Narodowe Laboratorium Technologii Kwantowych

dr Michał Zawada

Opracowanie utworu pod tytułem:

"Diagnostic and imaging of cold atoms" w ramach kursu zaawansowanego, organizowanego dniach 31.08 - 25.09.09 będącego kontynuacją szkoleń z zakresu eksploatacji i zarządzania dużą infrastrukturą badawczą organizowanego przez Narodowe Laboratorium Technologii Kwantowych

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Projekt współfinansowany ze środków Europejskiego Funduszu Rozwoju Regionalnego w ramach Programu Operacjnego Innowacyjna Gospodarka

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Diagnostic and imaging of cold atoms

FAMO
MT BEC GROUP

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How to probe Bose-Einstein condensate

Everything

we know about gaseous Bose-Einstein condensate has been obtained by optical diagnostics

Any contact probe would be way too big!

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How to probe Bose-Einstein condensate

The interaction of atoms with a beam of light:

- spontaneous absorption of photons
- re-emision of photons
- shifting the phase of transmitting light

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How to probe Bose-Einstein condensate

The interaction of atoms with a beam of light:

- spontaneous absorption of photons - absorptive imaging
- re-emision of photons - fluorescence imaging
- shifting the phase of transmitting light - dispersive imaging

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Outline

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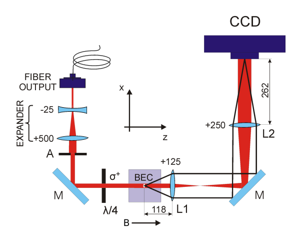
Absorption Imaging



Absorption

is the most prevalent diagnostic, unrivalled in its combination of simplicity and high signal to noise.

The number of atoms, the temperature and the density at each stage of the experiment can be detected by the absorption imaging.

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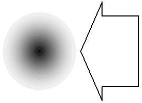
Absorption Imaging - idea



The short pulse

of the resonant laser light is fired into the cloud of atoms.

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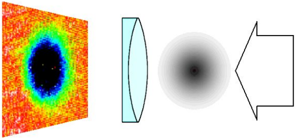

The short pulse

of the resonant laser light is fired into the cloud of atoms.

The cloud of atoms cast the absorption shadow on the CCD camera.

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Absorption Imaging - pros and cons

- Is preety simple
- High signal-to-noise ratio
- Brings plenty of information

- CCD cameras are slow
- Absorption imaging is destructive
- *In situ* imaging is hard or impossible
- Needs considerable optical access

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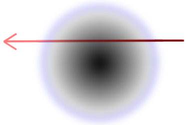
Absorption Imaging - image analysis



Index of refraction of a dilute atomic vapor n_{ref}

is directly related to the atomic density as

$$n_{ref} = 1 + \frac{\sigma_0 n \lambda}{4\pi}\left[\frac{i}{1+\sigma^2} - \frac{\sigma}{1+\sigma^2}\right] \qquad (1)$$

σ_0 is the resonant cross-section, λ is the wavelength of the probe light, and $\sigma = \frac{\omega - \omega_0}{\Gamma/2}$ is the detuning of the probe light from the atomic resonance frequency in half-line widths.

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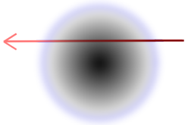

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Multilevel atom

The index of refraction arises from several resonances and will be generally polarisation dependent.

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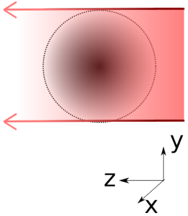


An atomic sample

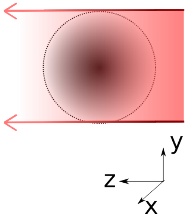
is illuminated uniformly by light propagating in the z direction. The complex electric field $\vec{E}(x, y)$ of the probe light after passage through the atomic sample is changed from $\vec{E}_0$ to

$$\vec{E}(x, y) = \vec{E}_0 \exp\left(-\frac{2\pi i}{\lambda}\int\left[n_{ref} - 1\right] dz\right) \quad (2)$$

$$= t\vec{E}_0 e^{i\phi} \quad (3)$$

t is the transmision and ϕ is the phase shift, both depend on the product of the column density $\tilde{n} = \int ndz$ and σ_0.

Absorption Imaging - image analysis



t is the transmision and ϕ is the phase shift, both depend on the product of the column density $\widetilde{n} = \int ndz$ and σ_0.

$$t = \exp\left(-\frac{\widetilde{n}\sigma_0}{2}\frac{1}{1+\delta^2}\right) = e^{\widetilde{D}/2} \tag{4}$$

$$\phi = -\frac{\widetilde{n}\sigma_0}{2}\frac{\delta}{1+\delta^2} = -\delta\frac{\widetilde{D}}{2} \tag{5}$$

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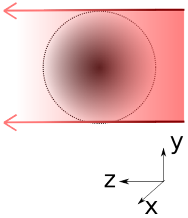

t is the transmission and ϕ is the phase shift, both depend on the product of the column density $\widetilde{n} = \int n dz$ and σ_0.

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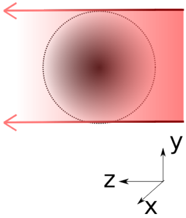
$$\phi = -\frac{\widetilde{n}\sigma_0}{2}\frac{\delta}{1+\delta^2} = -\delta\frac{\widetilde{D}}{2} \tag{5}$$

where

$$\widetilde{D}(x,y) = \frac{\sigma_0}{1+\delta^2}\int n(x,y,z)dz = \frac{\widetilde{n}\sigma_0}{1+\delta^2} \tag{6}$$

is the off-resonance optical density

Absorption Imaging - image analysis



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Because CCD camera photosensors aren't sensitive to phase, the absorption image shows the spatial variation of t^2. Thus $\tilde{D}(x,y) = -\ln t^2$

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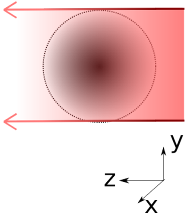

$t^2 \longmapsto$ Intensity I

The change of intensity I in the resonant probe laser beam during propagation through the sample in the z direction can be described as

$$\frac{dI}{dz} = -In\sigma_0 \tag{7}$$

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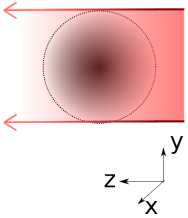

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The change of intensity I in the resonant probe laser beam during propagation through the sample in the z direction can be described as

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For a two-level atom, the cross-section is given by $\sigma_0 = \frac{3}{2}\frac{\lambda^2}{\pi}$

Solving Eq. (7) yields

$$\ln\left(\frac{I_f}{I_i}\right) = -\sigma_0\tilde{n}(x,y) \tag{8}$$

where I_i and I_f are the intesities before and after the sample

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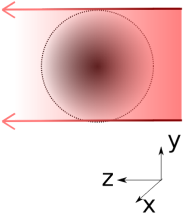
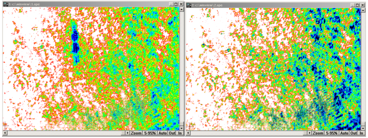
Absorption Imaging - image analysis

Solving Eq. (7) yields $\ln\left(\frac{I_f}{I_i}\right) = -\sigma_0 \tilde{n}(x, y)$.



CCD camera

I_f corresponds to the picture taken with the cloud,
I_i corresponds to the picture taken without the cloud



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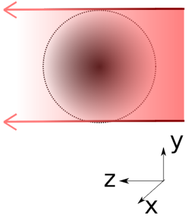

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I_f corresponds to the picture taken with the cloud,
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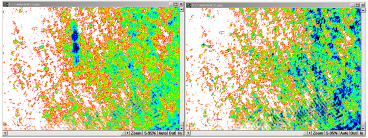
I_d, the dark field picture has to be substracted from both I_f and I



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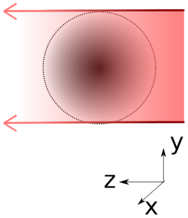

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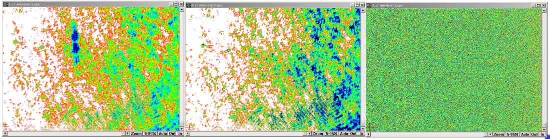
I_d, the dark field picture has to be substracted from both I_f and I

$$\ln\left(\frac{I_f - I_d}{I_i - I_d}\right) = -\sigma_0 \tilde{n}(x, y) \tag{9}$$



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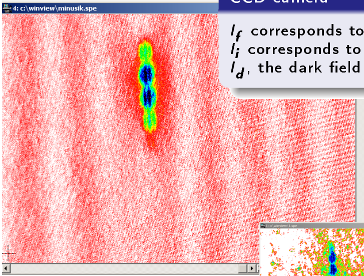

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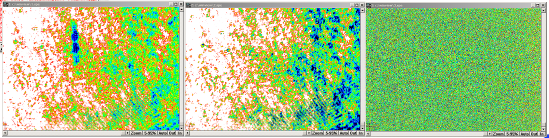

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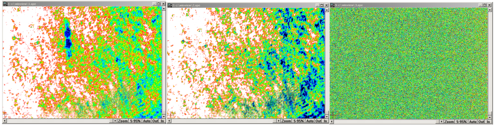
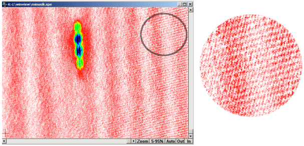
Absorption Imaging - defringing



There are interference fringes on the I_i and I_f pictures. If both the picture are made under the same conditions, the fringes are the same and substract themselves in the final image.



CCD cameras

are generally slow - digitalization of 16 bits pixels takes some time. Few seconds between both pictures is more than enough for the imaging system to fluctuate a bit.

