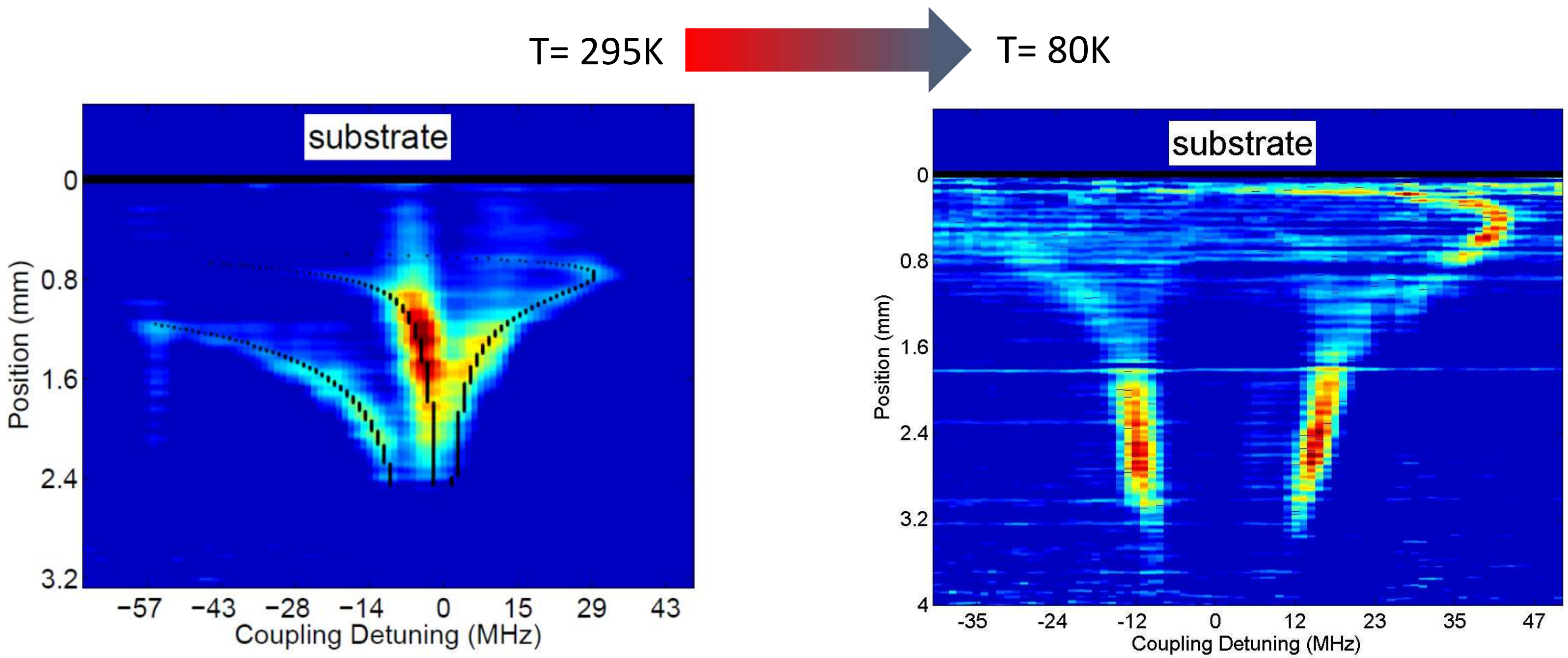


Chemisorption





Electric Field at Cryogenic Temperatures



$48D_{5/2} \quad |m_j| = 1/2,\ 3/2, (\ 5/2\ ).$

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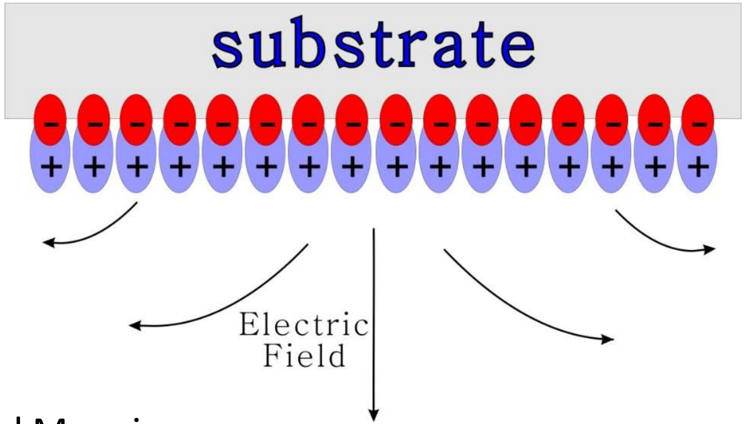
Room Temperature:



Determining Factors for Dipole Moment of Chemisorbed Atom

- Difference of the work function of the substrate and the ionization energy of the adsorbate

Physical Meaning:

Substrate work function > adsorbate ionization energy

↓

Charge transfer from adsorbate to substrate

↓

Form an electric dipole with electropositive charge on the surface and electronegative image charge inside the substrate

