The 10th US-Japan Joint Seminar

Fundamental Issues and Applications of Ultracold Atoms and Molecules

Experimental study of atomic Bose-Einstein condensates with internal degrees of freedom

Department of Physics,
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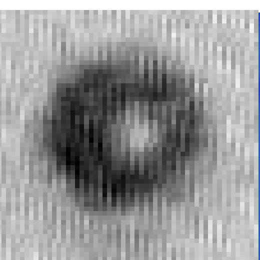
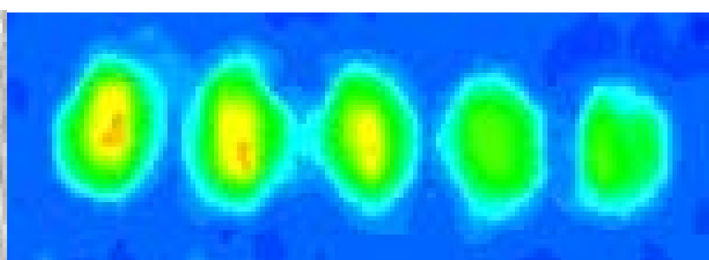
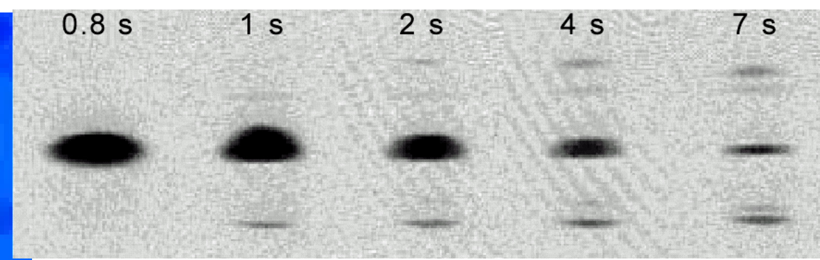
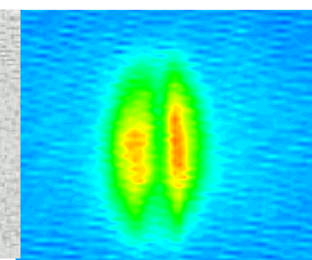




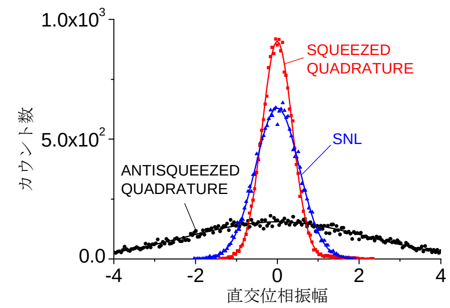


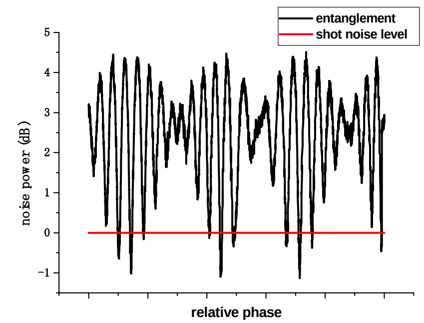


Experimental Quantum Optics Group at Gakushuin Univ.

Members

Prof.	T. Hirano
Res. Assoc.	S. Tojo (April 2006～)
Post. Doc.	Yun Zhang (March 2006～)
D1	Y. Eto,
M2	K. Ishihara, M. Iwata, K. Sirasaki, T. Tajima, T. Furuta
M1	S. Tokunaga, A. Furuki
B4	R. Okubo, Y. Sanada, M. Tamaki, A. Tomiyama, K. Nagashima, T. Hayashi

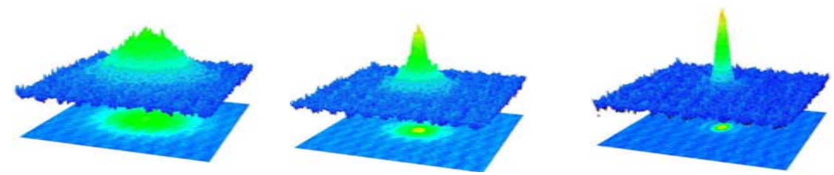




Topics

- BEC of Rb atoms
- Contineous-variable (CV) quantum information using pulsed light
  - Quantum cryptography using pulsed homodyne detection
    - "Plug & play" and free-space implementation at telecommunication. wavelength
  - CV quantum entanglement with pulsed light
  - Pulsed squeezing at telecomm. wavelength

Outline



1. Motivation
2. Experimental apparatus
3. Atomic BEC with internal degrees of freedom
    - Dynamical Properties of ^{87}Rb Spin-2 BEC
    - Optical Confinement of Binary BEC: simultaneous trap of F=1 and F=2
    - Vortex Formation via magnetic field reversal

Thanks to former members: T. Kuwamoto, H. Usuda, K. Hamazaki, Y. Nara

4. Summary

Motivations

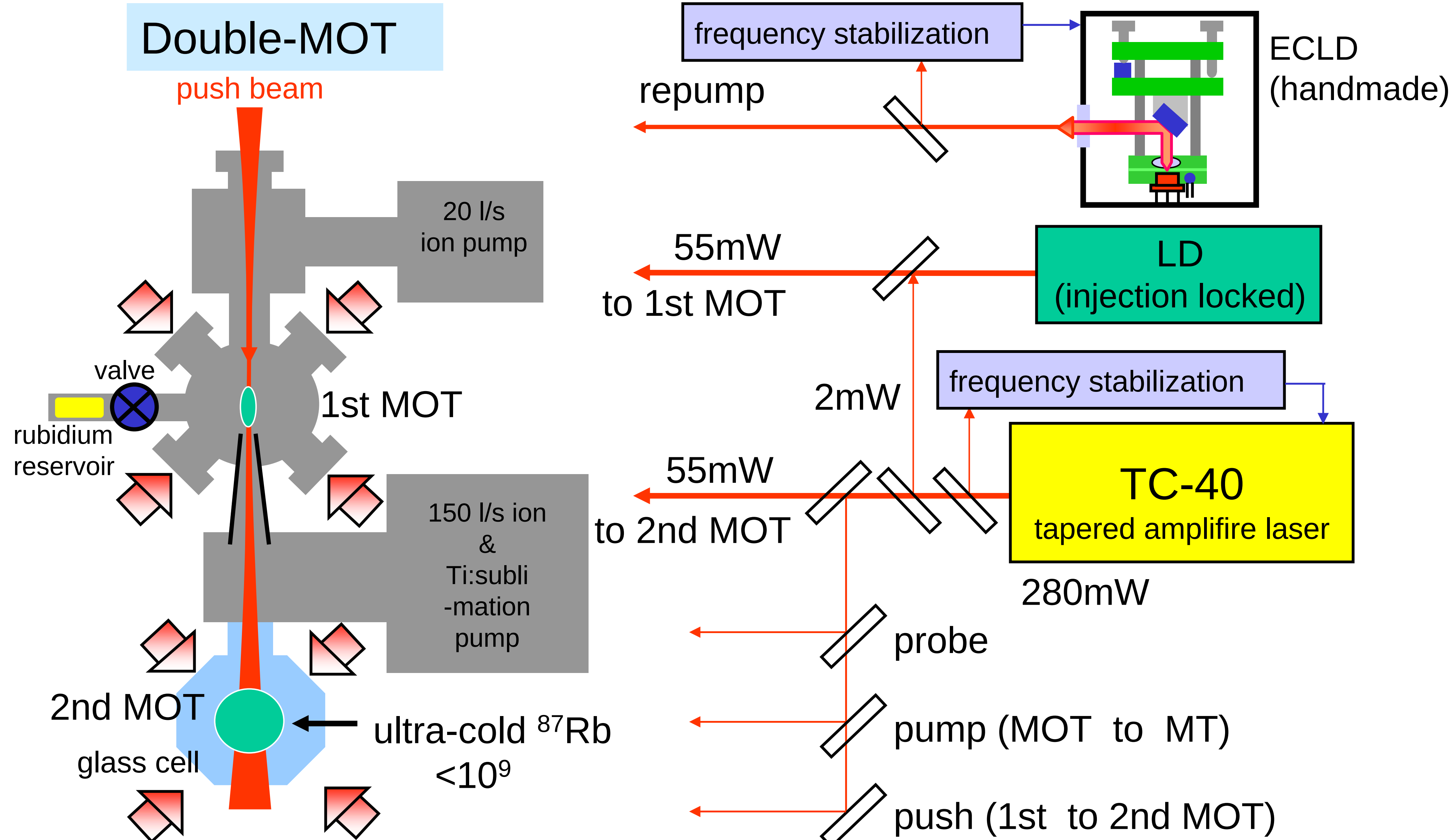
Spin degrees of freedom F=2 spinor condensate

- Is ground state of ^{87}Rb ferro, anti-ferro, or cyclic states?
- Mixture of F=1 & F=2 spinor BEC
- Vortex states in spinor BEC
- etc…

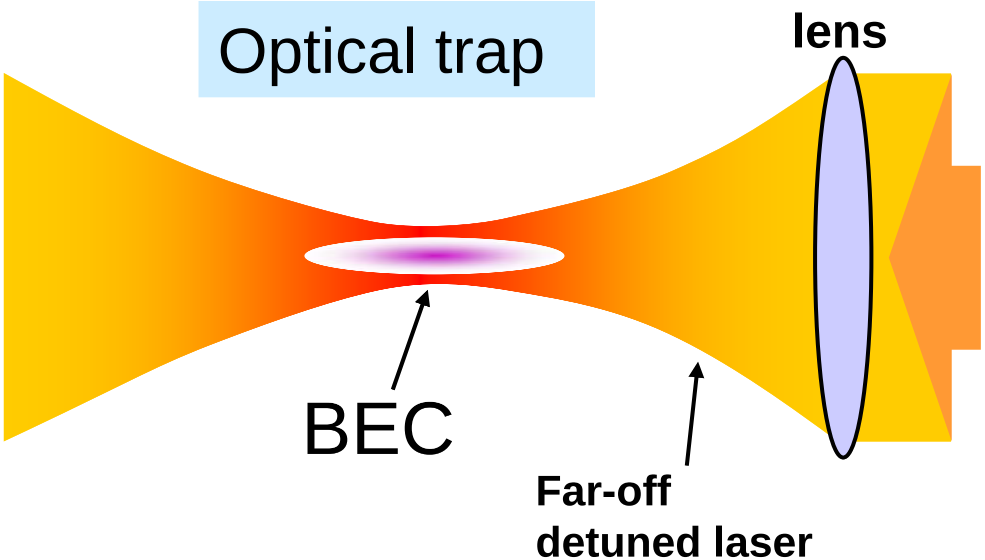
⇓

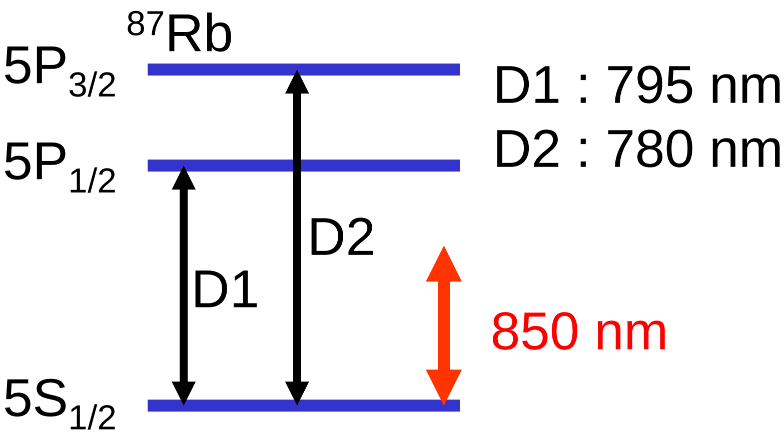
Novel Physics in Quantum Fluids with spin Degree of Freedom