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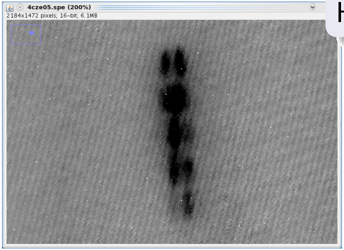
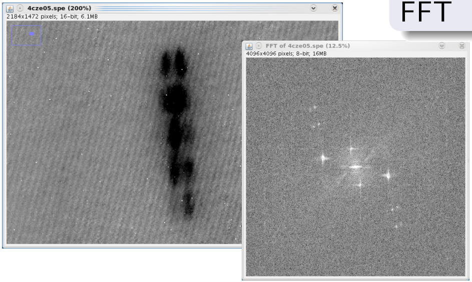


Heavily fringed image

Absorption Imaging - defringing



FFT

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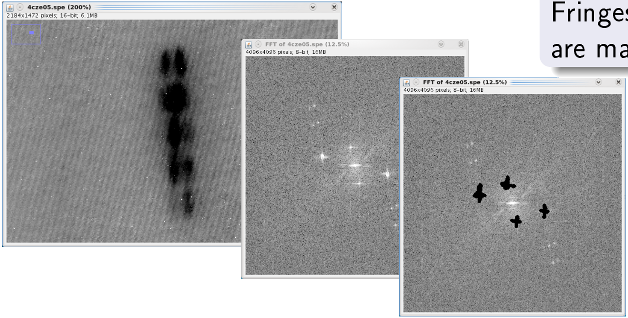

Fringes frequencies are masked.

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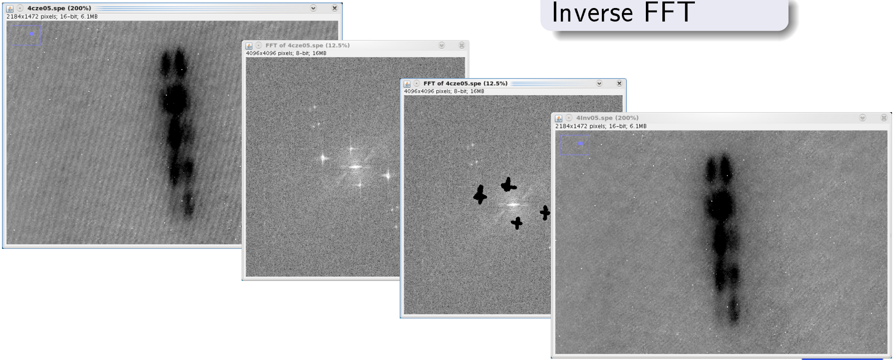
Absorption Imaging - defringing

Inverse FFT



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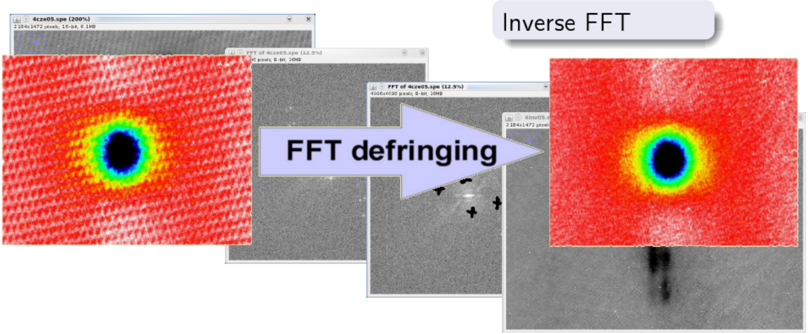

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Absorption Imaging - free-fall expansion

Why not *In situ?*

- Enormous Optical Density
- Detuning reduces OD, but produces nonlinear efects
- Condensate in the trap is very, very small
- Magnetic trap = Zeeman shifts

Advantages of free-fall expansion

- Temperature measurement
- Spatially separate thermal and degenerate clouds

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Absorption Imaging - free-fall expansion

Why not *In situ?*

- Enormous Optical Density
- Detuning reduces OD, but produces nonlinear efects
- Condensate in the trap is very, very small
- Magnetic trap = Zeeman shifts

Advantages of free-fall expansion

- Temperature measurement
- Spatially separate thermal and degenerate clouds

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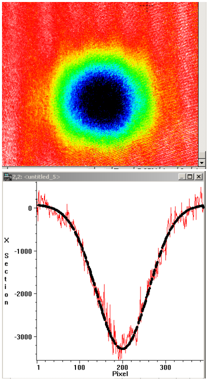
Absorption Imaging - cold atoms



Well above the critical temperature,

the density distribution in the thermal cloud can be described with the classical Boltzmann distribution. The column optical density is described then by the Gaussian function

$$OD_{Gauss}(x,y) = OD_{Gpeak}\ \exp\left[-\frac{1}{2}\left(\frac{x-x_c}{\sigma_x}\right)^2 - \frac{1}{2}\left(\frac{y-y_c}{\sigma_y}\right)^2\right] \quad (10)$$

with σ_x, σ_y being the half-width of the atomic density distribution, OD_{Gpeak} denotes the maximum value of the density, and (x_c, y_c) are spatial coordinates of the maximum.

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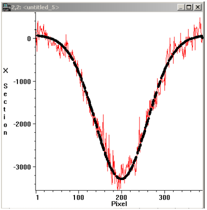

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with σ_x, σ_y being the half-width of the atomic density distribution, OD_{Gpeak} denotes the maximum value of the density, and (x_c, y_c) are spatial coordinates of the maximum.

By fitting the function (10) to the data, number of atoms $N_{th} = (2\pi)^{3/2}\,\frac{OD_{Gpeak}}{\sigma_0}\,\sigma_x^2(t)\sigma_y(t)$ and the initial atomic temperature $T = \frac{2\tau_r^2}{1+3\tau_r^2}T_r + \frac{1+\tau_z^2}{1+3\tau_z^2}T_z$ can be determined (where $T_i = (m/2k_B)\left[\omega_i^2\sigma_i^2(t)/(1+\tau_i^2)\right]$, trap is cigar-shape and $\tau_i = \omega_i t$ for $i = x, y$).

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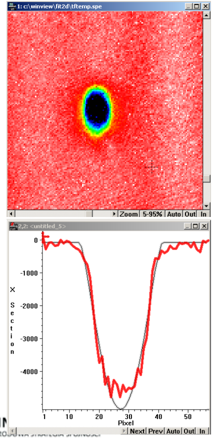
Absorption Imaging - BEC



Well below the critical temperature,

when the BEC is pure and contains big enough number of atoms, the density distribution can be described with the Thomas-Fermi distribution. The column optical density is described by the TF profile, a clipped parabola

$$OD_{TF}(x,y) = OD_{TFpeak} \max\left[0, \left(1 - \left(\frac{x - x_c}{R_x}\right)^2 - \left(\frac{y - y_c}{R_y}\right)^2\right)^{3/2}\right], \tag{11}$$

where R_x, R_y are the TF radii and OD_{TFpeak} denotes maximum of the condensate optical density.

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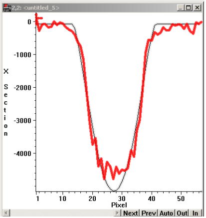

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where R_x, R_y are the TF radii and OD_{TFpeak} denotes maximum of the condensate optical density.

By fitting the function (11) to the data, number of atoms $N_{BEC} = \frac{8}{15}\pi \frac{OD_{TFpeak}}{\sigma_0} R_x^2(t) R_y(t)$ can be determined.

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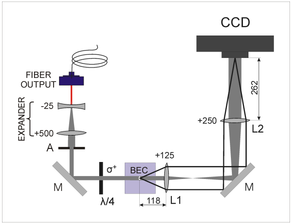
Absorption Imaging - actual realisation



- Beam is spatially filtered by a single-mode fiber
- Beam is expanded by a telescope
- A diaphragm selects the small, central, nost intense and uniform area
- Beam is circularly polarised and a low magnetic field is applied
- The absorption shadow of the sample is imaged throug a telescope onto the CCD camera

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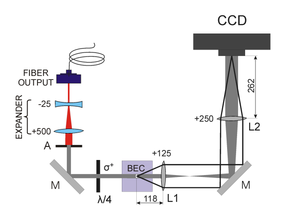

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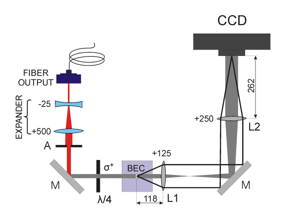

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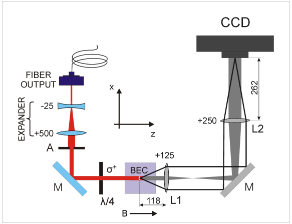

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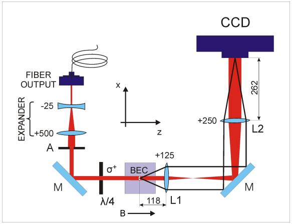

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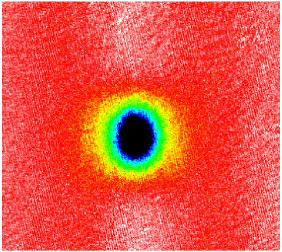
Absorption Imaging - finite temperature BEC

At finite tempetatures,

the BEC fraction is always associated with some fraction of thermal (noncondensed) atoms.
Each of the fractions has different density distribution and contributes differently to the recorded image.



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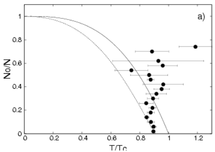

A simplistic analysis of such bimodal distributions by fitting them to a sum of the Gaussian and Thomas-Fermi functions corresponding to the thermal and condensate fractions, respectively, is not satisfactory and leads to systematic errors.

