Spectroscopy and evaporative cooling in a radio-frequency dressed trap

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PhD Defence

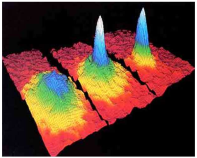
OUTLINE

- **INTRODUCTION**

Introduction

1995: Bose-Einstein condensation (BEC)

- BEC is a phenomenon in which, below a critical temperature T_C, a macroscopic number of bosons occupy the lowest single particle state with the rest distributed over the excited states.



$T>T_c$ $T<T_c$

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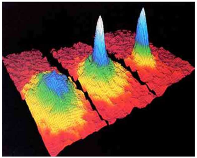
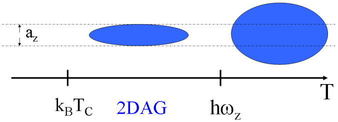


$T>T_c$ $T<T_c$

- In recent years, the investigation of quantum gases in low dimensional trapping geometries has significantly attracted the attention of the physics research community.

Introduction
A classical 2D gas

- A classical 2D gas is realized if the temperature satisfies the inequality $k_B T_C < k_B T < \hbar\omega_z$:



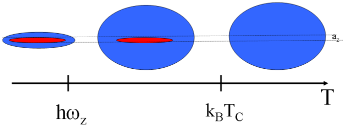
a_z is the harmonic oscillator length.

$$k_B T_C < \hbar\omega_z \Longrightarrow N < 1.2\frac{\omega_z^2}{\omega_x\omega_y}$$

Introduction

A quantum 2D gas.

- A quasi 2D quantum gas is realized if one has both $T < T_C$ and $\mu < \hbar\omega_z$



quasi 2D quantum gas surrounded by a 3D thermal gas

$$\mu < \hbar\omega_z \Longrightarrow N < 0.4\frac{a_z\omega_z^2}{a\omega_x\omega_y},$$

where a is the scattering length.

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- Adiabatic potentials are suitable to realize unusual geometries: quasi-2D 'bubble' traps, double wells, ring traps (see Olivier Morizot's thesis)...

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- Adiabatic potentials are suitable to realize unusual geometries: quasi-2D 'bubble' traps, double wells, ring traps (see Olivier Morizot's thesis)...
- rf evaporative cooling is possible in such traps, the effect of a second rf field was theoretically addressed in the group.

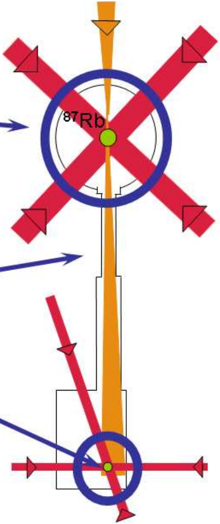
- **ULTRACOLD ATOMS CONFINED IN A RADIO-FREQUENCY DRESSED MAGNETIC TRAP**

Experimental set up

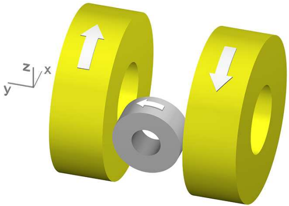
First MOT
Vapour-loaded
$P \sim 10^{-9}$mbar

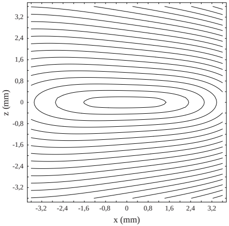
Pushing/guiding
beam
(far red-detuned)

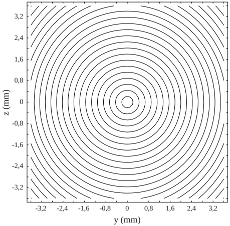
Second MOT
$P \sim 10^{-11}$mbar
$\tau_{life} \sim 60$s



Magnetic trap







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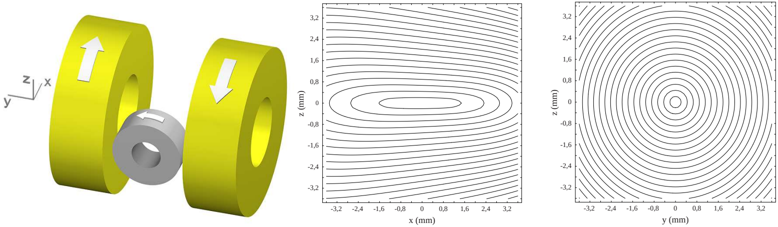
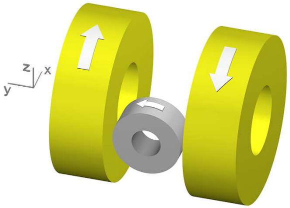
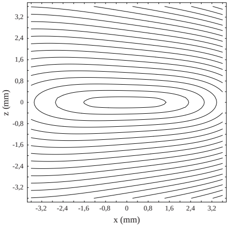
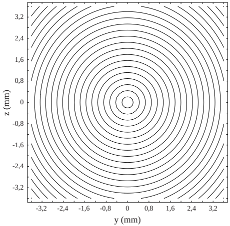


