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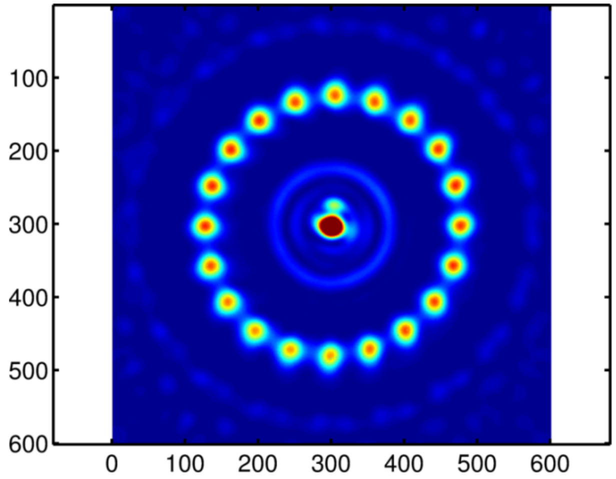
Singapore

Experimental Efforts Towards Exploring Condensed Matter Systems with AMO Physics

Rainer Dumke

Merging AMO and Solid state Physics

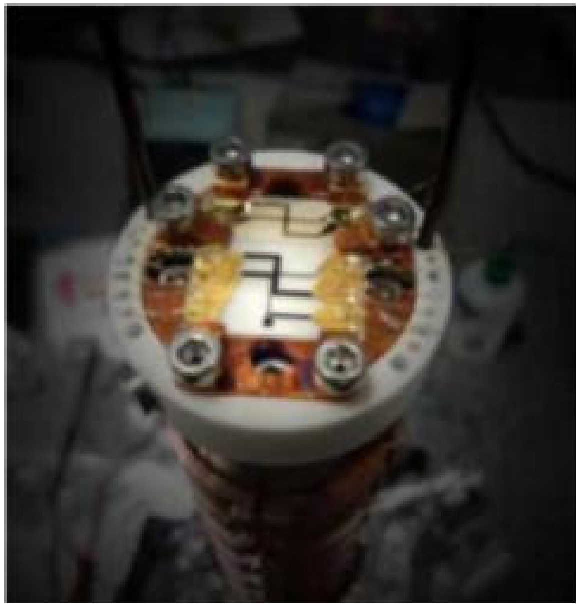


Emulating Solid State Systems with Neutral atoms in tailored potentials

In collaboration with:

Luigi Amico / Kwek Leong Chuan / Davit Aghamalyan

Probing Solid State Systems with neutral atoms.



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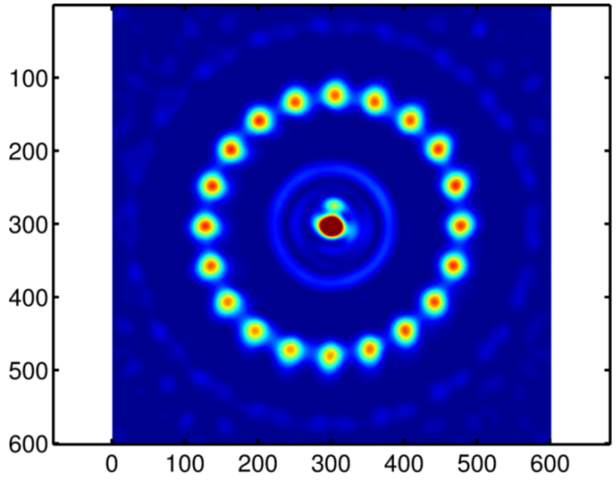
Merging AMO and Solid state Physics



Emulating Solid State Systems with Neutral atoms in tailored potentials

In collaboration with:
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Motivation:

Artificial tailor potentials for ultracold atoms to mimic materials, circuits, and devices based on electrons.

What we would like to do:

- Realize persistent current states of bosons in ring-lattices with similarities to other physical systems e.g. superconductors or metallic rings.

- Realization of ring-lattice stack geometries containing multiple rings.

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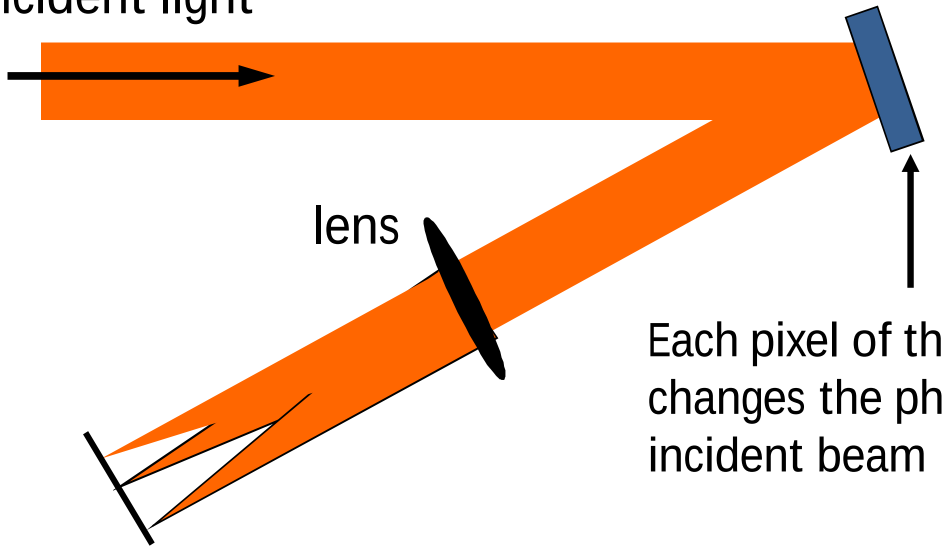
Technical Basis

An electro-optical device which imposes some form of spatially varying modulation on a beam of light

LCOS (Liquid crystal on silicone) display head (Holoeye)



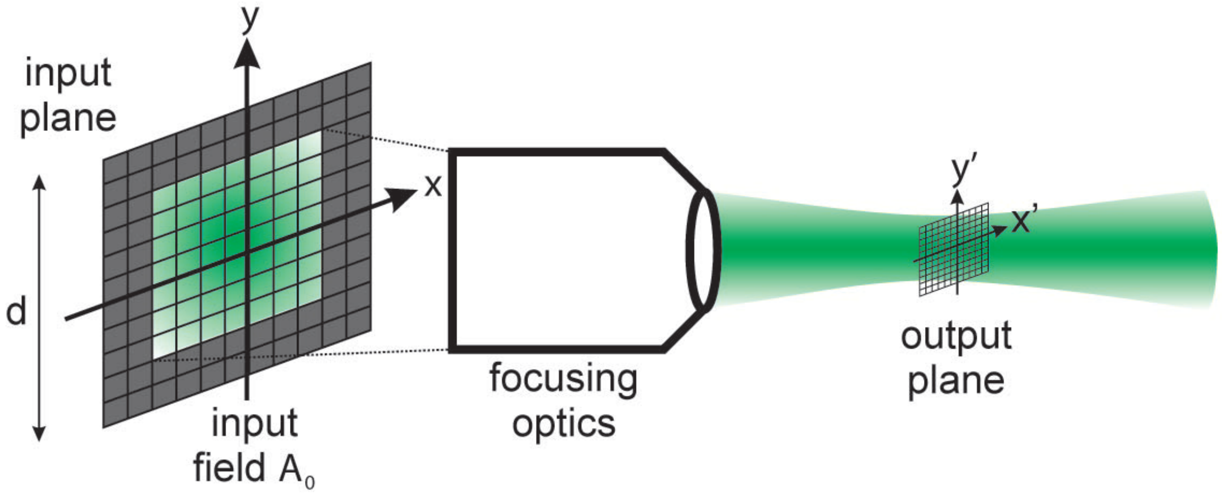
Incident light

lens

Each pixel of the SLM changes the phase of the incident beam

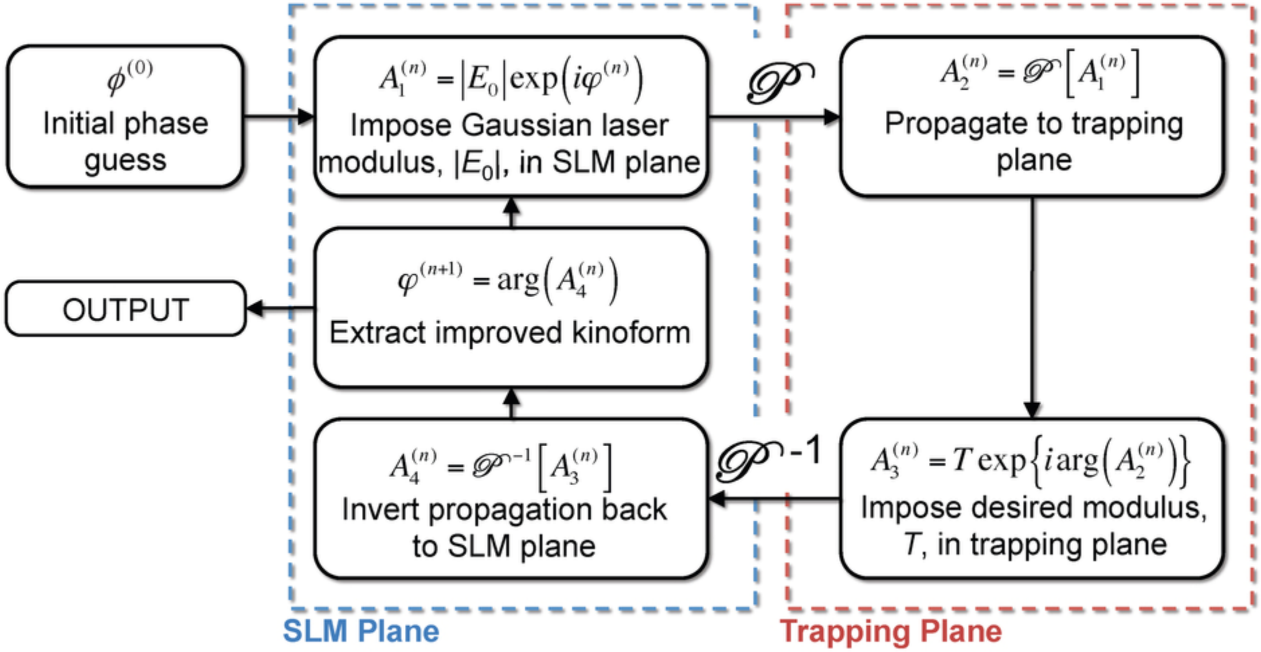
The diffracted waves interfere in the focal plane to produce the desired intensity pattern.

Problem Statement



Find the phase distribution at the input plane that will convert an input light field $A_0(x,y)$ to the desired intensity pattern in the output plane $I_0(x',y')$.

Iterative Fourier transform algorithm



$\phi^{(0)}$
Initial phase guess

$A_1^{(n)} = |E_0|\exp\left(i\varphi^{(n)}\right)$
Impose Gaussian laser modulus, $|E_0|$, in SLM plane

$\mathscr{P}$

$A_2^{(n)} = \mathscr{P}\left[A_1^{(n)}\right]$
Propagate to trapping plane

$A_3^{(n)} = T\exp\left\{i\arg\left(A_2^{(n)}\right)\right\}$
Impose desired modulus, T, in trapping plane

$\mathscr{P}^{-1}$

$A_4^{(n)} = \mathscr{P}^{-1}\left[A_3^{(n)}\right]$
Invert propagation back to SLM plane

$\varphi^{(n+1)} = \arg\left(A_4^{(n)}\right)$
Extract improved kinoform

OUTPUT

SLM Plane

Trapping Plane

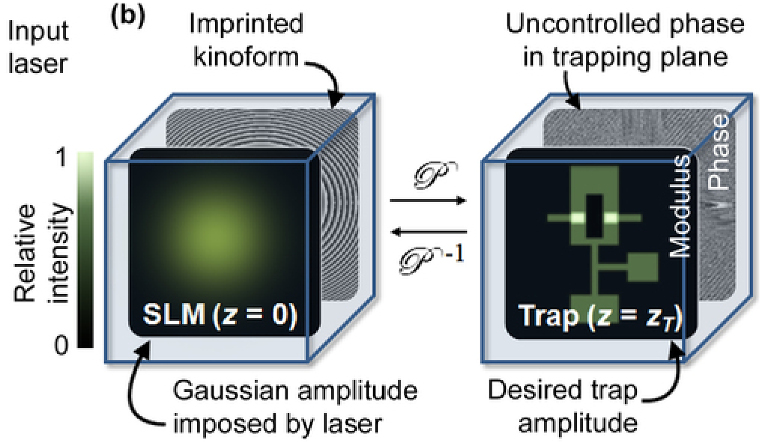
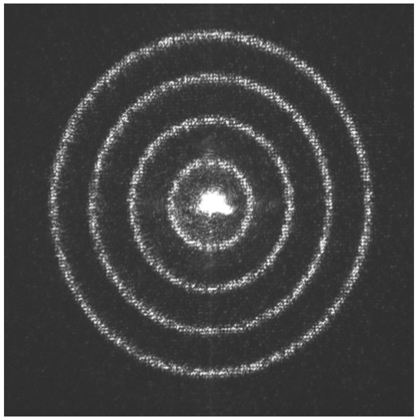
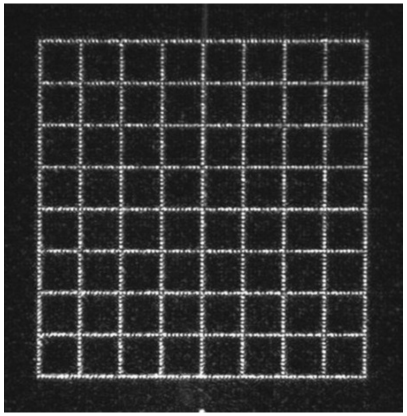


Figure source:
Robust Digital Holography For Ultracold Atom Trapping,
Alexander L. Gaunt & Zoran Hadzibabic
Nature Scientific Reports 2, 721, (2012)

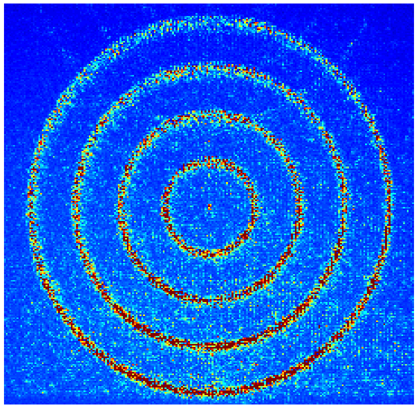
Gerchberg-Saxton in Practice



Concentric rings



Quadratic grid



Concentric rings, zero order shifted

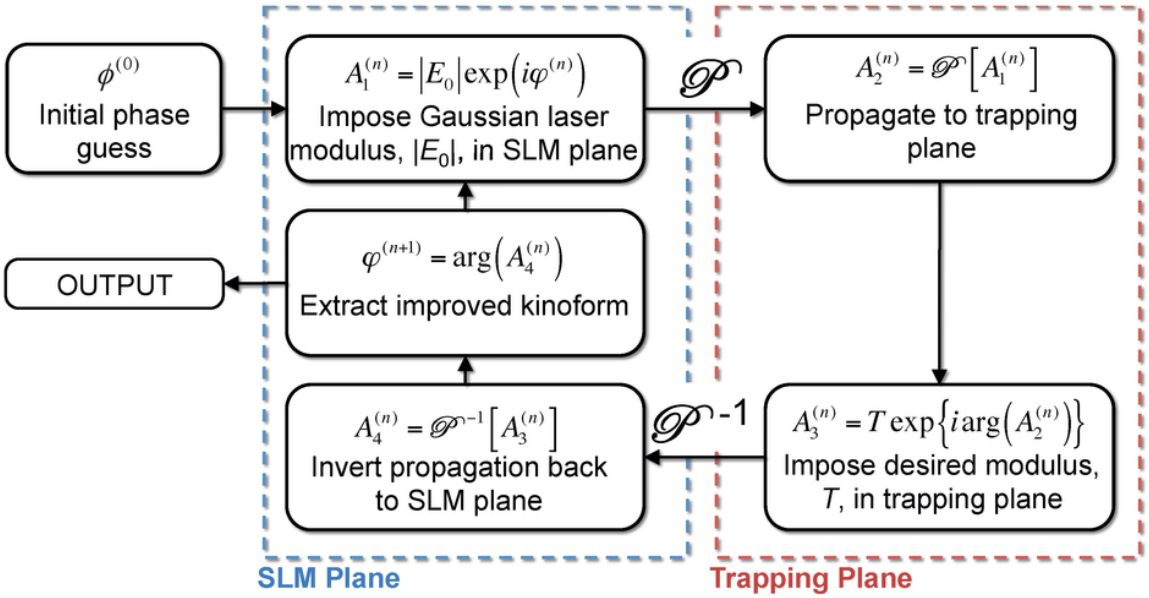
- Pixelated and non-smooth structures, not suitable for atom trapping
- Advantage: high diffraction efficiency

MRAF algorithm

(Mixed-Region-Amplitude-Freedom)

Idea:

Enhance convergence of the iterative algorithm in one region of the trapping plane (signal region) by giving up control of the remaining regions (noise region)



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$\mathscr{P}$ -1

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Invert propagation back to SLM plane

$\varphi^{(n+1)} = \arg\left(A_4^{(n)}\right)$
Extract improved kinoform

OUTPUT

SLM Plane

Trapping Plane

$$A_3^{(n)} = \begin{cases} \mathrm{m}\, T(R) \exp\{i \arg(A_2^{(n)})\} \\ (1-\mathrm{m})\, A_2^{(n)} \end{cases}$$

$$\mathrm{m} \approx 0.4$$

Best algorithms so far

MRAF (M. Passienski, B. deMarco, 2008):

- Strongly improved accuracy and smoothness compared to G-S
- Computationally efficient
- Wavefront propagation in paraxial regime

Offset-MRAF (A. Gaunt, Z. Hadzibabic, 2012):