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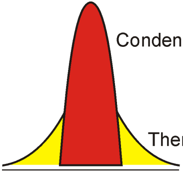

- The temperature is determined from the wings of the thermal distribution
- It is hard to tell where the degenerate region is and where is not
- Close to the T_C, thermal distibution is no longer the Gaussian but the so-called Boose-Enhanced Gaussian

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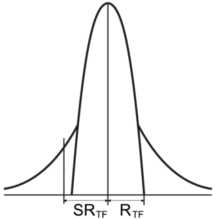

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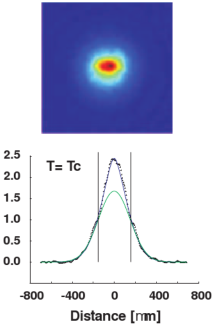

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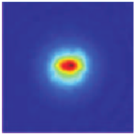
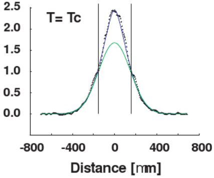
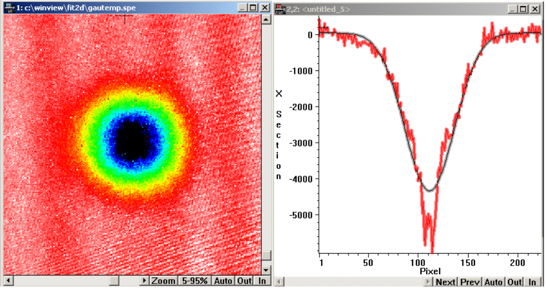




Close to the T_C, thermal distribution is no longer the Gaussian but the so-called Boose-Enhanced Gaussian (with chemical potential set to zero):



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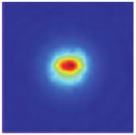

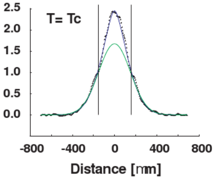

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$$OD_{EnhGauss}(x,y) = OD_{Gpeak} \frac{g_2\left[\exp\left[-\frac{1}{2}\left(\frac{x-x_C}{\sigma_x}\right)^2 - \frac{1}{2}\left(\frac{y-y_C}{\sigma_y}\right)^2\right]\right]}{g_2(1)}, \qquad (12)$$

where $g_2(x) = \sum_{n=1}^{\infty}(x^n)/\left(n^2\right)$ (see, e.g. K. Huang, *Statistical Mechanics*).

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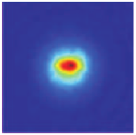

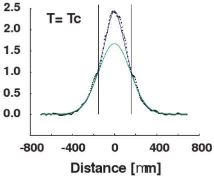

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where $g_2(x) = \sum_{n=1}^{\infty}(x^n)/\left(n^2\right)$ (see, e.g. K. Huang, *Statistical Mechanics*).

With an increase of the distance from the position of maximum density, the series terms in numerator of (12) decrease to zero. At appropriate distance, function (12) becomes the Gauss function (10) which justifies description of the density distribution at edges of the thermal fraction by function (10). Nevertheless, more accurate results are obtained if the first three terms of the series (12) are used instead. Higher terms do not improve meaningly the accuracy but they increase consumption of the computational power.

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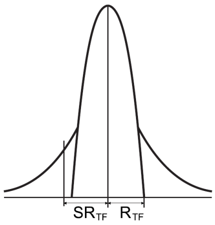
Absorption Imaging - finite temperature BEC



It is hard to tell where the degenerate region is and where is not

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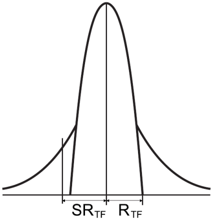

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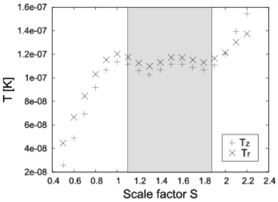

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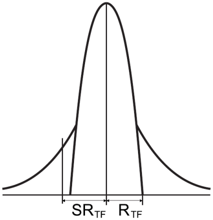

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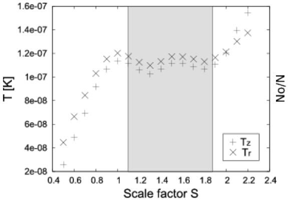

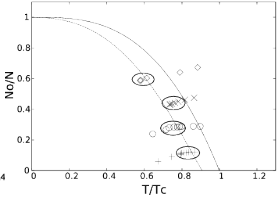

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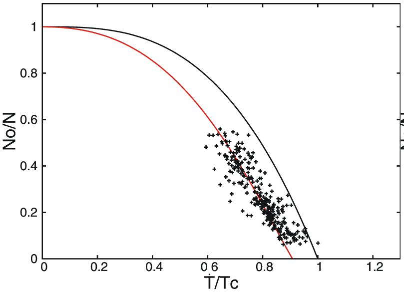
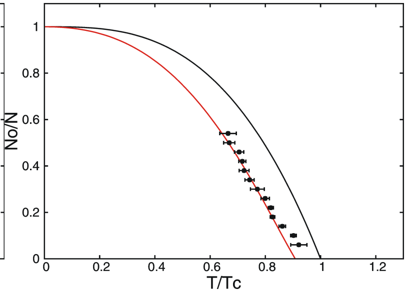
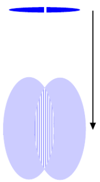


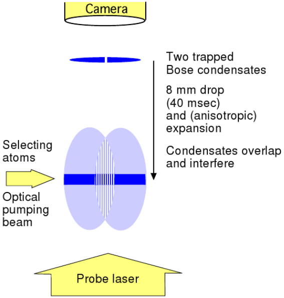


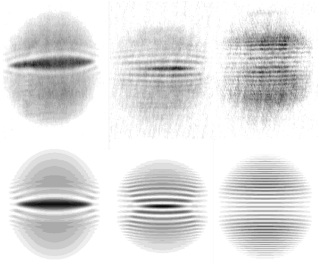
Absorption Imaging - condensate interferometry



- Two BECs expand freerly and overlap
- Do they interfere? - YES!
- Is the interference pattern pattern stable in time and space? - NO!
- If not, how can we see it?

Absorption Imaging - condensate interferometry





Detection

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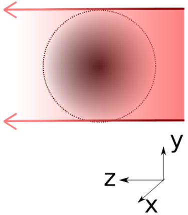
Phase-contrast



t is the transmision and ϕ is the phase shift, both depend on the product of the column density $\tilde{n} = \int ndz$ and σ_0.

$$t = \exp\left(-\frac{\tilde{n}\sigma_0}{2}\frac{1}{1+\delta^2}\right) = e^{\tilde{D}/2} \tag{13}$$

$$\phi = -\frac{\tilde{n}\sigma_0}{2}\frac{\delta}{1+\delta^2} = -\delta\frac{\tilde{D}}{2} \tag{14}$$

where

$$\tilde{D}(x,y) = \frac{\sigma_0}{1+\delta^2}\int n(x,y,z)dz = \frac{\tilde{n}\sigma_0}{1+\delta^2} \tag{15}$$

is the off-resonance optical density

Optical Density can be determined also by phase measurements. But how can we measure the phase?

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Phase-contrast

Absorption imaging is done by illuminating the atoms with a laser beam and imaging the shadow cast by the atoms onto a CCD camera. Because photosensors aren't sensitive to phase, the absorption image shows the spatial variation of t^2

To image a transparent object, information encoded in the phase shift of the light must be converted into intensity information which can be detected by a photosensor.

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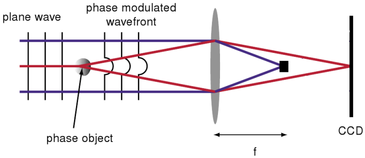

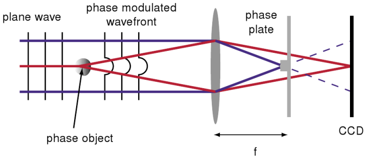

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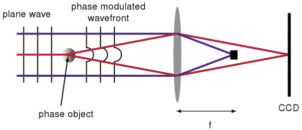
Phase-contrast - Dark Ground imaging

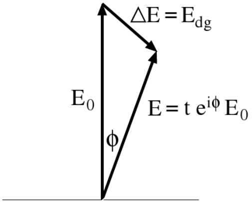


The simplest form of spatial filtering is to block the unscattered light by placing a small opaque object into the Fourier plane

The probe light field after passing through the atoms can be separated into the scattered and unscattered radiation

$$E = tE_0 e^{i\phi} = E_0 + \Delta E \tag{16}$$

Blocking the unscattered light gives the dark-ground signal



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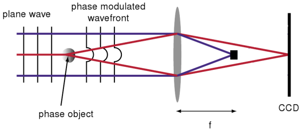

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$$E = tE_0 e^{i\phi} = E_0 + \Delta E \qquad (16)$$

Blocking the unscattered light gives the dark-ground signal

$$\langle I_{dg} \rangle = \frac{1}{2}|E - E_0|^2 = I_0 \left[1 + t^2 - 2t\cos\phi\right] \qquad (17)$$

For small ϕ the dark-ground signal is quadratic in ϕ.

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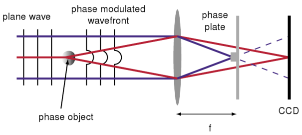
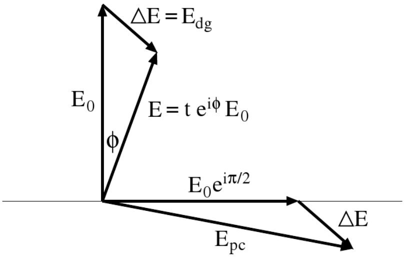
Phase-contrast - Phase Contrast imaging



Phase-contrast imaging is accomplished by shifting the phase of the unscattered light by $\pm\pi/2$ in the Fourier plane of the imaging lens

This is done with a "phase plate" which is an optical flat with a small bump or dimple in the centre.