$$\nu_x = 20.1\,\text{Hz}, \nu_y = \nu_z = 225\,\text{Hz},$$

Magnetic trap





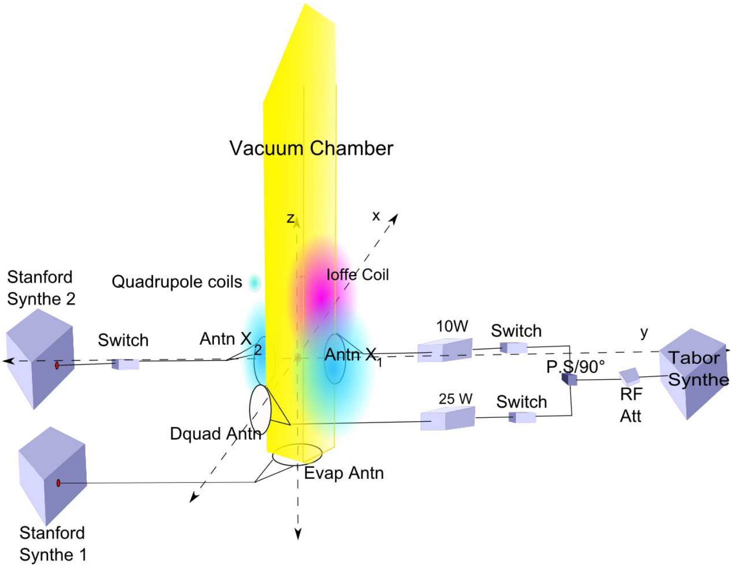


$$\nu_x = 20.1\,\text{Hz}, \nu_y = \nu_z = 225\,\text{Hz},$$

At the trap center:

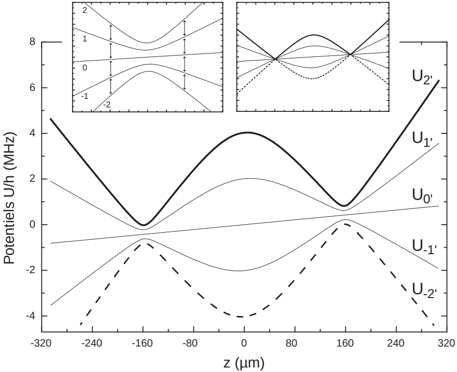
$$B_{\text{min}} = 1.8\,\text{G}$$
$$b' = 220\,\text{G/cm}$$

Radio frequency set up



Radio frequency dressed magnetic trap – an introduction

Adiabatic potentials are created by a combination of a static magnetic field and an oscillating magnetic field (radiofrequency field).



$|2'\rangle$........$|-2'\rangle$ are called 'dressed states'.

Hamiltonian of the system

We define as X, Y and Z the axes of a local frame attached to the static magnetic field, Z being the direction of dc magnetic field, chosen as quantization axis.

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Hamiltonian of this system:

$$H_T(\mathbf{r}, t) = \frac{g_F \mu_B}{\hbar} \mathbf{F}.[\mathbf{B_{dc}}(\mathbf{r}) + \mathbf{B_1}(\mathbf{r}, t)].$$

$$H_T(\mathbf{r}, t) = \omega_0(\mathbf{r}) F_Z + 2\Omega_1(\mathbf{r}) F_X \cos \omega_1 t \quad (1)$$

where $\Omega_1 = g_F \mu_B B_1/(2\hbar)$ is the Rabi frequency of the rf field and $\omega_0(\mathbf{r}) = g_F \mu_B B_0(\mathbf{r})/\hbar$ is the local Larmor frequency.

Spin evolution

- In the frame rotating at frequency ω_1, the 'Rotating wave approximation' leads to a time independent Hamiltonian:

$$\begin{aligned} H_A(\mathbf{r}) &= -\delta(\mathbf{r})F_Z + \Omega_1 F_X \\ &= \Omega(\mathbf{r})(\cos\theta F_Z + \sin\theta F_X) \\ &= \Omega(\mathbf{r})F_\theta. \end{aligned} \tag{2}$$

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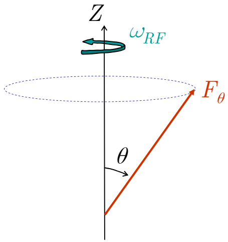
We have defined $\Omega(\mathbf{r}) = \sqrt{\delta(\mathbf{r})^2 + \Omega_1^2}$ and the flip angle θ by:

$$\tan\theta = -\frac{\Omega_1}{\delta(\mathbf{r})} \quad \text{with} \quad \theta \in [0, \pi]. \quad (3)$$

Spin Precession



In the presence of the rf field, the eigenstates of the spin are tilted by an angle θ from the Z axis and precess around it at the angular frequency ω_{RF} of the rf wave.