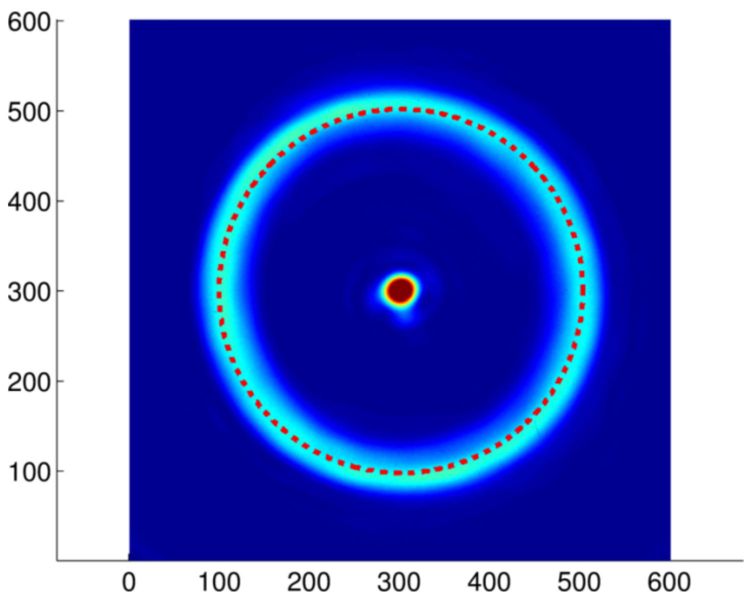
- Background potential is offset from zero
- Free of fringing artefacts
- Wavefront propagation beyond Frauenhofer regime

Our version: MRAF with angular spectrum propagator

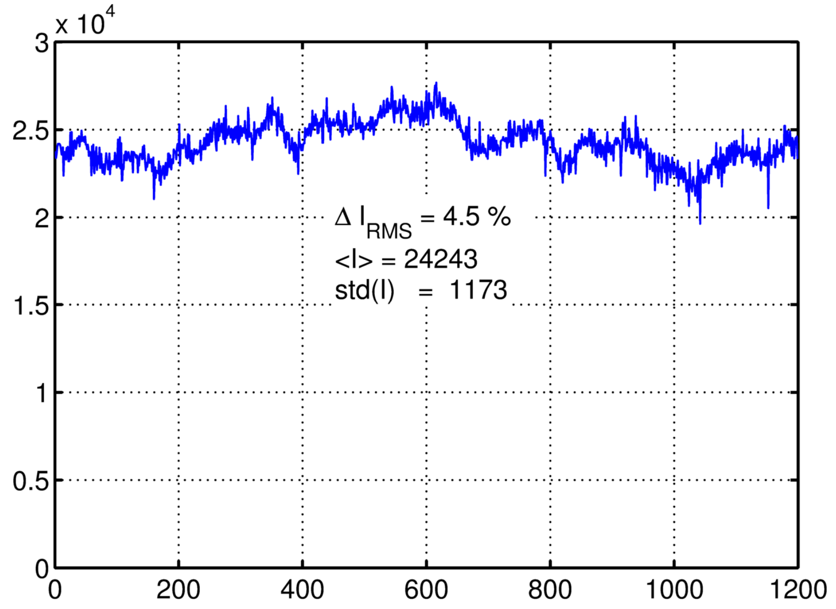
- Based on Passienski's code
- Wavefront propagation in full Helmholtz regime

MRAF Toroid - Roughness

Measurement circle for roughness estimation



Intensity variation along the rim of the potential



Δ I_{RMS} = 4.5 %
<I> = 24243
std(I) = 1173

$$\Delta I_{RMS} = 4.5\%$$

Intensity variation (in % relative to the mean value)
1200 measurement points taken along the rim

Ring Lattice with a weak link

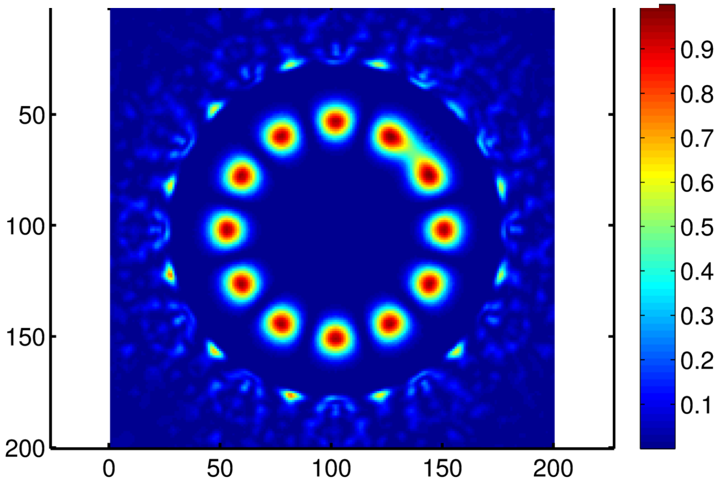
Ring lattice potential :

$$I(r,\varphi) = I_0 \exp^{-\frac{(r-R)^2}{2\sigma^2}} \cdot \cos^2(0.5 \cdot N_w \cdot \varphi)$$

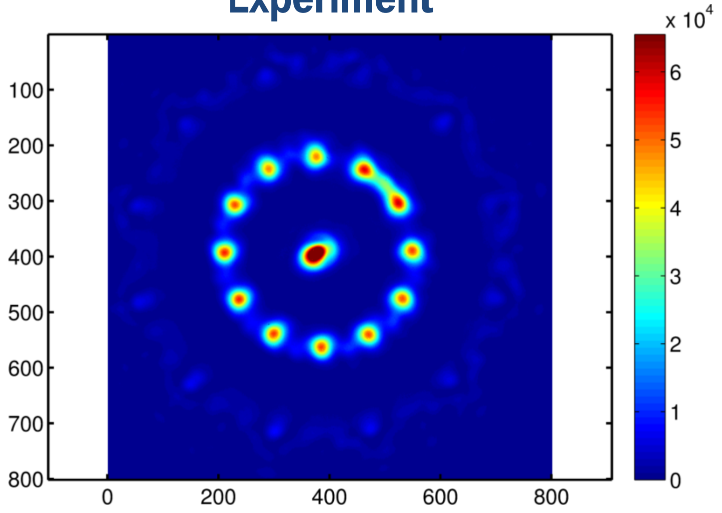
Weak link :
Gaussian dimple with amplitude 0.5 between two lattice sites

Localized defect potential can be used to implement single ring quantum gates with flow states

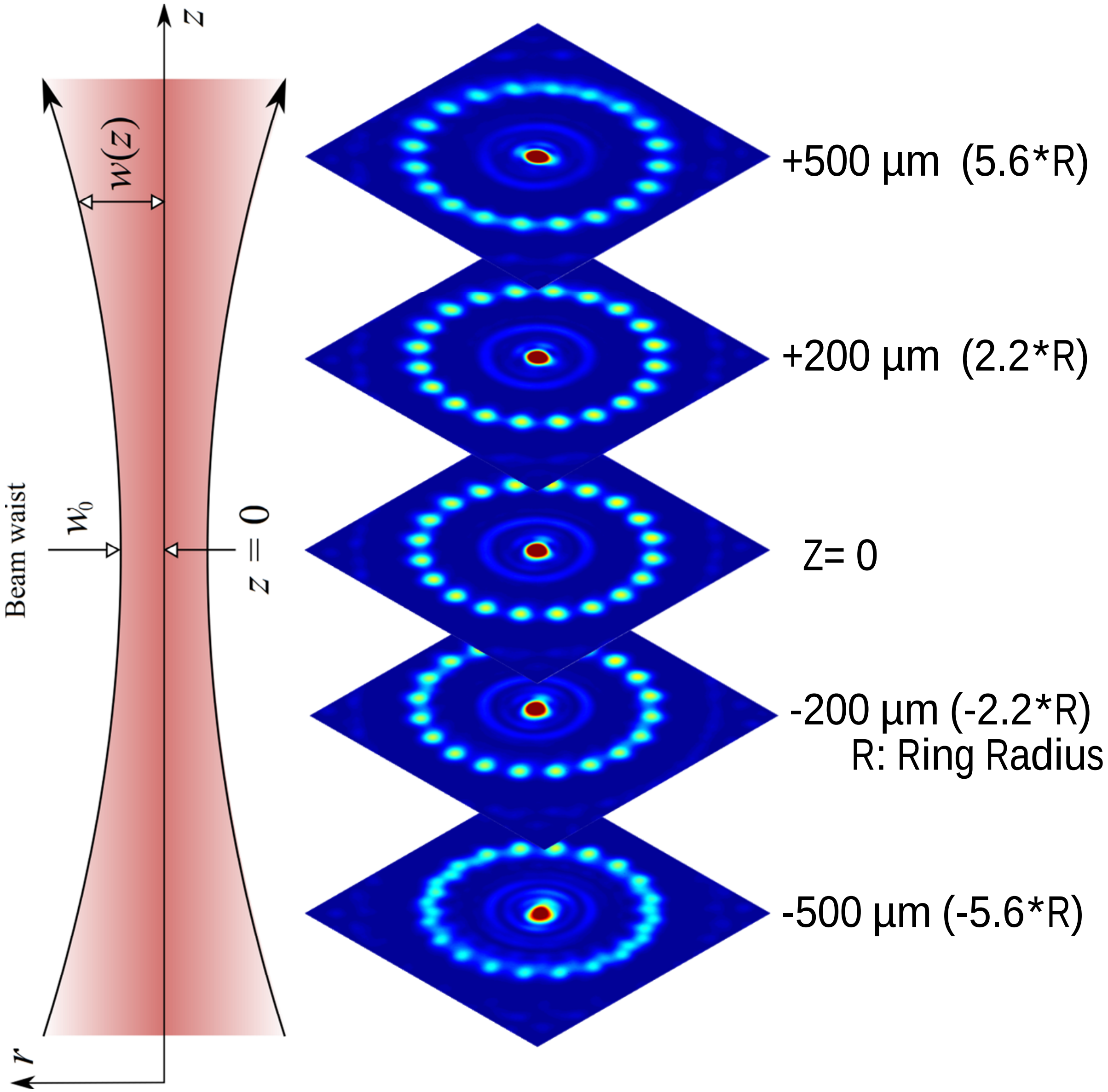
Simulation



Experiment



Ring Lattice – effects of axial shift



Left: Axial profile of a Gaussian beam for comparison
Right: Ring lattice intensity depending on axial distance Z from target plane

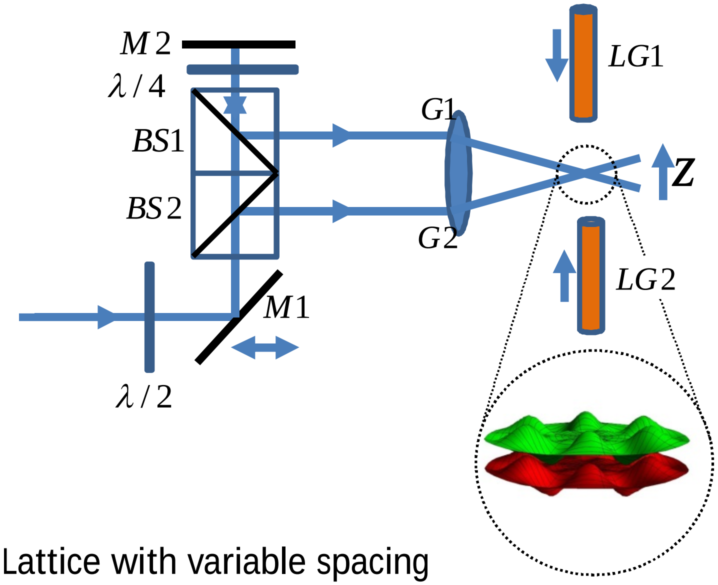
Image size: 250 x 250 µm
Image pixel size: 0.5 µm
Ring lattice radius: 90 µm
Lattice site spacing: 28 µm

Beam diameter on SLM 9 mm
Fourier lens focal length: 150 mm

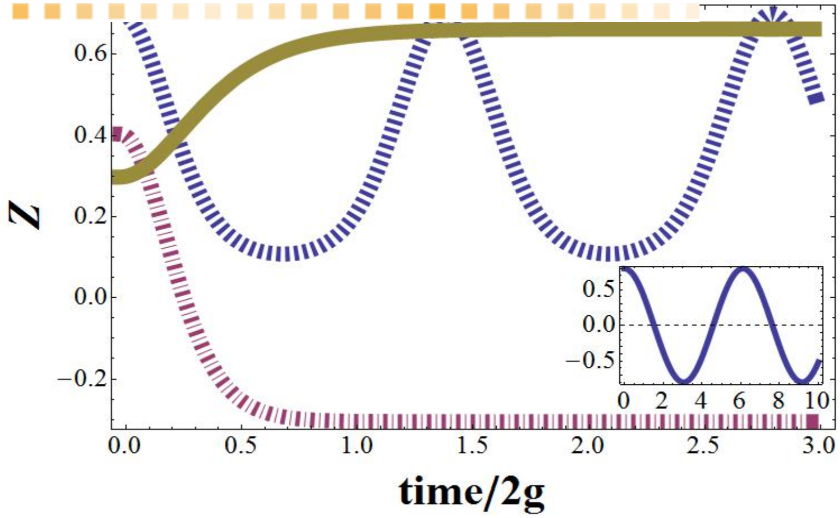
Gaussian beam parameter of an undiffracted beam in the focal plane: (No phase modulation by SLM)
$\omega 0 = 8 \mu m$, $Zr = 380 \mu m$
(Note: for comparison stated only , the phase modulated beam exiting the SLM is not Gaussian anymore!)

An axial shift away from the image plane leads to distortions of the intensity structure.
In a region of $\Delta Z = Z_0 \pm D$,
where D is the ring lattice diameter, the quality of the optical potentials is sustained.
This would allow building ring stacks with 12 rings, each axially separated by a distance equal to the intersite spacing.

Atomic flux qubit



Lattice with variable spacing
facilitates tuneable ring-ring interaction



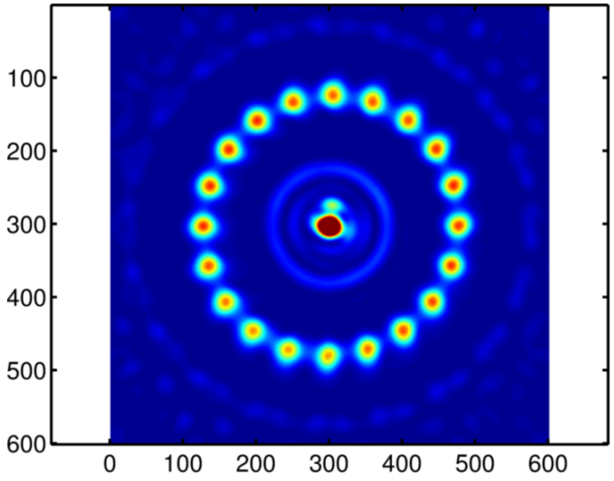
Population imbalance in two coupled rings:
Three regimes depending on the initial population imbalance (color coded)

- Prepare neutral currents in ring lattice stacks with variable tunneling
- Tunneling interaction between lattice stacks leads to superposition of flow states
- Time-of-flight imaging maps the phase winding into density modulations

Single site addressing not required, topological stable, long coherence times

L. Amico, D. Aghamalyan, H. Crepaz, F. Auksztol, R. Dumke, L.-C. Kwek;'Superfluid qubit systems with ring shaped optical lattices' *Scientific Reports* **4**, 4298.

Merging AMO and Solid state Physics



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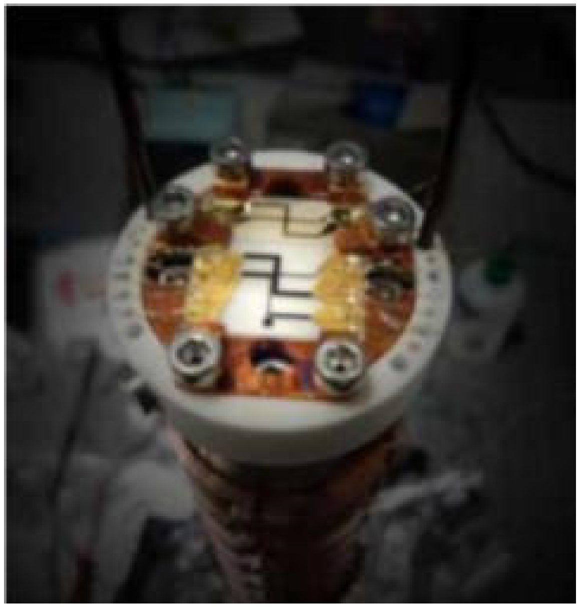


Merging AMO and Solid state Physics

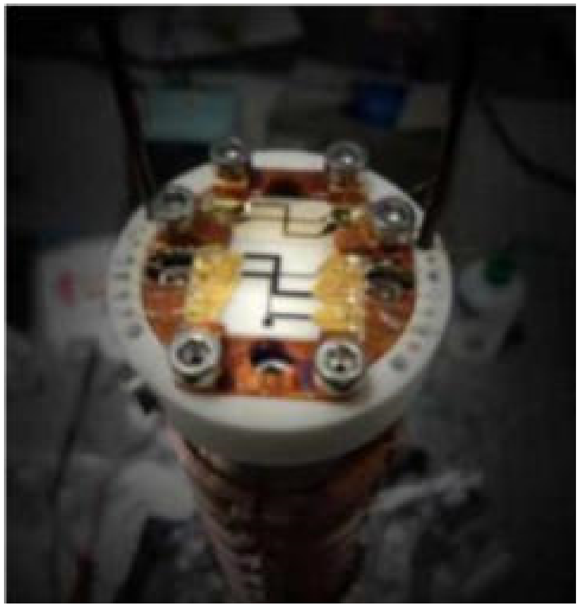
- **Brief overview:** Atom Chips limits and Superconducting Atom Chips.

- **Vortex based atom traps:** Concept and realization.

- **Electric Fields** in proximity to Superconducting Atom Chips.

- **Experimental** path **towards** the realization of **interfacing solid state** devices **with neutral atoms**

Probing Solid State Systems with neutral atoms.