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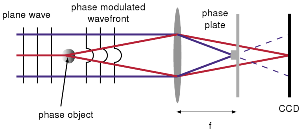

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This is done with a "phase plate" which is an optical flat with a small bump or dimple in the centre.

The intensity of a point in the image plane is then

$$\langle I_{pc} \rangle = \frac{1}{2} |E + E_0 \left(e^{\pm i \frac{\pi}{2}} - 1\right)|^2 = I_0 \left[2 + t^2 - 2\sqrt{2} t \cos\left(\phi \pm \frac{\pi}{4}\right)\right] \quad (18)$$

For small ϕ one obtains $\langle I_{pc} \rangle \simeq I_0 \left[t^2 + 2 - 2t \pm 2t\phi\right]$

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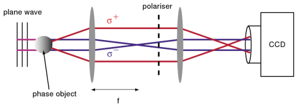
Phase-contrast - Polarisation Contrast imaging



Linearly polarised light with both σ^- and σ^+

components is incident on the con- densate. In the presence of high magnetic fields, the degeneracy of the transitions excited by these components is lifted, and the detuning can be chosen so that only one component interacts with a transition.

In the diagram, this is the σ^+ component. The polariser is rotated to either block out the unscattered light, or to cause the two polarisations to interfere.

This method is not universally applicable. *E.g.* the standard imaging geometry for a Ioffe-Pritchard trap involves a probe beam propagating perpendicular to the axis of a **low** magnetic bias field.

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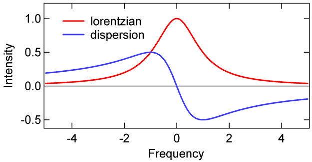
Phase-contrast - Non-destructive measurements



Optical detection of the condensate causes heating through photon absorption and spontaneous emission

- Phase-contrast imaging is indeed less destructive than an absorptive technique for an optically thick cloud such as a BEC.
- Using phase-contrast, multiple images of the same condensate can be taken.
- There is a catch. Phase contrast imaging is slow, because in its current incarnation, it relies on a CCD camera.

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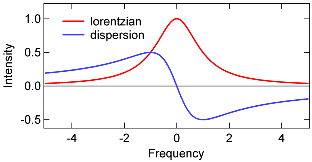

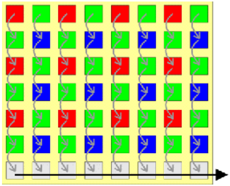

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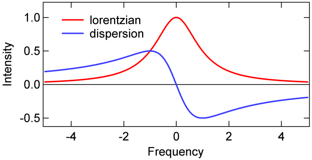

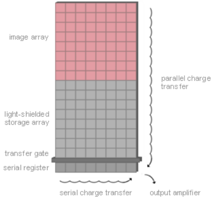

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Even utilizing frame-transfer, which can take sequential pictures at rates of kHz, only a maximum of approximately 20 images can be stored, and the time lag to downloading the data for feedback is on the order of seconds with the current technology.

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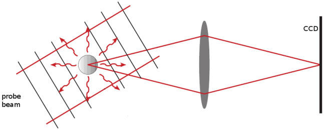
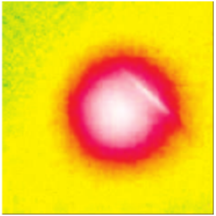
Fluorescence





Fluorescence is a technique that has several advantages over absorption

- It does not require optical access right through the glass cell
- Absence of interference fringes

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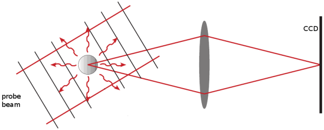

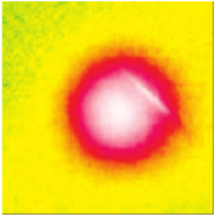

Fluorescence is a technique that has several advantages over absorption

- It does not require optical access right through the glass cell
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But

- It not self-calibrating
- In optically thick samples, only the fluorescence from the outer shell of the cloud will reach the camera without reabsorption.

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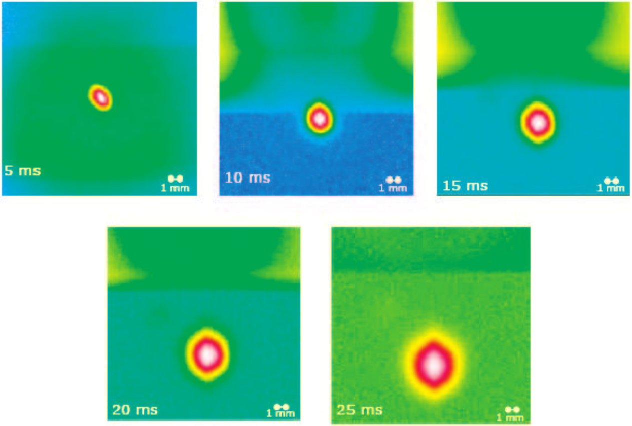
Fluorescence - temperature measurement



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Outline

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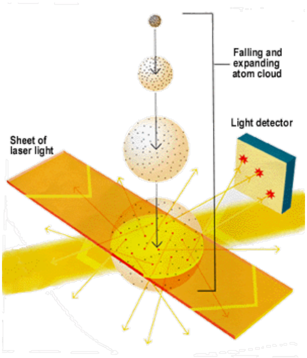
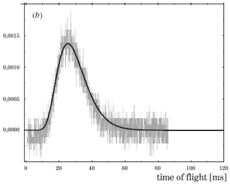
Time of flight



The so-called time-of-flight (TOF)

measurements are performed either by acquiring the absorption signal of the probe laser beam through the falling and expanding atomic cloud, or by measuring the fluorescence of the atoms excited by the resonant probe light.



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Time of flight

Maxwell distribution gives $\exp\left(-\frac{v^2}{2\langle v^2\rangle}\right) = \exp\left(-\frac{mv^2}{2k_B T}\right)$

thus the temperature in a MOT $T = \frac{m}{k_B}\left\langle v^2\right\rangle$

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Distribution of v and t in the distance y below the trap center:$0 = gt\Delta t + \Delta v_0 t + \langle v_0\rangle \Delta t$
Since $\langle v_0\rangle = 0$ in the trap,

$$\Delta v_0 = -g\Delta t \tag{19}$$

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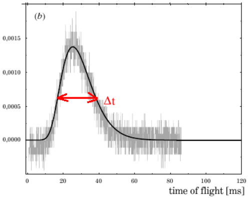

$$T = \frac{m}{k_B}(g\Delta t)^2$$

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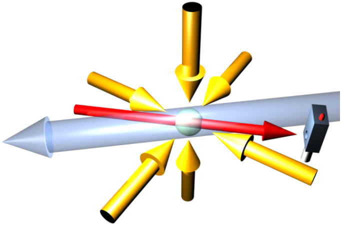
Pump-probe spectroscopy in an operating trap



Geometry

- yellow = mot beams
- blue = pump beam
- red = probe beam, frequency-scanned around the pump beam

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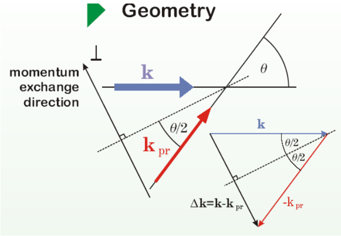
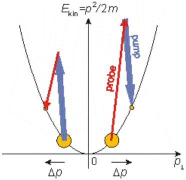
Recoil-Induced Resonances (RIR)



Raman transitions between the atomic momentum states. The resonance occurs whenever the probe-pump detuning coincides with the kinetic energy difference and results in atomic momentum change Δp.



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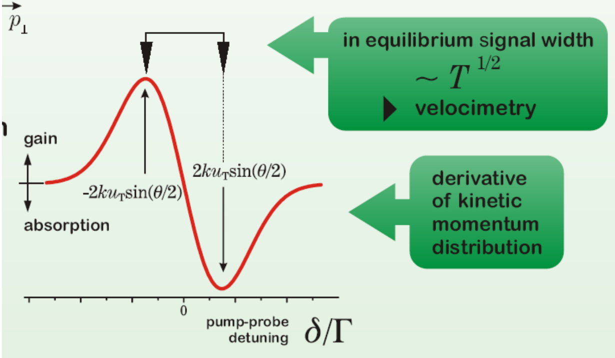
Recoil-Induced Resonances (RIR)

Probe beam transmission



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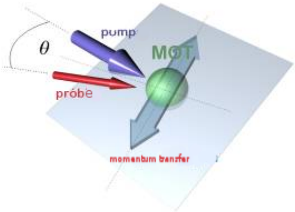

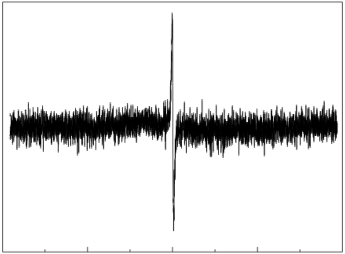

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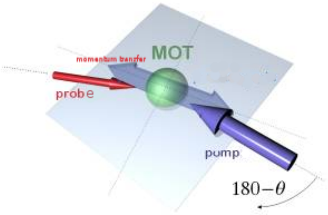

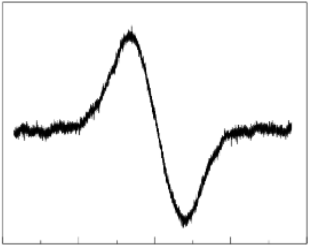

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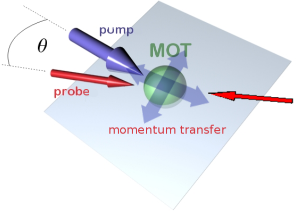