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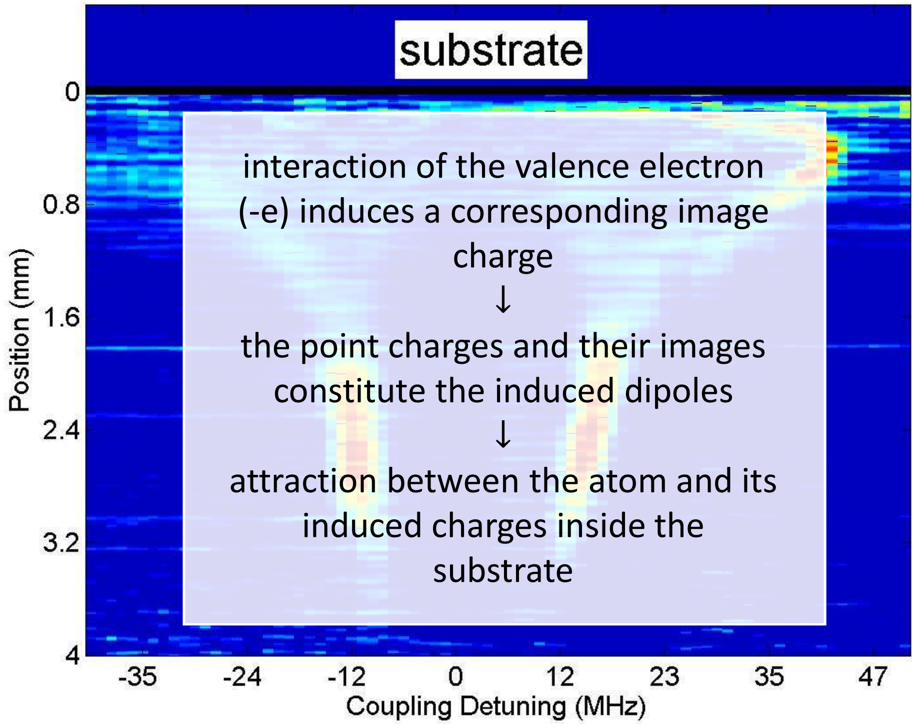
Cryogenic Temperature:

Physisorption on YSZ



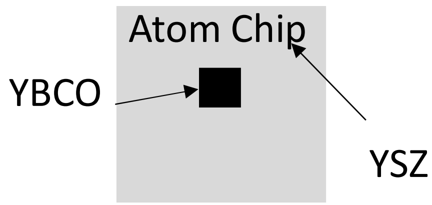
interaction of the valence electron (-e) induces a corresponding image charge