Experimental setup (1)



Atoms in an optical trap





Optical trap potential

$$U = -\frac{1}{2}\alpha \cdot |E|^2$$

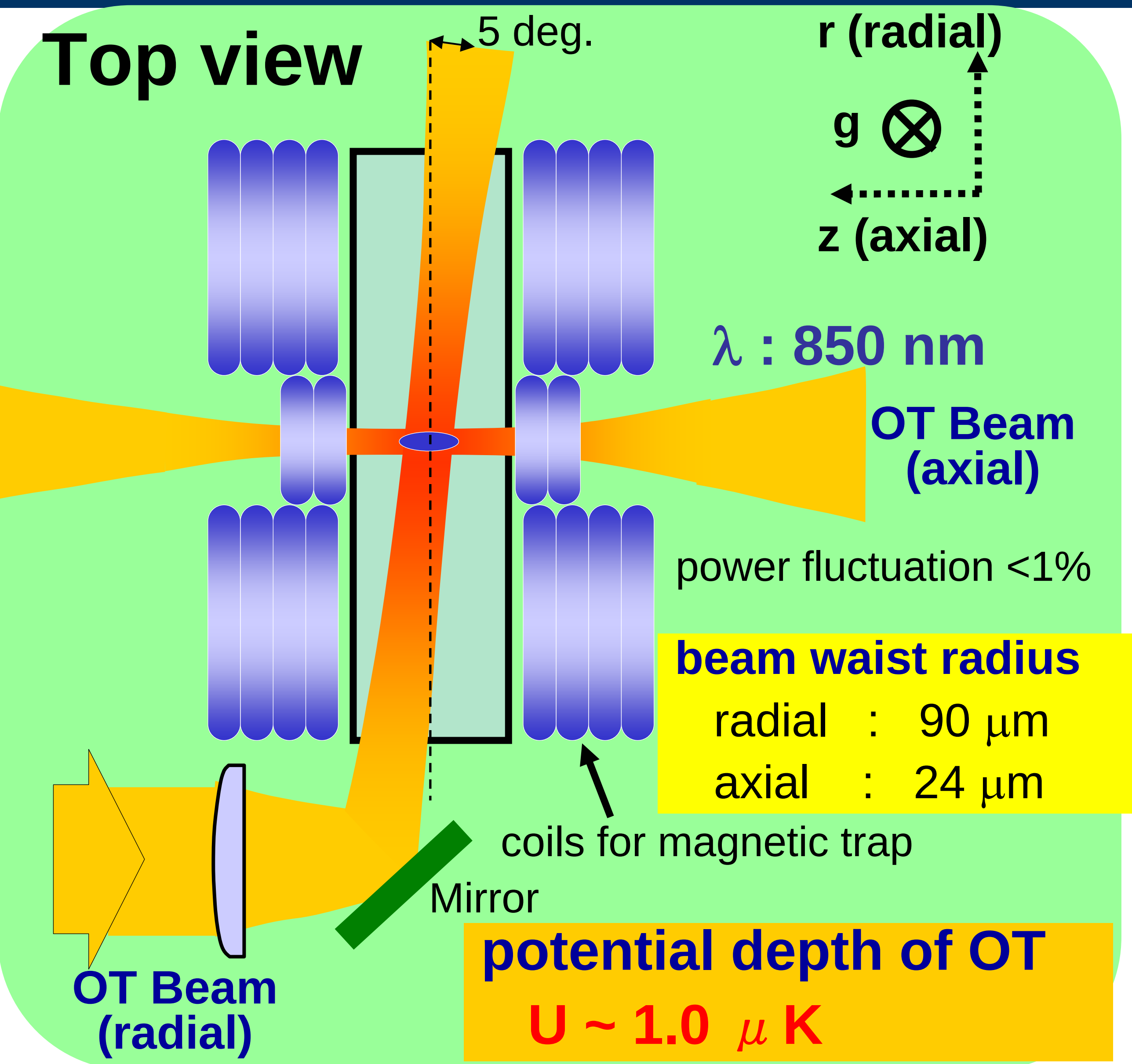
$$\propto -\frac{P}{\Delta}$$

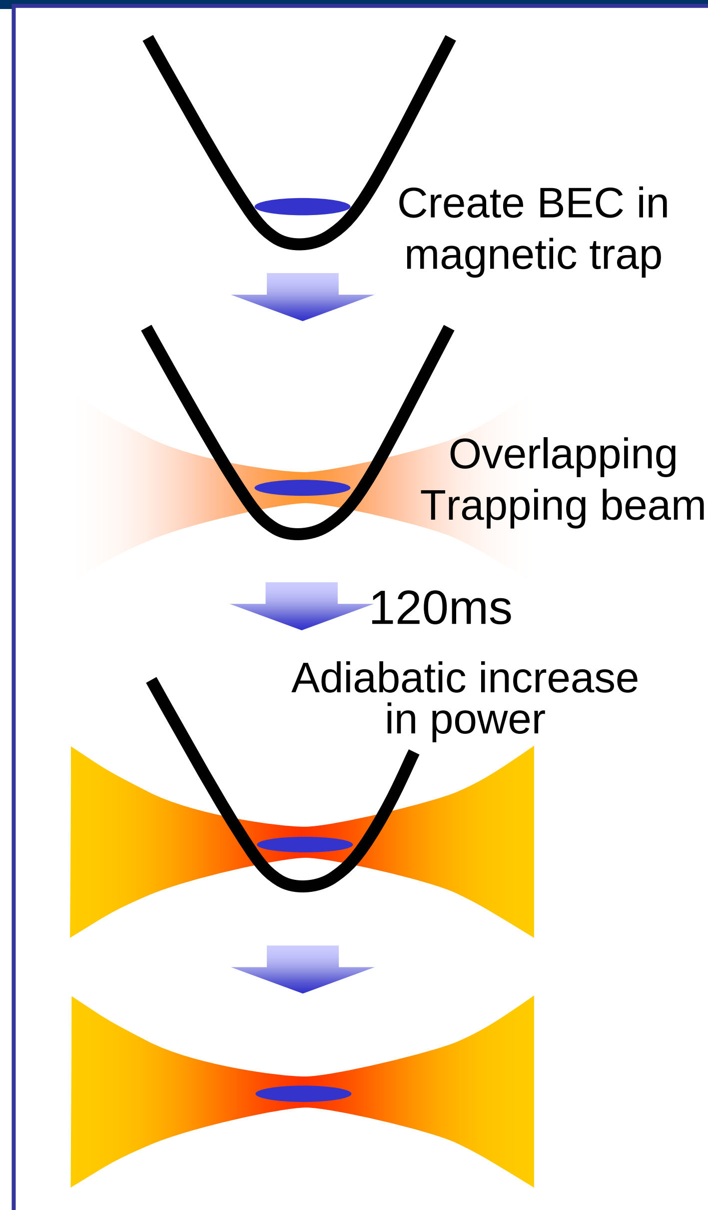
α : polarizability, E :electric field
P : laser power
Δ : detuning (f_{laser}-$f_{resonace}$)

Spin degrees of freedom are liberated in an optical trap.

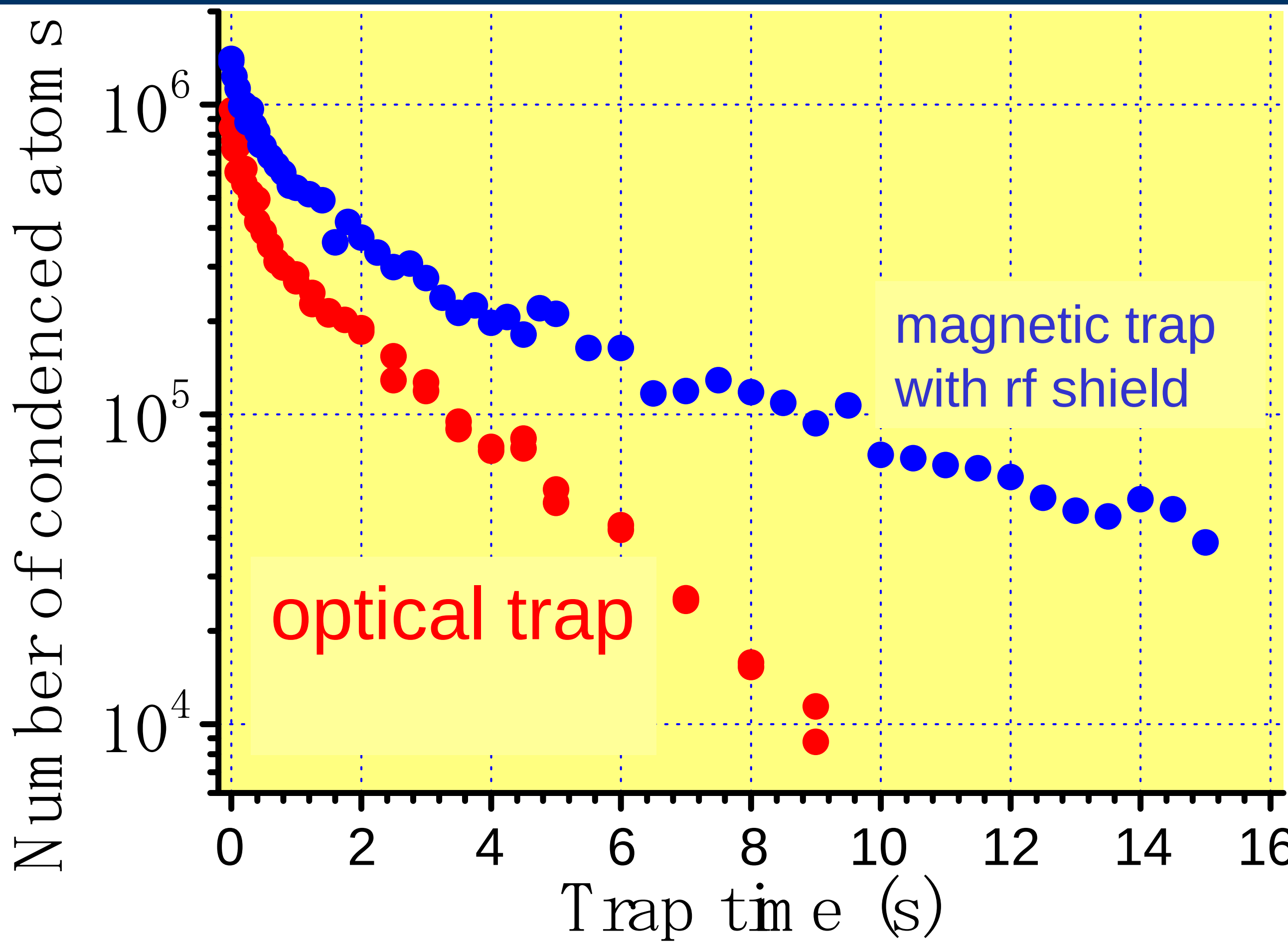
First success in Jan. 2000

Setup of Optical Trap





Lifetime of BEC in Optical Trap - Stretched State ($F=2$, $m_F=-2$) -



loss rate

(in the region of $N < 1\times10^5$)