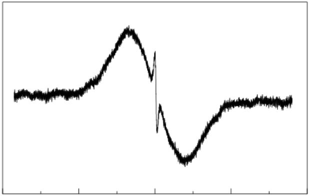

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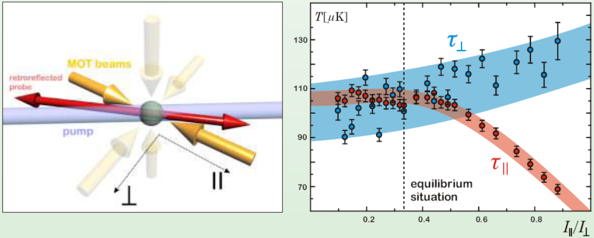
RIR + 1D MOT

uneven partition of the MOT beam intensities:



first observation of the anisotropy of momentum distribution in a MOT

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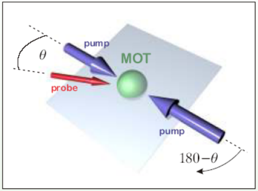
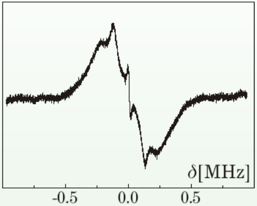
RIR + lattice

Retroreflected pump beam

- narrow and wide RIR signal + optical lattice signal





Advantages:

- simultaneous determination of momentum distributions in two perpendicular directions
- 1D optical lattice in a MOT
  co-existence of free and localized atoms

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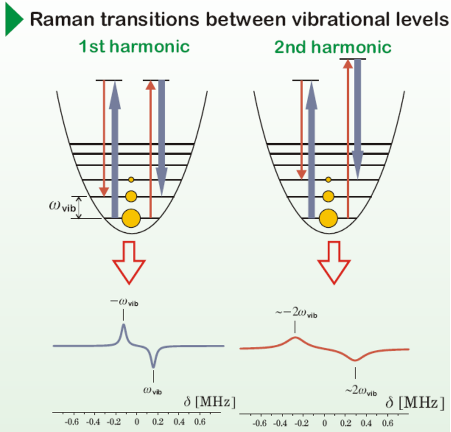
RIR + lattice



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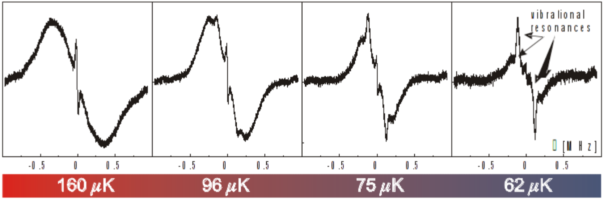

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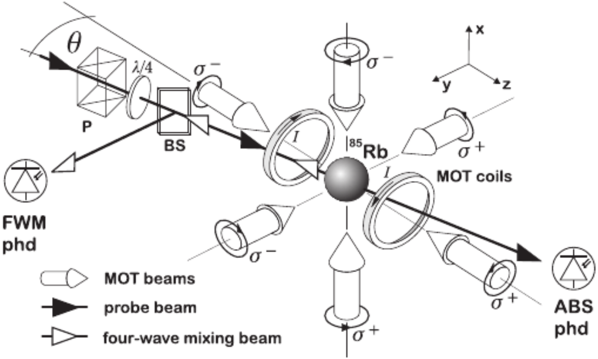
Four Wave Mixing (FWM)



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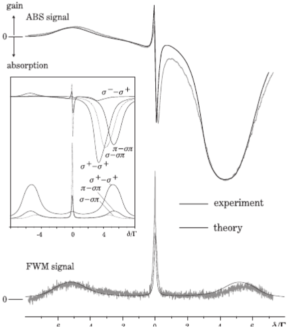

Experimental absorption (ABS) and four-wave mixing (FWM) spectra (grey lines) and their theoretical modeling (black lines).

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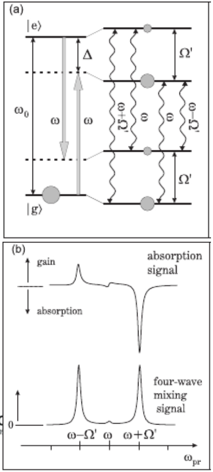
Four Wave Mixing (FWM)



a Two-level atom dressed by photons of monochromatic laser field of frequency ω, red-detuned by δ from atomic transition frequency ω_0 . Wavy arrows indicate possible transitions between dressed levels, sizes of the grey circles symbolize populations of the respective levels

b Absorption and four-wave mixing spectra as a function of the probe beam detuning, ω_{pr}

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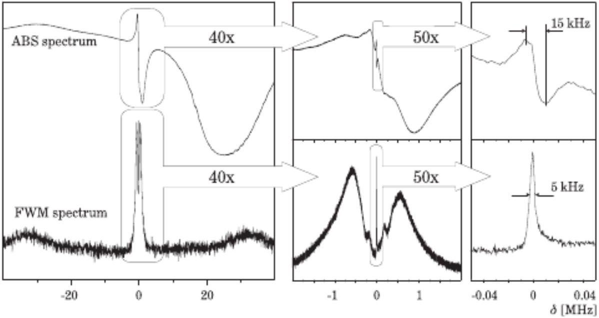

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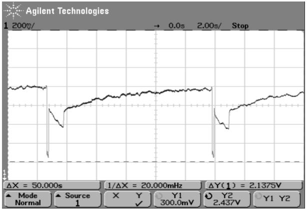
Release and recapture (RR)



Trapped cloud in a mot can be described by a thermal gas

$$dN_{gas}(v) = N_0 \exp\left(= \frac{v^2}{2\tilde{v}^2} \right) \qquad (20)$$

with $\tilde{v}^2 = \left\langle v^2 \right\rangle$ and temperature $T = \frac{m}{k_B}\tilde{v}^2$

The atom velocity, as we allready know, can be measured by releasing trapped atoms by turning off the trapping lasers and observe the time evolution of the expansion of the cloud.

Atoms are loaded into the MOT. At the time t = 0 the trapping laser beams are switched off. In the dark the atomic cloud starts to expand. The trapping and slowing laser beams are turned on again at the time $\Delta t = t_{off}$. Atoms which remain in the trapping volume are recaptured and drift back to the trap center.

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Release and recapture (RR)

The distance, $r(t)$, of an atom from the trap center increases with time t as $r(t) = vt$
The spatial distribution of the cloud of atoms is found by substituting the velocity v with the radius $r(t)$ in Eqn. (20).

$$dN_{gas}(r) = \sqrt{\frac{2}{\pi}} \frac{r(t)^2}{t^3 \tilde{v}^3} \exp\left(-\frac{r(t)^2}{2t^2\tilde{v}^2}\right) dr \tag{21}$$

The fraction, $f(r_0; t_{off})$, of atoms remaining within a volume of radius r_0 can be obtained by integrating Eqn. (21)

$$f(r_0; t_{off}) = \int_0^{r_0} \frac{dN_{gas}(r)}{dr} d^3 r \tag{22}$$

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$$f(r_0; t_{off}) = \int_0^{r_0} \frac{dN_{gas}(r)}{dr} d^3 r = \text{erf}\left(\frac{r_o^2}{\sqrt{(}2)t_{off}\tilde{v}}\right) - \sqrt{\frac{2}{\pi}} \frac{r_0}{t_{off}\tilde{v}} \exp\left(-\frac{r_0^2}{2t_{off}^2\tilde{v}^2}\right) \tag{22}$$

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Parametric resonance

With proper analysis, TOF and RR methods give very precise results. However, they are destructive as they lead to the loss of cold atomic sample. There are some nondestructive methods.

For example, one can rely on the balance between kinetic (thermal) and potential energy of atoms in the trapped gas:

$$k_B T = k \left\langle x^2 \right\rangle$$

where k is the spring constant of the trapping pottential and $\left\langle x^2 \right\rangle$ is a mean square of the atomic position relative to the trap center.

Measuring this distance (equivalent to the cloud extension) and calculating constant k from the independent measurement of atomic oscillation in the trap, one can easily calculate the cloud temperature without switching off the trap

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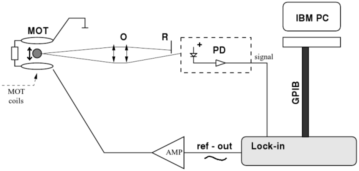
Parametric resonance



- $k = m\omega_0^2$
- An external periodic force $F = F_0 \cos(\omega t)$ is applied to the cloud
- The cloud can be described as 1D, driven, damped harmonic oscillator $F = m\ddot{x} - \alpha\dot{x} - kx$
- The solution is $x(t) = A(\omega)\cos(\omega t - \phi(\omega))$
- $\phi(\omega)) = \arctan\left(\frac{\alpha\omega}{k - m\omega^2}\right) = \arctan\left(\frac{\gamma\omega}{\omega_0^2 - \omega^2}\right)$

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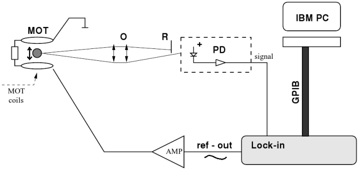

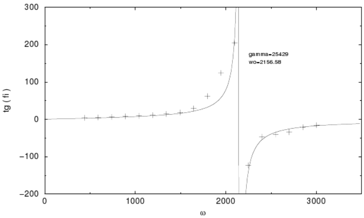

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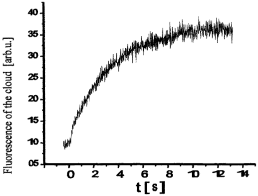
Studies of the cold atoms collisions

When an atomic sample reaches temperatures of about 1 mK or lower, the atomic movement becomes extremely slow. In such conditions, the collisions between atoms and their corresponding interactions last much longer than in standard temperatures. It allows high sensitivity studies of very weak atomic interactions



The collision rates or cross-sections are determined by analysis of the fluorescence signal emitted by atoms during the trap loading. After the trap switch on the processes of slowing and trapping compete with the heating and escaping of atoms due to collisions. This competition is reflected onto the evolution of the number of trapped atoms N, which can be described by the following equation

$$\frac{dN}{dt} = L - \alpha N - \beta \frac{N^2}{V} \tag{23}$$

where L denotes the trap loading rate, V is its volume, and α and β denote the rates of collisions of cold atoms with hot atom background and with other cold atoms, respectively.