Adiabaticity condition

The adiabaticity condition states that the variation rate $\dot{\theta}$ of the eigenstates of the spin Hamiltonian H_A must be very small as compared to the level spacing $\Omega(\mathbf{r})$ in the dressed basis:

$$|\dot{\theta}| \ll \sqrt{\delta^2 + \Omega_1^2}.$$

or equivalently

$$|\Omega_1 \dot{\delta} - \dot{\Omega}_1 \delta| \ll (\delta^2 + \Omega_1^2)^{3/2}. \quad (4)$$

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At resonance (around $\delta = 0$), it is more restrictive: $|\dot{\delta}| \ll \Omega_1^2$.

Adiabatic potentials

The total potential for the dressed state m'_F reads:

$$U_{m'_F}(\mathbf{r}) = m'_F \hbar \sqrt{\delta(\mathbf{r})^2 + \Omega_1^2} + Mgz$$
$$= m'_F \sqrt{(\hbar\omega_1 - g_F \mu_B B(\mathbf{r}))^2 + \hbar^2 \Omega_1^2} + Mgz. \quad (5)$$

iso-B surface $B(\mathbf{r}) = \frac{\hbar\omega_1}{g_F \mu_B}$, *i.e.* Larmor frequency $\omega_0(\mathbf{r}) = \omega_1$.

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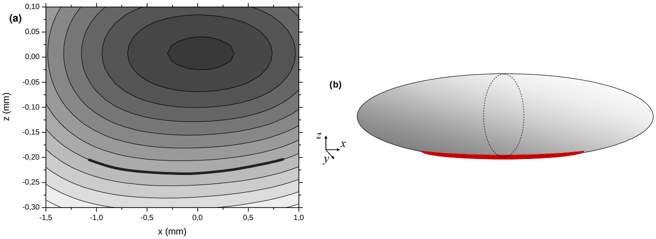
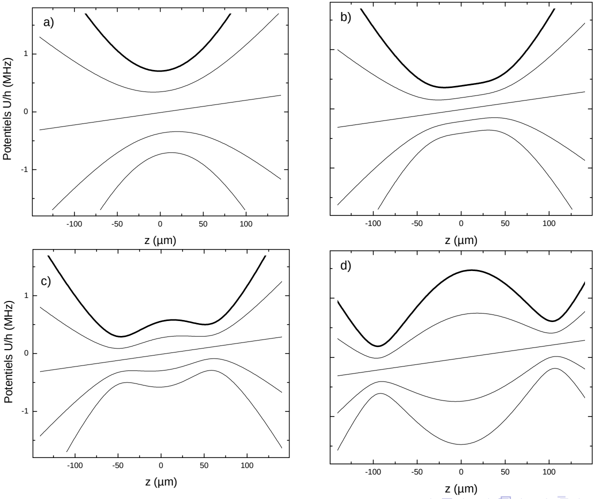


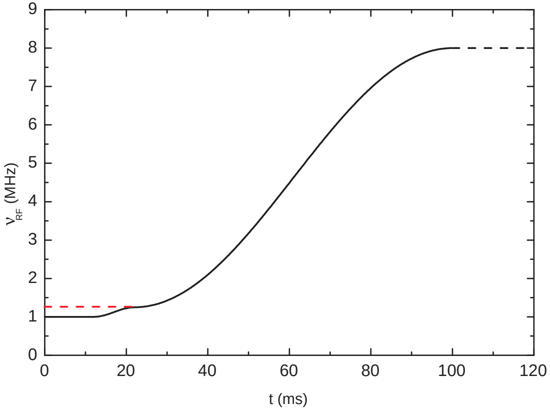
Loading atoms into the radio-frequency trap

Trap loading stage: The energy diagram is plotted at constant rf coupling strength $\frac{\Omega_1}{2\pi} = 180\,\text{kHz}$, for different detunings $\omega_1 - \omega_{min}$:

$\delta = -1.94\,\Omega_1$ (a), $-0.27\,\Omega_1$ (b), $0.83\,\Omega_1$ (c), $3.61\,\Omega_1$ (d)



Typical loading ramp



rf dressed trap oscillation frequencies

- The oscillation frequency in the z direction can be inferred from the coupling strength Ω_1 and the vertical gradient:

$$\omega_\perp = \alpha(z_0)\sqrt{\frac{2\hbar}{M\Omega_1}} \approx 2\pi \times 0.5\,\text{kHz to}\,2\pi \times 1.5\,\text{kHz} \qquad (6)$$

where $\alpha(z_0) = g_F \mu_B b'(z_0)/\hbar$ is the local magnetic gradient in units of frequency.