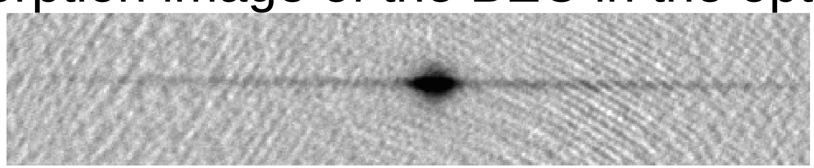
$\tau_{\text{magnetic trap}} \sim 7$ s

$\tau_{\text{optical trap}} \sim 4$ s

photon scattering rate

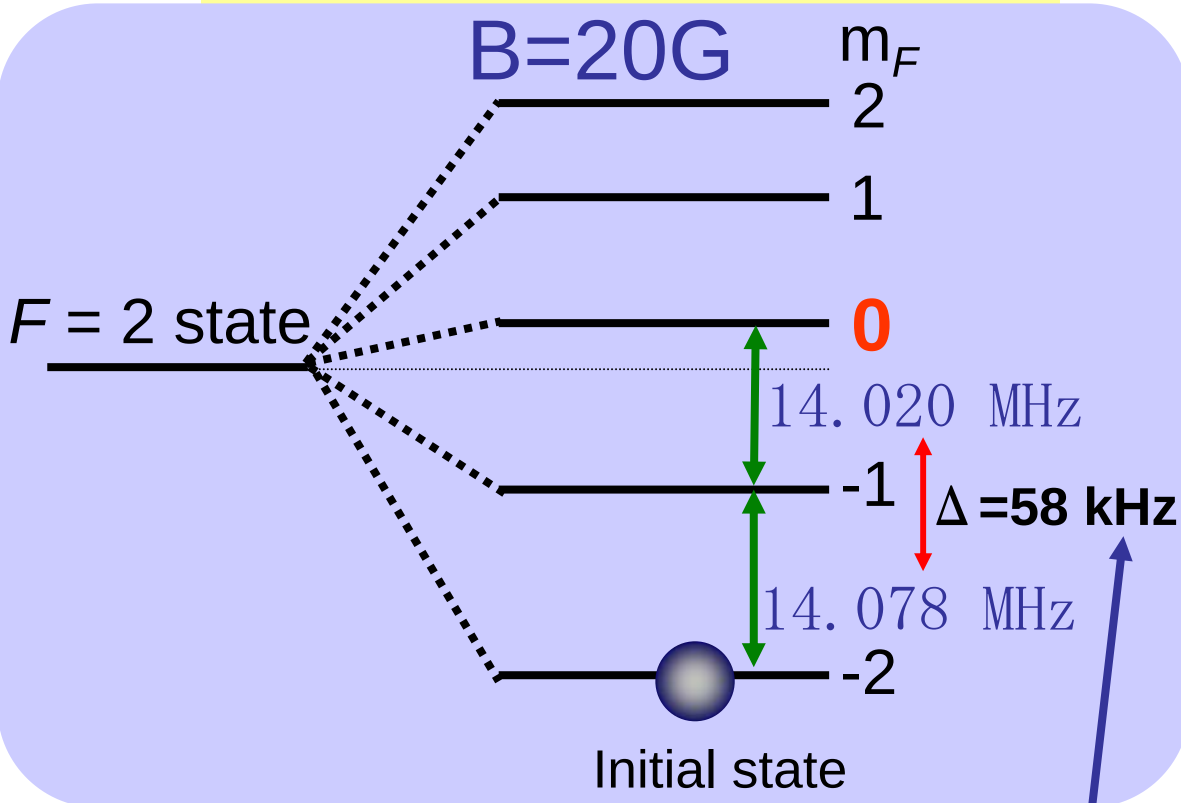
2×10^{-3} /s

absorption image of the BEC in the optical trap



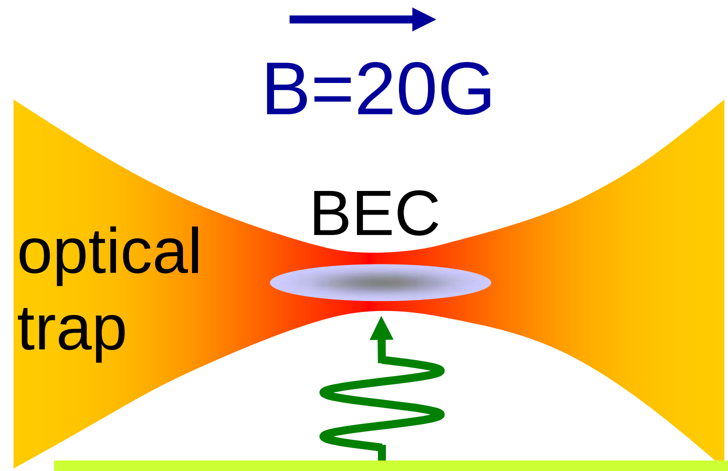
Manipulation of Spin States

energy level diagram of ^{87}Rb
ground hyperfine states



It is possible to selectively prepare any states.

homogeneous magnetic field



rf field
(Frequency is swept)

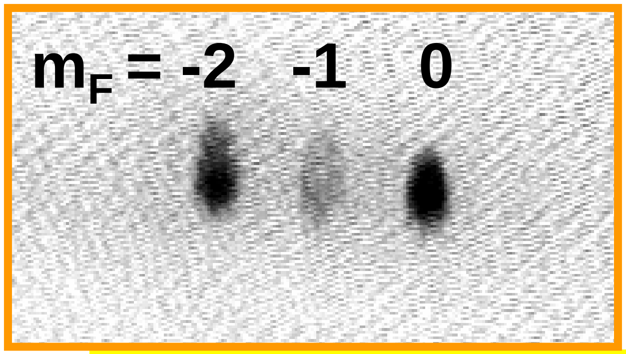
Parameter of rf field

center frequency	:	14.078 MHz
sweep range	:	80 kHz
sweep time	:	1～3 ms

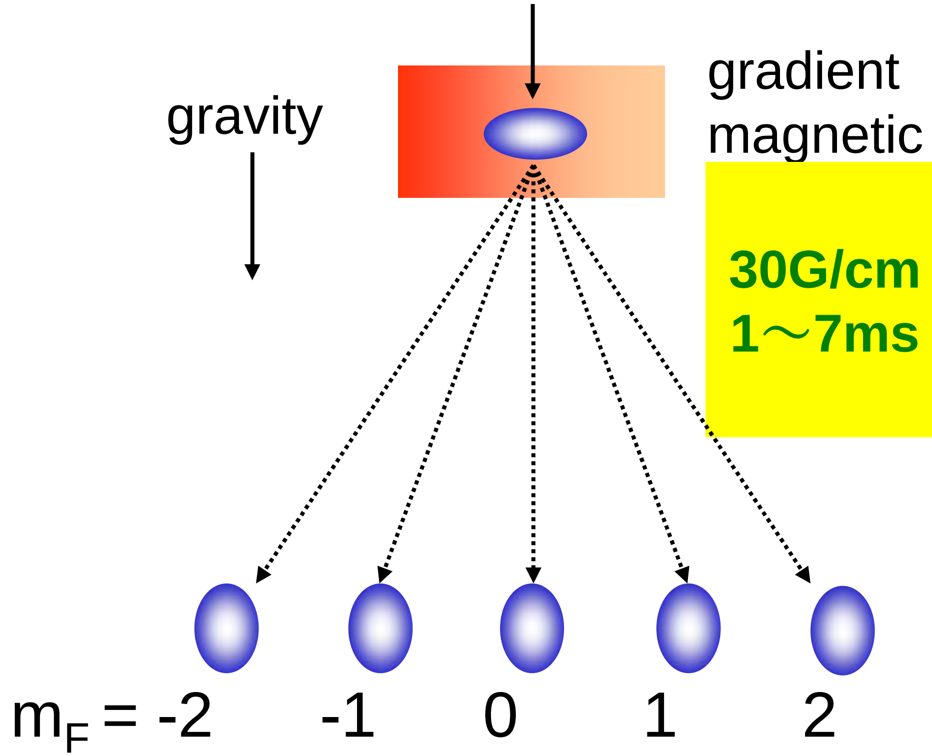
Creation of BEC in m_F = 0 state

Spatial separation by Stern-Gerlach method

m_F = -2 & 0 mixed BEC



| -2 > : | 0 > = 1:1



We could prepare highly polarized (almost pure) m_F=0 BEC.