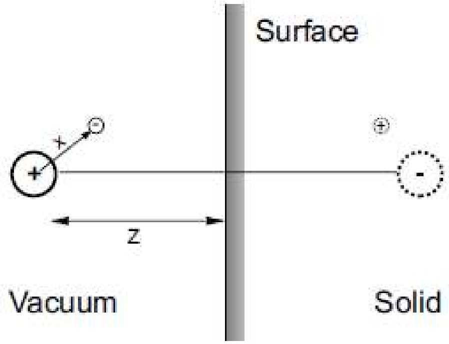
↓

the point charges and their images constitute the induced dipoles

↓

attraction between the atom and its induced charges inside the substrate

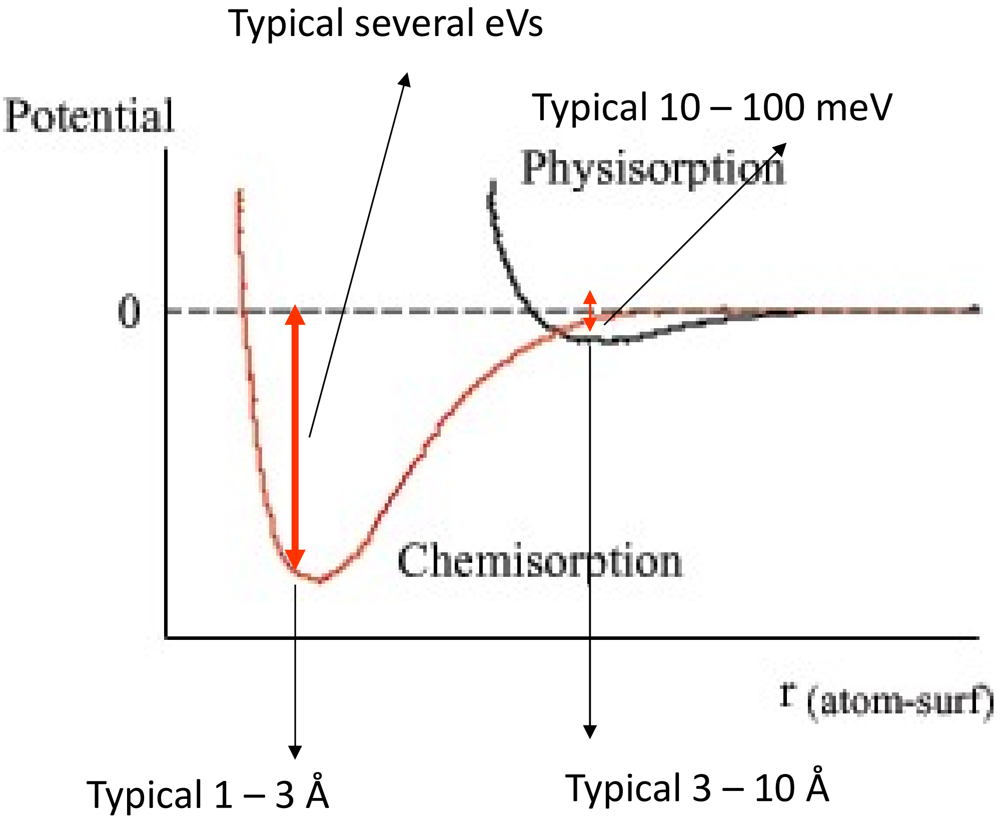




Superconducting Chip: High Temperature / LN2

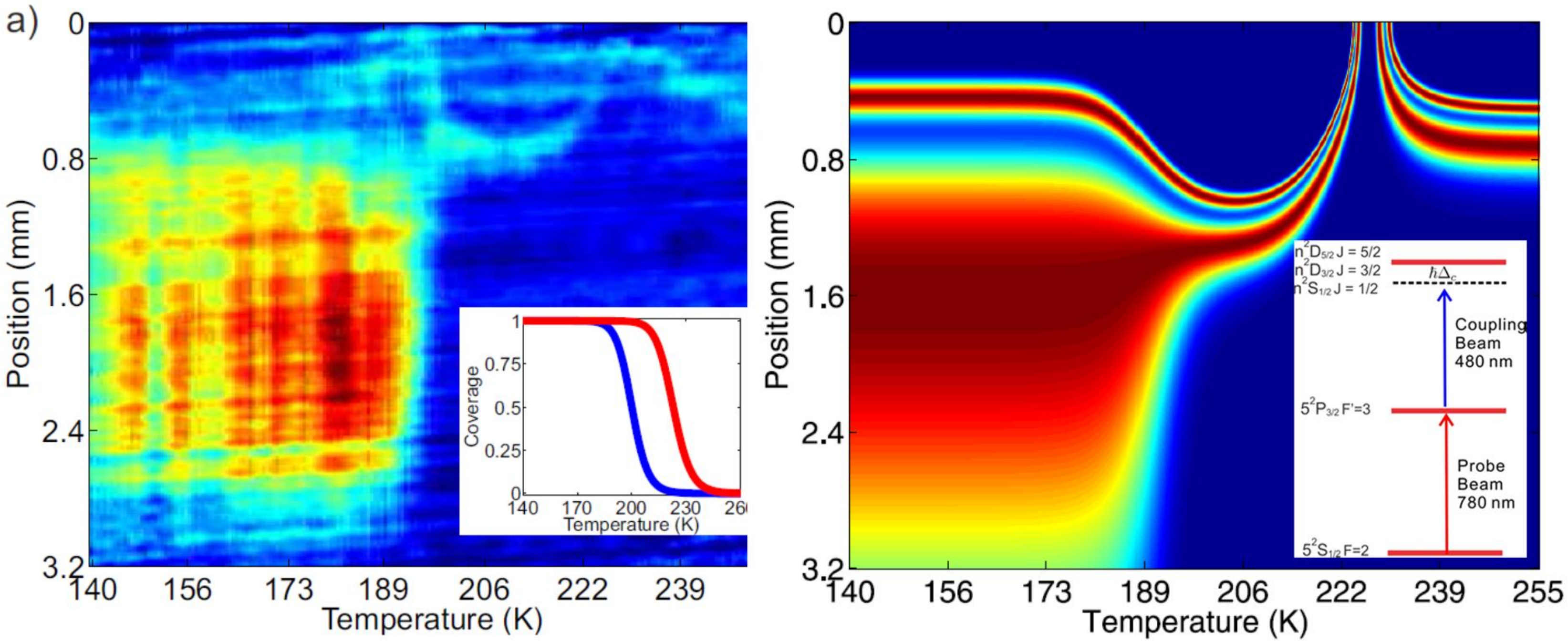
Physisorption
1. Van der Waals bonding (dipole)
2. Weak (<0.4 eV)
3. always atomic/molecular
4. Reversible and fast
5. surface symmetry insensitive
6. may form multilayers

Chemisorption
1. Covalent/metallic/ionic
2. Strong (>0.4 eV)
3. May be dissociative
4. Often irreversible
5. surface symmetry specific
6. limited to monolayer