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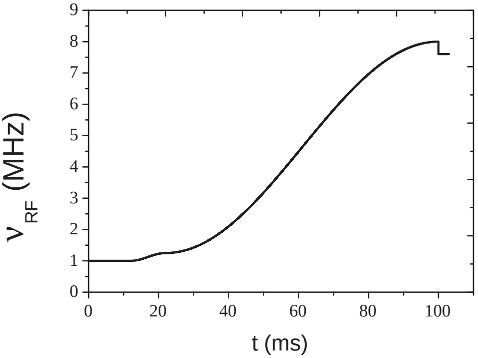
- The horizontal 'pendulum' frequencies ω_{h1} and ω_{h2} corresponding, respectively, to the y and x directions read:

$$\omega_{h1} = \sqrt{\frac{g}{|z_0|}} \approx 2\pi \times 20\,\text{Hz to } 2\pi \times 40\,\text{Hz}, \qquad (7)$$

$$\omega_{h2} = \sqrt{\frac{g}{|z_0|}\frac{\omega_x}{\omega_z}} \approx 2\pi \times 4\,\text{Hz}. \qquad (8)$$

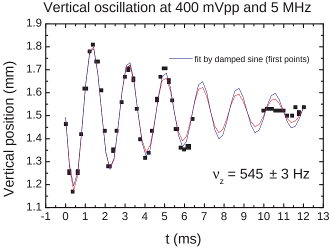
Measurement of the transverse oscillation frequency $\omega_\perp$

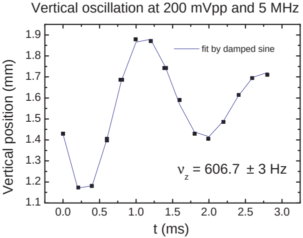
The oscillation frequency in the transverse direction is measured by displacing suddenly the atomic cloud in the vertical direction and recording the oscillation of its centre of mass velocity. This is done by using a rf ramp with a frequency jump:



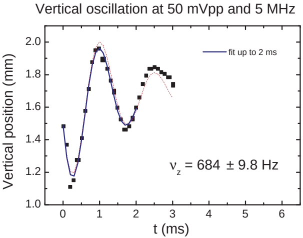
Measurement of the transverse oscillation frequency $\omega_\perp$

(a)





(b)



(c)

Is this a trap for a 2D BEC?

- The typical values for the oscillation frequencies in the rf dressed trap are:
  $\omega_z = 2\pi \times 1\,\mathrm{kHz}$
  $\omega_y = 2\pi \times 20\,\mathrm{Hz}$
  $\omega_x = 2\pi \times 4\,\mathrm{Hz}.$
- The trap is very anisotropic

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  $\omega_z = 2\pi \times 1\,\text{kHz}$
  $\omega_y = 2\pi \times 20\,\text{Hz}$
  $\omega_x = 2\pi \times 4\,\text{Hz}$.
- The trap is very anisotropic
- 2D criterion for a degenerate gas: $N < 400\,000$
- 2D criterion for a thermal gas: $N < 20000$

Conclusion:
Our typical BEC would be in the 2D regime in this trap...
.... if it is still degenerate after the loading procedure.

rf Issues

- Non adiabatic transfer of the atoms from the QUIC trap to the rf dressed trap: the BEC is destroyed.
- Heating could originate from excitations along the transverse direction, due to rf frequency noise, phase jumps...
- A thorough study on the influence of different properties of the rf source on the rf dressed trap is necessary.

- **INFLUENCE OF THE RADIO-FREQUENCY SOURCE PROPERTIES ON THE RF BASED ATOM TRAPS**

Influence of the radio-frequency source properties

Sensitivity to rf defects

The quality of the rf source is very important in the rf based traps as the cloud position is directly linked to the rf trapping frequency. Defects in the rf field inducing atom losses or heating can be:

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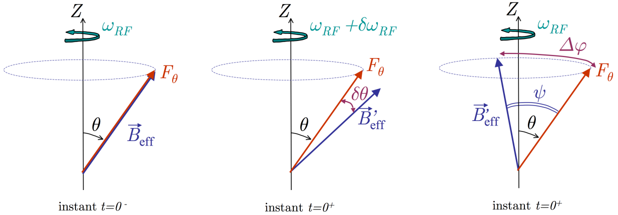
- frequency jumps
- phase jumps
- frequency noise
- amplitude noise



Radio frequency issues

- **Frequency noise: dipolar excitation heating**
  Linear heating rate

$$\dot{E} = \frac{1}{4} M\omega_\perp^4 S_z(\nu_\perp) \propto S_{\mathrm{rel}}(\nu_\perp)$$

For Bose-Einstein condensation experiments, a linear temperature increase below $0.1\,\mu\mathrm{K}\cdot\mathrm{s}^{-1}$ is desirable. This rate corresponds to $S_{\mathrm{rel}}(\nu_\perp) = 118\,\mathrm{dB}\cdot\mathrm{Hz}^{-1}$.