Transfer rate > 90%

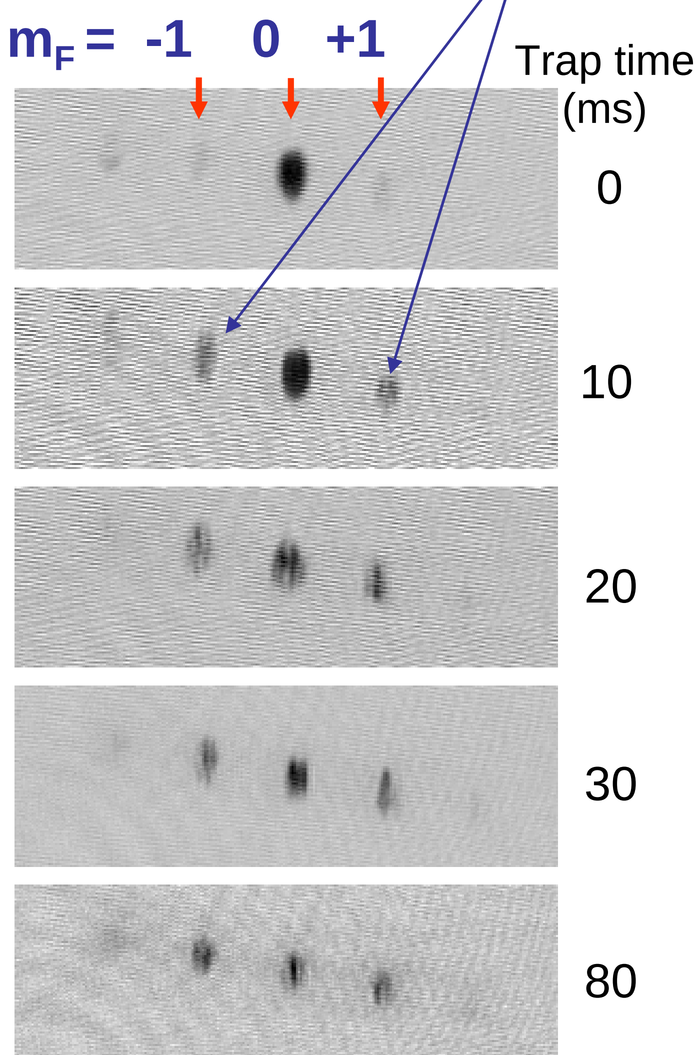
Decay of F=2, m_F=0 BEC in OT at B = 1.5G

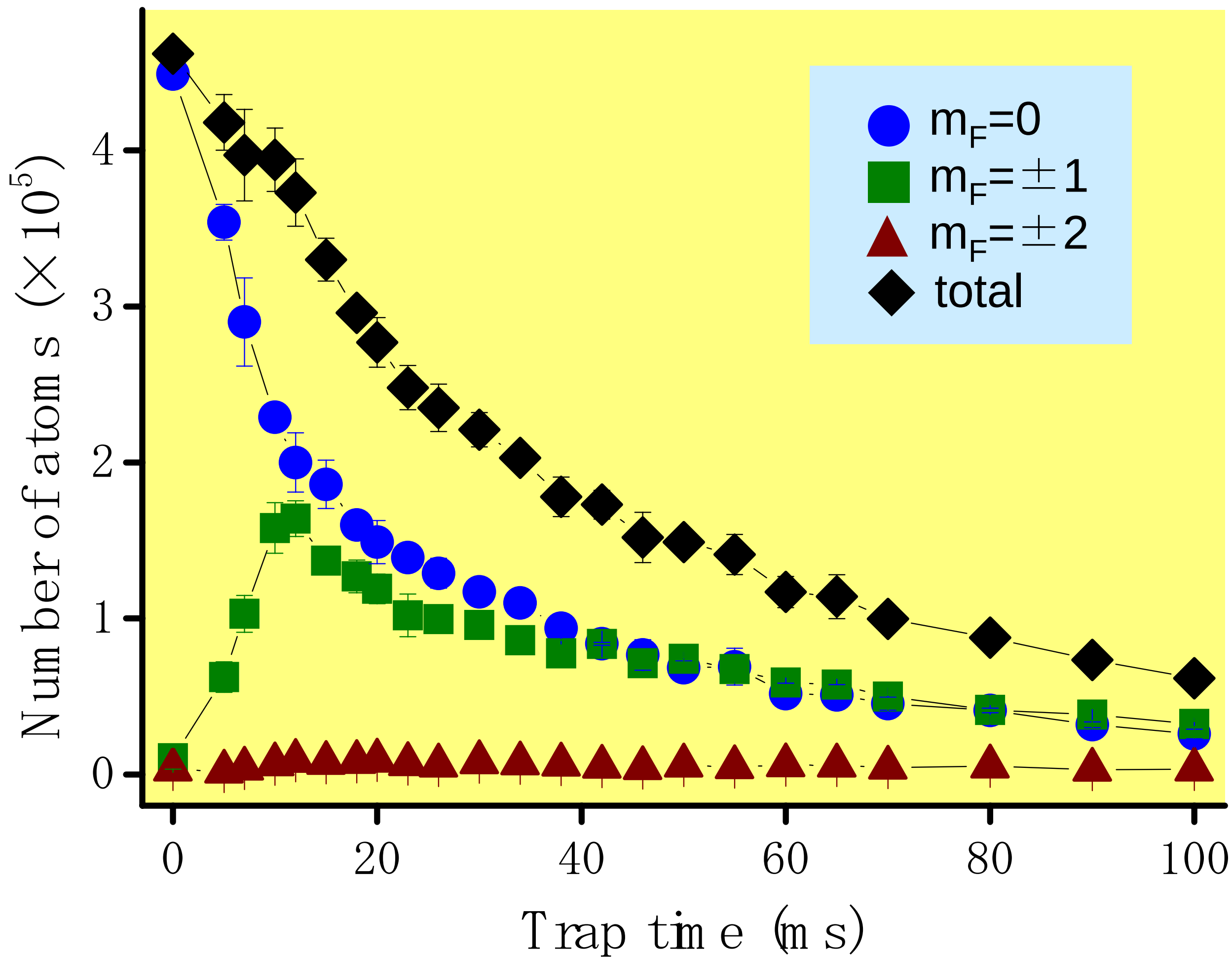
Atoms in BEC initially polarized in F=2, m_F=0 state.

m_F=±1 components appeared during decay process.

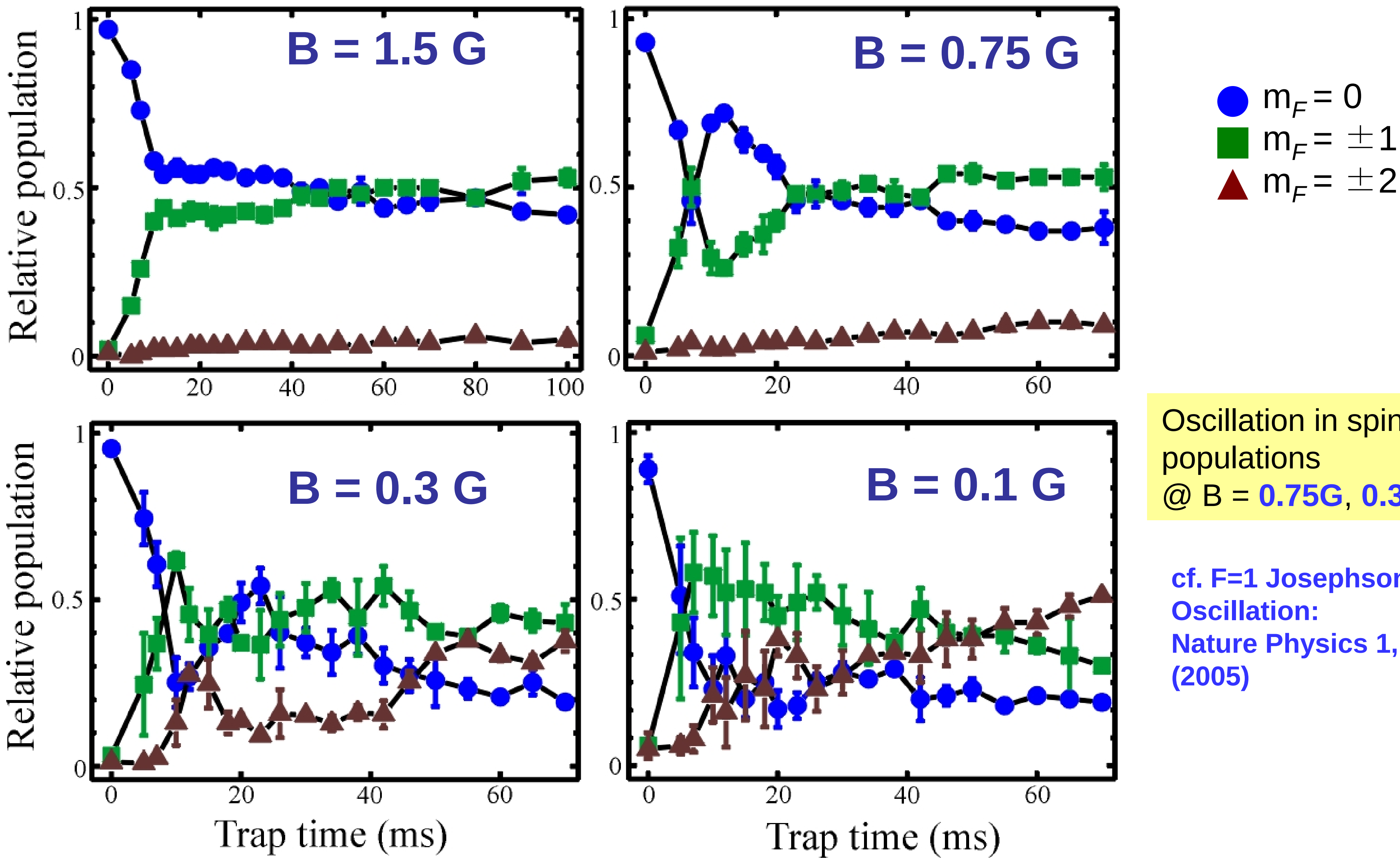
Time evolution

Total-spin-conserved spin-relaxation process





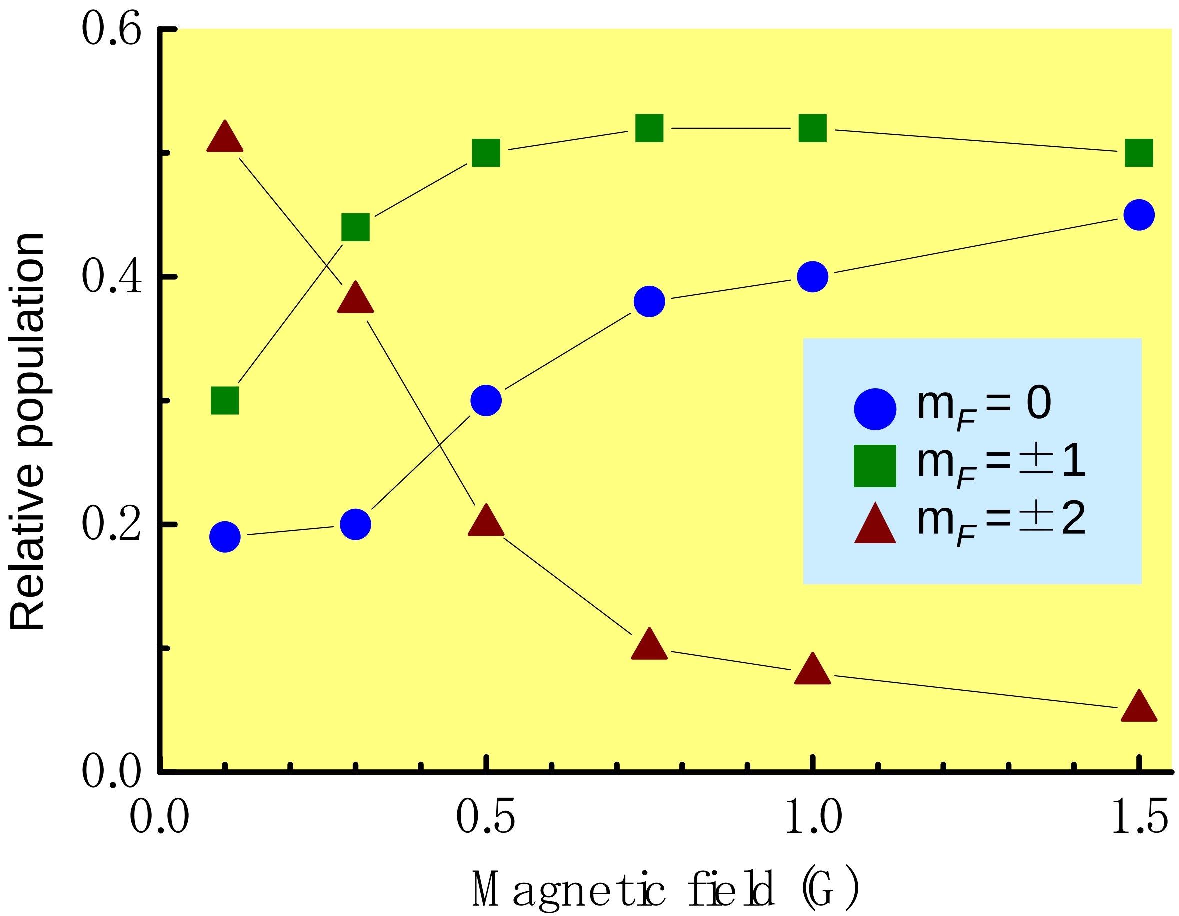
Magnetic field dependence of spin-mixing dynamics