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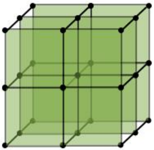
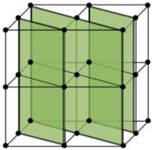
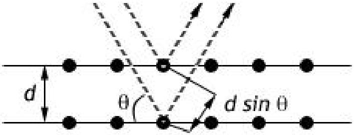
Bragg diffraction



When x-rays are scattered from a crystal lattice, peaks of scattered intensity are observed which correspond to the following conditions:

- The angle of incidence = angle of scattering.
- The pathlength difference is equal to an integer number of wavelengths.





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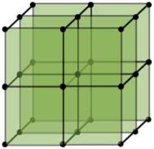

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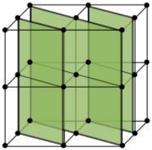

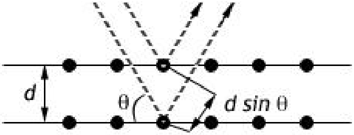

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The Bragg's low: $2d \sin\theta = n\lambda$

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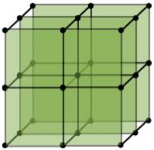
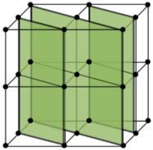
Bragg diffraction





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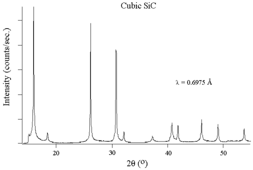

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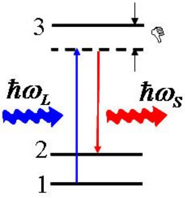
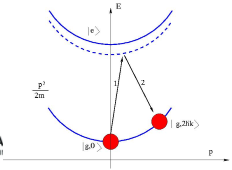
RIR revisited



Raman transitions between the atomic momentum states. The resonance occurs whenever the probe-pump detuning coincides with the kinetic energy difference and results in atomic momentum change Δp.



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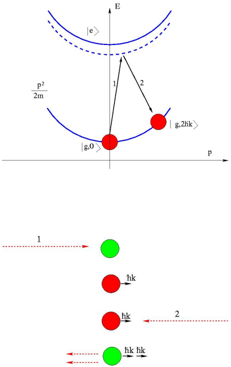

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Both absorption and stimulated emission change the atomic momentum by $\hbar k$

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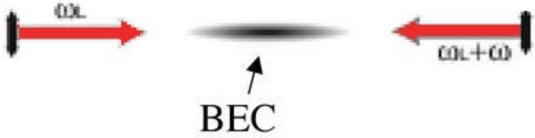
Bragg (RIR) and BEC



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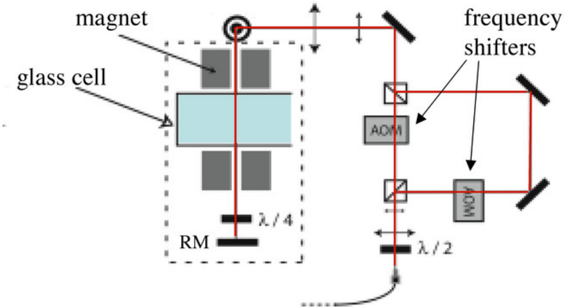
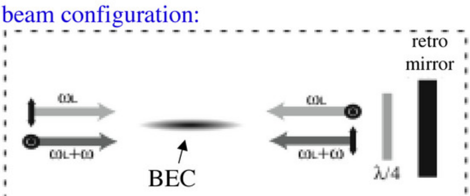
Bragg (RIR) and BEC- experiment





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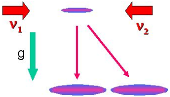
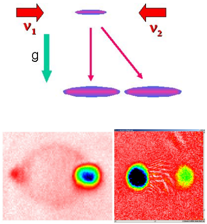
Bragg - BEC



Part of the BEC is coherently moved to the other momentum state. This can be seen in the free-fall expasion.

Bragg - BEC



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Two momentum states of the same groud state.

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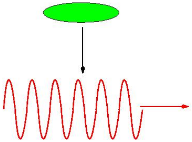
Why the "Bragg scattering"?



Two counter-propagating laser beams with relative detuning $\Delta\nu$ creates a moving, optical standing wave in the laboratory frame. The velocity of the lattice is equal to $v = \lambda\Delta\nu/2$.

The velocity depeds on $\Delta\nu$

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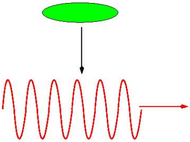

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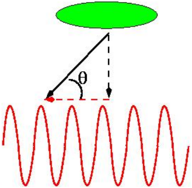

In a frame moving with respect to the laboratory frame, were the lattice is standing still, the condensate hits the lattice at some angle. The angle depends on v, therefore it also depends on $\Delta\nu$

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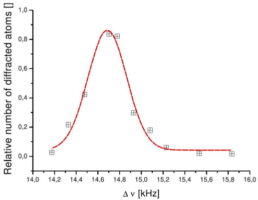
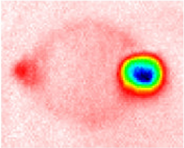
Bragg spectroscopy

Bragg spectroscopy – dependence of the relative number in the scattered condensate on the detuning $\Delta\nu$.

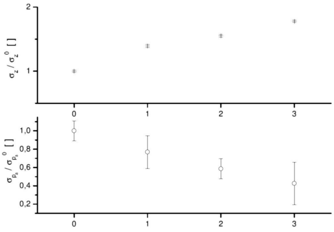




The shape of this resonance corresponds to the momentum distribution of BEC. Direct measurement of the momentum distribution of the condensate wave function

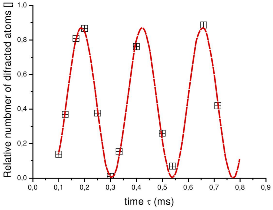
Quadrature squeezing of the BEC

Bragg spectrosopy can be used e.q. to detect squeezed states of the condensate wave function



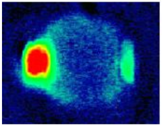
When the uncertainty of momentum is reduced, the uncertainty of position grows

Rabi oscillations

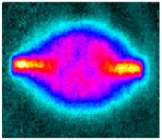


Varying the duration of the Bragg lasers pulse one can detect oscillations of the number of atoms in the scattered condensate. These oscillations are nothing else than the Rabi oscillations $\Omega = V_{dip}/(2\hbar)$.

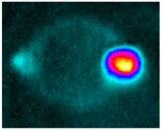
$\Omega' t < \pi/2$



$\Omega' t = \pi/2$



$\Omega' t \approx \pi$



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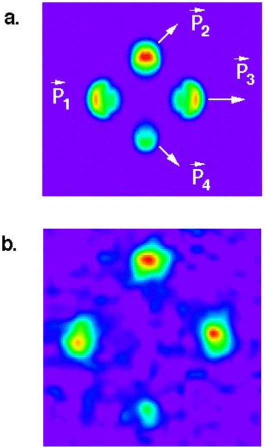
Four wave mixing



Bragg diffraction can be treated as a colision of two wave packets

$\vec{p_1}$ is the original codensate

Two perpenducular Bragg diffractions produces two scattered condensates $\vec{p_2}$ i $\vec{p_4}$. Additionally, the fourt condensate appears, $\vec{p_3}$ in the process analogous to the FWM.

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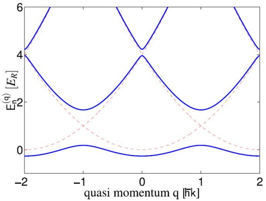
Bloch band formalism



Band structure theory orginates from a study of the electron motion in a crystal lattice

In the periodic potential the atom-latice system has an

energy spectrum that exhibits a band structure

Propagation of a particle with mass m in a one dimensionalperiodic potential is identicalto propagation of a free particle with effective mass defined as m^*

$$m^*_{n,q} = \hbar^2 \left(\frac{\partial^2 E_{n,q}}{\partial q^2} \right)^{-1}$$

and velocity in the lattice rest frame (Bloch velocity)

$$v_{n,q} = \frac{1}{\hbar} \frac{\partial E_{n,q}}{\partial q}$$

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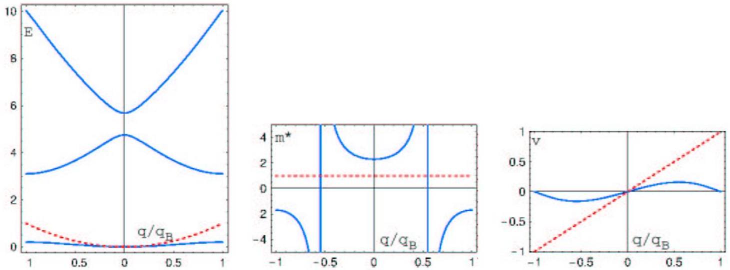
First Brillouin zone



(a) Energy bands (b) Effective mass (c) Velocity

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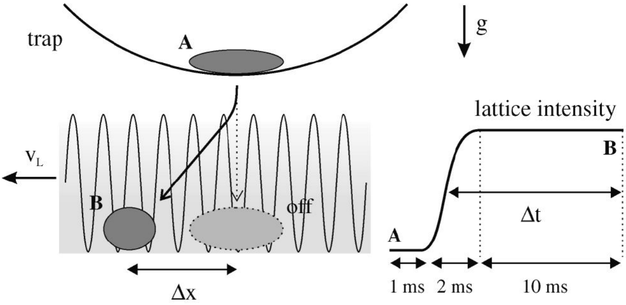
Bloch states and a BEC