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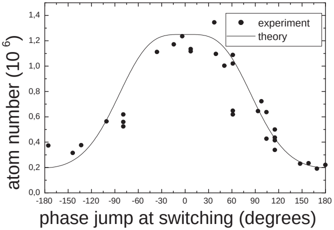
- **Amplitude noise: parametric heating**
  Exponential heating at a rate

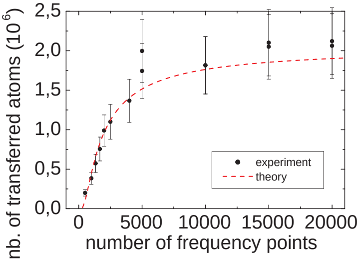
$$\Gamma = \pi^2 \nu_\perp^2 S_a(2\nu_\perp).$$

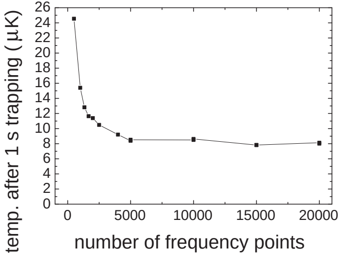
  In order to perform experiments with the BEC within a time scale of a few seconds, Γ should not exceed $10^{-2}\,\mathrm{s}^{-1}$. This rate corresponds to $S_a < -90\,\mathrm{dB}\cdot\mathrm{Hz}^{-1}$.

Results

Phase jumps and **Frequency jumps**

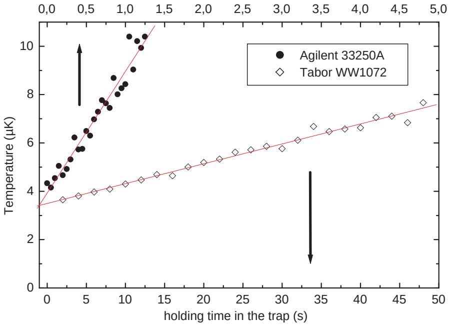






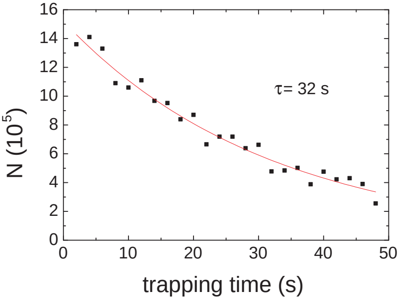
Results

- **Frequency noise** Measurement of the linear heating rate in two configurations:
  1. Agilent 33250A driven by an external voltage $\dot{T} \approx 5\,\mu\mathrm{K/s}$.
  2. Tabor WW1072 DDS $\dot{T} \approx 80\,\mathrm{nK/s}$.



Results

- Life time in the rf dressed trap using the Tabor DDS:



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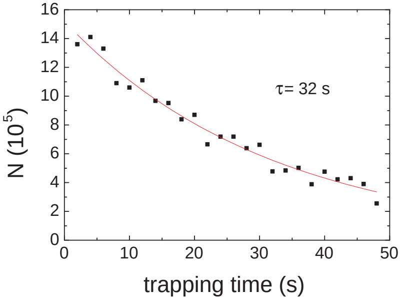

The lifetime reaches 32 s in this situation – before with the Agilent it was 400 ms.

Conclusions

- With the new Tabor synthesizer we could reduce the heating rate and increase dramatically the life time in the rf dressed trap.
- The adiabaticity condition is still difficult to satisfy in the x direction due to the low oscillation frequency in this direction (a few Hz).
- This heating is difficult to avoid and we failed in transferring directly a BEC into the rf dressed trap.
- The long life time and the low heating rate in the rf dressed trap allow the implementation of rf evaporative cooling in the rf dressed trap.
- This can be done by the adjunction of a second rf source, as studied theoretically in our group.

- **SPECTROSCOPY AND EVAPORATIVE COOLING IN A RF DRESSED TRAP**

Spectroscopy and evaporative cooling

Why performing spectroscopy?

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3. Unlike for the case of a static magnetic trap, not only one but multiple resonance frequencies are identified.
4. These transitions are used to induce evaporative cooling in the rf dressed trap.

Hamiltonian for the rf spectroscopy

- In the presence of two rf sources, in the case where $\omega_2 \approx \omega_1$ and the probe rf polarization $\perp$ to Z direction, the Hamiltonian is:

$$H_T(\mathbf{r}, t) = \omega_0(\mathbf{r})\, F_Z + 2\Omega_1 \cos\omega_1 t\, F_X + 2\Omega_2 \cos\omega_2 t\, F_X .$$

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- After a first rotating wave approximation, the Hamiltonian reads:

$$H(\mathbf{r}, t) = H_A(\mathbf{r}) + \Omega_2[\cos(\Delta t) F_X + \sin(\Delta t) F_Y]$$

$\Delta = \omega_2 - \omega_1$ and $H_A(\mathbf{r}) = \Omega(\mathbf{r}) F_\theta$, $|\Delta| \ll \omega_1$.