Superconductors

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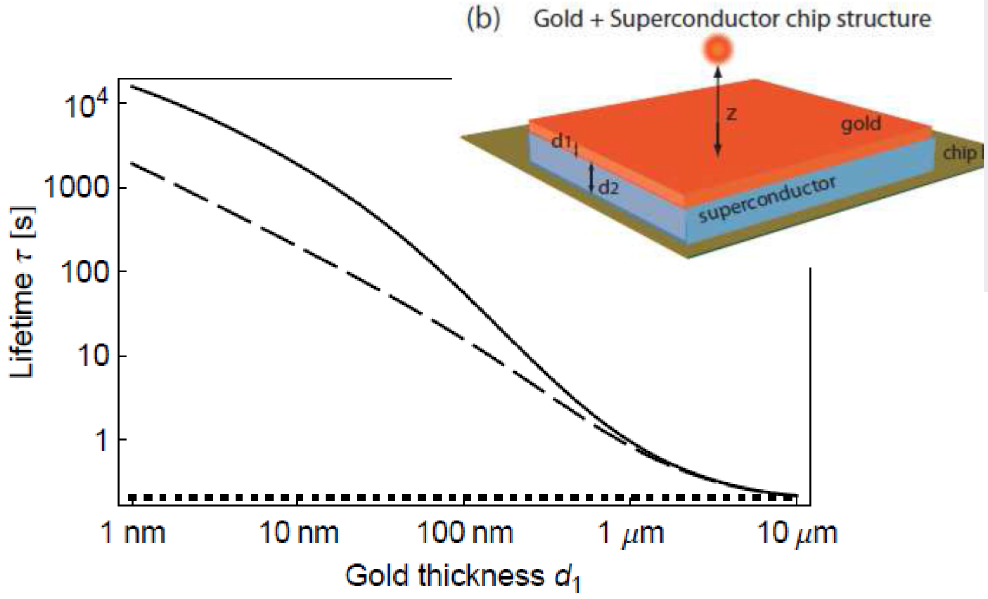
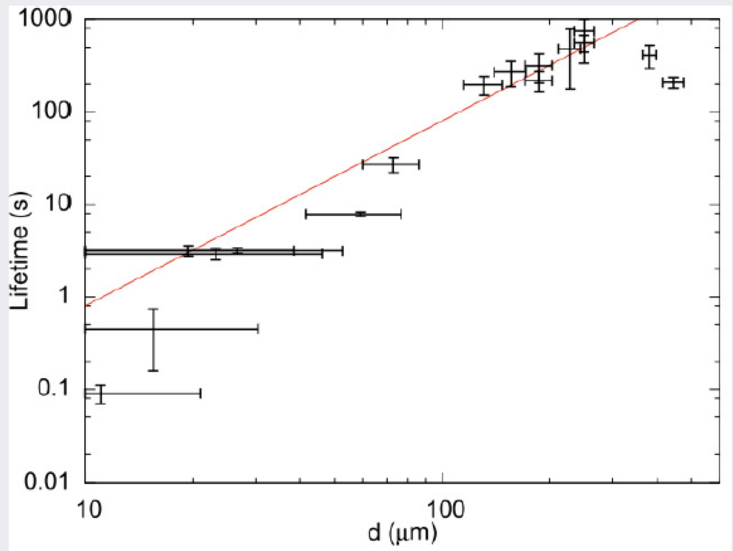
Atom Chips limits and Superconducting Atom Chips.

-Thermal fluctuations and resistivity result in noisy currents and leads to fluctuating electromagnetic fields at the materials surface.

- The atom interacts with those fields and spin flips can lead to atomic loss.





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)

Spin flip lifetime of an atom 1 μm above a superconducting chip with a variable thickness gold layer on top.

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

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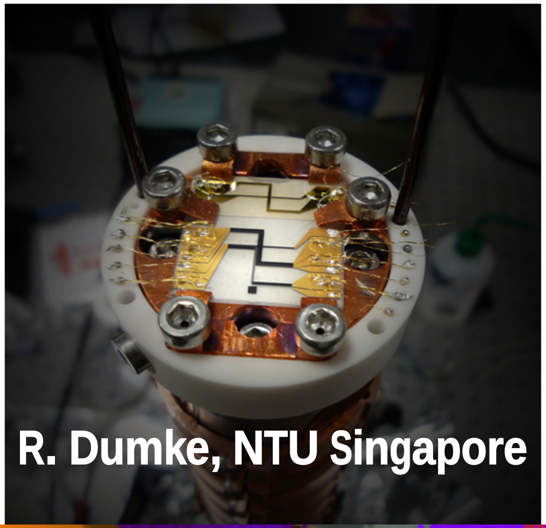
R. Fermani, T. Müller, B. Zhang, M. J. Lim, and R. Dumke,
J. Phys. B: At. Mol. Opt. Phys. 43, 095002 (2010).

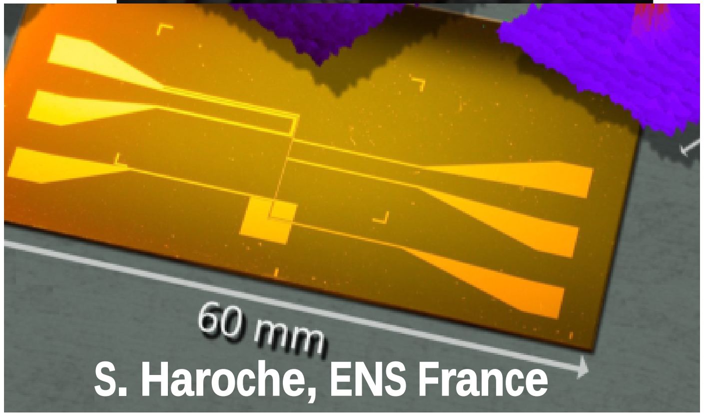
Superconducting Atom Chips

<u>Advantages:</u>

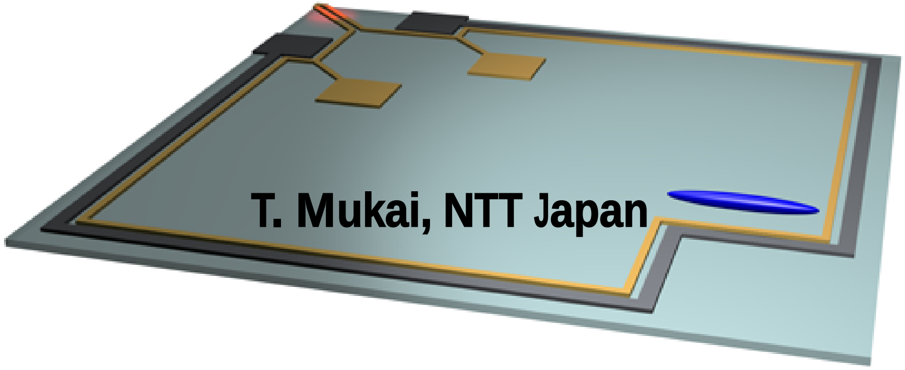
- Suppression of thermal noise
- Eliminate heating
- Longer coherence time
- Compatibility with hybrid system



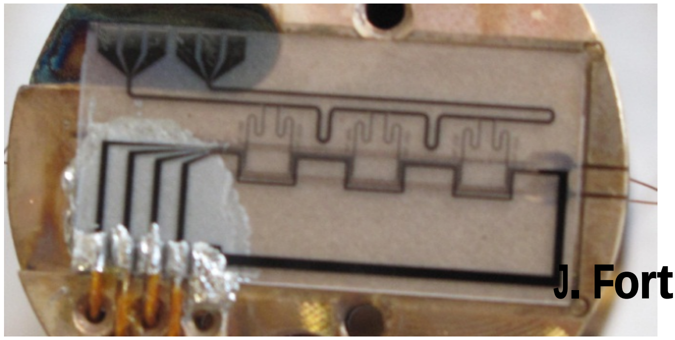
R. Dumke, NTU Singapore



S. Haroche, ENS France



T. Mukai, NTT Japan



J. Fortágh, Tübingen

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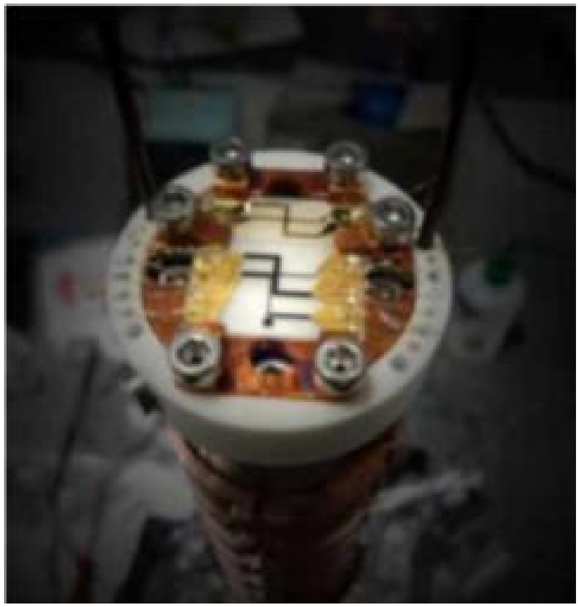


Superconductors

Chip Substrate

Basis of atom chip:

-thin film of $YBa_2Cu_3O_{7-x}$ (YBCO)

-substrate Yttria Stabilized Zirconia (YSZ)

YBCO film:

typically 600-800nm

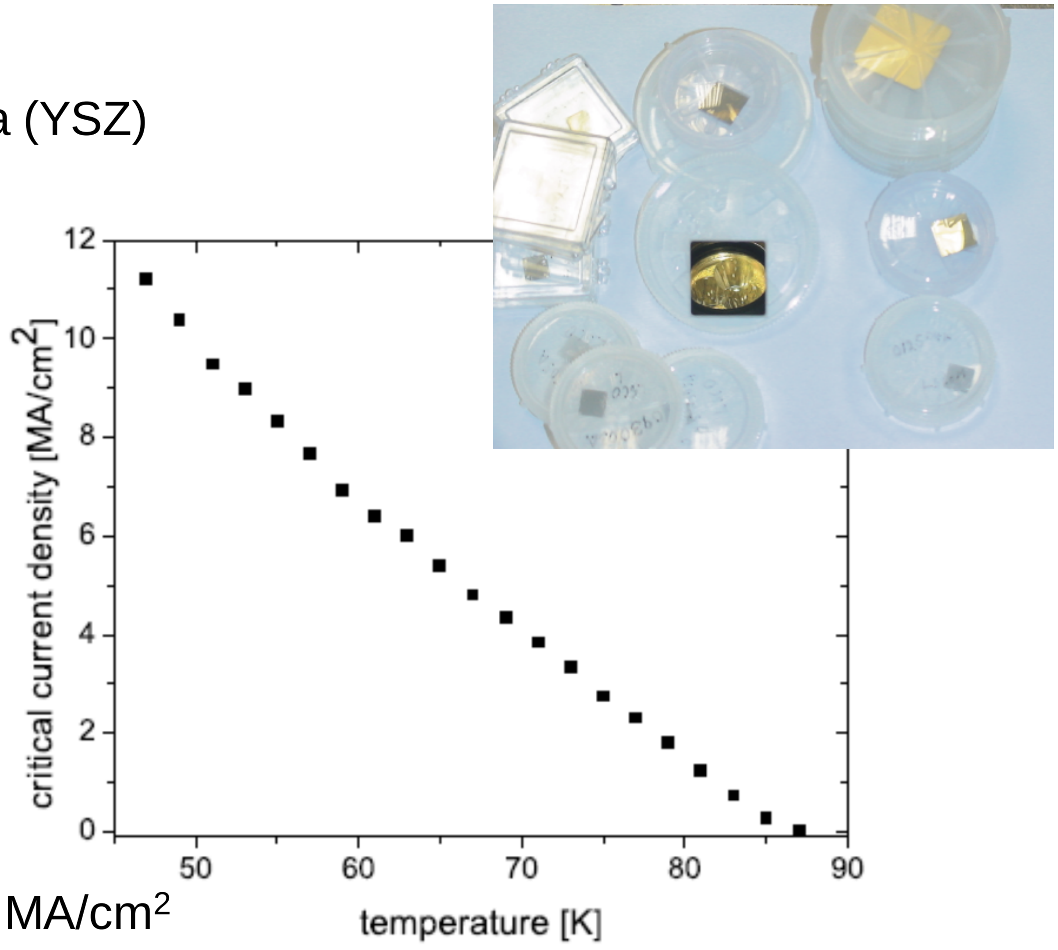
(in current chip 800nm)

Critical temperature:

approx: 87 K

Critical current density:

2 MA/cm^2 @ LN2



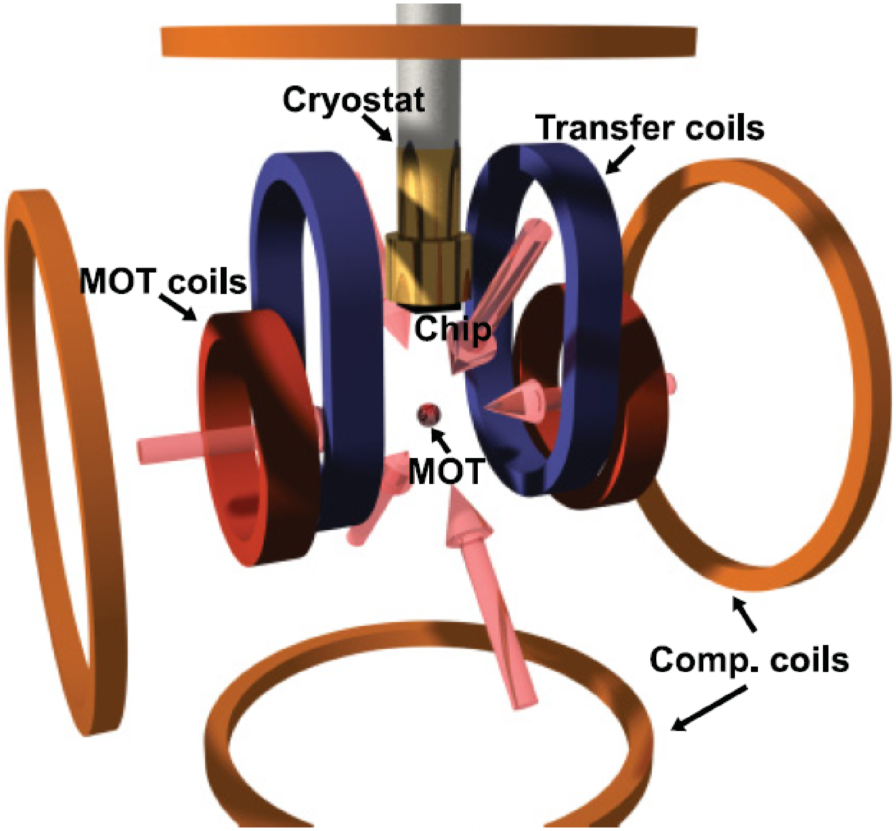
@ liquid Helium temp., 4.2K >10^7 MA/cm^2

Experimental Setup

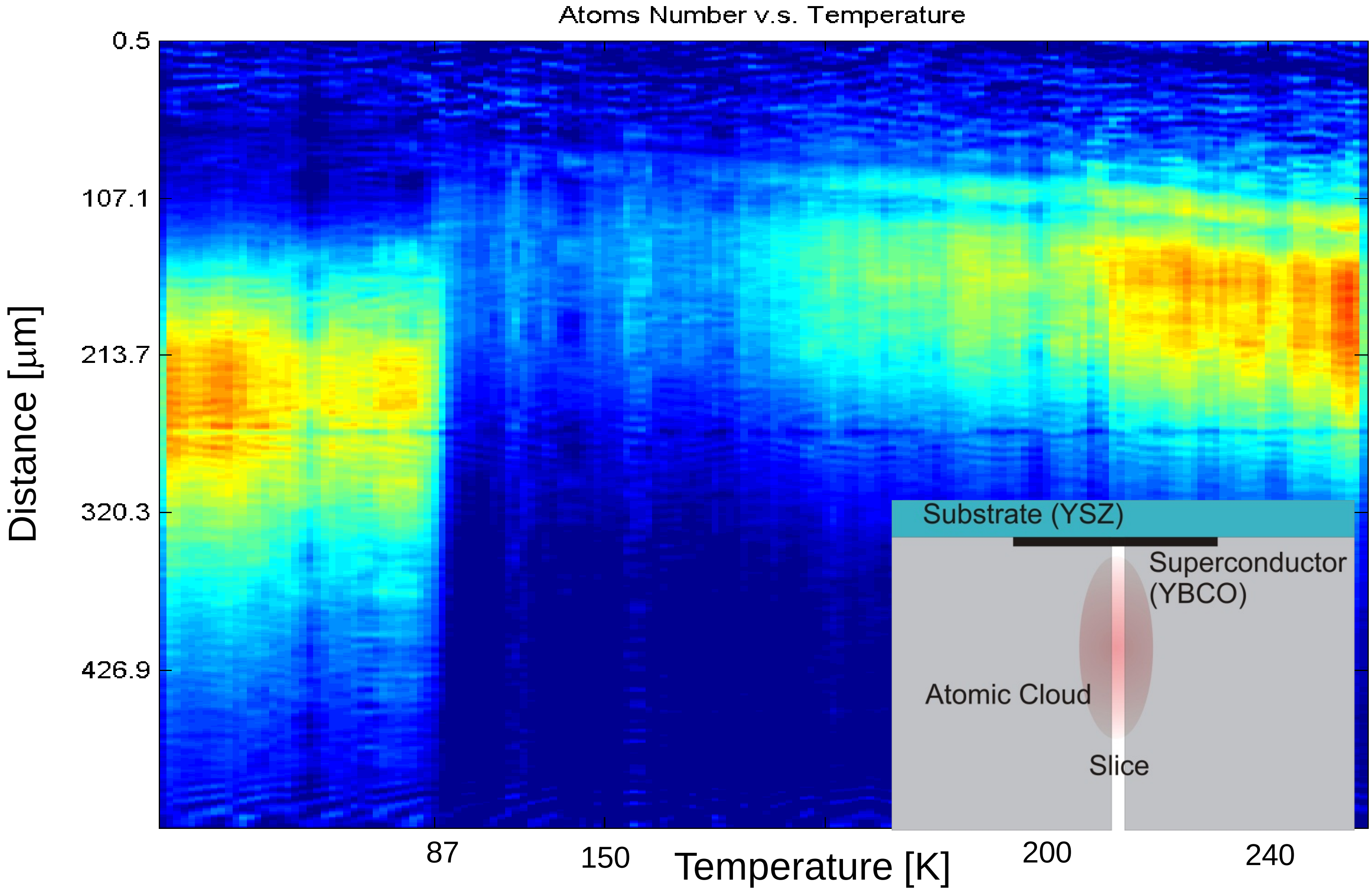
- Load atoms from a MOT into a quadrupole magnetic trap produced by external MOT coils.