*www.physics.nus.edu.sg/~phygaoxy/12Adsorption.**ppt***

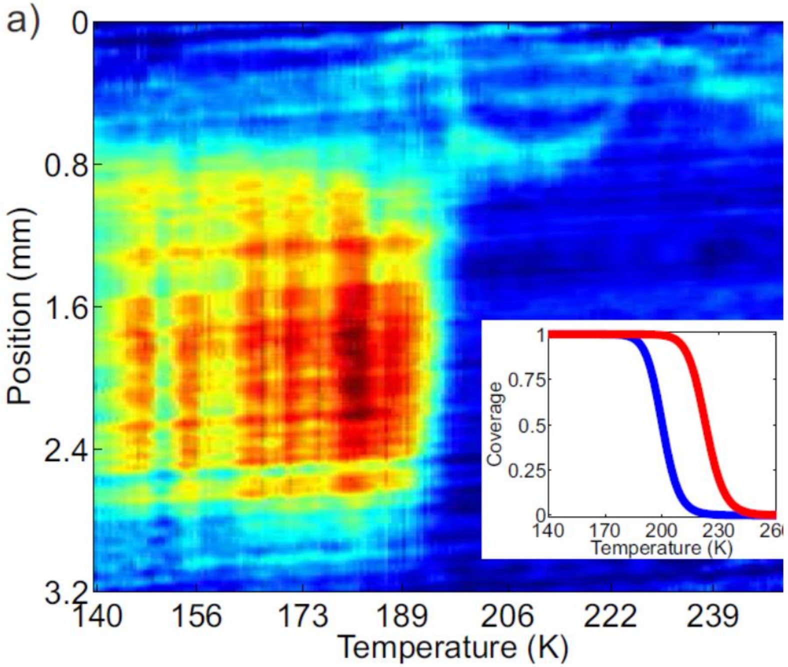
Adsorption Crossover

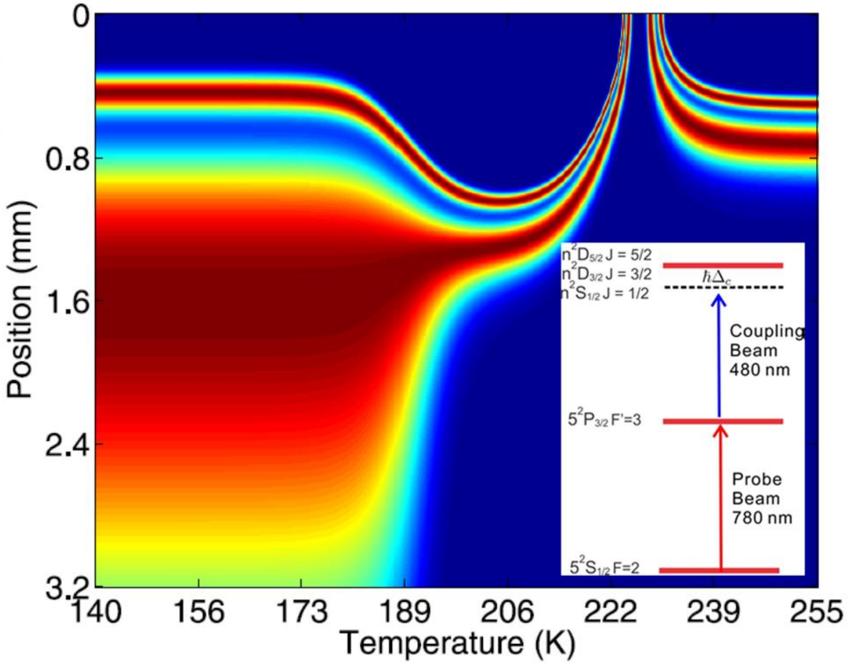


Rydberg spectroscopy 52D5/2 mj = ½ state below the YBCO square in dependence of the temperature.

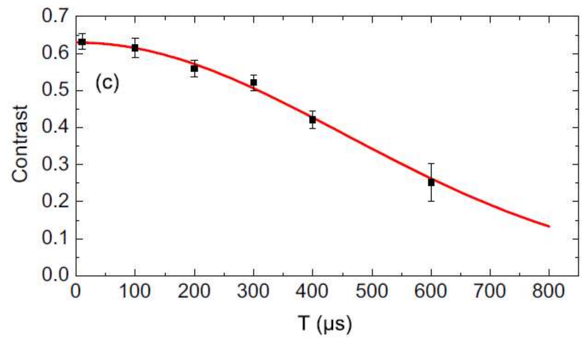
K.S. Chan, M. Siercke, C. Hufnagel, R. Dumke, Phys. Rev. Lett. 112, 026101, (2014)

Adsorption Crossover





- It has been shown that Rydberg states show extremely long coherence times in cryogenic environment



C. Hermann-Avigliano, R. Celistrino-Terixeira, T.L. Nguyen, T. Cantat-Moltrecht, G. Nogues, I. Dotsenko, S. Gleyzes, J.M. Raimond, S. Haroche, M Brune Phys Rev. A 90, 040502

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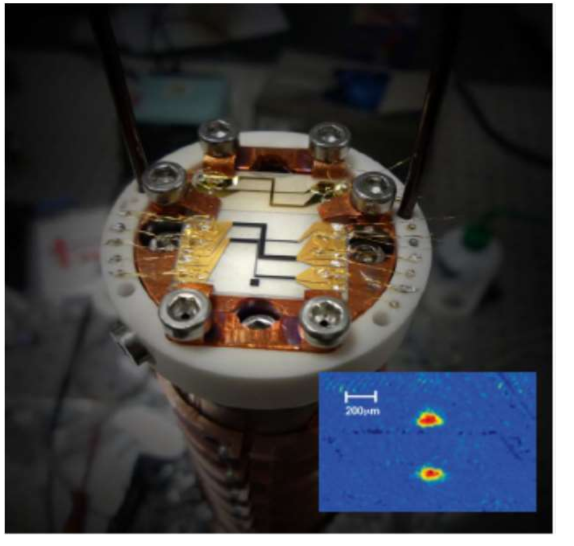