Hamiltonian for the rf spectroscopy

- In the presence of two rf sources, in the case where $\omega_2 \approx \omega_1$ and the probe rf polarization $\perp$ to Z direction, the Hamiltonian is:

$$H_T(\mathbf{r}, t) = \omega_0(\mathbf{r})\, F_Z + 2\Omega_1 \cos \omega_1 t\, F_X + 2\Omega_2 \cos \omega_2 t\, F_X .$$

- After a first rotating wave approximation, the Hamiltonian reads:

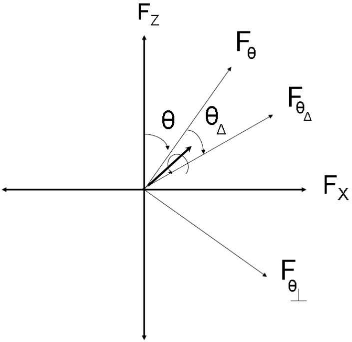
$$H(\mathbf{r}, t) = H_A(\mathbf{r}) + \Omega_2[\cos(\Delta t)F_X + \sin(\Delta t)F_Y]$$

$\Delta = \omega_2 - \omega_1$ and $H_A(\mathbf{r}) = \Omega(\mathbf{r})F_\theta$, $|\Delta| \ll \omega_1$.

- We introduce a rotation at frequency $|\Delta| = \varepsilon\Delta$ around F_θ and apply a 'second rotating wave approximation':

$$H'_A(\mathbf{r}) = -(|\Delta| - \Omega(\mathbf{r}))F_\theta + \frac{\Omega_2}{2}(1 + \varepsilon \cos\theta(\mathbf{r}))F_{\perp\theta} = \Omega_\Delta(\mathbf{r})F_{\theta_\Delta} .$$

Spin evolution



$$F_{\theta_\Delta} = \cos(\theta_\Delta) F_\theta + \sin(\theta_\Delta) F_{\perp\theta}$$

with $\tan(\theta_\Delta) = -\dfrac{\Omega_2[1+\varepsilon\cos\theta(\mathbf{r})]}{2(|\Delta|-\Omega)}$ for $\theta_\Delta \in [0,\pi]$.

Resonant coupling for the rf probe

$E_\Delta = m_F'' \hbar \Omega_\Delta(\mathbf{r})$, where

$$\Omega_\Delta(\mathbf{r}) = \sqrt{(|\Delta| - \Omega(\mathbf{r}))^2 + \frac{\Omega_2^2}{4}(1 + \varepsilon \cos\theta(\mathbf{r}))^2}.$$

m_F'' states are called 'doubly dressed states'.

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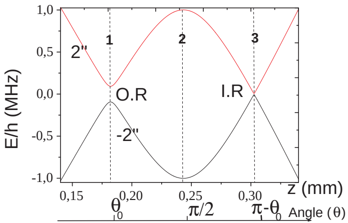

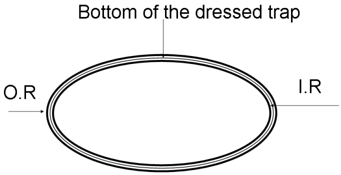

The expected resonances

- **Two resonances around the dressing frequency $\omega_2 \sim \omega_1$:** From the expression of the Hamiltonian, a resonance appears for $|\Delta| = \Omega(\mathbf{r}) \gtrsim \Omega_1$, that is for $\omega_2 \gtrsim \omega_1 + \Omega_1$ $(\Delta > 0)$ or $\omega_2 \lesssim \omega_1 - \Omega_1$ $(\Delta < 0)$.

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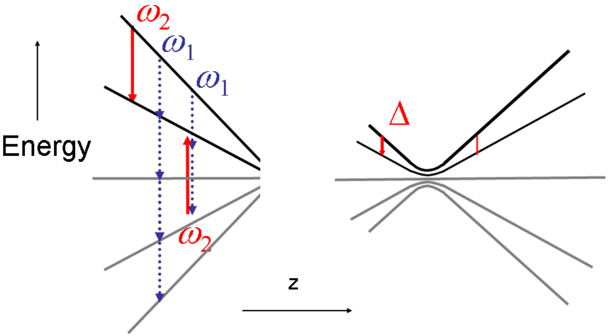
- **One additional low frequency resonance $\omega_2 \sim \Omega_1$:** For a π-polarized coupling *i.e.* if the probe rf field is oriented along the direction of the static magnetic field, we can derive the time independent Hamiltonian

$$H_A'' = (\Omega(\mathbf{r}) - \omega_2) F_\theta + \frac{\Omega_1 \Omega_2}{\omega_2} F_{\theta\perp}.$$

A resonance at $\omega_2 = \Omega(\mathbf{r})$ appears naturally, with a coupling strength $\frac{\Omega_1 \Omega_2}{\omega_2}$.