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

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

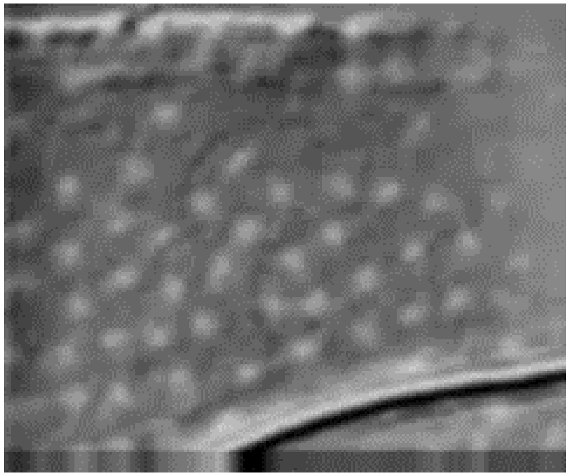


Experiment


Atoms Number v.s. Temperature
Distance [µm]
0.5
107.1
213.7
320.3
426.9
Temperature [K]
87
150
200
240
Substrate (YSZ)
Superconductor
(YBCO)
Atomic Cloud
Slice

Outline

Vorticies Entering Superconductor



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

Dendritic Avalanches

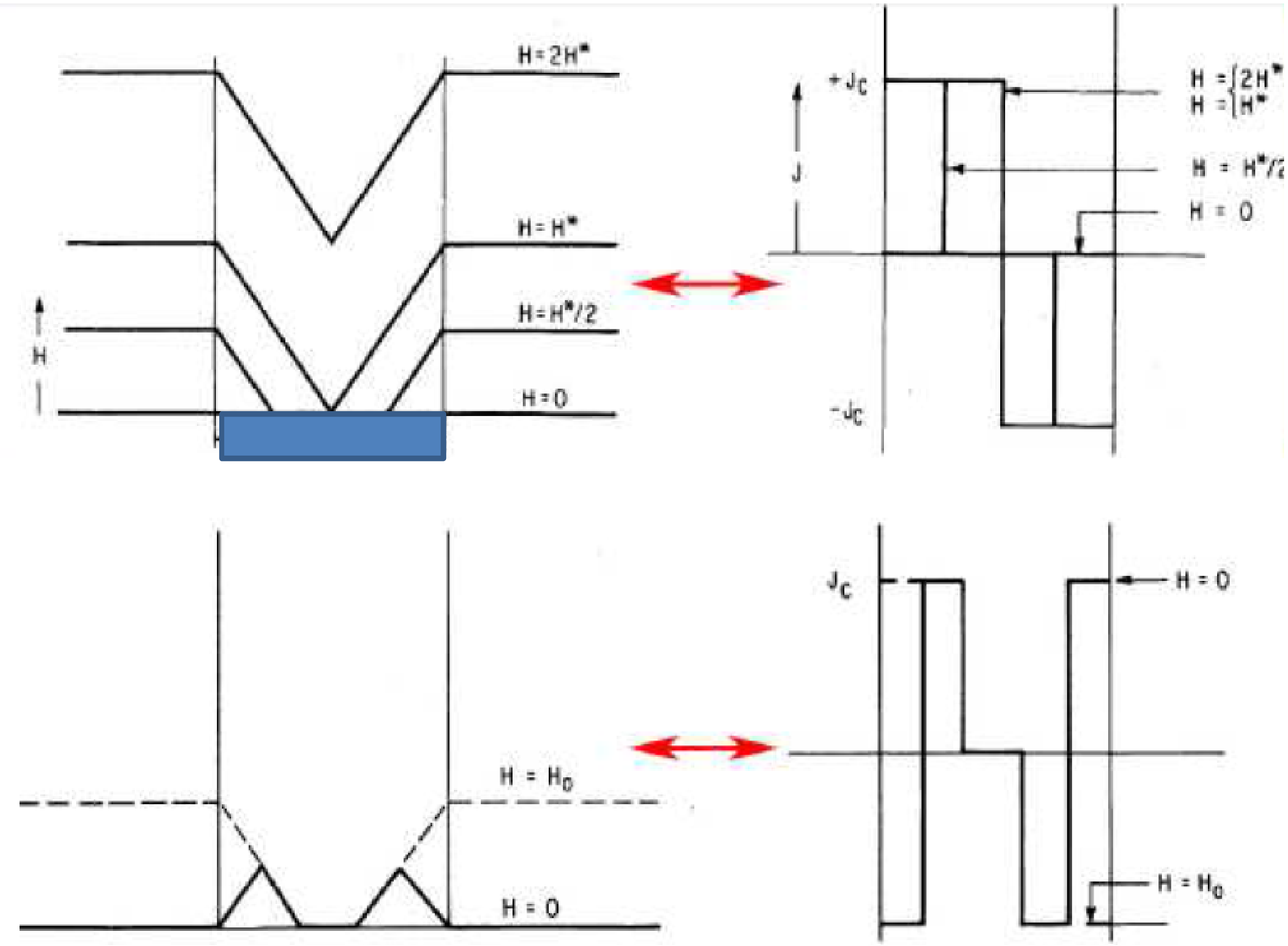
Predictable Vortex Distribution

Bean's model

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

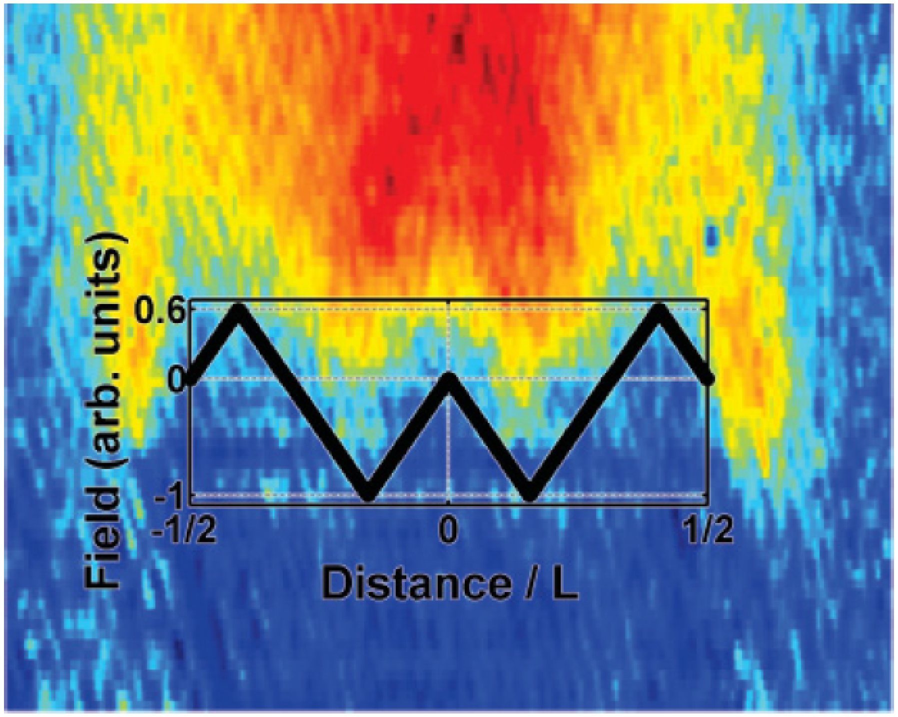


Exp. Bean's model

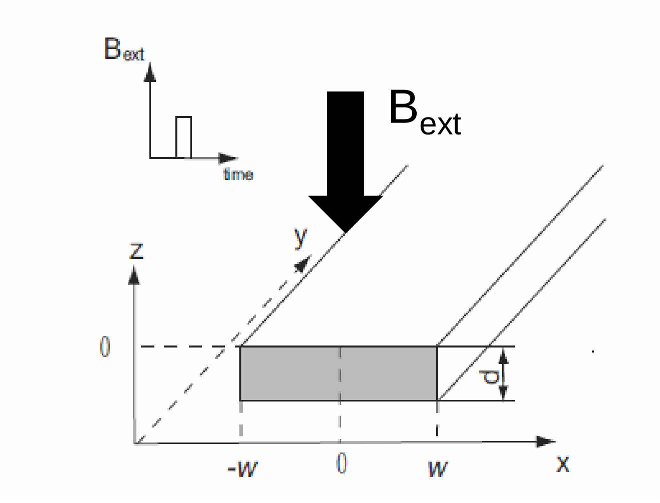
Probing vortex induced current distribution with atoms.

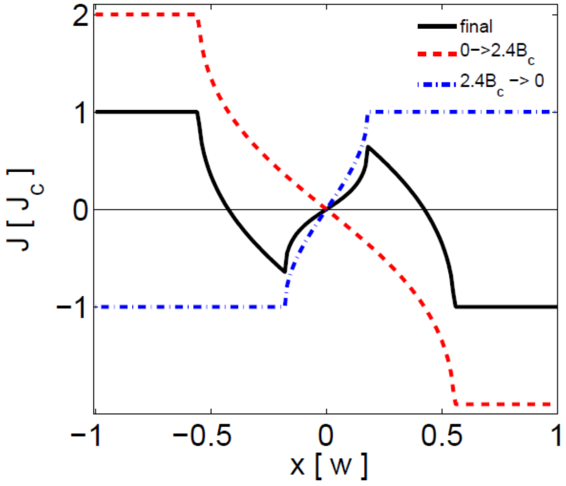
- Induced magnetic field along x at the surface of the square according to Bean's model.
- The square carries supercurrents loaded by two mag. field pulses pulses.
- The atoms display a triangular structure closely resembling the magnetic field once they are close to the super-conducting surface.

Absorption image of ultracold atoms in vicinity of superconducting square.



Beyond Bean’s model

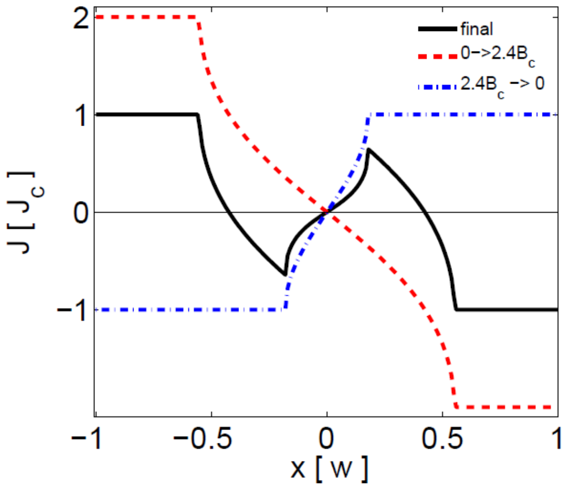


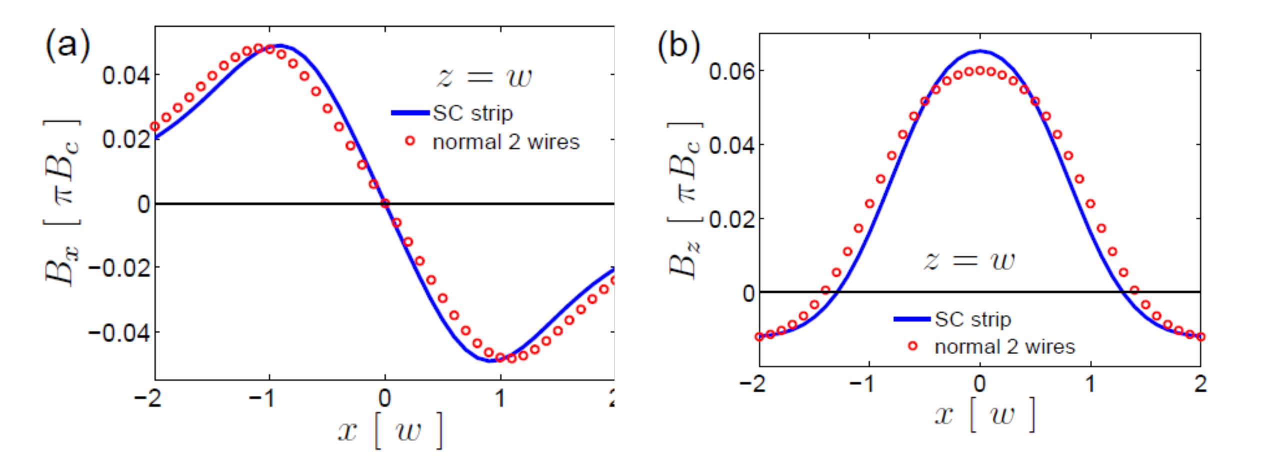


Beyond Bean’s model -> more sophisticated **Brandt’s model**.

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

Beyond Bean's model





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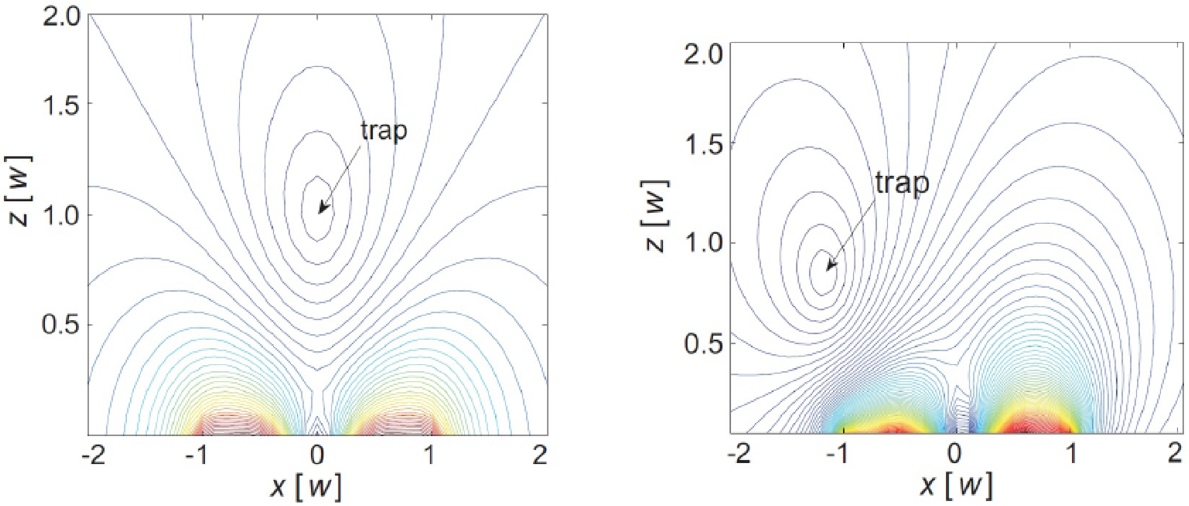
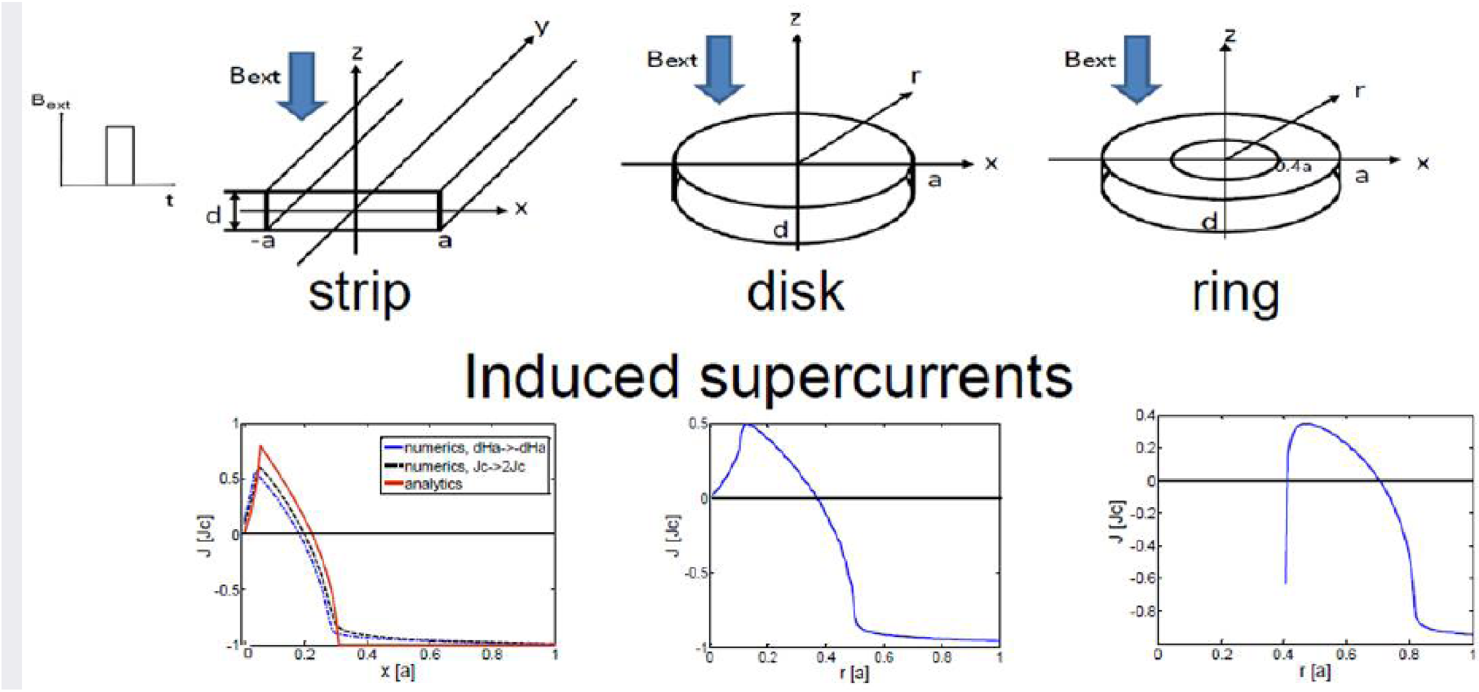


B. Zhang, R. Fermani, T. Müller, M. J. Lim, and R. Dumke
Phys. Rev. A 81, 063408 (2010)

2D Geometries

- extend investigation of vortex based microtrap geometries to type-II superconducting disks and rings.
- superconducting disks or rings create symmetric full 3D traps.