BEC is loaded into adiabatically switched on optical lattice

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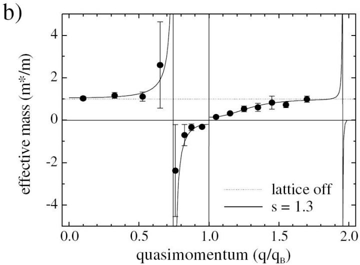
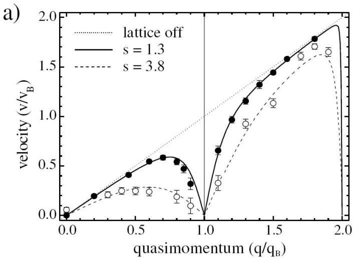
Bloch states and a BEC - single-particle-like effects



effective mass



velocity in the moving lattice frame

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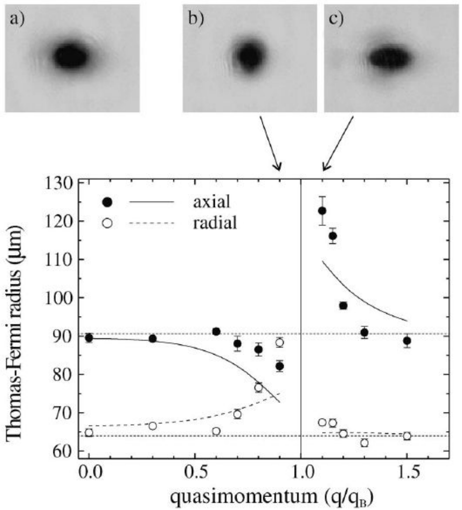
Lensing effet on the BEC



Tuning the effective mass of the condensate allows to focus or desfocus the BEC

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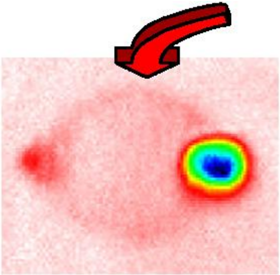
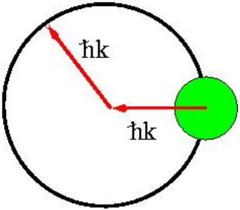
Two condensates colide





Two condensates colide - atoms in the condensates collide

Spherically symemtric s-wave scattering is the dominant type of interactions

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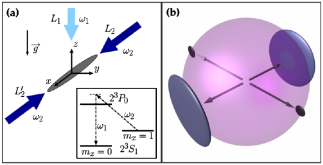
Elastic scattering losses from colliding Bose-Einstein condensates



Transition from spontaneous to stimulated scattering - Spontaneous Four-Wave Mixing

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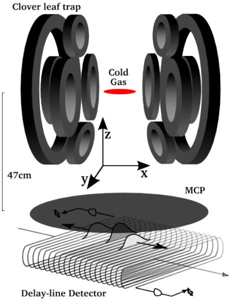

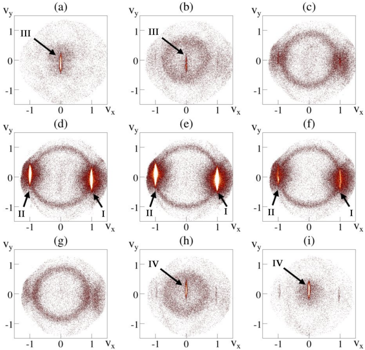

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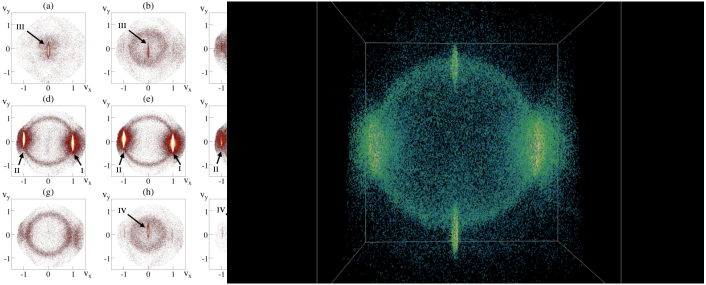

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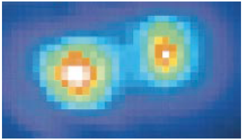
Spinor condensates



First spinor condensates, JILA 1996

$F = 1, m_F = -1$ and $F = 2, m_F = 2$

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Spinor condensates

GP equations:

$$-\frac{\hbar^2}{2m_1}\nabla^2\psi_1 + V_1(\mathbf{r})\psi_1 + U_{11}|\psi_1|^2\psi_1 + U_{12}|\psi_2|^2\psi_1 = \mu_1\psi_1$$

$$-\frac{\hbar^2}{2m_2}\nabla^2\psi_2 + V_2(\mathbf{r})\psi_2 + U_{22}|\psi_2|^2\psi_2 + U_{12}|\psi_1|^2\psi_2 = \mu_2\psi_2$$

equilibrium: $U_{11} > 0, \quad U_{22} > 0, \qquad U_{11} - \frac{U_{12}^2}{U_{22}} > 0$

$$n_1 = \frac{U_{22}(\mu_1 - V_1) - U_{12}(\mu_2 - V_2)}{U_{11}U_{22} - U_{12}^2}$$

$$n_2 = \frac{U_{11}(\mu_2 - V_2) - U_{12}(\mu_1 - V_1)}{U_{11}U_{22} - U_{12}^2}$$

Thomas-Fermi approx.

$$\begin{aligned} V_1(\mathbf{r}) &= m_1\omega_1^2 r^2/2 \\ V_2(\mathbf{r}) &= m_2\omega_2^2 r^2/2 \end{aligned} \qquad n_2 = \frac{\mu_2}{U_{22}}\left(1 - \frac{r^2}{R_2^2}\right)$$

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$$n_1 = \frac{U_{22}(\mu_1 - V_1) - U_{12}(\mu_2 - V_2)}{U_{11}U_{22} - U_{12}^2}$$

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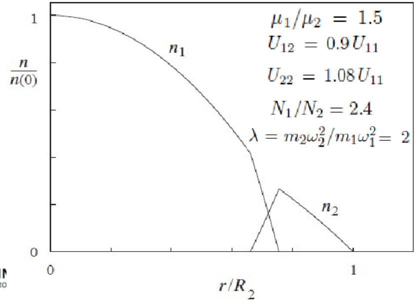
$$V_1(\mathbf{r}) = m_1\omega_1^2 r^2/2 \qquad n_2 = \frac{\mu_2}{U_{22}}\left(1 - \frac{r^2}{R_2^2}\right)$$
$$V_2(\mathbf{r}) = m_2\omega_2^2 r^2/2$$

Thomas-Fermi approx.



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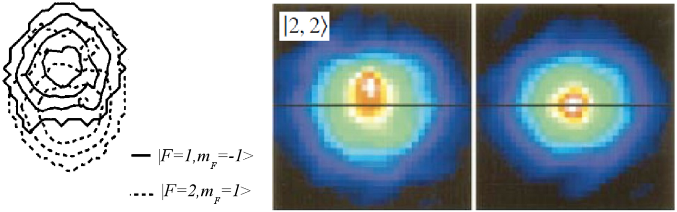
Spinor condensates



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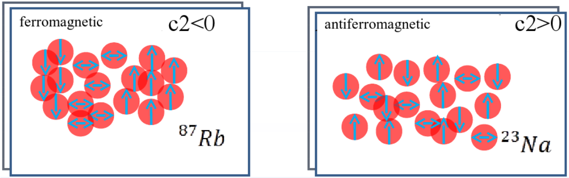
Spinor condensates - spin domains

$$c_2 = 4\pi\hbar^2(a_2 - a_0)/3m$$



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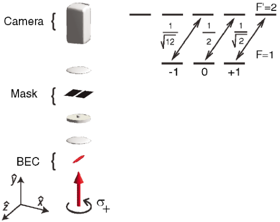
Spinor condensates - spin domains



- ^{87}Rb BEC is prepared in the dipole trap in the $|F=1, m_F=0>$ state
- spin dependent energy per particle: $c_2 n < \vec{\hat{F}} >^2 + q < \hat{F}_z^2 >$, where $\vec{\hat{F}}$ denotes the dimensionless spin vector operator.
- $c_2 = (4\pi\hbar^2/3m)(a_2 - a_0) < 0$ and $q = (h \times 70Hz/G^2)B^2$ is the quadratic Zeeman shift
- BEC is prepared at a high quadratic Zeeman shift $(q \gg 2|c_2|n)$
- By rapidly reducing the magnitude of the applied magneticfield, the system is quenched to conditions in which the ferromagnetic phase is energetically favored $(q \ll 2|c_2|n)$
- At variable times T_{hold} after the quench, high-resolution maps of the magnetization vector density were obtained using magnetization - sensitive phase contrast imaging

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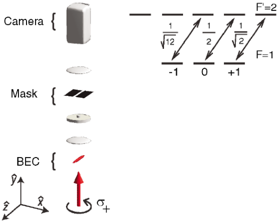
Spinor condensates - spin domains



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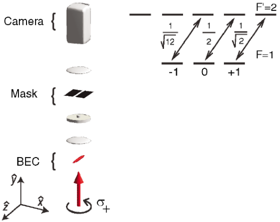
Spinor condensates - spin domains



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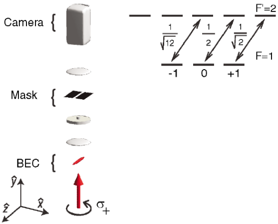
Spinor condensates - spin domains



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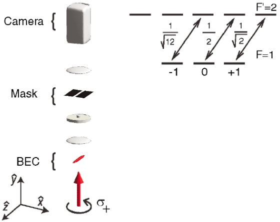