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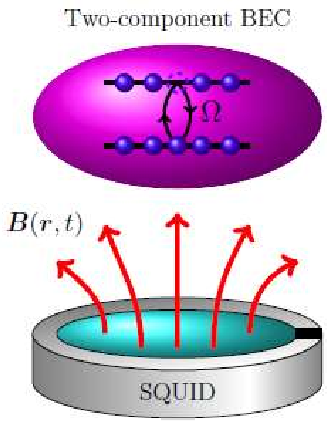
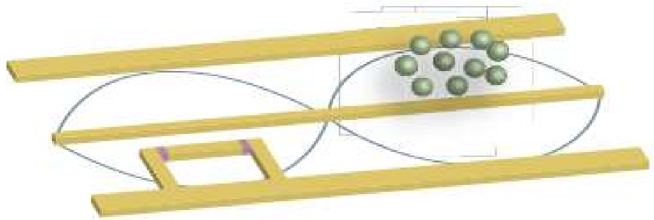
Experimental path **towards** Hybrid Systems
Interfacing solid state devices **with neutral atoms:**

Interaction with neutral atoms :
- **Magnetic moment**
- **Electrical dipole moment**
- **Electro magnetic coupling**

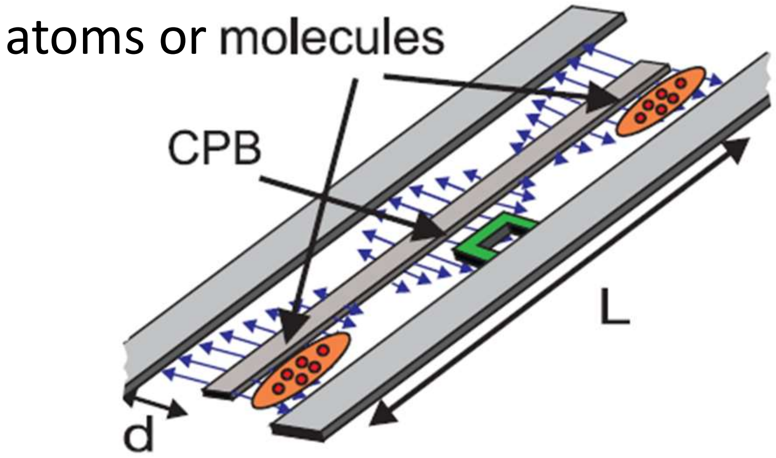


Kelly R. Patton and Uwe R. Fischer
Phys. Rev. A 87, 052303 (2013).



K. Tordrup and K. Molmer, PRA 77, 020301(R) (2008)

Hybrids Cavity Mediated Coupling



- Superconducting circuits
  - the rapid quantum processor
- Coplanar waveguide resonator
  - a quantum data bus
- Atomic systems
  - the long-time quantum memory

Weaknesses:

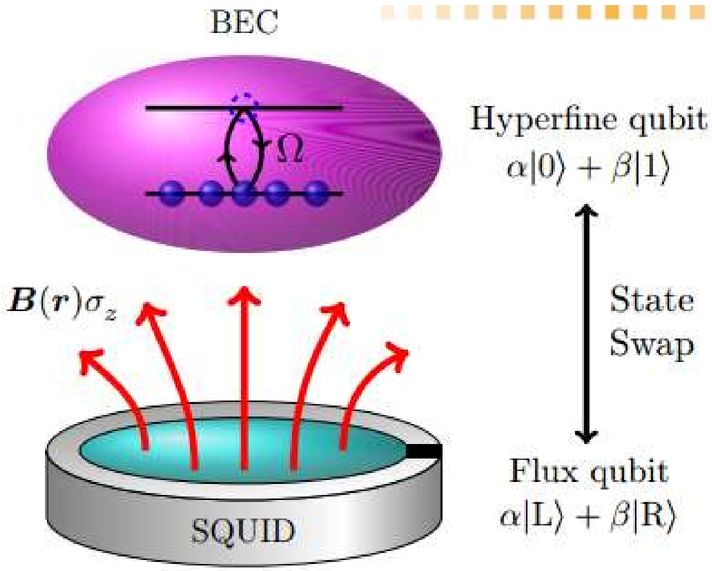
1. the extra cavity loss
2. the weak inter-subsystem coupling, $g{\sim}2\pi \times 10$ kHz

Long-range quantum gate via Rydberg states of atoms in a thermal microwave cavity

L. Sárkány, J. Fortágh, and D. Petrosyan; Phys. Rev. A **92**, 030303(R)

P. Rabl, D. DeMille, J. M. Doyle, M. D. Lukin, R. J. Schoelkopf, and P. Zoller Phys. Rev. Lett. **97**, 033003 (2006).

Hybrid systems based on the direct coupling



Weaknesses:

1. Still a weak coupling
2. Large fluctuation of atomic number
3. The atom-atom interactions

Magnetic dipole interaction

$$V = -\boldsymbol{\mu} \cdot \boldsymbol{B}.$$

For single atom, extremely small V.