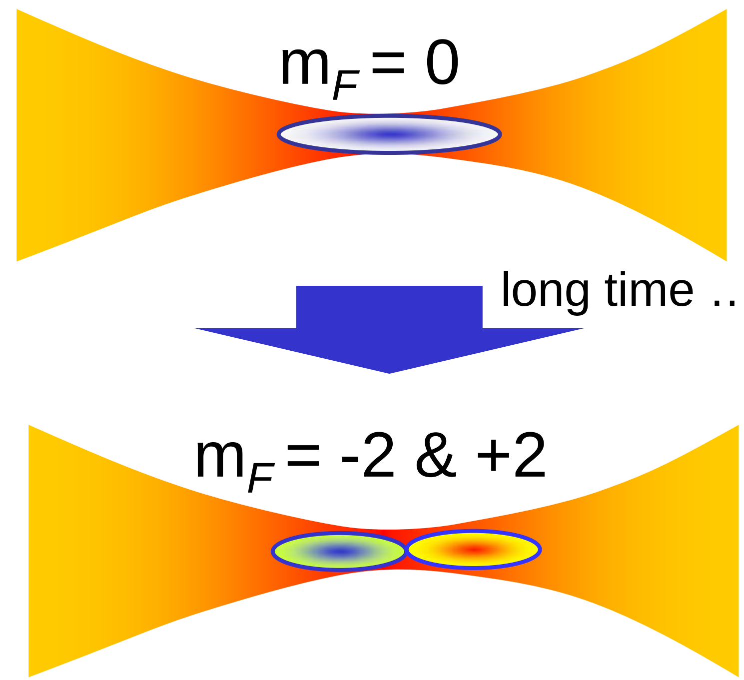
Oscillation in spin populations
@ B = **0.75G**, **0.3G**

cf. F=1 Josephson Oscillation:
Nature Physics 1, 111 (2005)

Relative Populations of Each Component after 70-ms Evolution
- Magnetic Field Dependence -



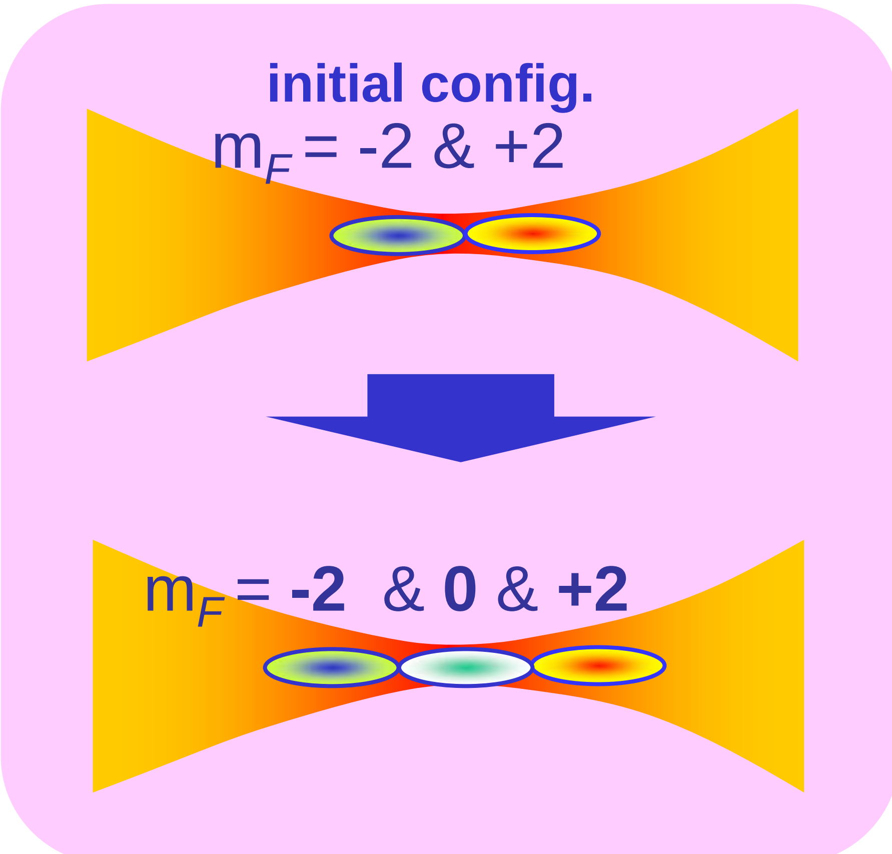
Kuwamoto et al.
Phys. Rev. A 69, 063604 (2004).



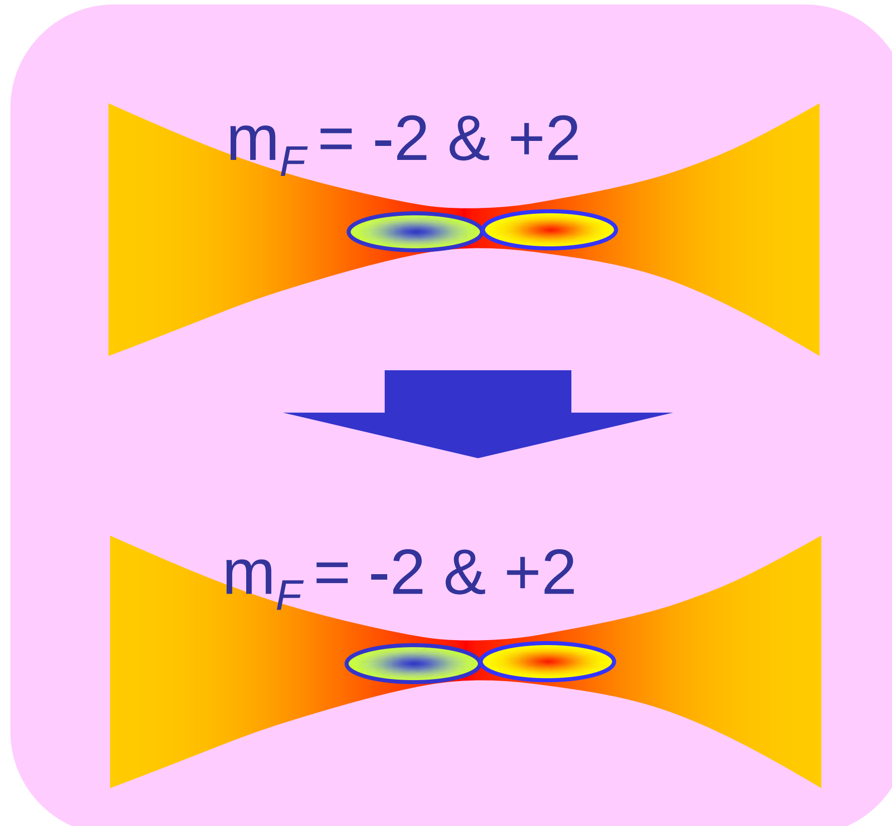
If the $F = 2$ ^{87}Rb BEC has anti-ferromagnetic properties, the mixture of $m_F = -2$ and $m_F = +2$ is one of the ground states at a zero magnetic field. [M.Ueda & M.Koashi, PRA, 65, 063602 (2002)]

Magnetism of F=2 ^{87}Rb BEC

If cyclic

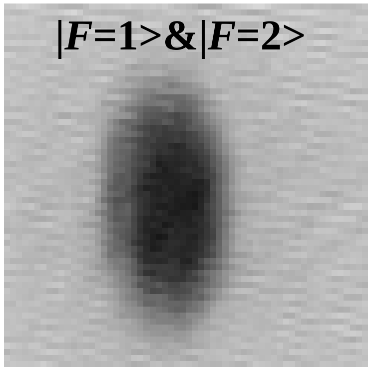


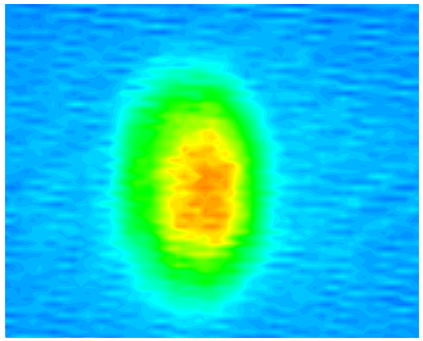
actually…

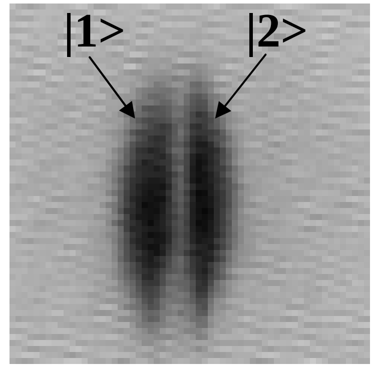


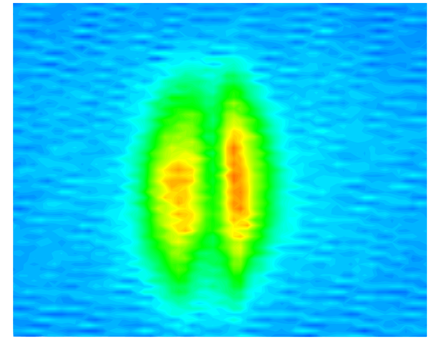
indicates anti-ferromagnetic,
but **small popuration in $m_F=\pm1$…**