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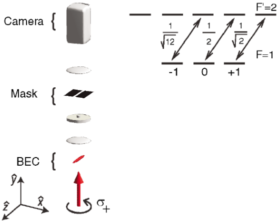

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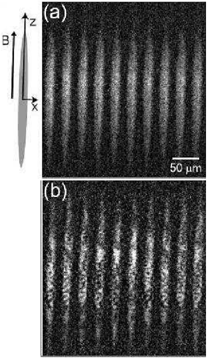

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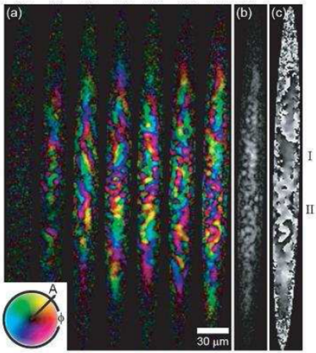

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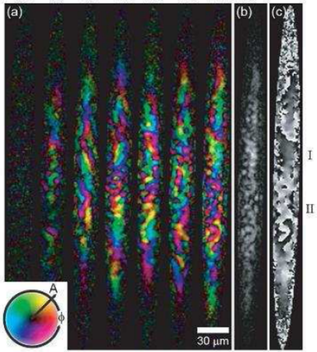

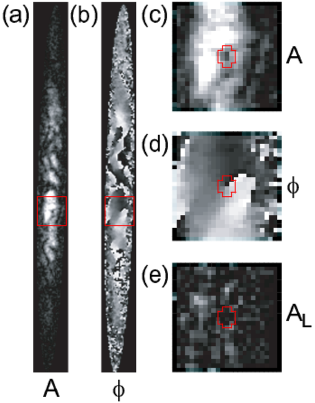

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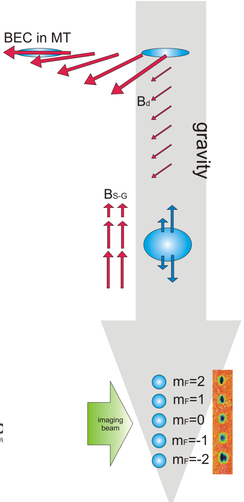
Stern-Gerlach detection



The field of the magnetic trap is adiabatically replaced by a homogeneous, weak magnetic field B_d in a given direction.

Atoms start to fall freely under gravity and their spins follow the magnetic field direction.

After a given time of free fall expansion (1-20 ms), the MT field is nonadiabatically pulsed for duration of 1-2 ms.
The atomic spins are projected on the direction of the strong gradient of the magnetic field (B_{SG}).

The Stern-Gerlach force separates the condensates.

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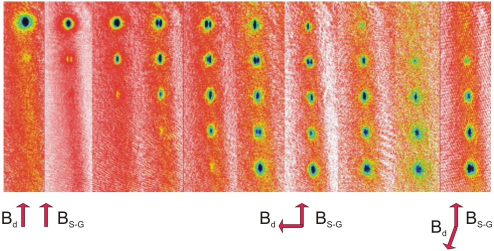
Population control



Absorption images of the spinor condensates expanded by the Stern-Gerlach force taken for different orientation of the B_d vs the B_{SG} field.

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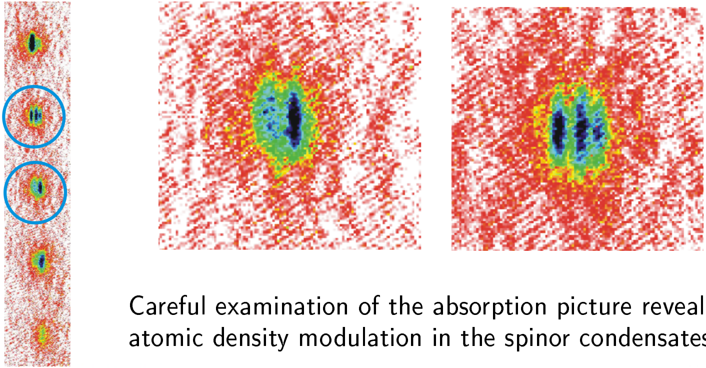
Spatial modulation – spinor domains



Careful examination of the absorption picture reveals atomic density modulation in the spinor condensates.

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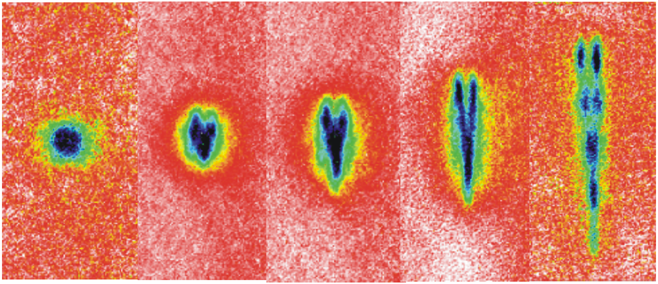
Spatial modulation – spinor domains



Absorption images of the spinor condensates taken during their separation after the Stern-Gerlach pulse.

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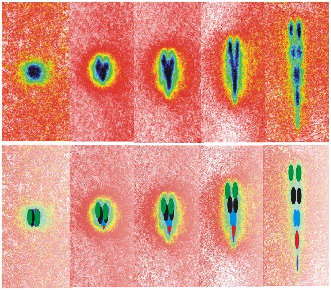
Spatial modulation – spinor domains



The spatial modulation of the spinor condensates is most likely caused by the presence of spin domains before the B_{SG} field.

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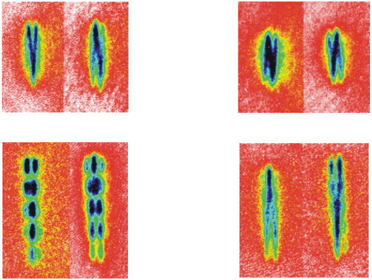
Spatial modulation – spinor domains



The modulation, i.e. the position of spin domains varies under constant experimental conditions.

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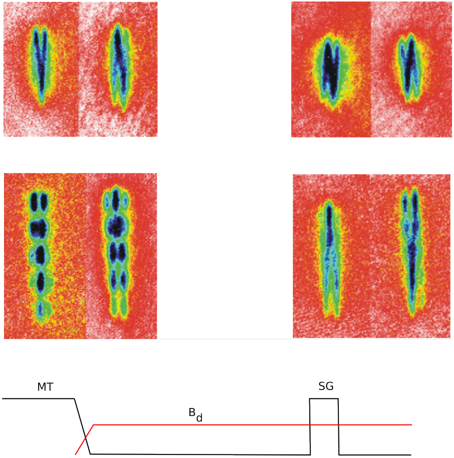
Spatial modulation instability – preliminary results



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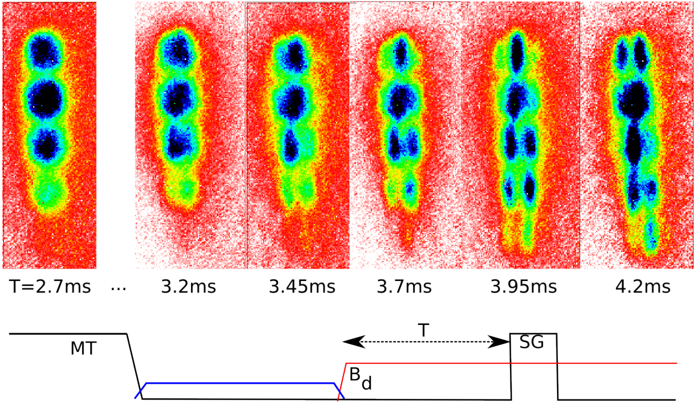
Spatial modulation – spinor domains



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Colective oscillations (cigar trap)

	BEC superfluid	ideal gas collisional	ideal gas collisionless
m=0 radial	$2\omega_\perp$	$\sqrt{10/3}\omega_\perp$	$2\omega_\perp$
m=0 axial	$\sqrt{5/2}\omega_z$	$\sqrt{12/5}\omega_z$	$2\omega_z$
m=2,-2 radial	$\sqrt{2}\omega_\perp$	$\sqrt{2}\omega_\perp$	$2\omega_\perp$

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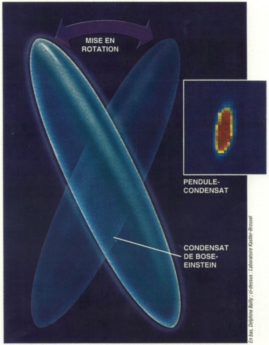
Scissors mode



Scissors mode above T_c: the gas oscillates with frequencies $\omega_x \pm \omega_y$

Scissors mode below T_c: the superfluid oscillates with frequency $\sqrt{\omega_x^2 + \omega_y^2}$

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UNIA EUROPEJSKA
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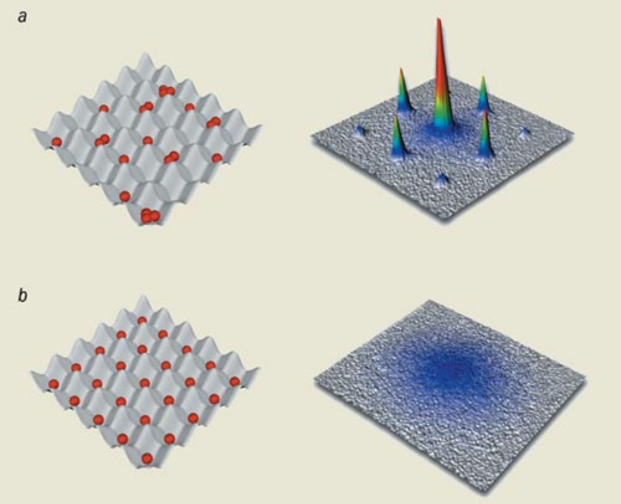
ROZWOJU REGIONALNEGO

Mott insulator - superfluid transition



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