Employ the BEC qubit

$$|0\rangle_B = \frac{1}{\sqrt{N!}}\left(a_\downarrow^\dagger\right)^N |vac\rangle.$$

$$|1\rangle_B = \frac{1}{\sqrt{(N-1)!}}\left(a_\downarrow^\dagger\right)^{N-1} a_\uparrow^\dagger |vac\rangle.$$

Thus, $V \sim -\sqrt{N}\boldsymbol{\mu} \cdot \boldsymbol{B}$ can reach $2\pi \times 10$ MHz with $N \sim 10^6$.

Kelly R. Patton and Uwe R. Fischer
Phys. Rev. A 87, 052303 (2013).

Coupling of Rydberg Atoms to charge Qubit

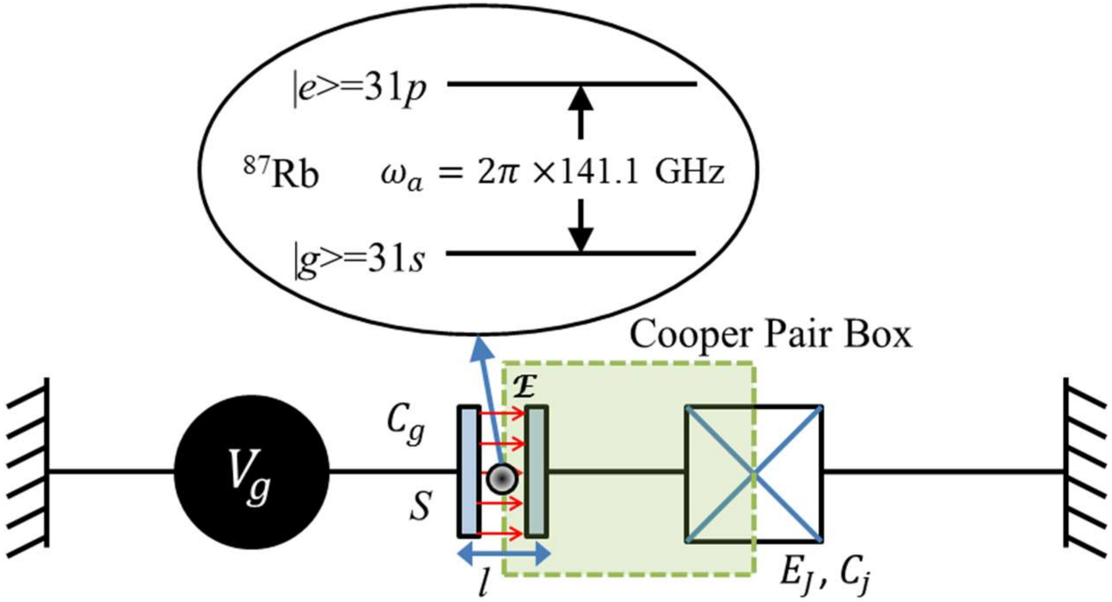
Cooper pairs tunneling into or out of the box varies the internal electric field $\mathcal{E}$.

The expectation value of $\mathcal{E}$ $\langle \mathcal{E} \rangle \approx \mathcal{E}_0 \cos \omega_0 t$

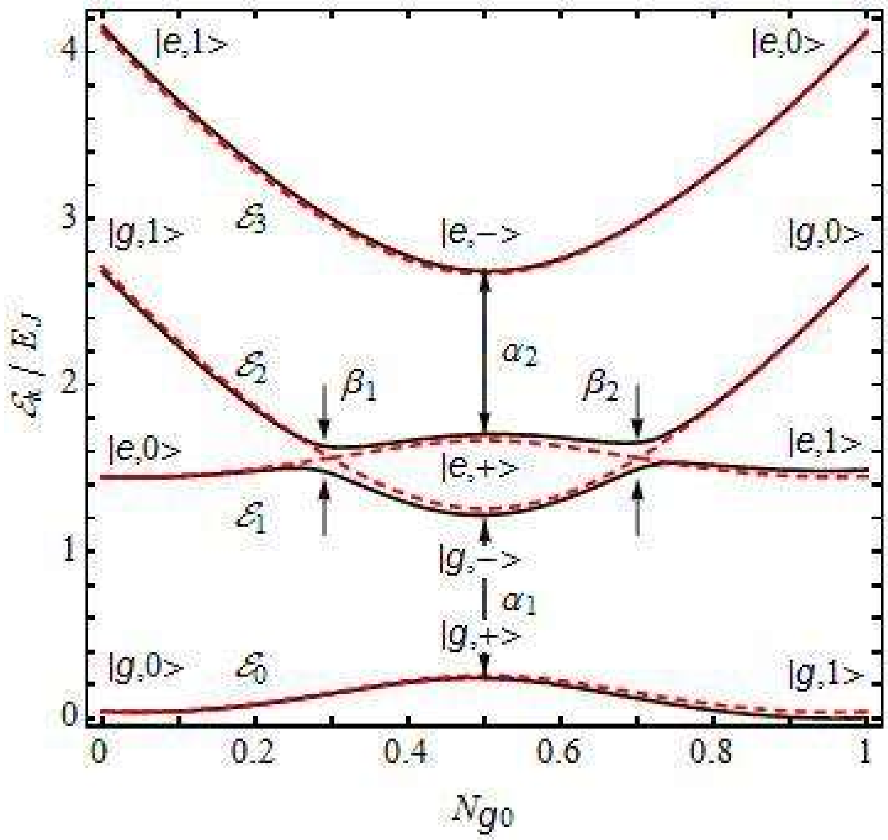
Amplitude $\mathcal{E}_0 \propto \mathrm{N}_R$ Frequency $\omega_0 = \Omega_R$