Optical Trap of *F*=1 and *F*=2 Bose-Einstein Condensates







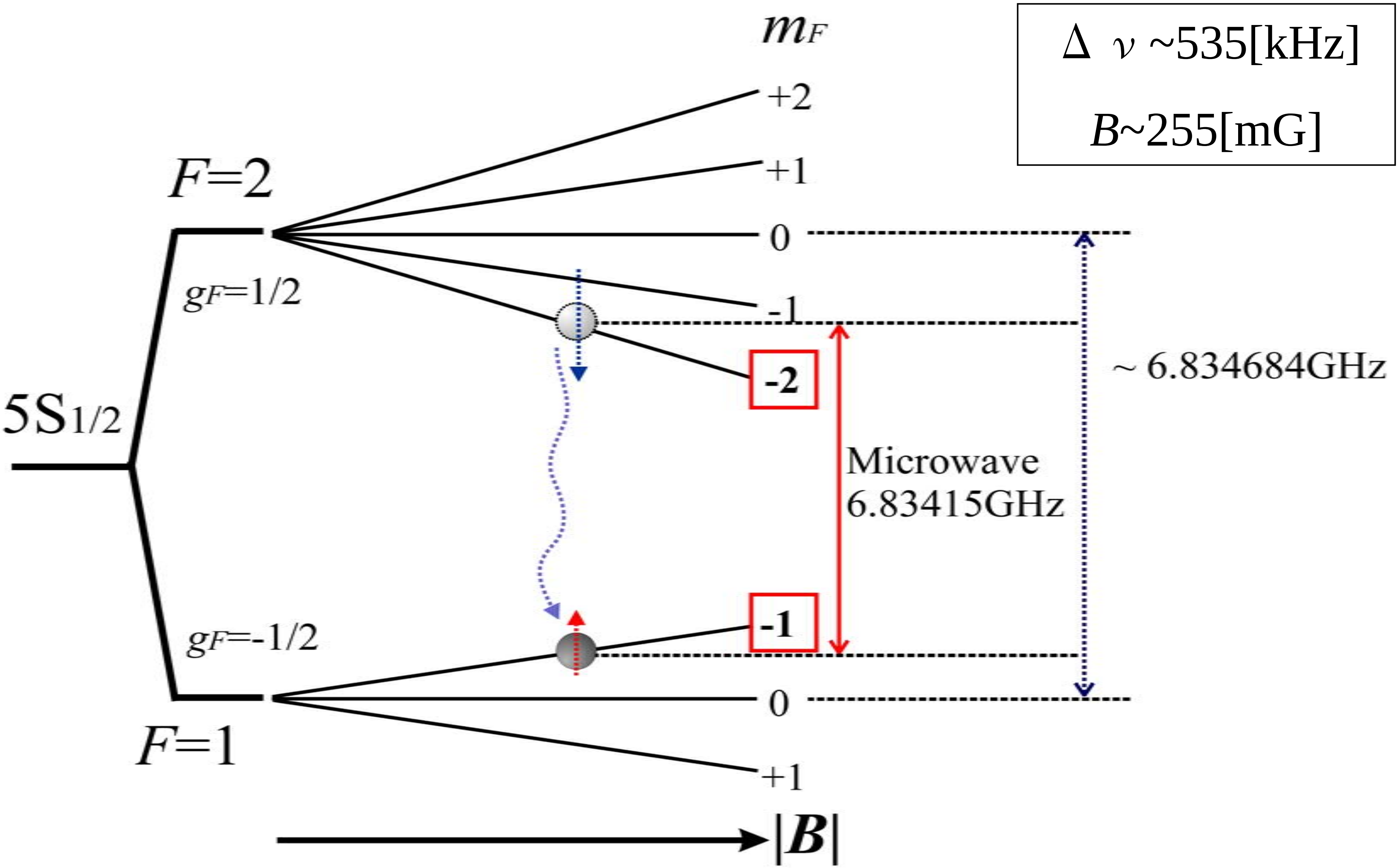


Simultaneous trap of F=1 and F=2 Rb BEC

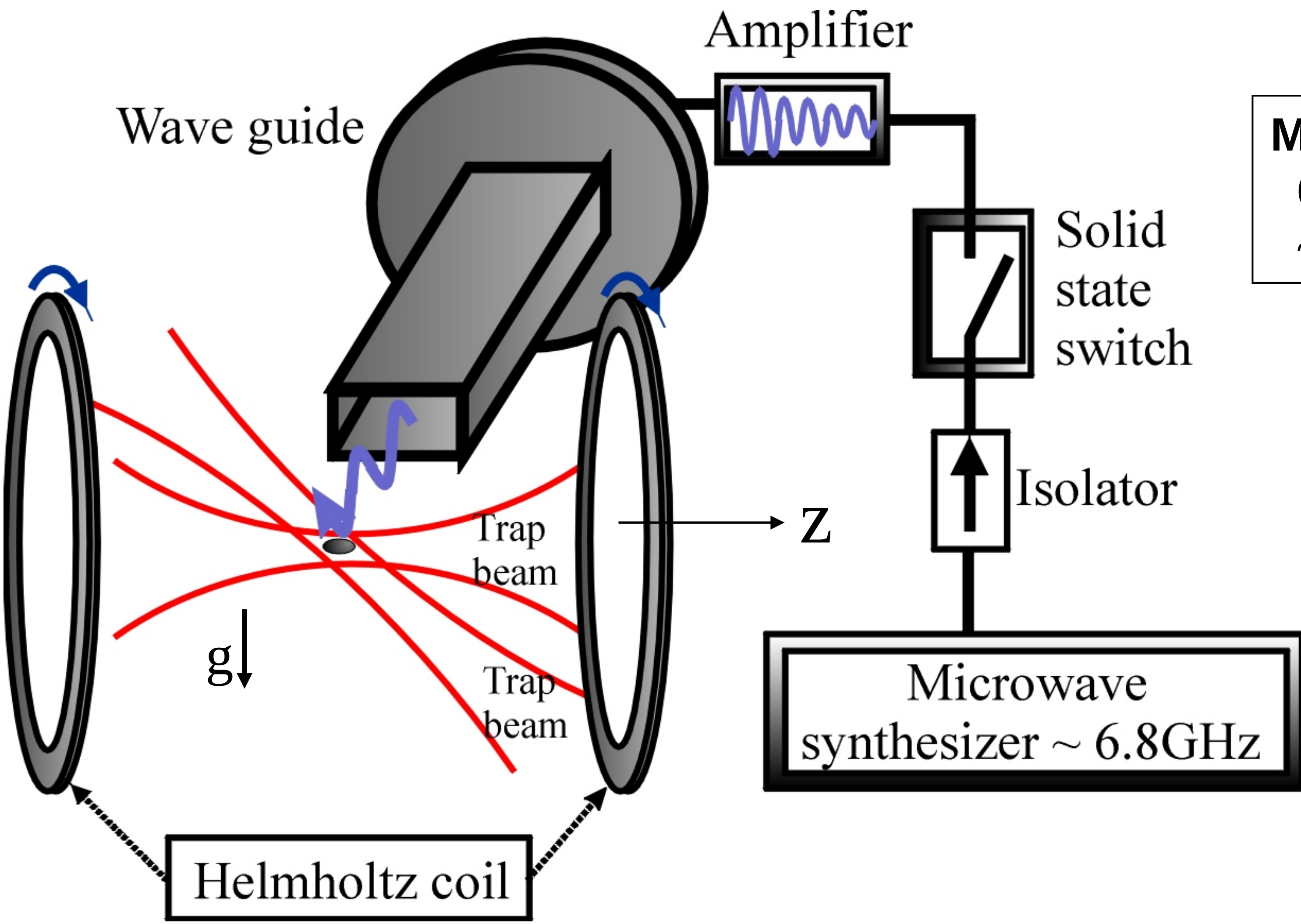
JILA : magnetic trap
capable of trapping only weak field seeking states

Our experiment : optical trap
capable of trapping any states, even for anti-parallel magnetic moment
Control of magnetic field