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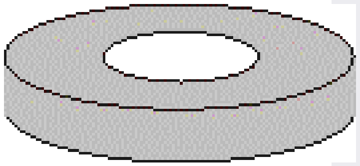
Ring Structure

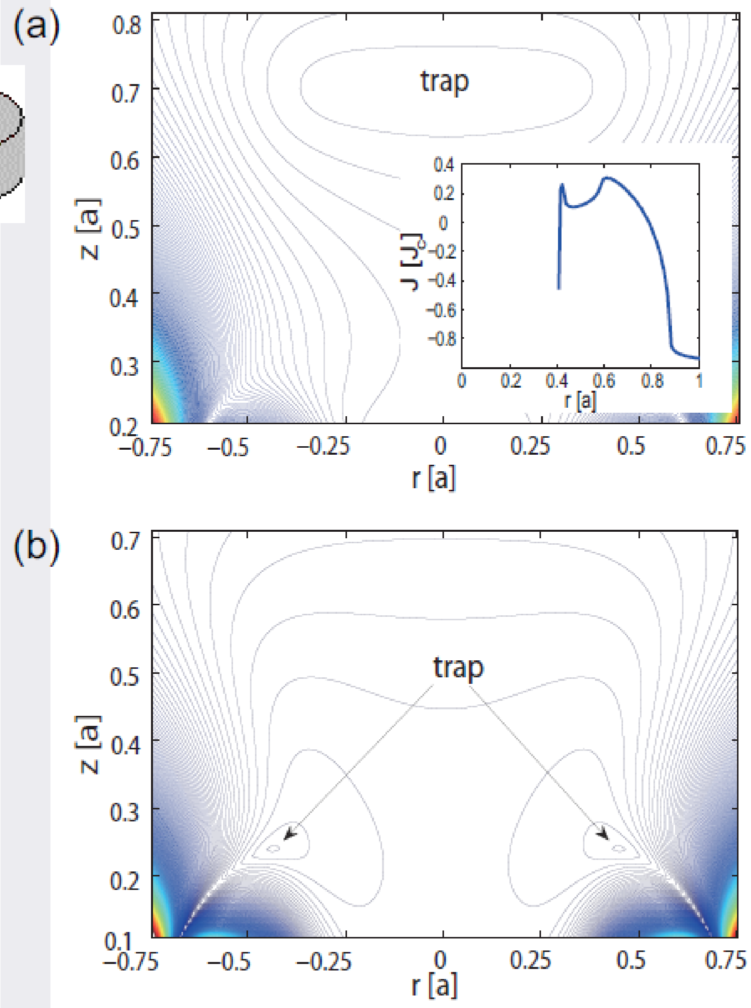
Employing superconducting rings:



- Simple generation of magnetic ring traps.

- One and two pulse sequences generate ring geometries.

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



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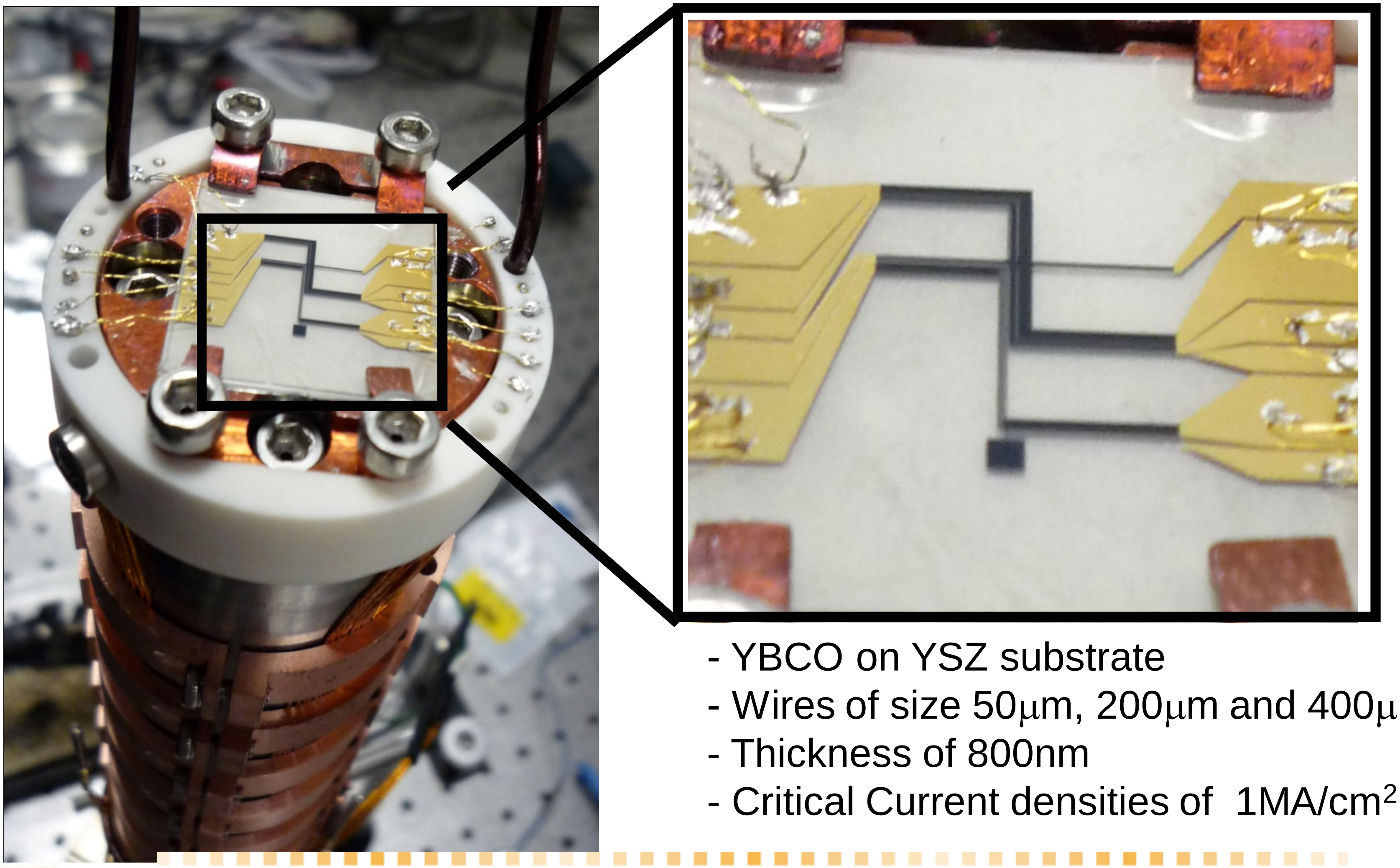
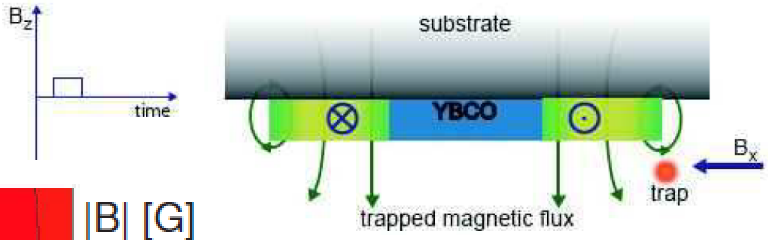
B. Zhang, M. Siercke, K. S. Chan, M. Beian, M. J. Lim, and R. Dumke, Phys. Rev. A 85, 013404 (2012)

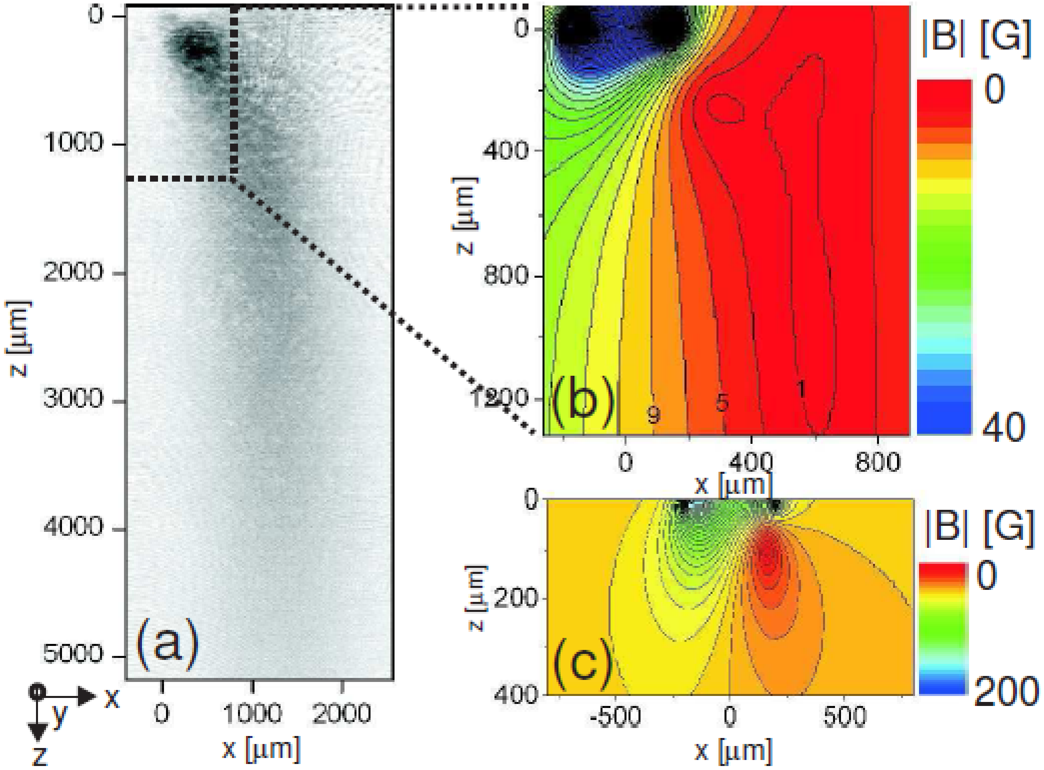
HTS Atom Chip



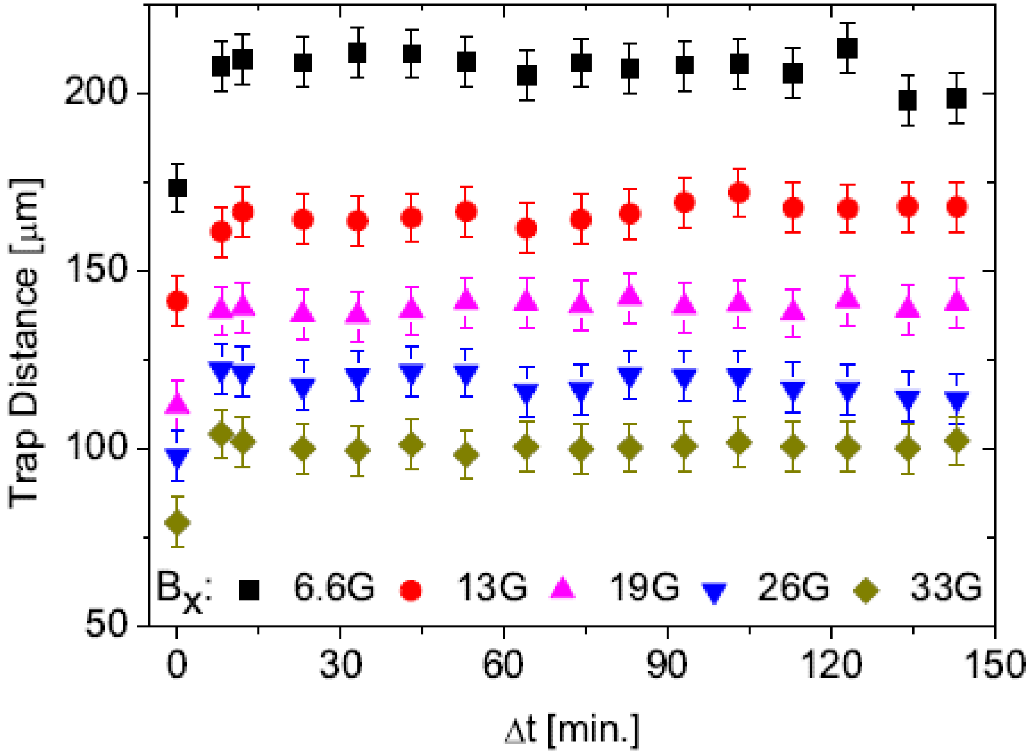
- YBCO on YSZ substrate
- Wires of size 50μm, 200μm and 400μm
- Thickness of 800nm
- Critical Current densities of 1MA/cm^2

Characterization

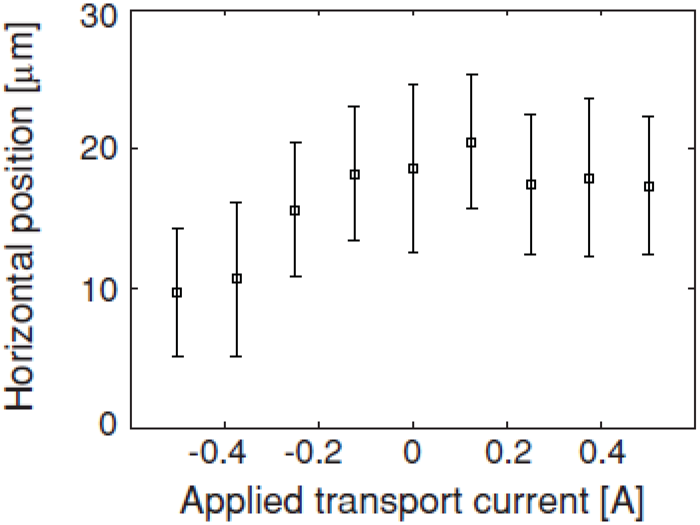




Vortex stability

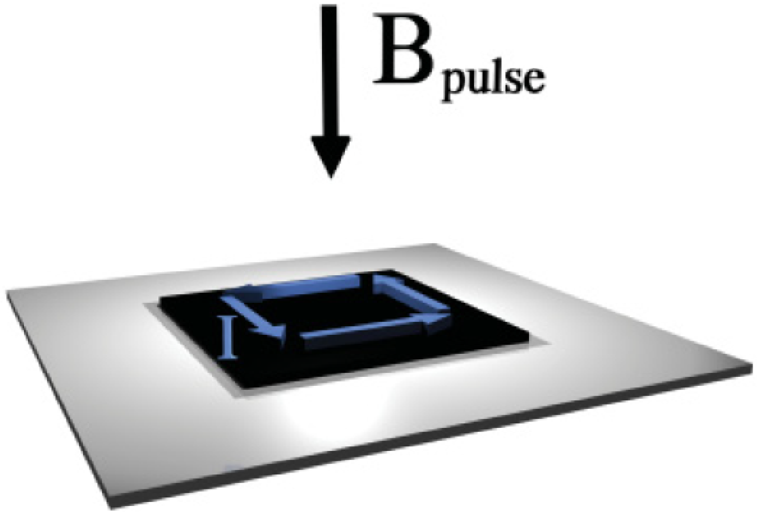


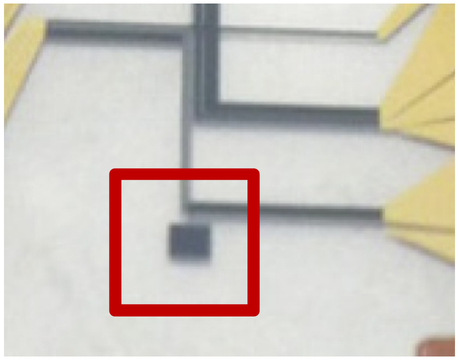
Transport current changes vortex distribution



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).

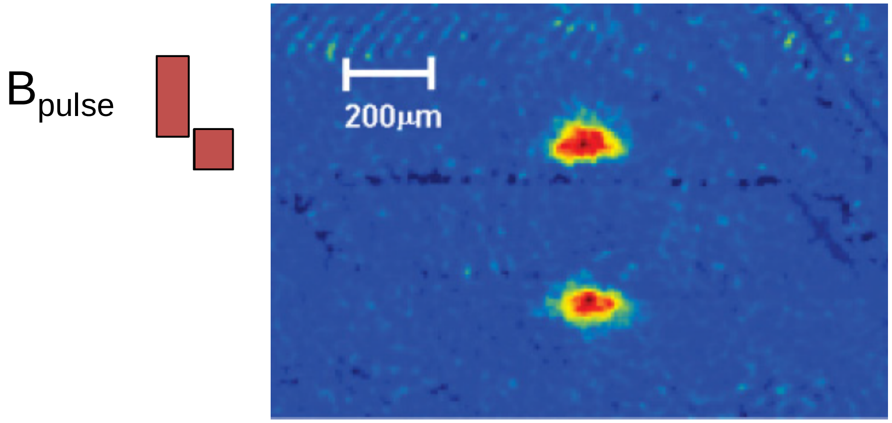
SC Square





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)

Merging AMO and Solid state Physics

- **Brief overview:** Atom Chips limits and Superconducting Atom Chips.

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- **Electric Fields** in proximity to Superconducting Atom Chips.