This oscillatory electric field can be applied to drive a two-level atom!

Hybrid system =
Charge qubit +
Atomic qubit



Hybrid systems based on the direct coupling



1) the whole energy structure consists of two sets of the charge-qubit-like spectra with the Josephson-tunneling-induced anti-crossings labelled as $\alpha_{1,2}$, whose energy spacings are approximately equal to $\hbar\Delta_1=E_J$, at N_{g0}=0.5.

2) two other avoided crossings labelled as $\beta_{1,2}$ at N_{g0}=0.3 and at N_{g0}=0.7, respectively. the energy spacing approximates $\hbar\Delta_2$=0.22E_J.

3) the eigenstates at several specific N_{g0}.

Deshui Yu, M. M. Valado, C. Hufnagel, L. C. Kwek, Luigi Amico and R. Dumke; submitted for publications

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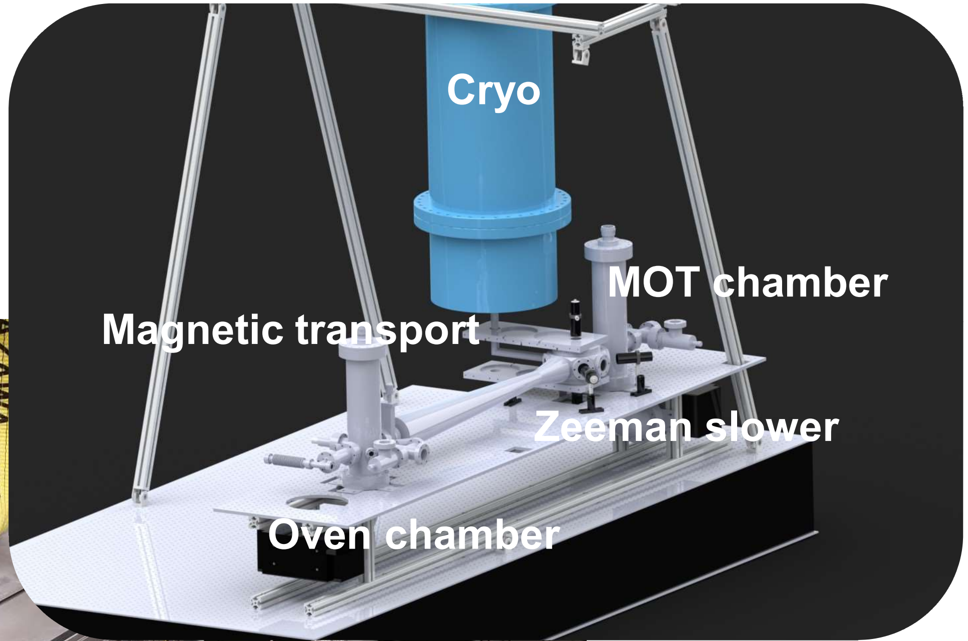
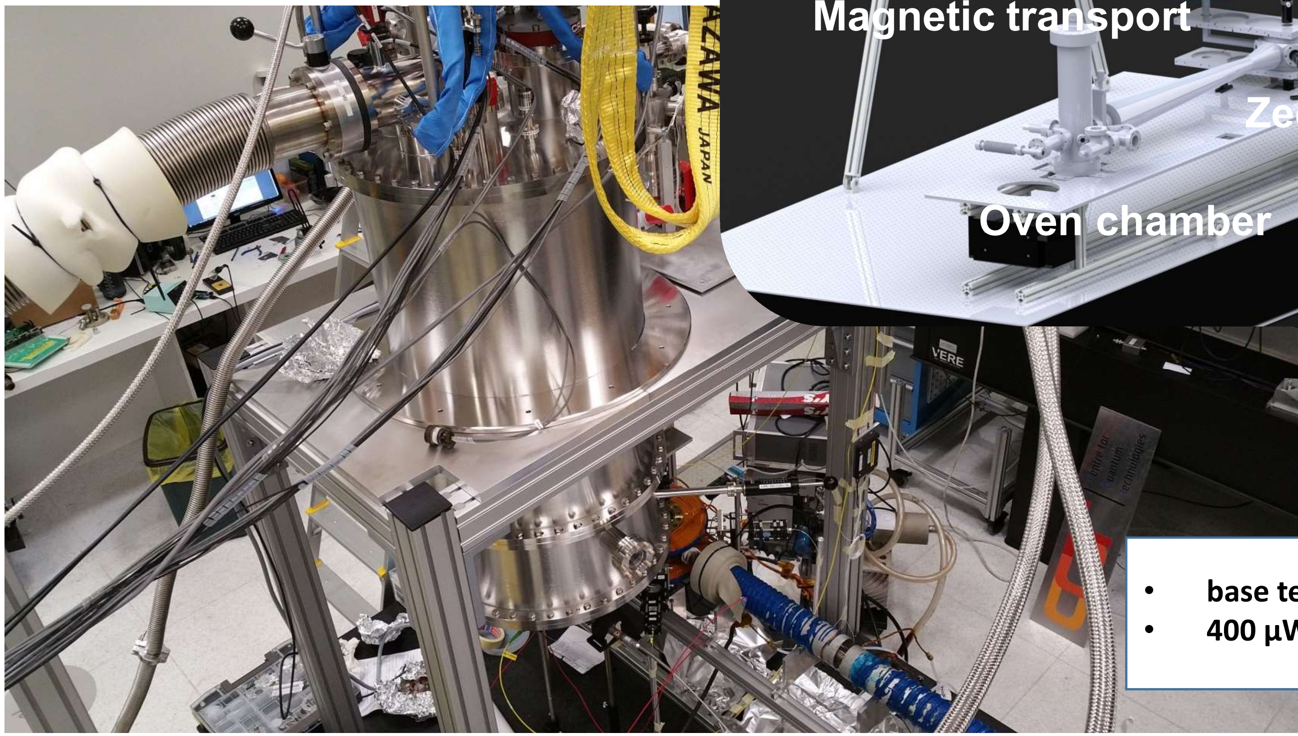
Superconducting Chip: Low Temperature