Interpretation of the resonances in terms of photon transfer



(a)

$\Delta > 0$, $\omega_2 \simeq \omega_1 + \Omega(\mathbf{r})$

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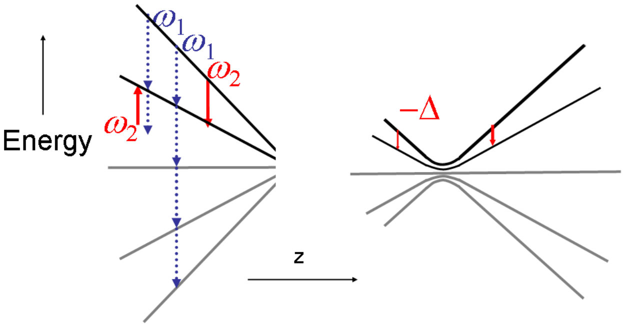

(b)

$\Delta < 0$, $\omega_2 \simeq \omega_1 - \Omega(\mathbf{r})$

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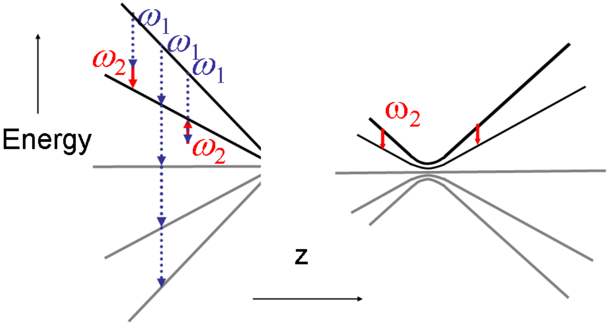
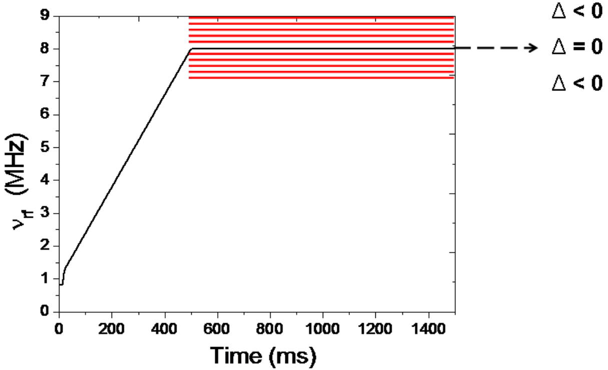


(c)

$\omega_2 \simeq \Omega_1$

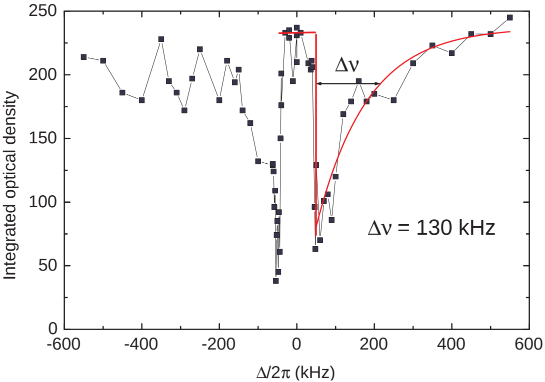
Spectroscopy of the rf-dressed QUIC trap

Time sequence:



Results

Resonances close to dressing rf frequency

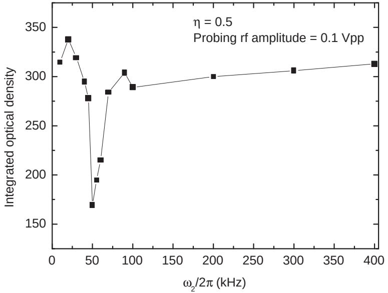


$\eta = 0.5$

The rf attenuator is controlled from the computer using a parameter η between 0 and 1, setting the relative rf amplitude: $\Omega_1 = \eta\Omega_{max}$.

Results

The low frequency resonance:



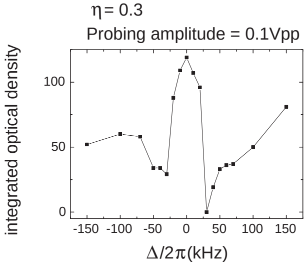
Direct probing of the resonance at $\omega_2 \approx 2\pi\times 50\,\mathrm{kHz}$.

This is an efficient way to measure the rf coupling strength Ω_1.