- **Experimental** path **towards** the realization of **interfacing solid state** devices **with neutral atoms**

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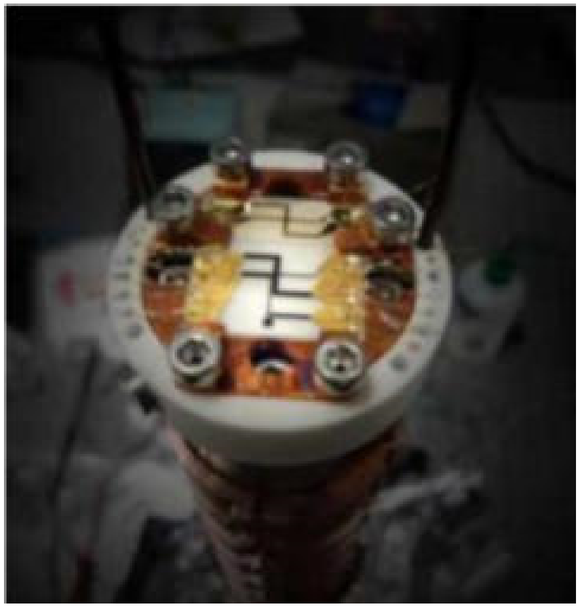
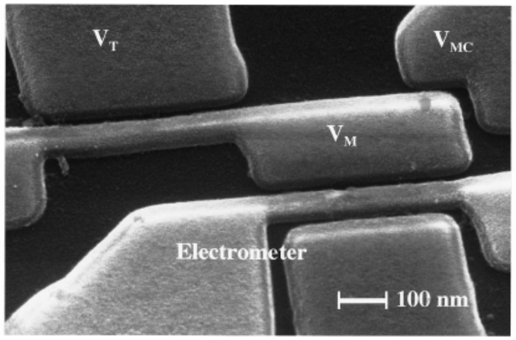
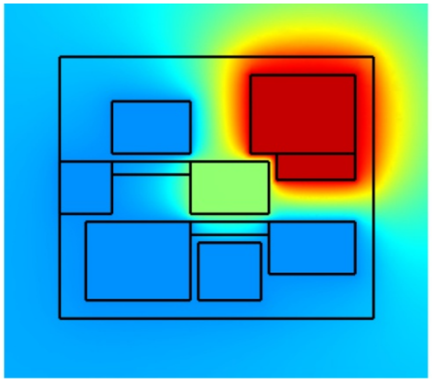


Superconductors

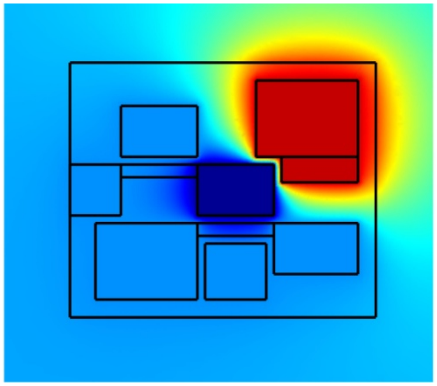
Rydberg Electrometer



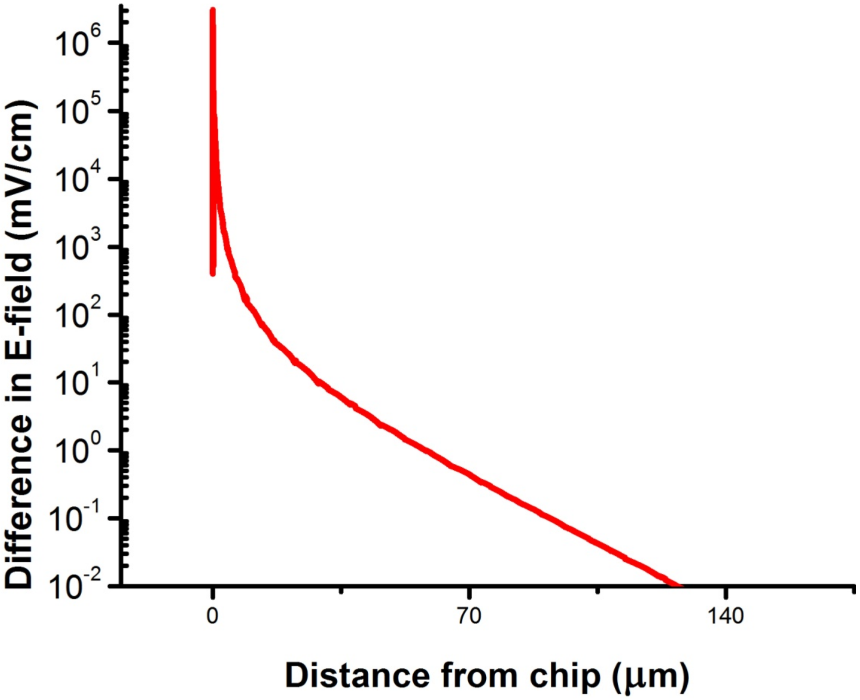
N. J. Stone and H. Ahmed, Appl. Phys. Lett. 73, 2134 (1998)



Unloaded trap



Electric field emitted by 30 electrons with an applied gate voltage



Sensitivity of 10mV/cm demonstrated by Abel et.al, PRA 84, 023408 (2011)

Electric field is detectable for typical trap to surface distance of atom chip

Potentially coupling between atomic quantum system and solid state quantum system

However

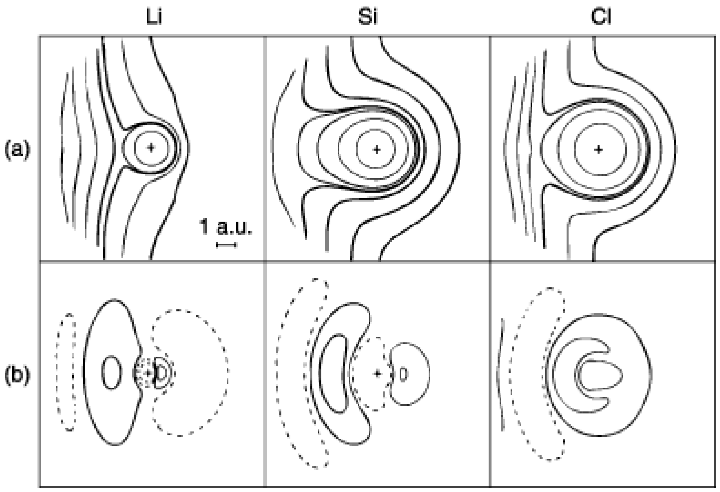
Obstacle of electric field coupling between solid state system and atomic system → Adsorbates

- Adsorbates accumulate at the atom chip surface.
- These adsorbates form a density distribution of dipole moments and produce an electric field.

Adsorbates on Atom Chip

Chemisorption:

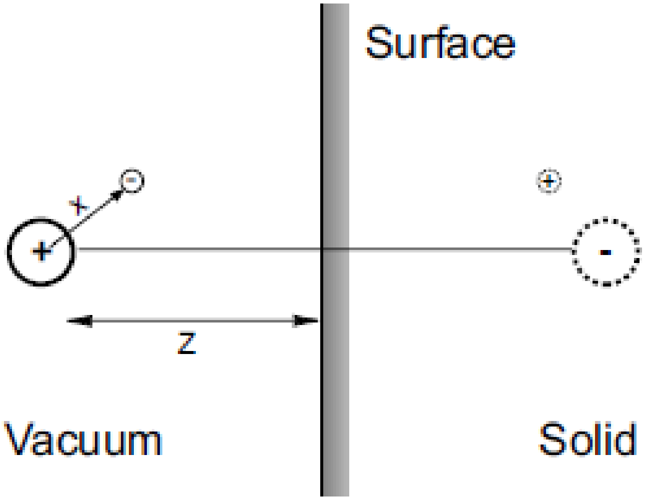
- Substrate work function > adsorbate ionization energy
- Charge transfer from adsorbate to substrate
- Form an electric dipole with electropositive charge on the surface and electronegative image charge inside the substrate
- Bonding has some ionic character



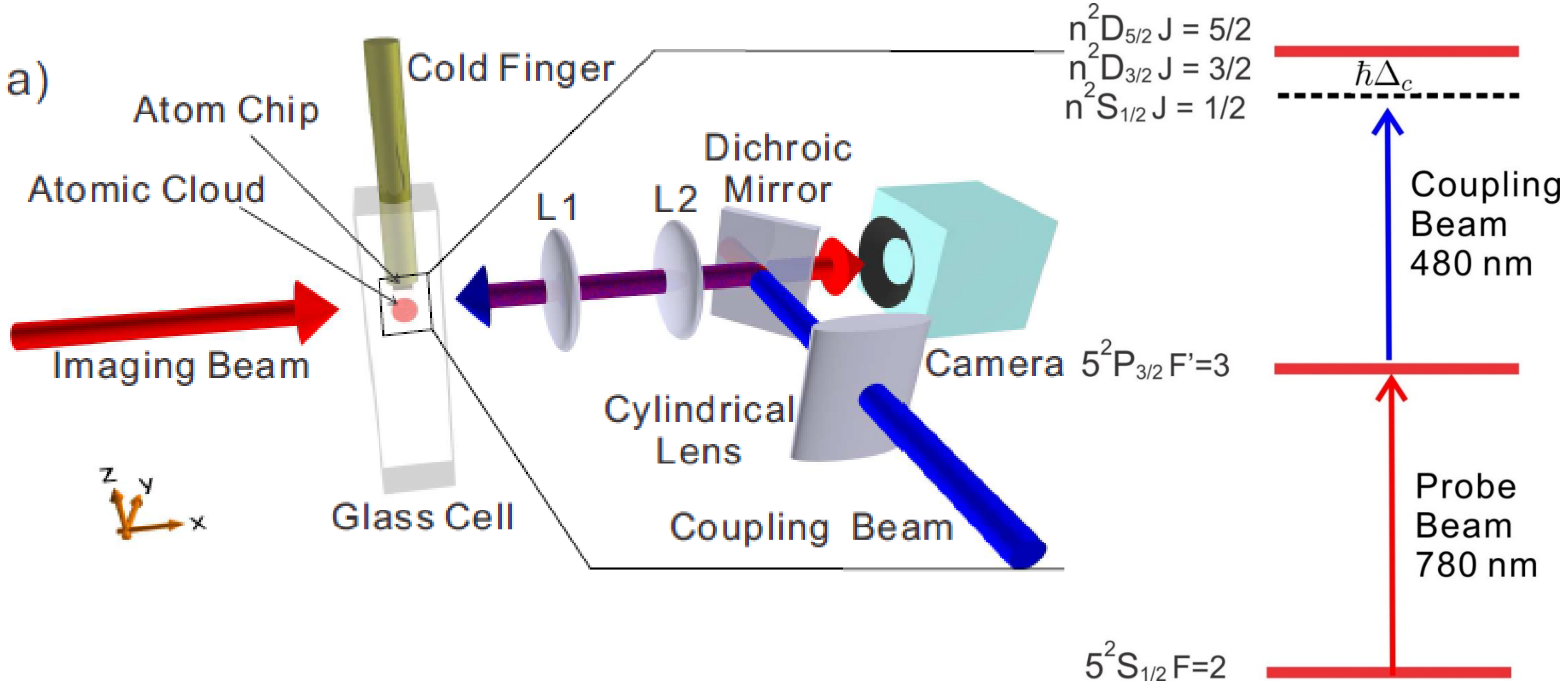
N.D. Lang and A.R. Williams Phys. Rev. B **18**, 616 (1978).

Physisorption

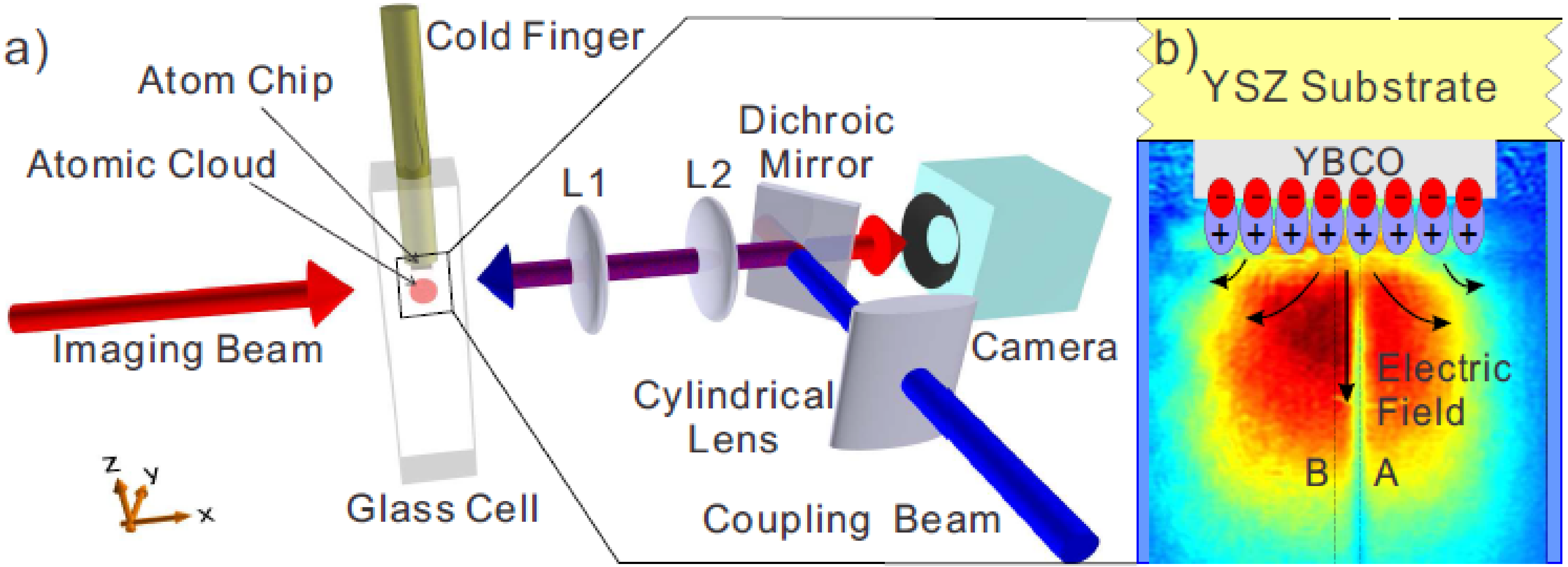
interaction of the valence electron (-e) induces a corresponding image charge the point charges and their images constitute the induced dipoles attraction between the atom and its induced charges inside the substrate