Experimental Status:





- base temperature 10 mK
- 400 μW cooling power

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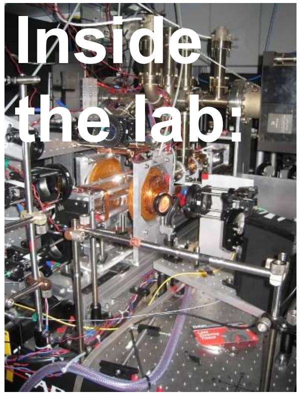
Conclusion:

Superconducting atom chips promise to solve the problems low lifetimes/decoherence near the chip surrface.

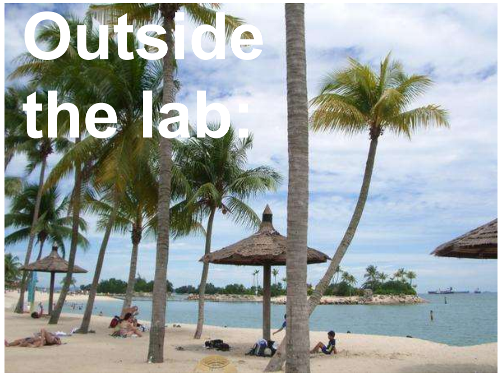
Type-II superconductors offer unique ways to produce Novel complex magnetic trap structures.

Trapping atoms near superconductors gives a natural way of coupling and probing the two systems with each other.

Thank You



Dr. Christoph Hufnagel
Dr. Maria Martinez Valado
Dr. Deshui Yu
Dr. Paul Condylis



Atomtronics Experiment

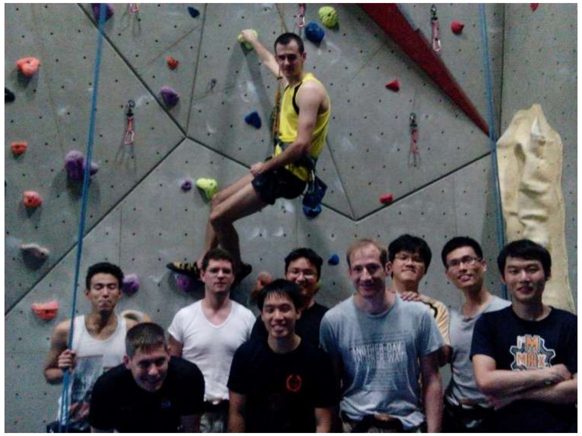
Filip Auksztol
Gan Koon Siang
Tin Nghia Nguyen

mK-Experiment

LIM Chin Chean
EW Chee Howe
Alessandro Landra

HTC- Experiment

LEY Li Yuen
Francesca Tosto
Phyo Baw Swe



Former Group Members:
Tobias Mueller
Rachele Fermani
Zhang Bo
Chan Kin Sung

Collaborators/Visiting Prof:
Michael Lim
Luigi Amico
Kwek Leong Chuan