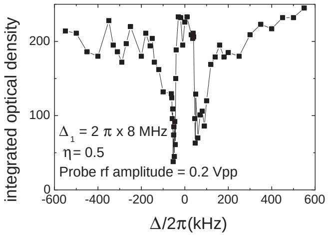
Results

Variation with dressing amplitude

(*a*)



(*b*)



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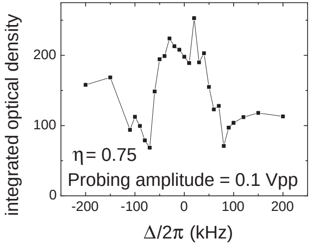

(*a*): $\eta = 0.3,\ \Delta_{res} = \pm 30\,\text{kHz}$
(*b*): $\eta = 0.5,\ \Delta_{res} = \pm 50\,\text{kHz}$
(*c*): $\eta = 0.75,\ \Delta_{res} = \pm 75\,\text{kHz}$

Results
Variation with dressing frequency

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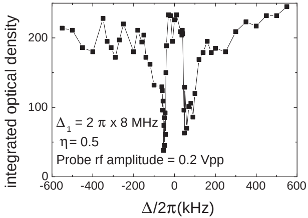

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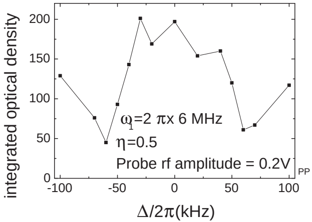
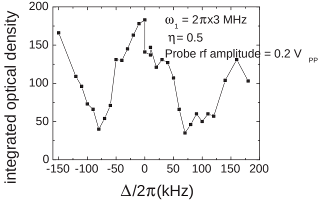


(c)



(a): $\omega_1 = 8\,\text{MHz},\ \Delta_{res} = \pm 50\,\text{kHz}$
(b): $\omega_1 = 6\,\text{MHz},\ \Delta_{res} = \pm 60\,\text{kHz}$
(c): $\omega_1 = 3\,\text{MHz},\ \Delta_{res} = \pm 80\,\text{kHz}$

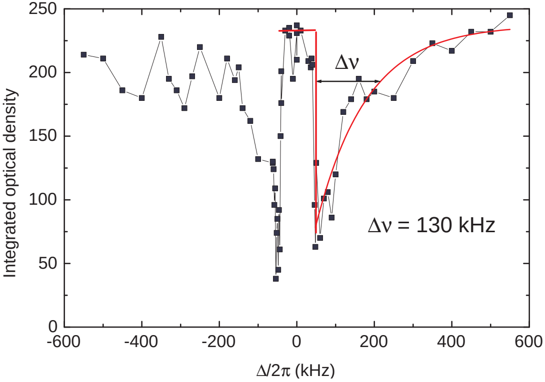
Evaporative cooling in the rf dressed trap

- The rf which was used to probe the spectroscopy is now used to perform evaporative cooling.
- In order to remove dynamically the higher energy atoms a linear rf ramp is applied either around $\omega_1 \pm \Omega_1$ or around Ω_1.
- Evaporative cooling is more efficient close to Ω_1
- This may be due to a more symmetric outcoupling which involves a 2 photon process at both O.R. and I.R.

Results

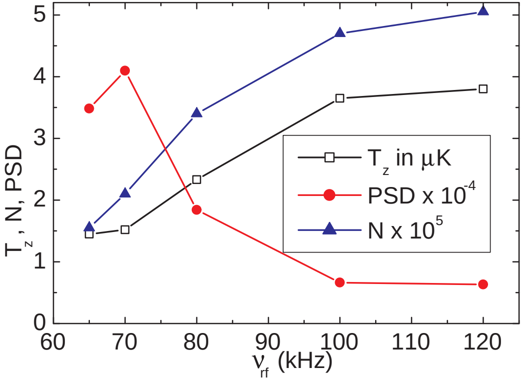
Resonances close to dressing rf frequency

RECALL



$\eta = 0.5$

Results: Evaporative cooling in the rf dressed trap: preliminary results



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- In our case this parameter η_{evap} decreases during evaporation from 6 to 2.5.
- The initial density of $\approx \times 10^{11}\mathrm{cm}^{-3}$ is too low, as well as the $\approx$2 collisions per second, compared to the usual 500 or more collisions per second.

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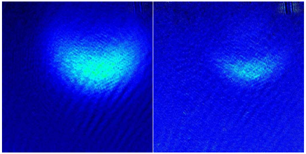
- The horizontal oscillation frequencies are indeed larger in this case.

Atoms in a dressed quadrupolar trap



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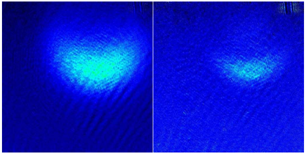

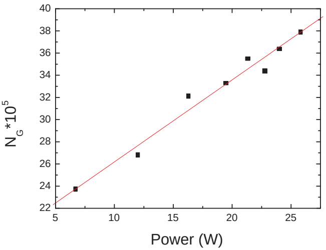

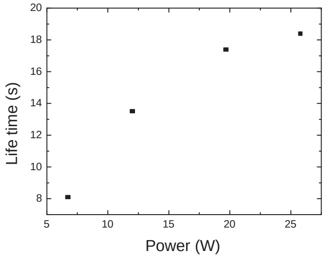

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  2. Improve the initial density in the rf dressed trap
  3. Perform evaporative cooling inside the rf dressed trap

Prospects

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$\Rightarrow$ a renewed experiment is currently under construction!

The end

Thank you for your attention.