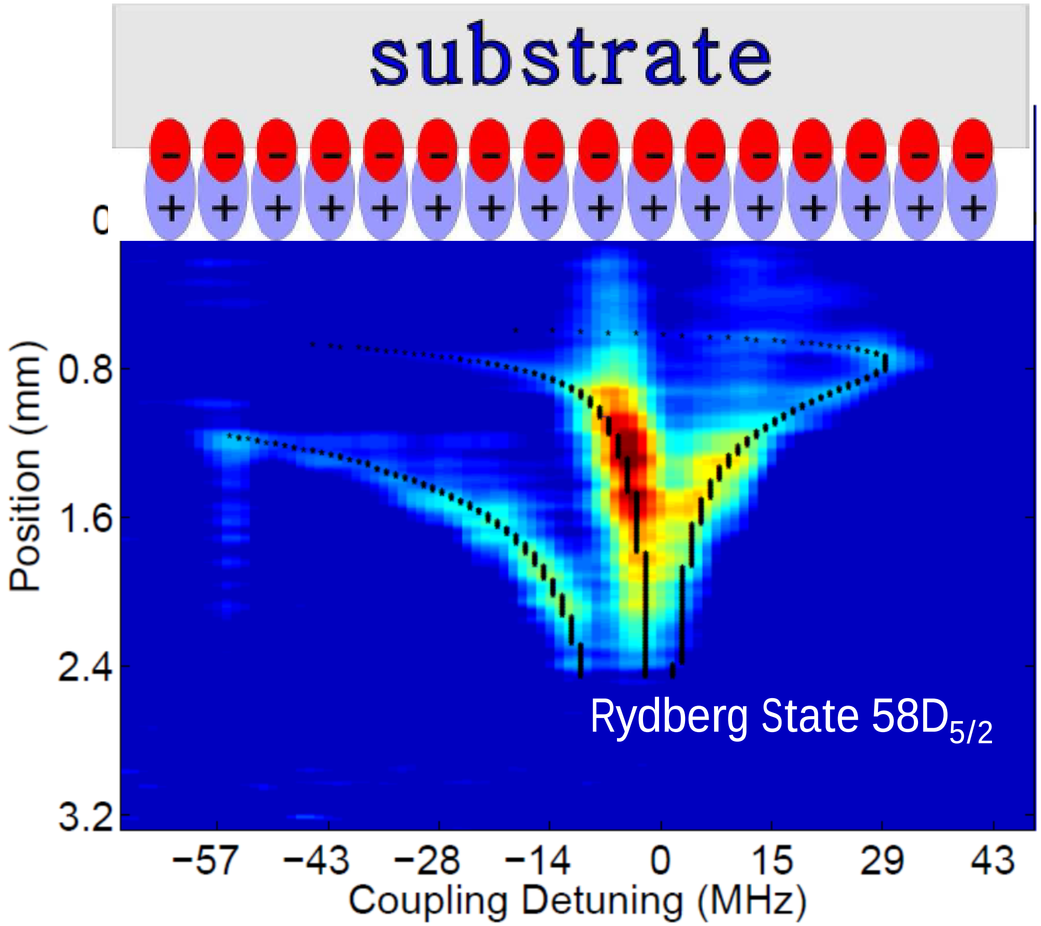
Atomic Electrometry

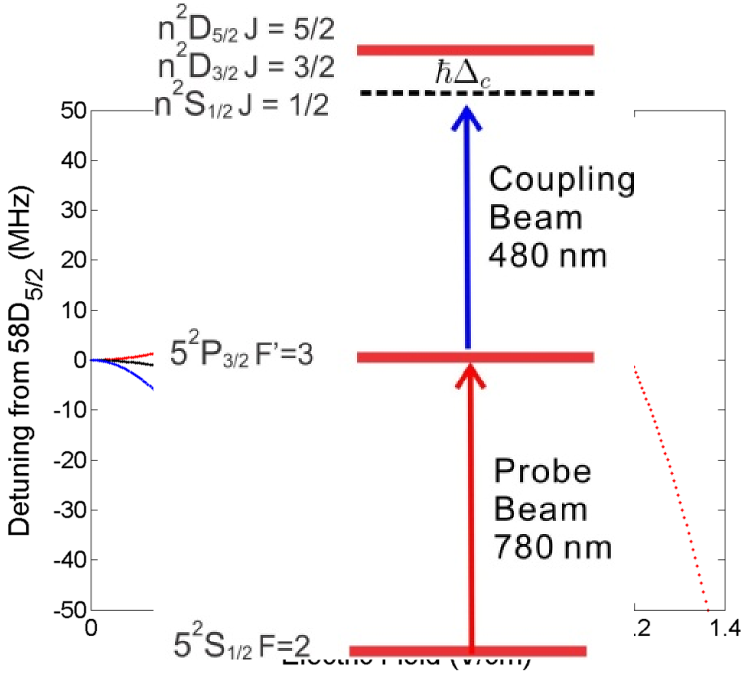


Atomic Electrometry



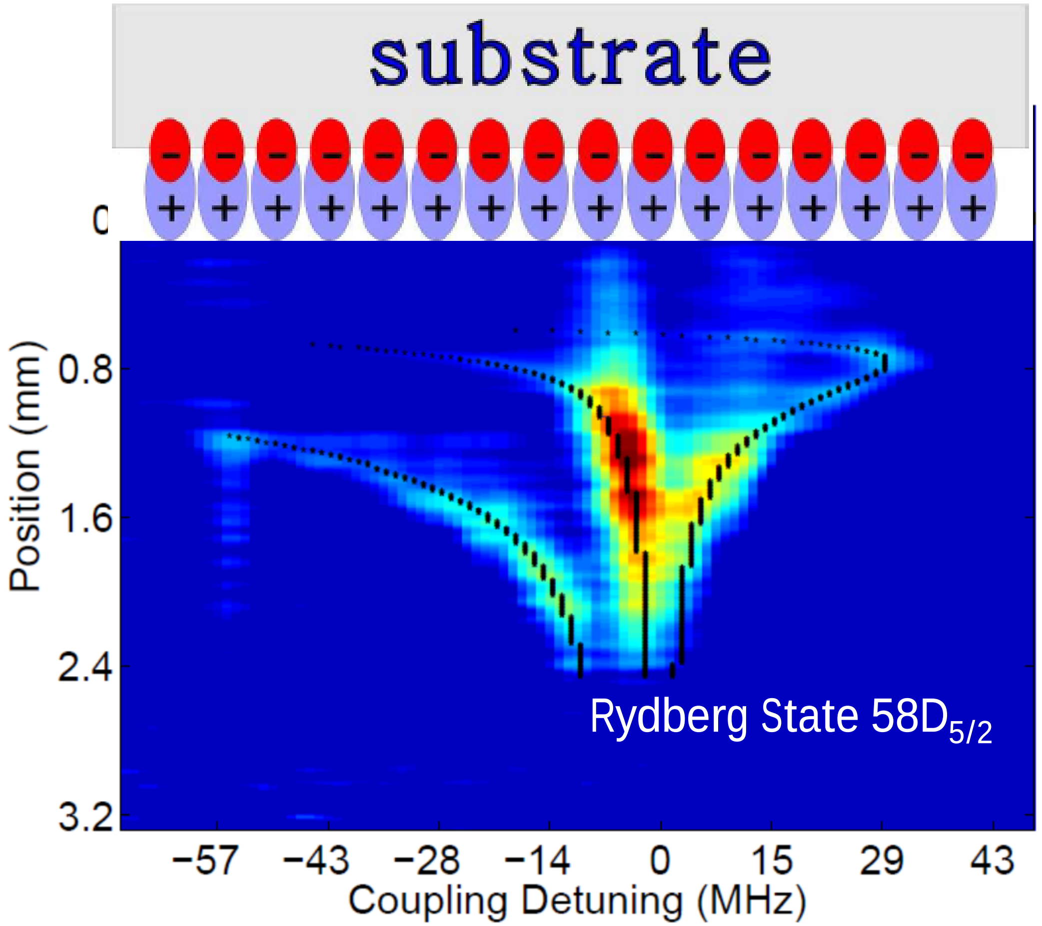
Chemisorption

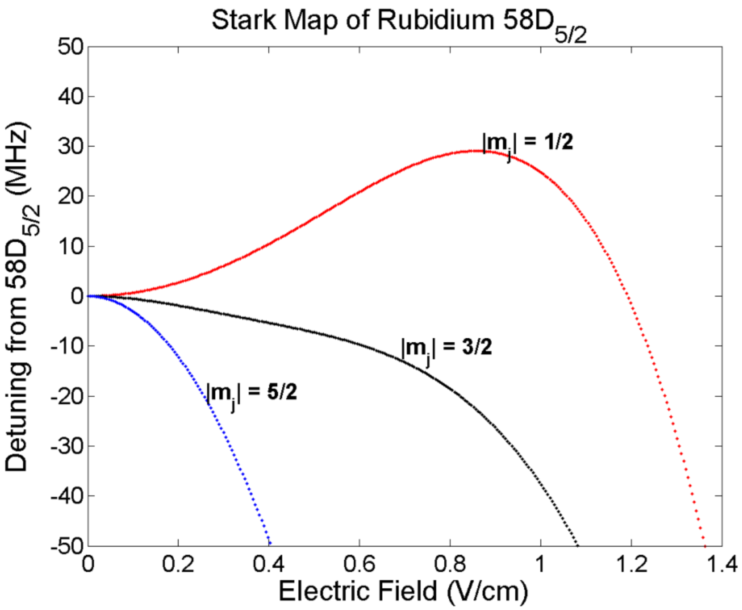




(room temperature ~ 21 Celsius)

Chemisorption





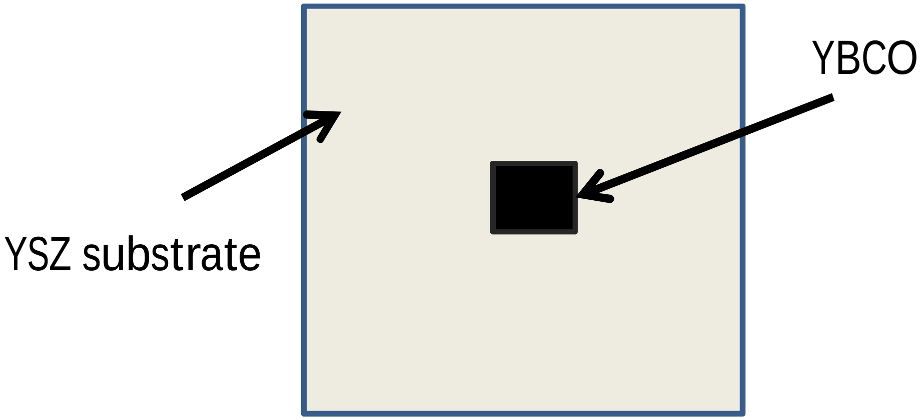
(room temperature ~ 21 Celsius)

Chemisorption

Fit shows that surface charge produced from the adsorbates on the YBCO square structure of size 1mm.

At room temperature, these adsorbates are formed due to **chemisorption.**

Due to difference in work function of the YBCO and YSZ – Yttria Stabilized Zirconia, adsorbates formed preferably on top of the YBCO film.



Electric Field at Cryogenic Temperatures

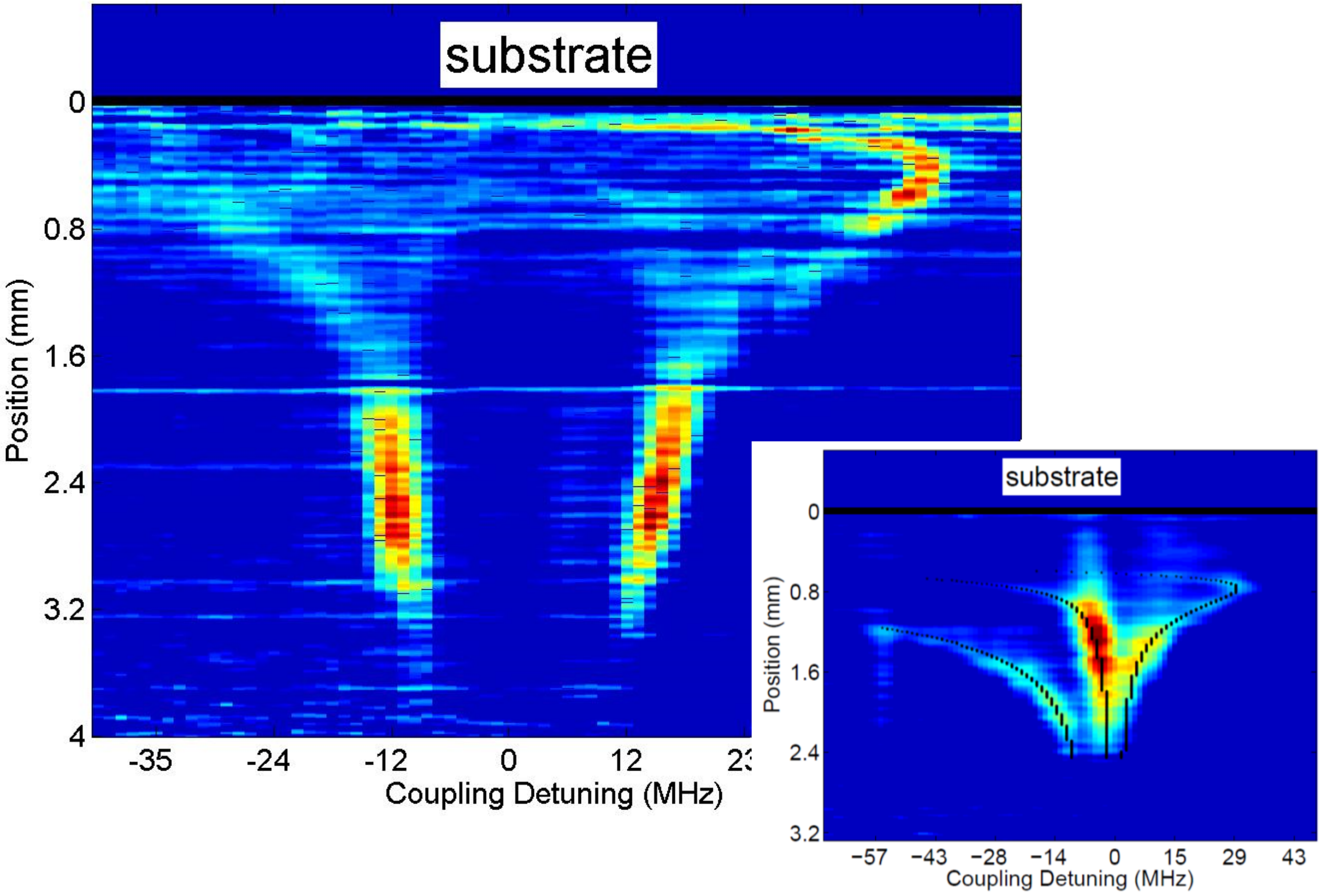
- Decreasing the chip temperature to 83K

- Decreasing the chip temperature to 83K

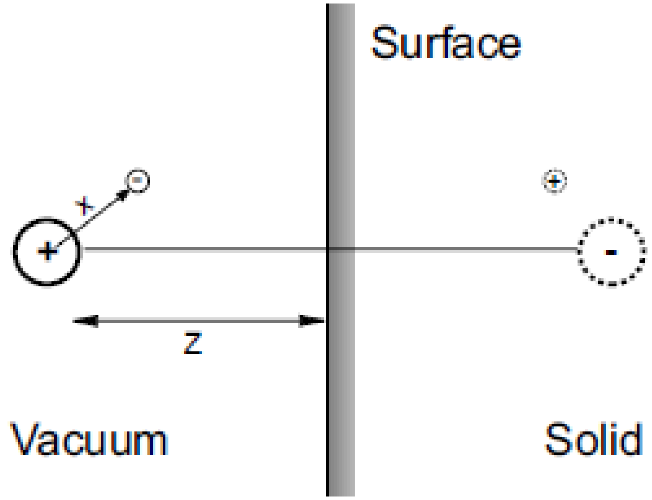
- Clear separation of spectral lines far away from chip surface.

48D$_{5/2}$

$|m_j| = 1/2,\ 3/2, (5/2).$



Physisorption



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

↓

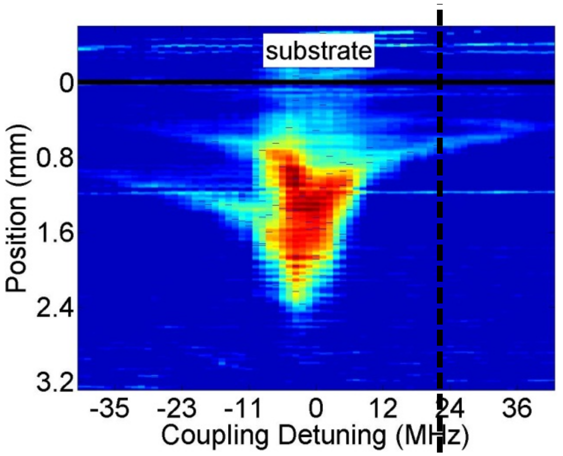
the point charges and their images constitute the induced dipoles

↓

attraction between the atom and its induced charges inside the substrate

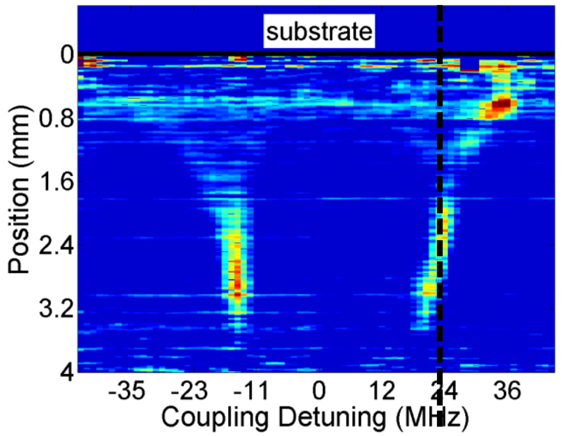
Simulating the Adsorption Crossover

Room Temperature



52D Rydberg State

Cryogenic Temperature



Model:

Simulation using Langmuir equation – Langmuir Isobar:

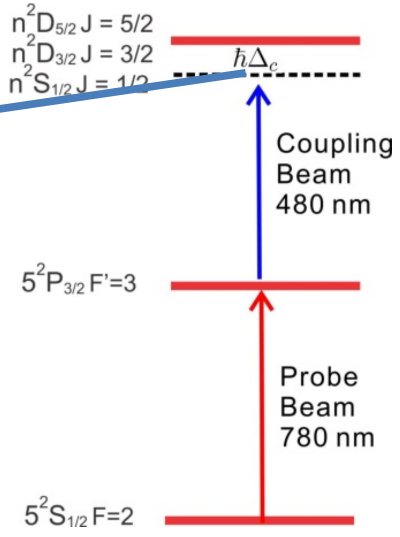
Coverage dependence of Temperature

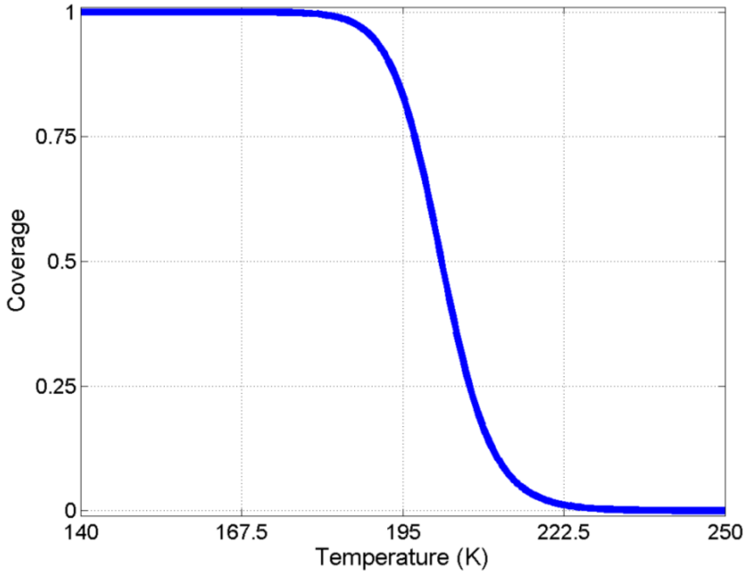
↓

Charge density dependence of Temperature

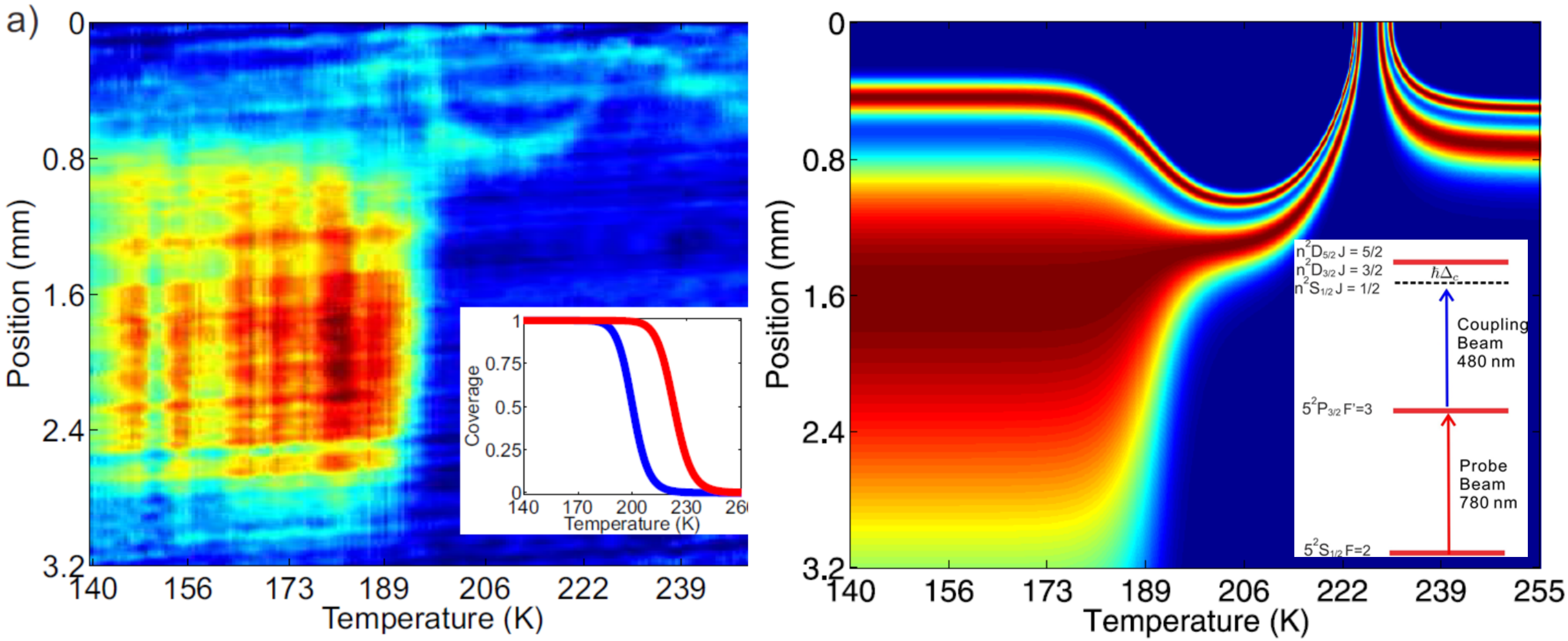
↓

Decrease charge density of physisorbed layer according to Langmuir Isobar equation