Microwave transition



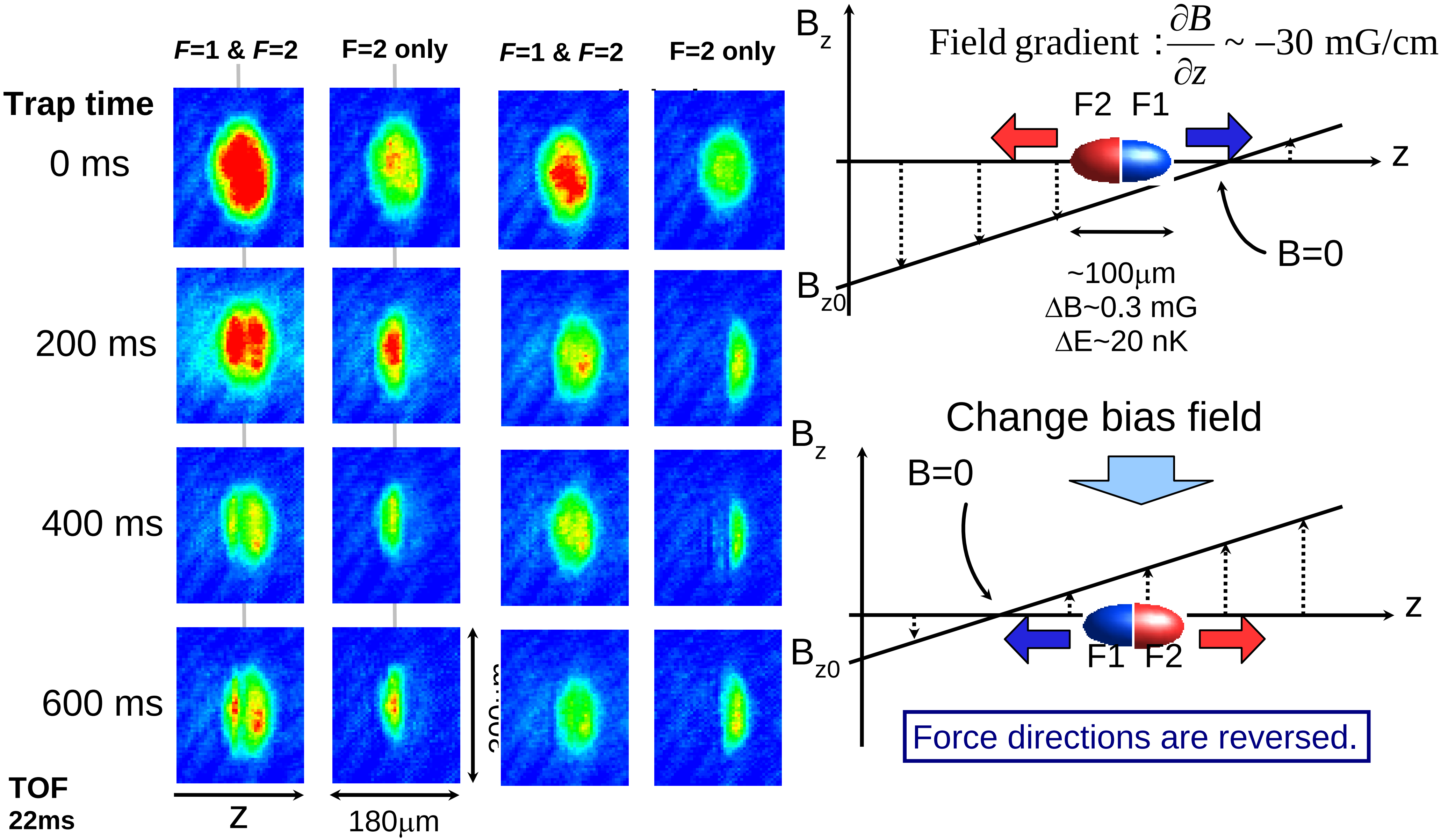
Experimental setup



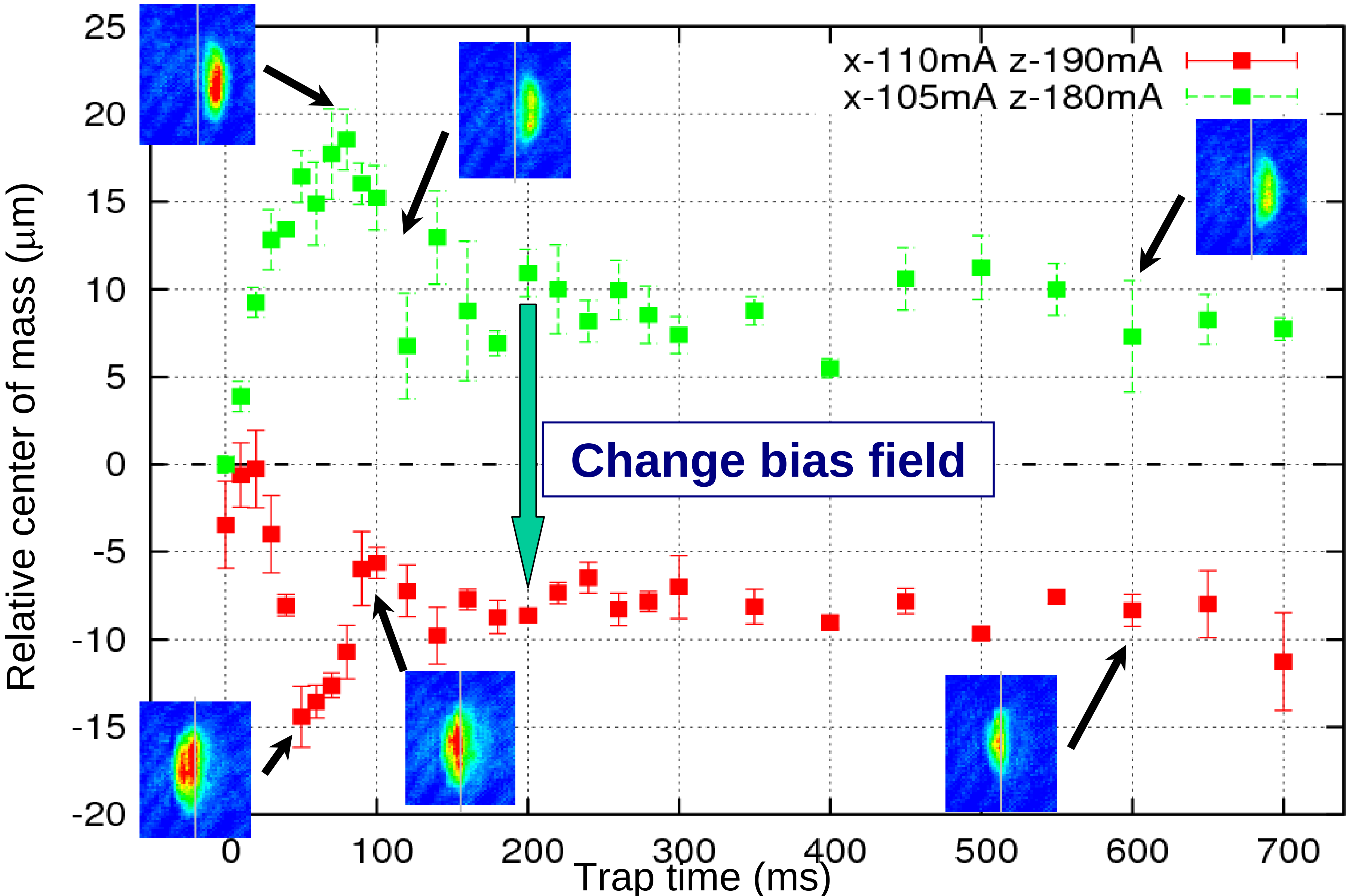
Microwage
6.83415GHz
~ 15dBm

Optcal trap
850nm
υ_r ~237 Hz
υ_z ~21 Hz

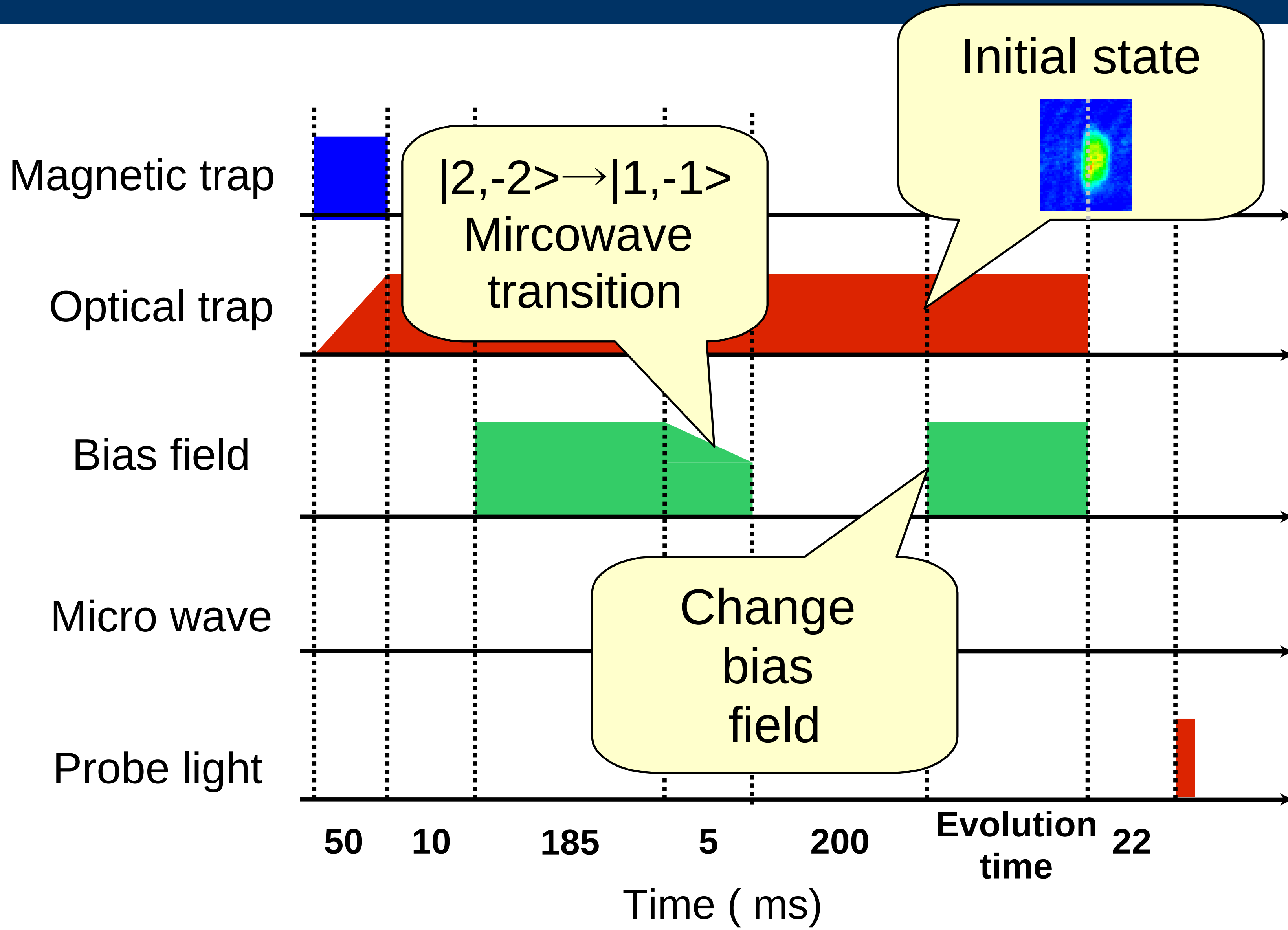
Time evolution for $N_{F=1} \fallingdotseq N_{F=2}$ (without Stern-Gerlach)



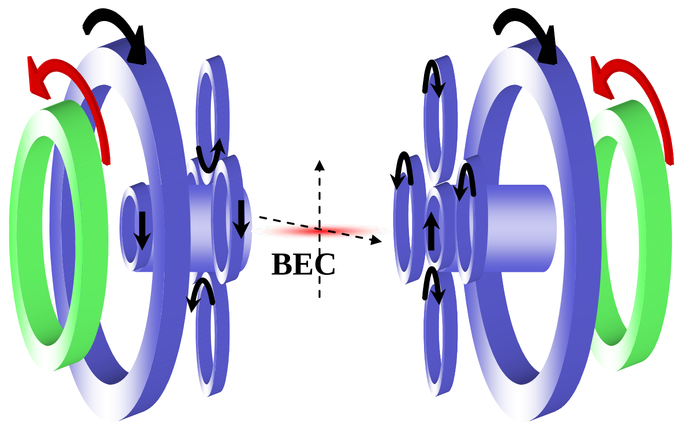
Center of mass movement of F=2 component

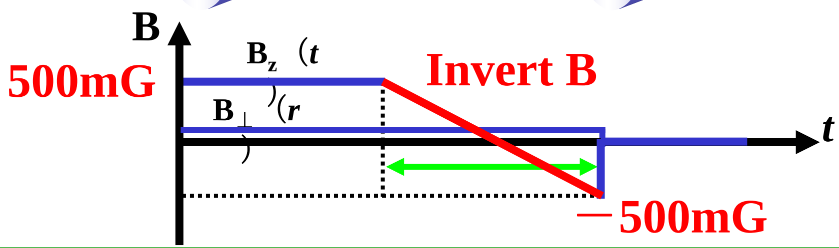


Experimental procedure



Topological Vortex Nucleation in Bose-Einstein Condensates





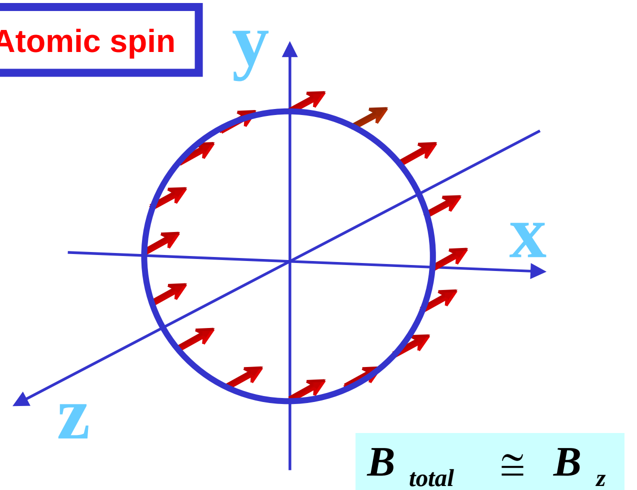
^{87}**Rb** : F=2, m_F = 2

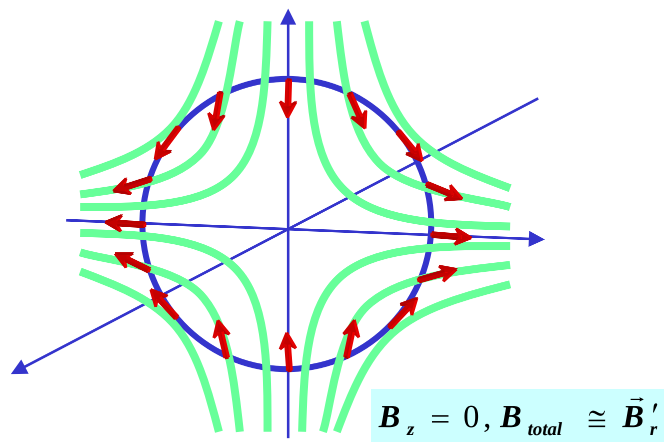
$$\oint_c \vec{V}_s \cdot d\vec{s} = \frac{\hbar}{m} 8\pi = \frac{\hbar}{m} 2\pi \cdot 4$$

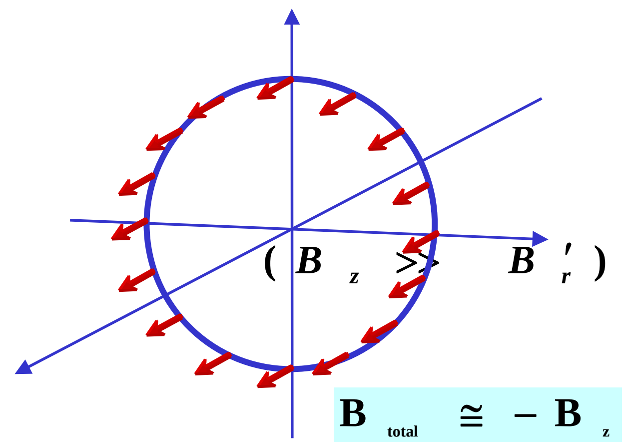
M. Nakahara, *et al.*, Physica (Amsterdam) 284-288B, 17(2000).
T. Isoshima, *et al.*, Phys. Rev. A 61, 063610 (2000).
S.-I. Ogawa, *et al.*, Phys. Rev. A 66, 013617 (2002).

^{23}Na (F=1, m_F = -1)
A. Leanhardt, *et al.*, Phys. Rev. Lett. 89, 190403 (2002).
^{87}Rb (F=2, m_F = 2)
Kyoto group, Annual meeting JPS, 2004, 27aXG-3

Atomic spin





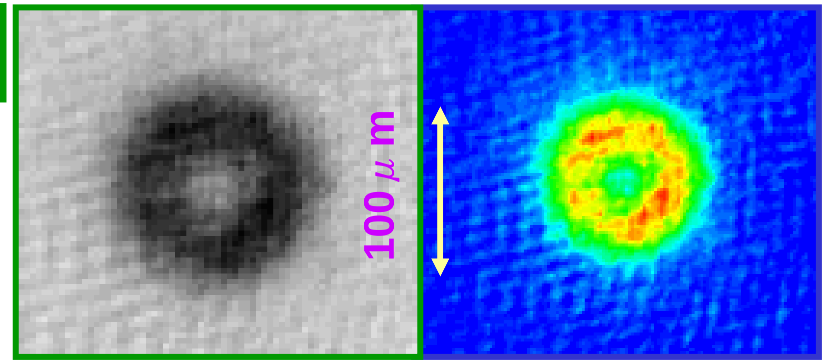


Observation of vortex

Experimental procedure

1. Create BEC in a magnetic trap
2. Invert the magnetic field
3. Absoption imaging

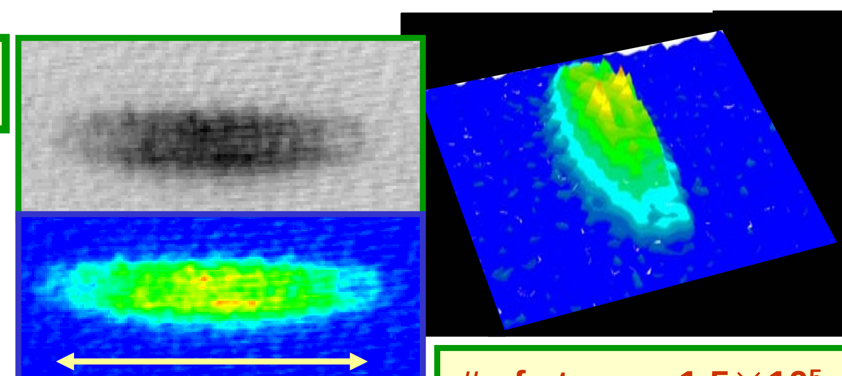
Axial dir.



gravity

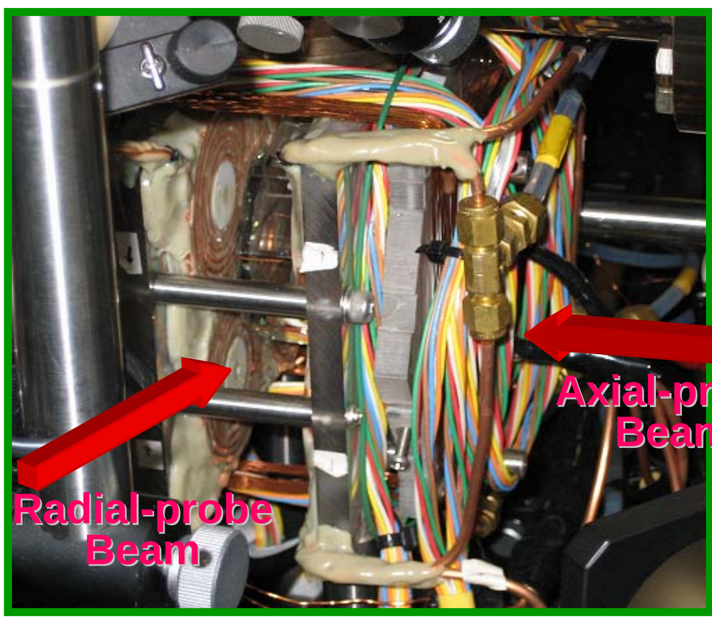
# of atoms : 3×10^5
TOF : 19ms
Inverting time: 5ms
Trap time : 5ms

Radial dir.

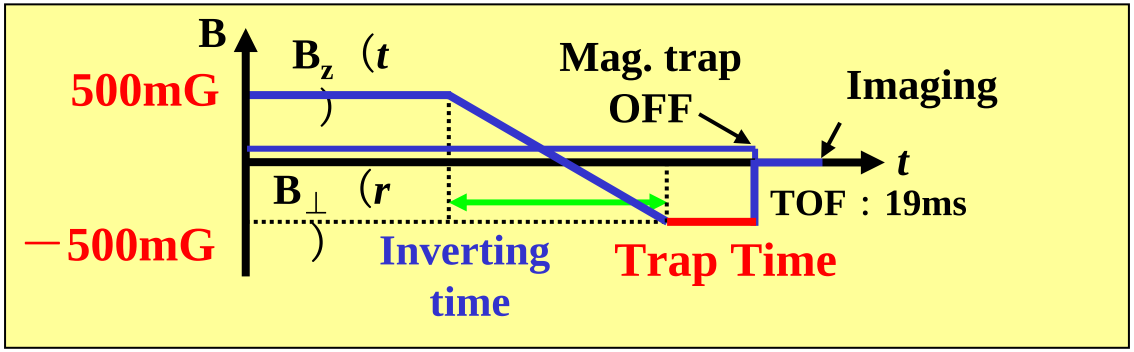


400 μ m

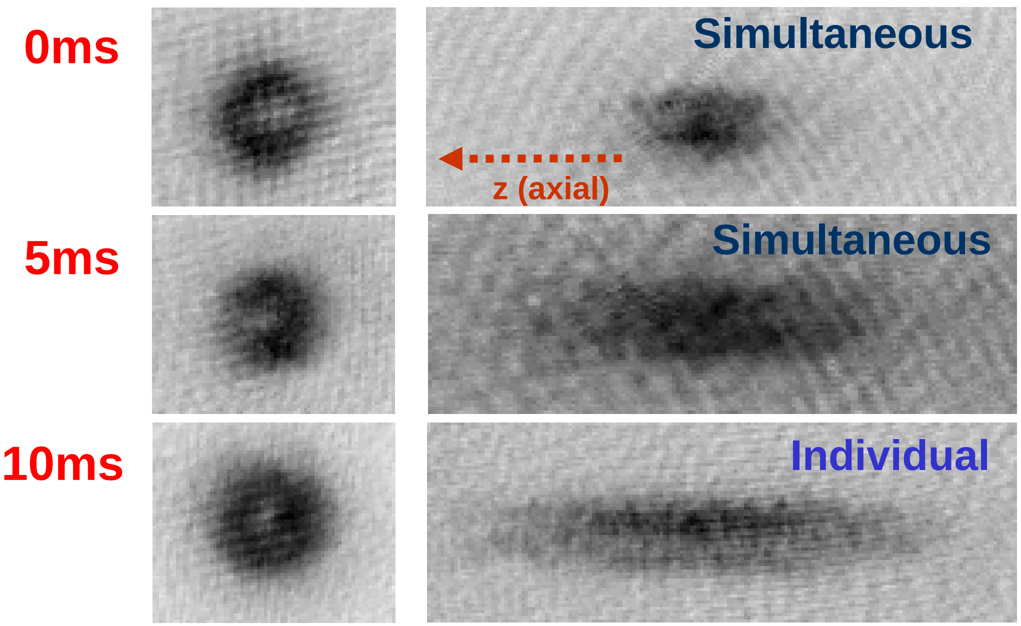
# of atoms : 1.5×10^5
TOF : 15ms
Inverting time : 5ms
Trap time : 5ms



Simultaneous imaging from two directions



Invering time：3~13ms



TOF : 19ms, Inverting time : 5ms

- No trapping potential along z axis after inverting the bias field
- We cloud observe vortex up to 10ms trap-time

Summary

- Ground state of ^{87}Rb Spin-2 BEC

  For $m_F=0$ initial state, decay at various magnetic field strengths

  $\rightarrow$ Spin relaxation, population oscillation

  For $m_F=\pm2$ initial state, atoms remain in $m_F=\pm2$

  ⇨ Antiferromagnetic

- Optical Confinement of Binary BEC: F=1 and F=2

  Spatial separation, center of mass movement,

  domain structure were observed.

- Vortex Formation via magnetic field reversal

  Charge 4 vortex, simultaneous imaging from two directions

  up to 10 msec in magnetic trap,

  up to ~20 msec in optical trap.