Adsorption Crossover



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

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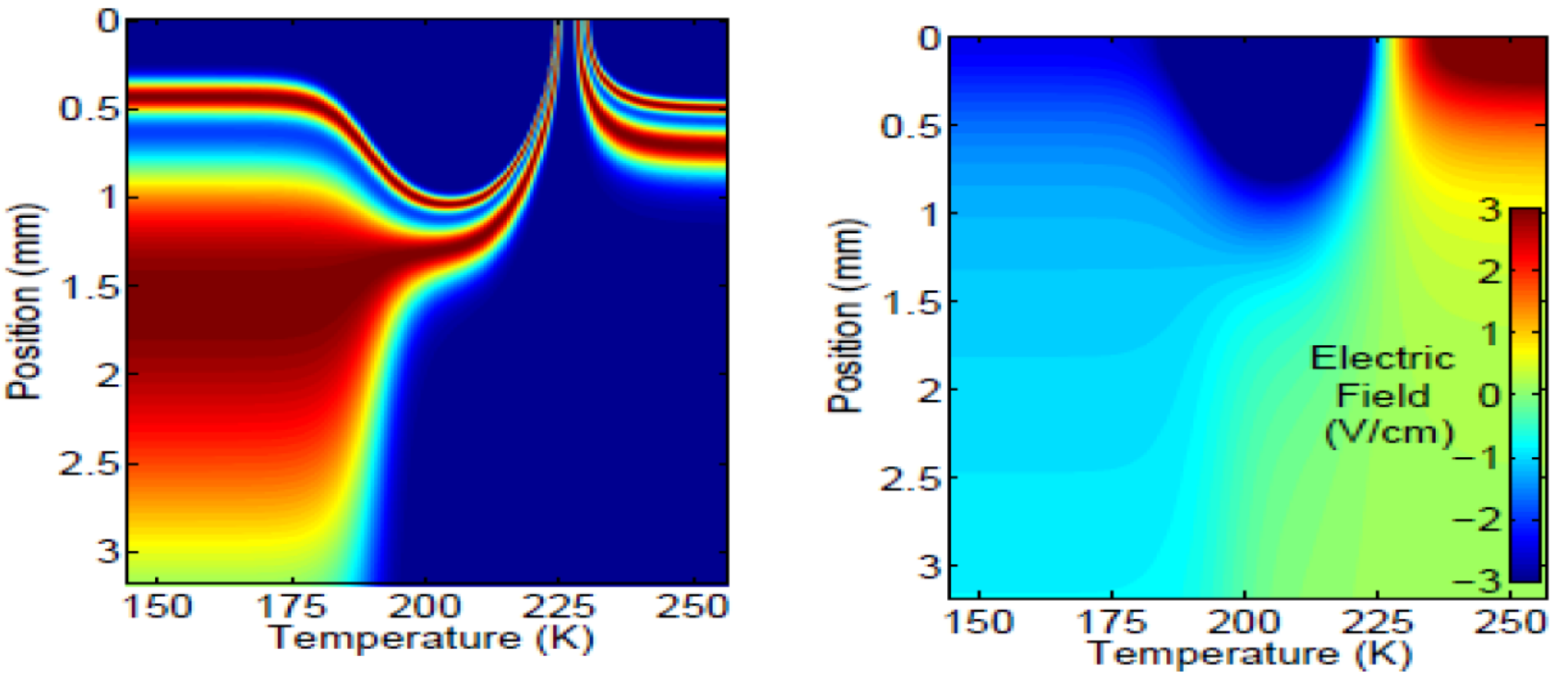
Quantum
Technologies

Adsorption Crossover



NANYANG TECHNOLOGICAL UNIVERSITY

K.S. Chan, M. Siercke, C. Hufnagel, R. Dumke 'Adsorbate Electric Fields on a Cryogenic Atom Chip' Phys. Rev. Lett. 112, 026101, (2014)

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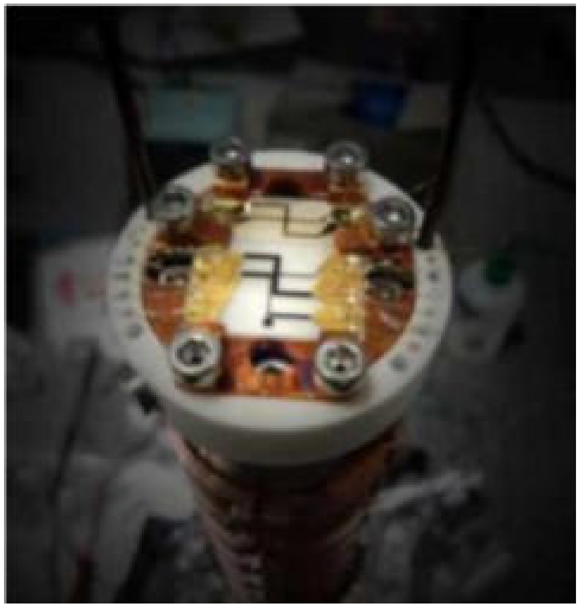
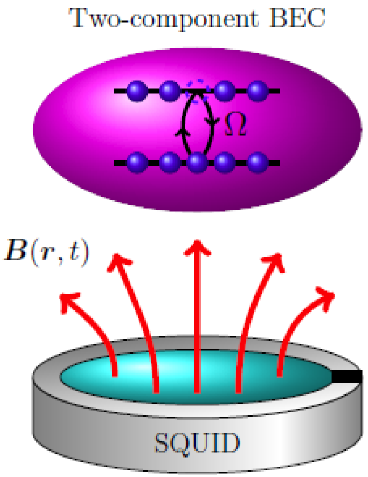


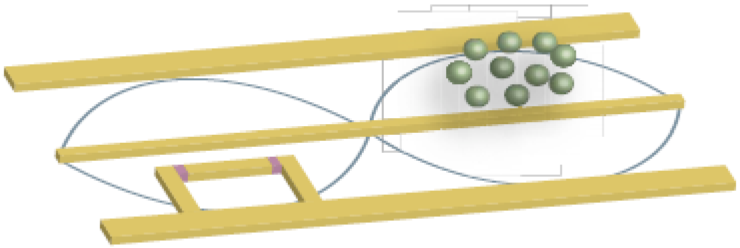
Superconductors

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

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



Kelly R. Patton and Uwe R. Fischer
arXiv:1201.5060v2 (2012)



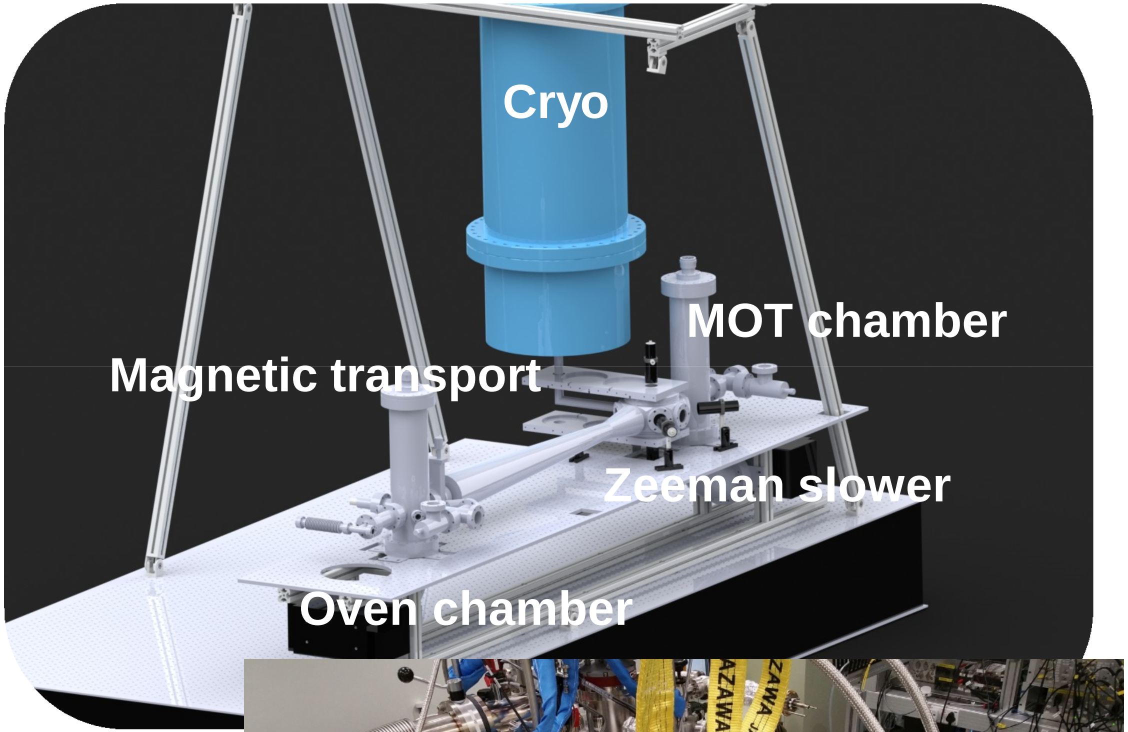
K. Tordrup and K. Molmer, PRA 77, 020301(R) (2008)

Interfacing

Coupling ultracold atoms to cryogenic solid state devices is a challenging task

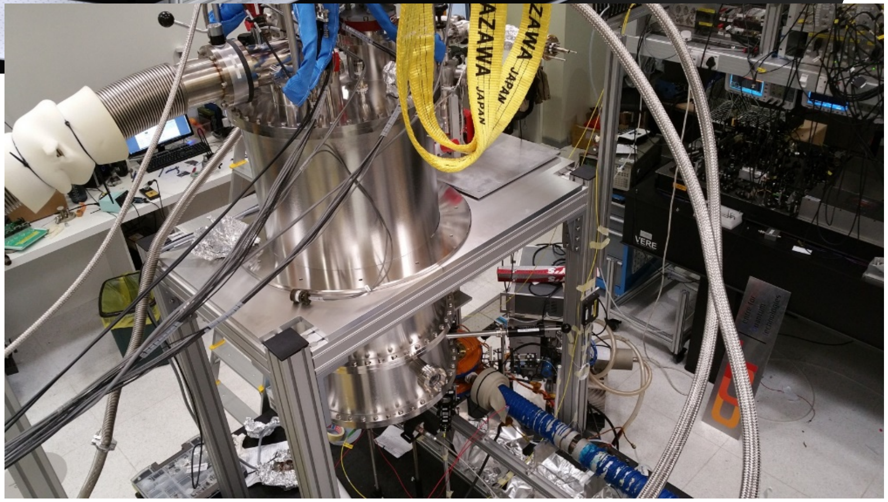
Our approach :

- two chamber setup
- atoms are trapped and precooled in a room temperature chamber
- afterwards transferred into a dilution cryostat

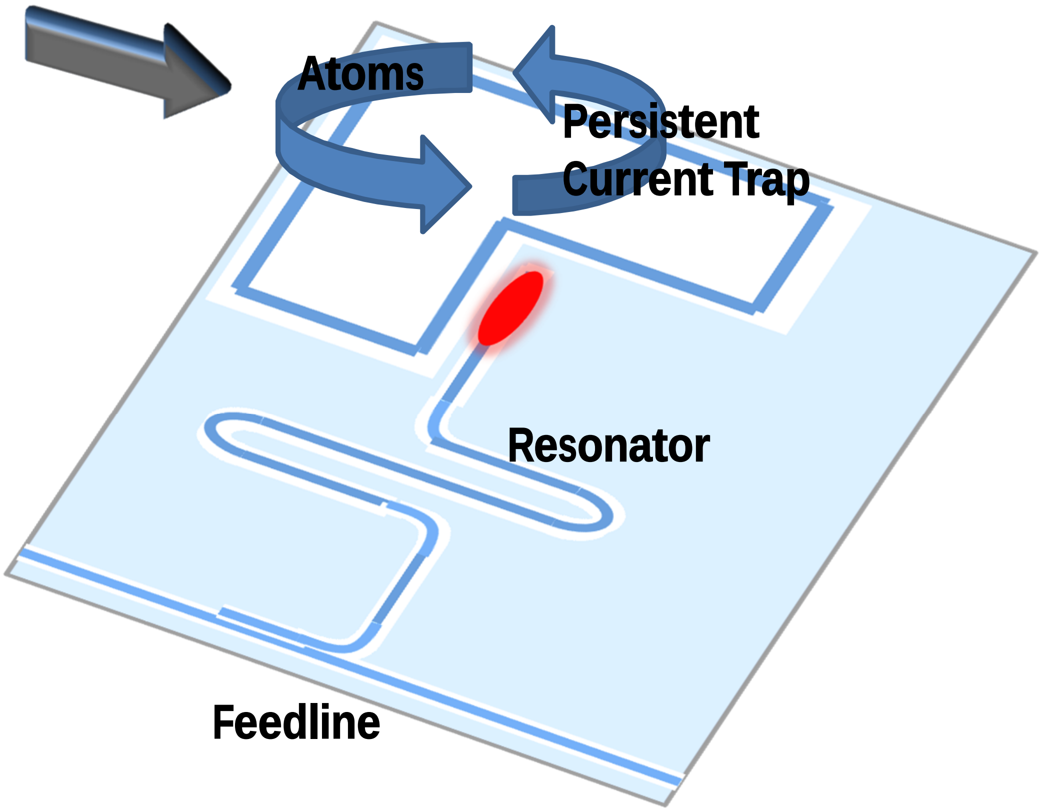


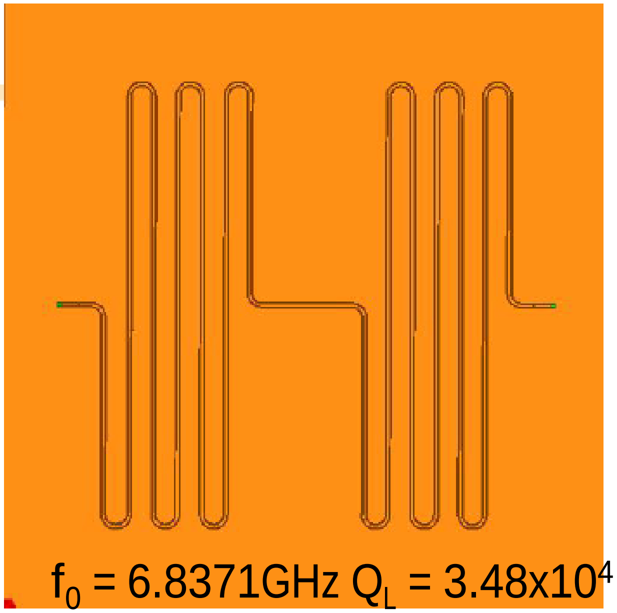
Dilution fridge :

- base temperature : 14mK
- cooling power : 400µW @100mK

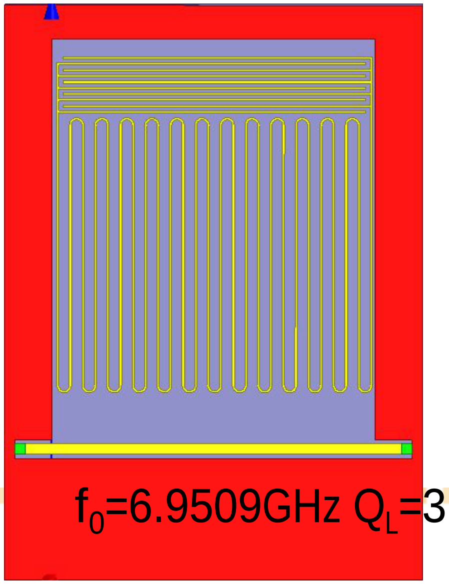


Interfacing





f_0 = 6.8371GHz Q_L = 3.48x10^4



f_0=6.9509GHz Q_L=3.39x10^4

Summary

- Using Atoms to mimic solid state systems by employing tailored optical potentials.
- Using Atoms to measure properties of cryogenic/superconducting solid state systems.
- First steps towards coupling atomic quantum systems and solid state quantum systems

Thank You

Inside the lab:

Dr. Christoph Hufnagel

CHAN Kin Sung
LIM Chin Chean
OON Fong En
LEY Li Yuen
Filip Auksztol
Phyo Baw Swe
GAN Koon Siang
EW Chee Howe

Outside the lab: