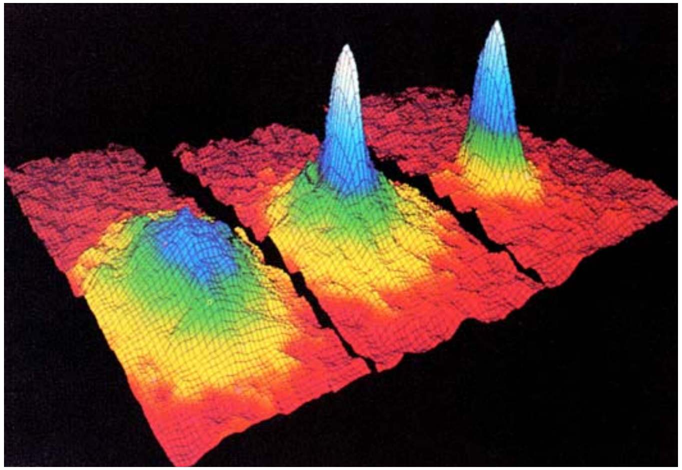


ELTE TTK
Fizikai Intézet

Hideg atomok csapdában

Csordás András

Statisztikus és Biológiai Fizika Kutatócsoport

2010. Január 28.

A csapdapotenciálról:

Rugóerő (A megnyúlást az egyensúly helyzettől mérjük):

$$F_{rugó} = -D\,x$$

Rugó potenciális energiája

$$V_{rugó}(x) = ½\,Dx^2$$

Hasson egy testre a 3 irányból rugó-erő:

$$V(x,y,z) = ½\,D_x\,x^2 + ½\,D_y\,y^2 + ½\,D_z\,z^2$$

Ez a V(x,y,z) csapdapotenciál középen tud tartani (csapdázni) részecskéket

Van másmilyen csapdapotenciál is pl.:

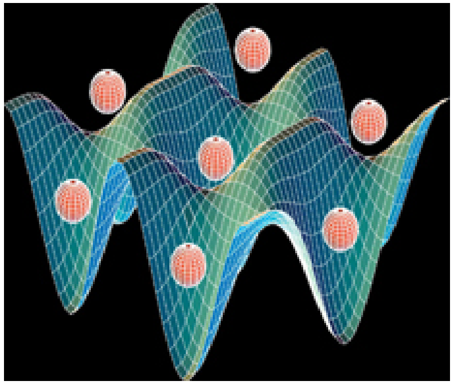
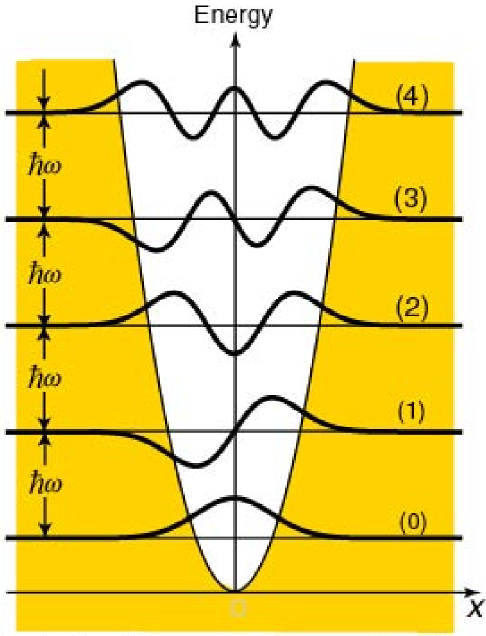
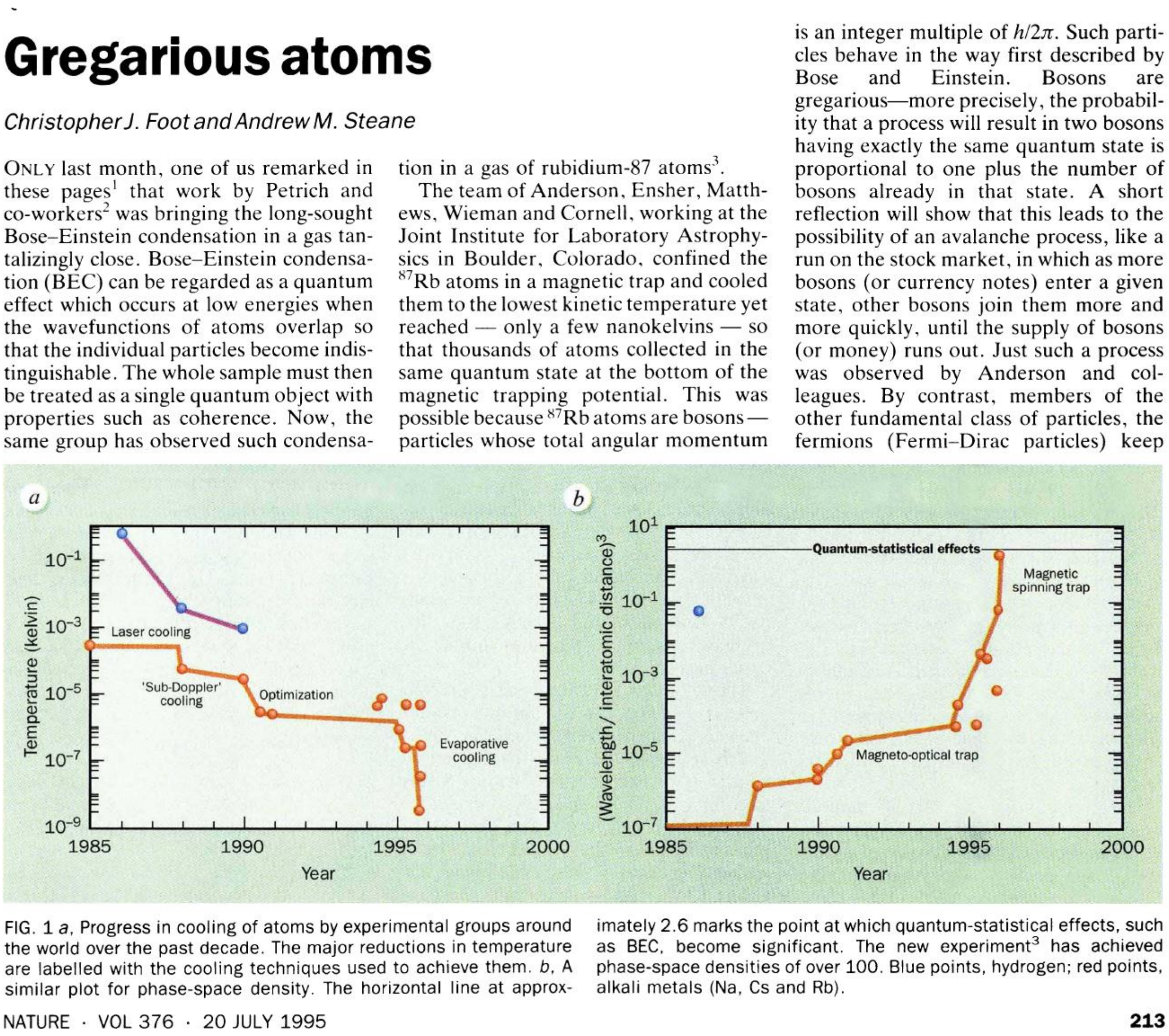


Fig. (C)



The thick solid curves are the wave functions.
(0) : the ground state
(1) (2) (3) . . . : the excited states

Elért legalacsonyabb hőmérsékletek 1995 előtt:



Gregarious atoms

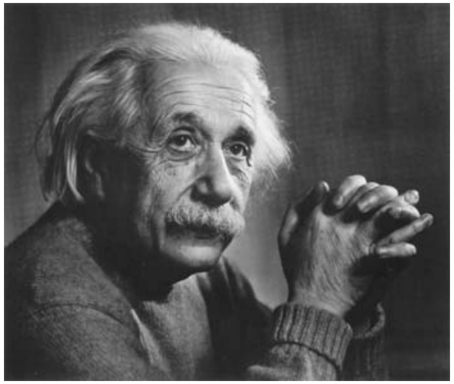
Christopher J. Foot and Andrew M. Steane

ONLY last month, one of us remarked in these pages[1] that work by Petrich and co-workers[2] was bringing the long-sought Bose–Einstein condensation in a gas tantalizingly close. Bose–Einstein condensation (BEC) can be regarded as a quantum effect which occurs at low energies when the wavefunctions of atoms overlap so that the individual particles become indistinguishable. The whole sample must then be treated as a single quantum object with properties such as coherence. Now, the same group has observed such condensation in a gas of rubidium-87 atoms[3].

The team of Anderson, Ensher, Matthews, Wieman and Cornell, working at the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, confined the ^{87}Rb atoms in a magnetic trap and cooled them to the lowest kinetic temperature yet reached — only a few nanokelvins — so that thousands of atoms collected in the same quantum state at the bottom of the magnetic trapping potential. This was possible because ^{87}Rb atoms are bosons — particles whose total angular momentum is an integer multiple of $h/2\pi$. Such particles behave in the way first described by Bose and Einstein. Bosons are gregarious—more precisely, the probability that a process will result in two bosons having exactly the same quantum state is proportional to one plus the number of bosons already in that state. A short reflection will show that this leads to the possibility of an avalanche process, like a run on the stock market, in which as more bosons (or currency notes) enter a given state, other bosons join them more and more quickly, until the supply of bosons (or money) runs out. Just such a process was observed by Anderson and colleagues. By contrast, members of the other fundamental class of particles, the fermions (Fermi–Dirac particles) keep

FIG. 1 *a*, Progress in cooling of atoms by experimental groups around the world over the past decade. The major reductions in temperature are labelled with the cooling techniques used to achieve them. *b*, A similar plot for phase-space density. The horizontal line at approximately 2.6 marks the point at which quantum-statistical effects, such as BEC, become significant. The new experiment[3] has achieved phase-space densities of over 100. Blue points, hydrogen; red points, alkali metals (Na, Cs and Rb).

Bose-Einstein kondenzáció (BEC):



Satyendra Nath Bose és Albert Einstein

Annak aki többet akar tudni (Nagyon jó, de sajna angolul!):

http://www.colorado.edu/physics/2000/bec/index.html

(Érdemes elmenni erre a honlapra tanárnak és diáknak egyaránt!)

JILA: Joint Institute for Laboratory Astrophysics
A hőmérsékletről (animáció)

Mi az a Bose-Einstein kondenzáció? (animáció)

Mi az a párologtatásos hűtés? (Animáció)

A BEC ^{4}He-ban: (Szuperfolyékonyság)

Ez is egy szuper folyadék

de most a szuperfolyadékokról lesz szó:

A szuperfolyékony hélium meglepő tulajdonságai:

(http://www.youtube.com/watch?v=2Z6UJbwxBZI)

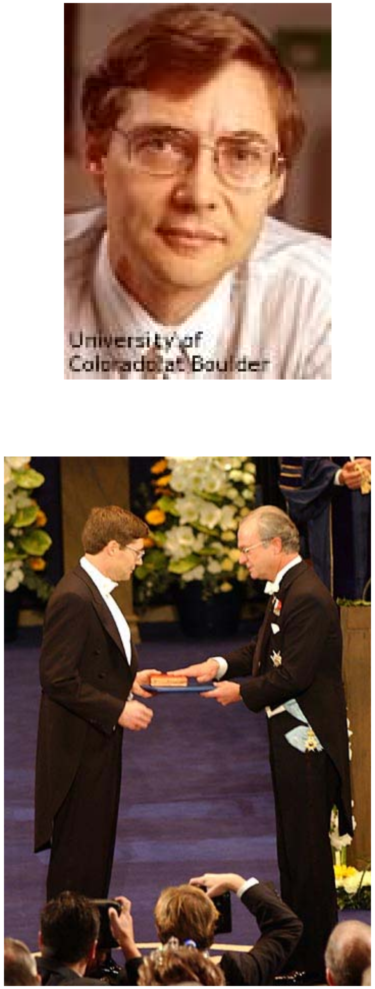
A hélium szökőkút:

(http://www.youtube.com/watch?v=kCJ24176enM)

Nobel-díj 2001

Eric A. Cornell

Wolfgang Ketterle



Carl E. Wiemann

Közvetlen bizonyíték a BEC-re (JILA 1995, ^{87}Rb)

Science **269,** 198 (1995)

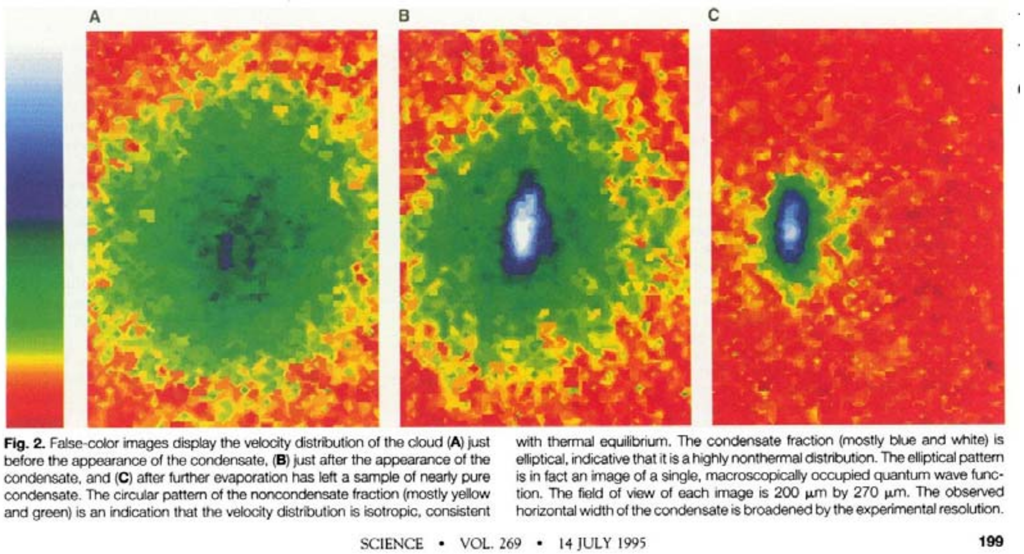
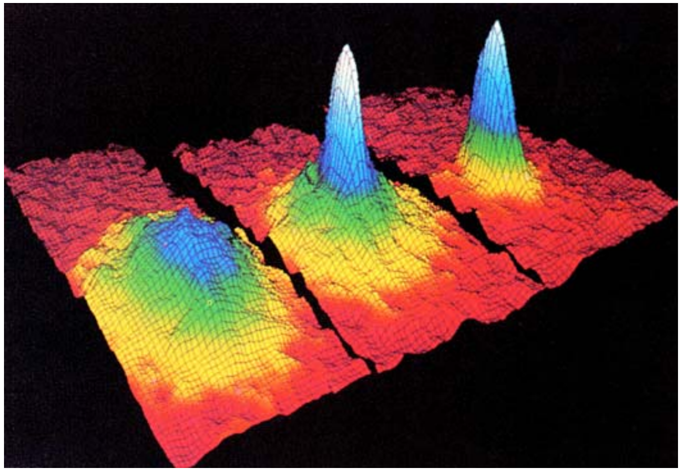


Fig. 2. False-color images display the velocity distribution of the cloud (**A**) just before the appearance of the condensate, (**B**) just after the appearance of the condensate, and (**C**) after further evaporation has left a sample of nearly pure condensate. The circular pattern of the noncondensate fraction (mostly yellow and green) is an indication that the velocity distribution is isotropic, consistent with thermal equilibrium. The condensate fraction (mostly blue and white) is elliptical, indicative that it is a highly nonthermal distribution. The elliptical pattern is in fact an image of a single, macroscopically occupied quantum wave function. The field of view of each image is 200 μm by 270 μm. The observed horizontal width of the condensate is broadened by the experimental resolution.

SCIENCE • VOL. 269 • 14 JULY 1995 **199**

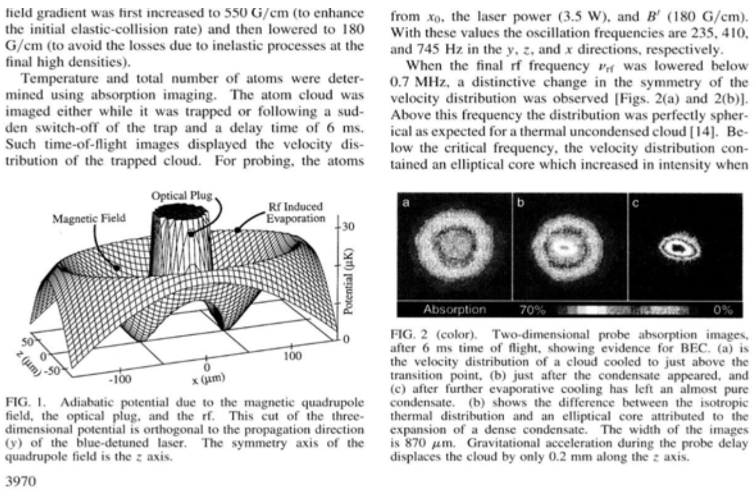


Kulcsszavak: TOF-mérés (time of flight), CCD-kamera, abszorpció mérés

Tipikus adatok: 10^5 atom a kondenzátumban, 170 nK-en

BEC az MIT-ban ^{23}Na-mal

(MIT: Massachusetts Institute of Technology)



field gradient was first increased to 550 G/cm (to enhance the initial elastic-collision rate) and then lowered to 180 G/cm (to avoid the losses due to inelastic processes at the final high densities).

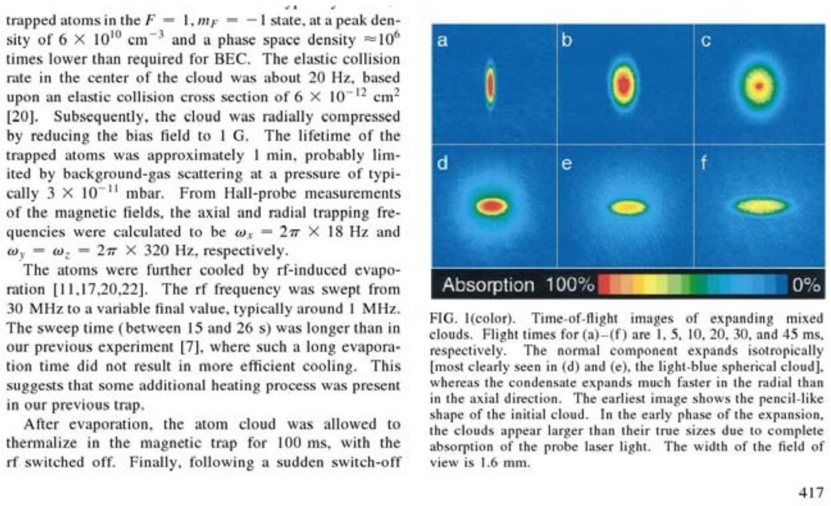
Temperature and total number of atoms were determined using absorption imaging. The atom cloud was imaged either while it was trapped or following a sudden switch-off of the trap and a delay time of 6 ms. Such time-of-flight images displayed the velocity distribution of the trapped cloud. For probing, the atoms from x_0, the laser power (3.5 W), and B' (180 G/cm). With these values the oscillation frequencies are 235, 410, and 745 Hz in the y, z, and x directions, respectively.

When the final rf frequency ν_{rf} was lowered below 0.7 MHz, a distinctive change in the symmetry of the velocity distribution was observed [Figs. 2(a) and 2(b)]. Above this frequency the distribution was perfectly spherical as expected for a thermal uncondensed cloud [14]. Below the critical frequency, the velocity distribution contained an elliptical core which increased in intensity when

FIG. 1. Adiabatic potential due to the magnetic quadrupole field, the optical plug, and the rf. This cut of the three-dimensional potential is orthogonal to the propagation direction (y) of the blue-detuned laser. The symmetry axis of the quadrupole field is the z axis.

FIG. 2 (color). Two-dimensional probe absorption images, after 6 ms time of flight, showing evidence for BEC. (a) is the velocity distribution of a cloud cooled to just above the transition point, (b) just after the condensate appeared, and (c) after further evaporative cooling has left an almost pure condensate. (b) shows the difference between the isotropic thermal distribution and an elliptical core attributed to the expansion of a dense condensate. The width of the images is 870 μm. Gravitational acceleration during the probe delay displaces the cloud by only 0.2 mm along the z axis.

Physical Review Letters **75**, 3969 (1995)



trapped atoms in the $F = 1, m_F = -1$ state, at a peak density of 6×10^{10} cm^{-3} and a phase space density $\approx 10^6$ times lower than required for BEC. The elastic collision rate in the center of the cloud was about 20 Hz, based upon an elastic collision cross section of 6×10^{-12} cm^2 [20]. Subsequently, the cloud was radially compressed by reducing the bias field to 1 G. The lifetime of the trapped atoms was approximately 1 min, probably limited by background-gas scattering at a pressure of typically 3×10^{-11} mbar. From Hall-probe measurements of the magnetic fields, the axial and radial trapping frequencies were calculated to be $\omega_x = 2\pi \times 18$ Hz and $\omega_y = \omega_z = 2\pi \times 320$ Hz, respectively.

The atoms were further cooled by rf-induced evaporation [11,17,20,22]. The rf frequency was swept from 30 MHz to a variable final value, typically around 1 MHz. The sweep time (between 15 and 26 s) was longer than in our previous experiment [7], where such a long evaporation time did not result in more efficient cooling. This suggests that some additional heating process was present in our previous trap.

After evaporation, the atom cloud was allowed to thermalize in the magnetic trap for 100 ms, with the rf switched off. Finally, following a sudden switch-off

FIG. 1(color). Time-of-flight images of expanding mixed clouds. Flight times for (a)–(f) are 1, 5, 10, 20, 30, and 45 ms, respectively. The normal component expands isotropically [most clearly seen in (d) and (e), the light-blue spherical cloud], whereas the condensate expands much faster in the radial than in the axial direction. The earliest image shows the pencil-like shape of the initial cloud. In the early phase of the expansion, the clouds appear larger than their true sizes due to complete absorption of the probe laser light. The width of the field of view is 1.6 mm.

Physical Review Letters **77**, 416 (1996)

Néhány kísérleti csoport honlapja:

Wolfgang Ketterle csoportja (MIT)

Eric Cornell csoportja (JILA)

Debby Jin csoportja (JILA)

Rudi Grimm csoportja (Innsbruck)

C. Salomon csoportja (ENS Paris)

Ted Haensch csoportja (LMU München)

Fortágh József csoportja (Tübingeni egyetem)

Massimo Inguscio (LENS Firenze)

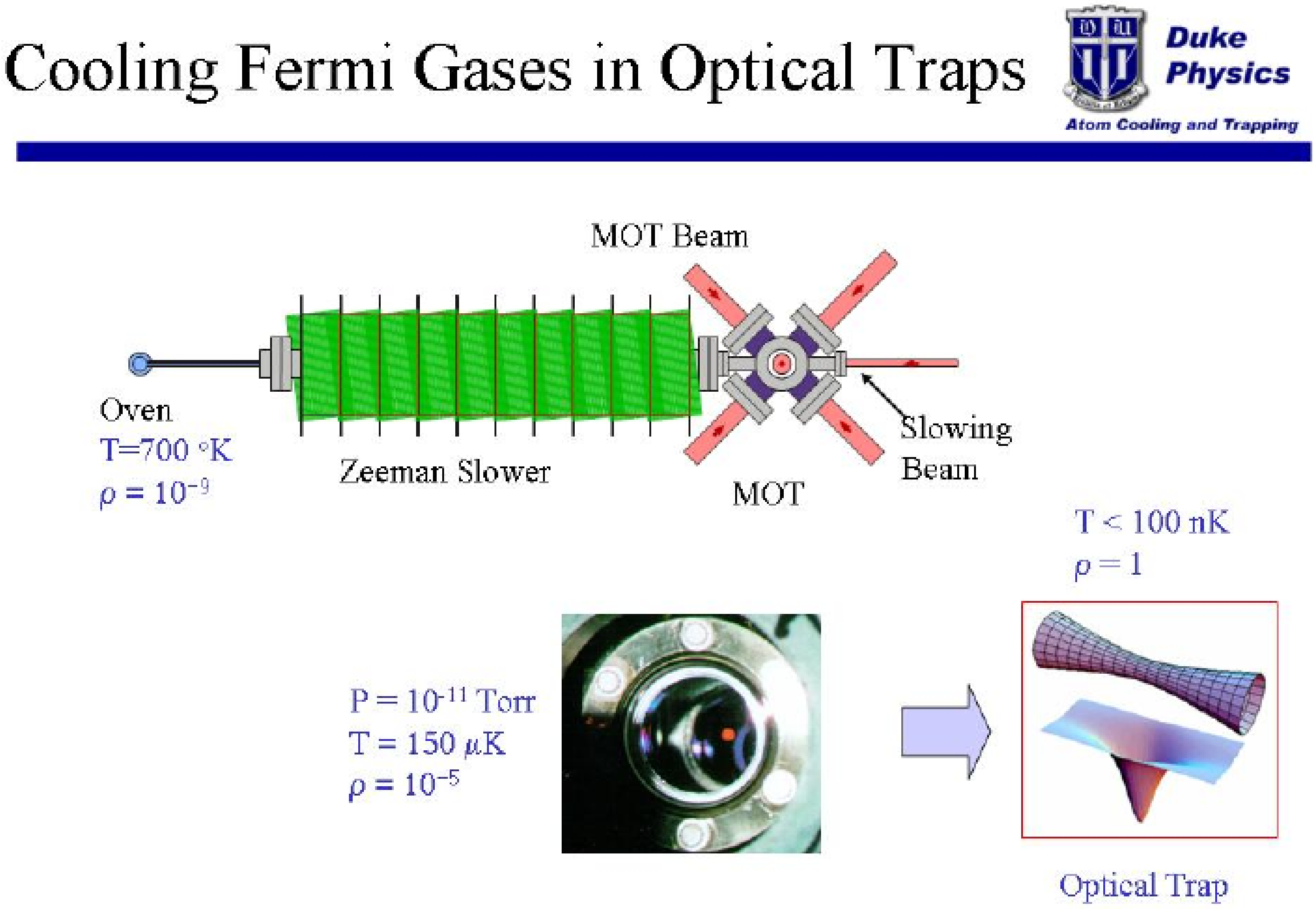
Tillmann Esslinger csoportja (ETH Zürich)

M. Ueda csoportja (Japán)

Imanuel Bloch csoportja (Mainzi egyetem)

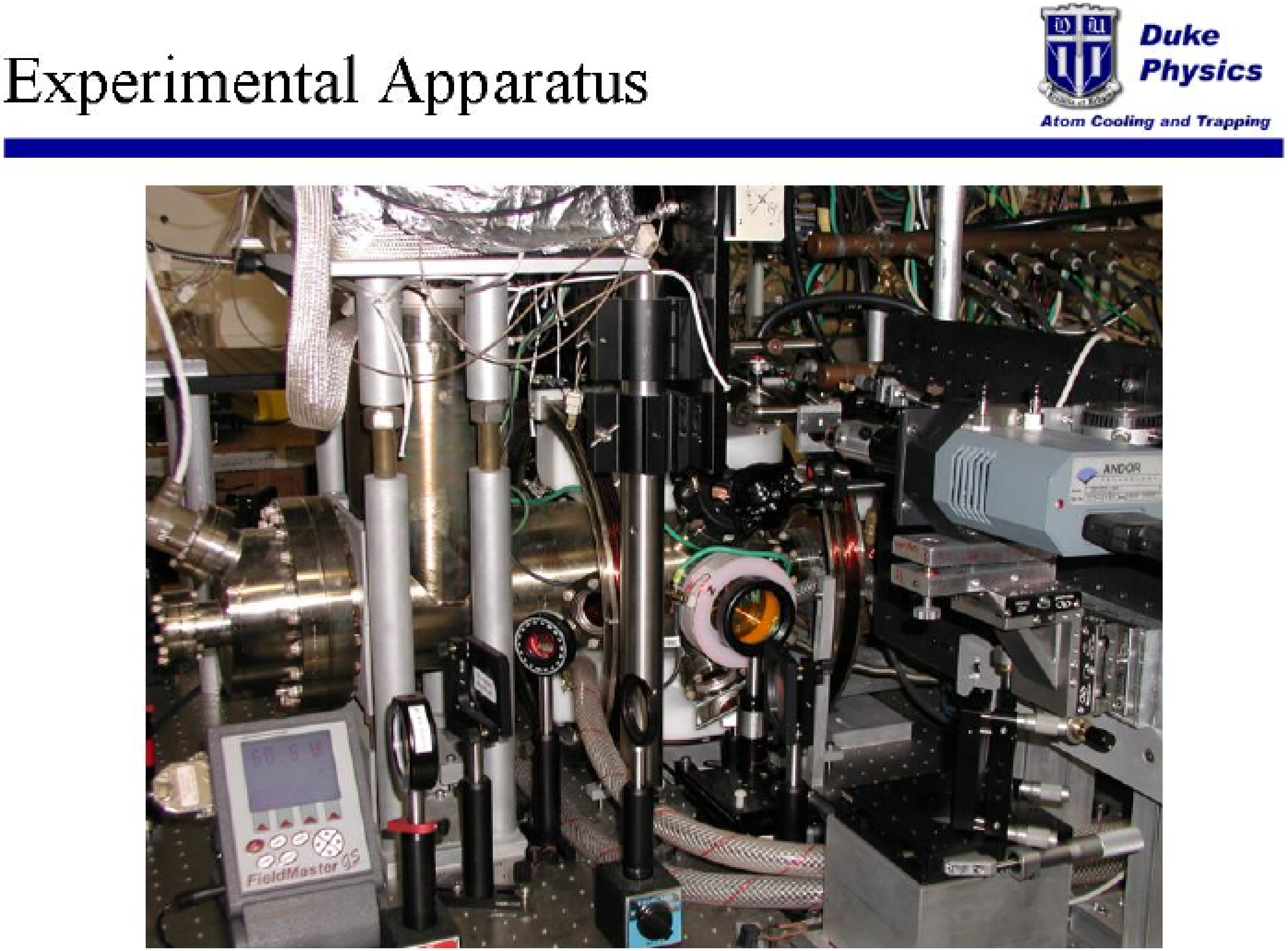
Thomas csoportja (Duke-egyetem)

Thomas-csapda sematikusan: (Duke-egyetem)



Cooling Fermi Gases in Optical Traps

A Thomas-csapda a valóságban:



Experimental Apparatus

Duke
Physics
Atom Cooling and Trapping

Különböző csapdák:

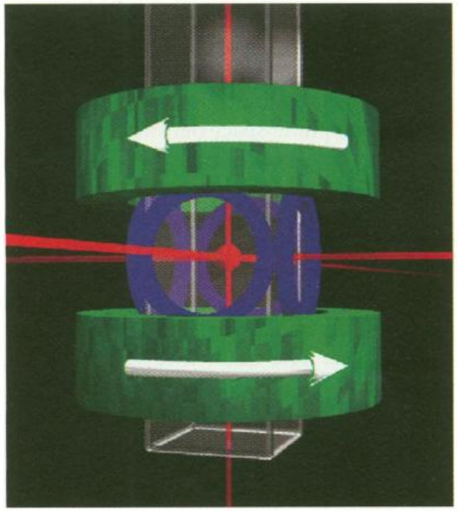
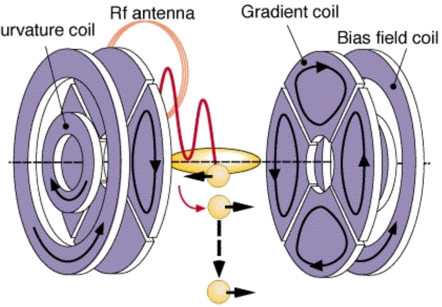


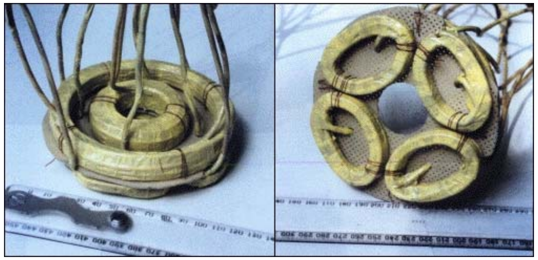
Fig. 1. Schematic of the apparatus. Six laser beams intersect in a glass cell, creating a magneto-optical trap (MOT). The cell is 2.5 cm square by 12 cm long, and the beams are 1.5 cm in diameter. The coils generating the fixed quadrupole and rotating transverse components of the TOP trap magnetic fields are shown in green and blue, respectively. The glass cell hangs down from a steel chamber (not shown) containing a vacuum pump and rubidium source. Also not shown are coils for injecting the rf magnetic field for evaporation and the additional laser beams for imaging and optically pumping the trapped atom sample.

TOP csapda (JILA)

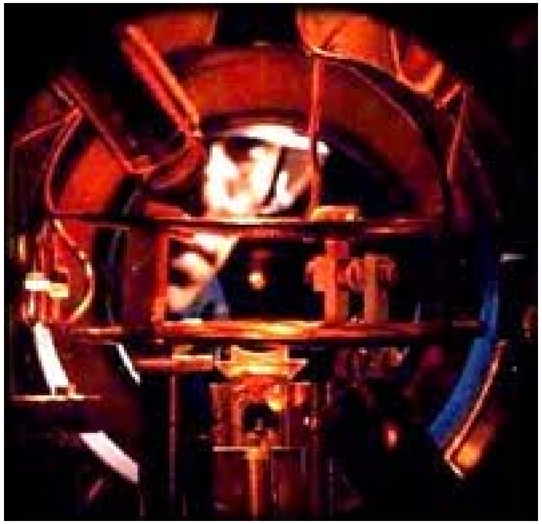
BEC in a "cloverleaf" magnetic trap



MIT, March '96 [M.-O. Mewes et al., PRL 77, 416 (1996)]

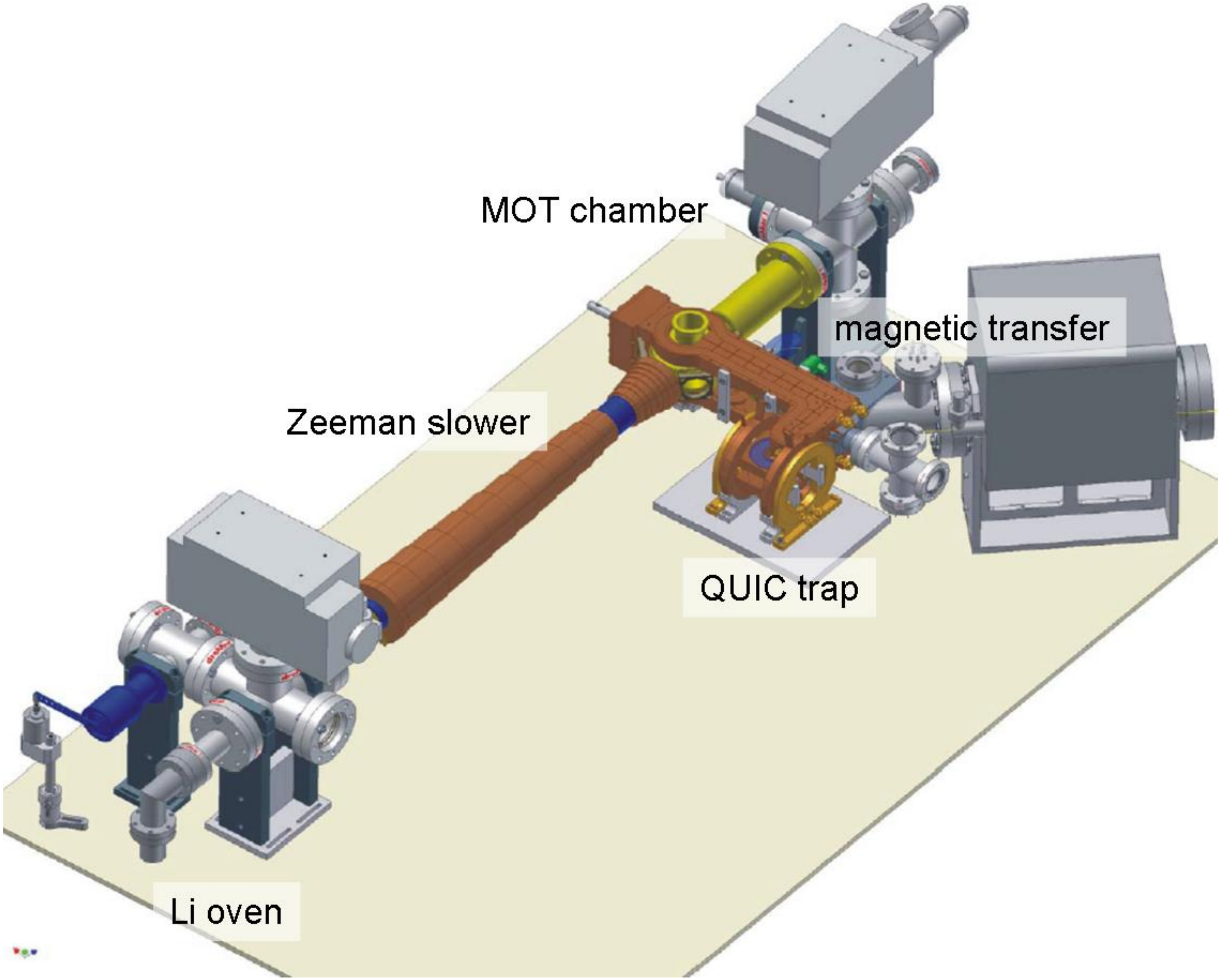


Lóhere csapda (MIT)

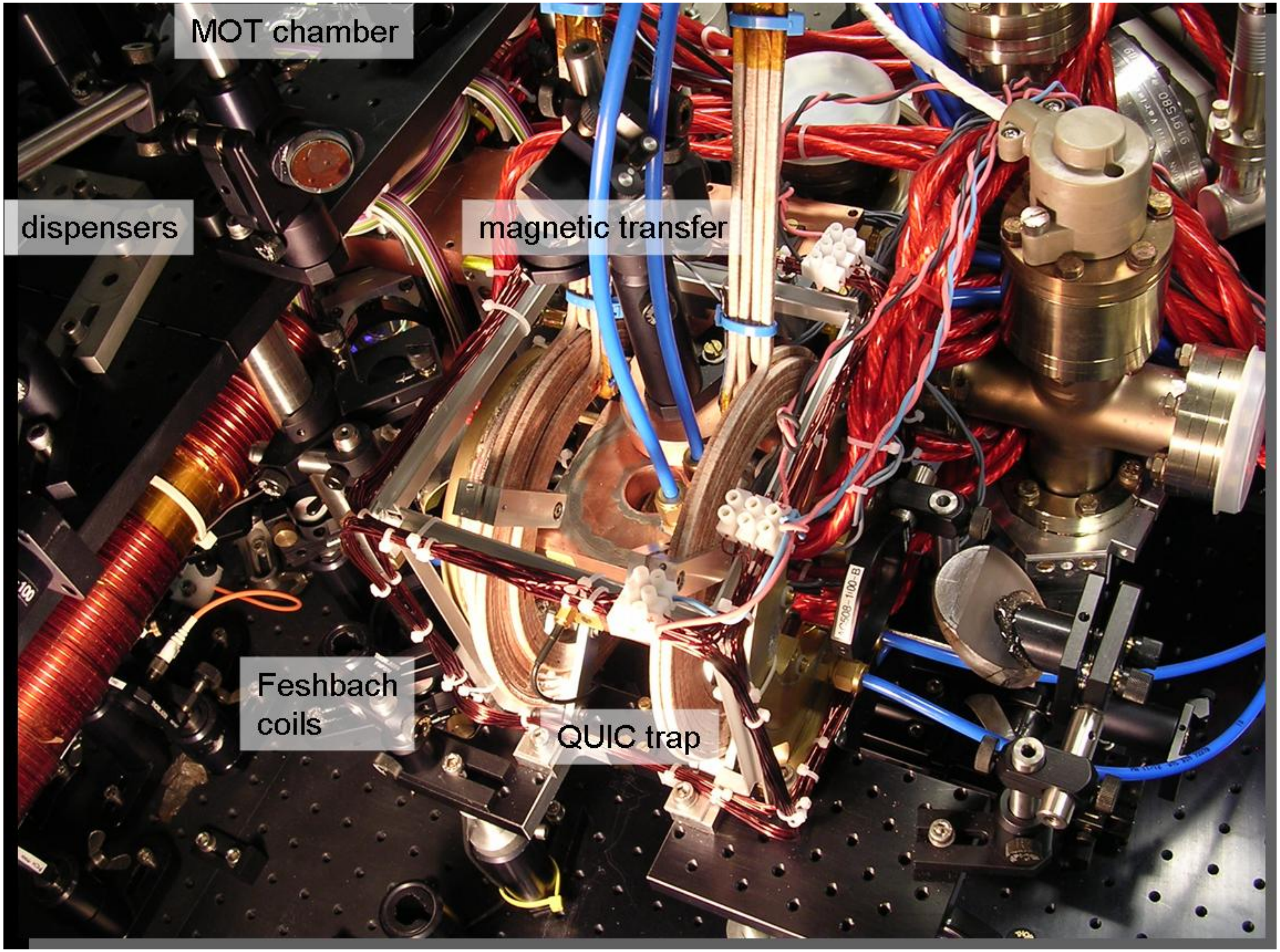


TOP csapda (NIST)

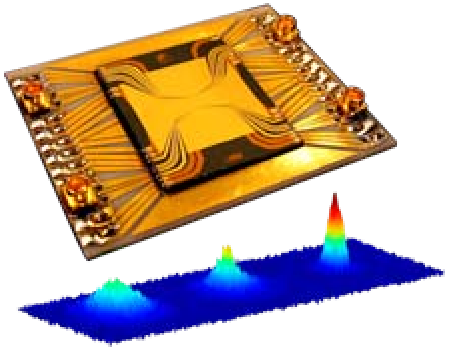
A müncheni berendezés sematikusan:



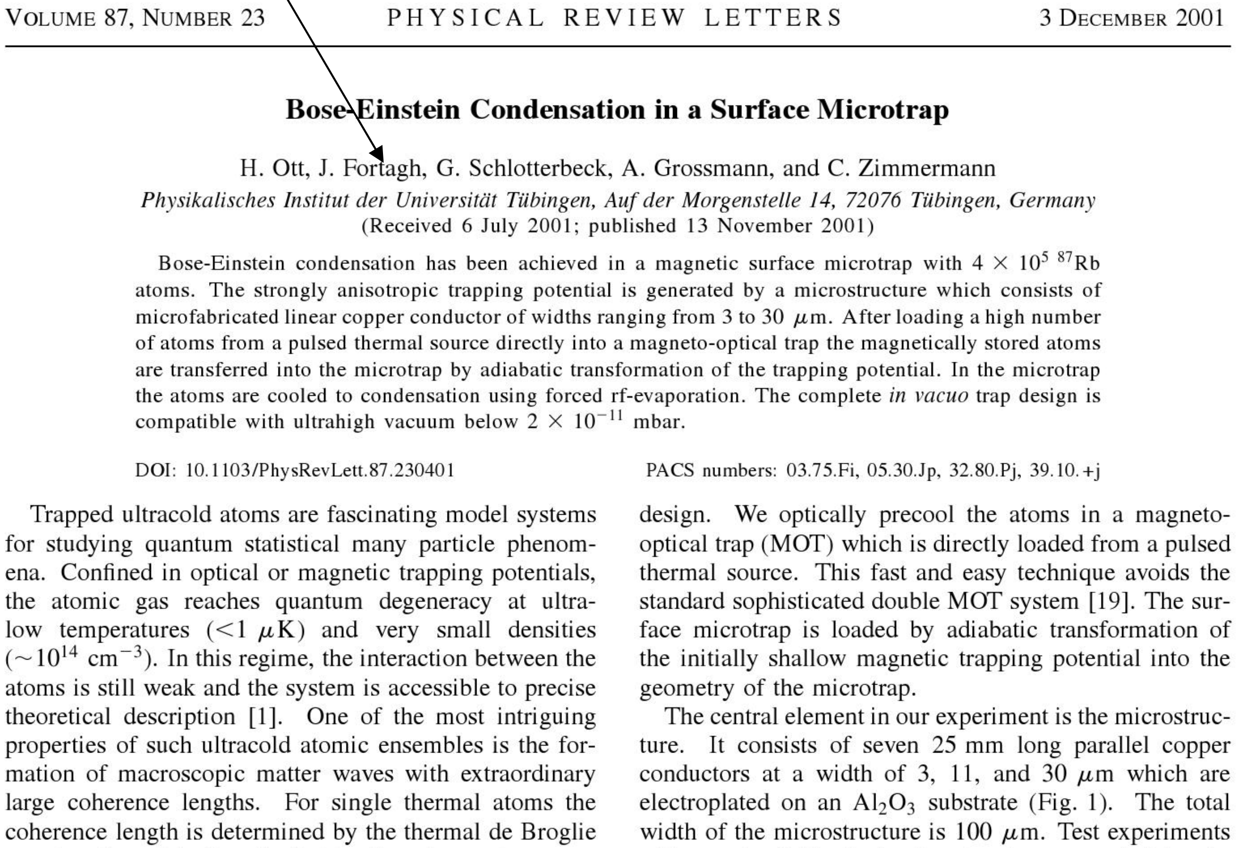
A müncheni berendezés a valóságban:



Mikrocsapdák:



München



VOLUME 87, NUMBER 23 PHYSICAL REVIEW LETTERS 3 DECEMBER 2001

Bose-Einstein Condensation in a Surface Microtrap

H. Ott, J. Fortagh, G. Schlotterbeck, A. Grossmann, and C. Zimmermann
Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany

(Received 6 July 2001; published 13 November 2001)

Bose-Einstein condensation has been achieved in a magnetic surface microtrap with 4×10^5 ^{87}Rb atoms. The strongly anisotropic trapping potential is generated by a microstructure which consists of microfabricated linear copper conductor of widths ranging from 3 to 30 μm. After loading a high number of atoms from a pulsed thermal source directly into a magneto-optical trap the magnetically stored atoms are transferred into the microtrap by adiabatic transformation of the trapping potential. In the microtrap the atoms are cooled to condensation using forced rf-evaporation. The complete *in vacuo* trap design is compatible with ultrahigh vacuum below 2×10^{-11} mbar.

DOI: 10.1103/PhysRevLett.87.230401 PACS numbers: 03.75.Fi, 05.30.Jp, 32.80.Pj, 39.10.+j

Trapped ultracold atoms are fascinating model systems for studying quantum statistical many particle phenomena. Confined in optical or magnetic trapping potentials, the atomic gas reaches quantum degeneracy at ultralow temperatures (<1 μK) and very small densities ($\sim 10^{14}$ cm^{-3}). In this regime, the interaction between the atoms is still weak and the system is accessible to precise theoretical description [1]. One of the most intriguing properties of such ultracold atomic ensembles is the formation of macroscopic matter waves with extraordinary large coherence lengths. For single thermal atoms the coherence length is determined by the thermal de Broglie

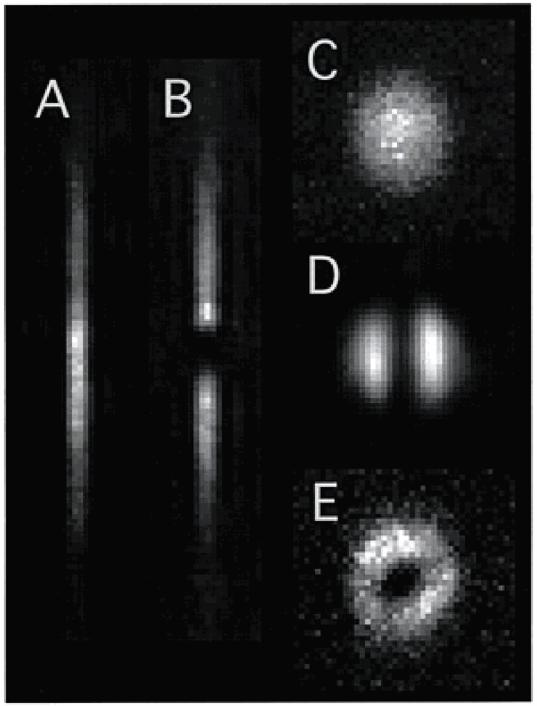
design. We optically precool the atoms in a magneto-optical trap (MOT) which is directly loaded from a pulsed thermal source. This fast and easy technique avoids the standard sophisticated double MOT system [19]. The surface microtrap is loaded by adiabatic transformation of the initially shallow magnetic trapping potential into the geometry of the microtrap.

The central element in our experiment is the microstructure. It consists of seven 25 mm long parallel copper conductors at a width of 3, 11, and 30 μm which are electroplated on an Al_2O_3 substrate (Fig. 1). The total width of the microstructure is 100 μm. Test experiments

Tübingen

A gázfelhő (kondenzátum) manipulálása lézerrel:

W. Ketterle (MIT)



Shaping condensates
with magnetic fields and
(far off-resonant) light

A kondenzátum arrébb tolása:

(München)

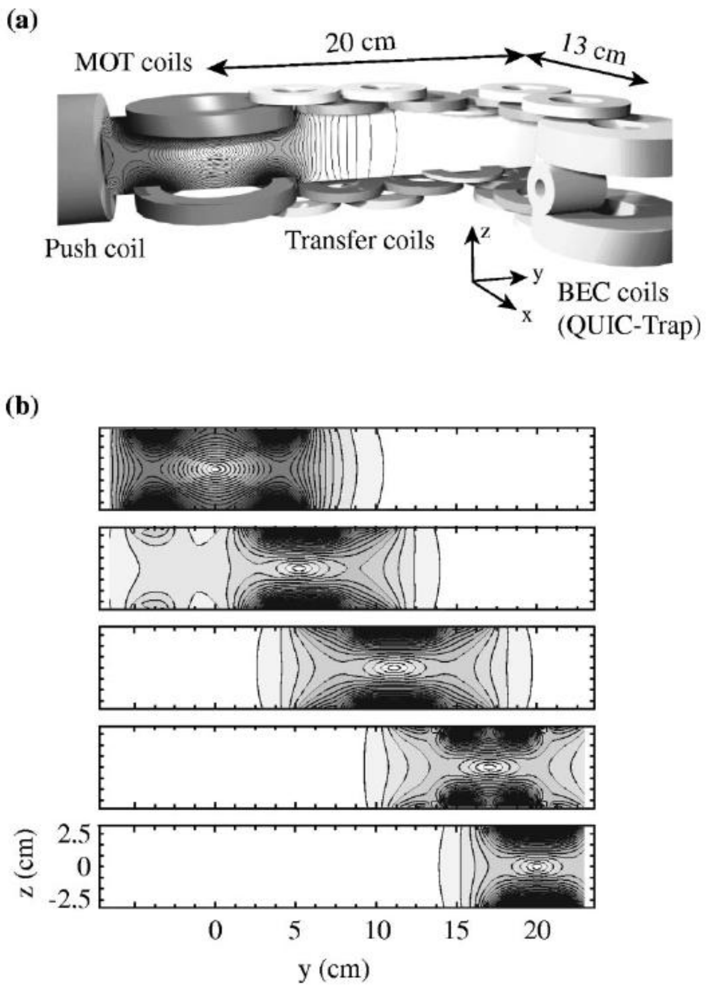


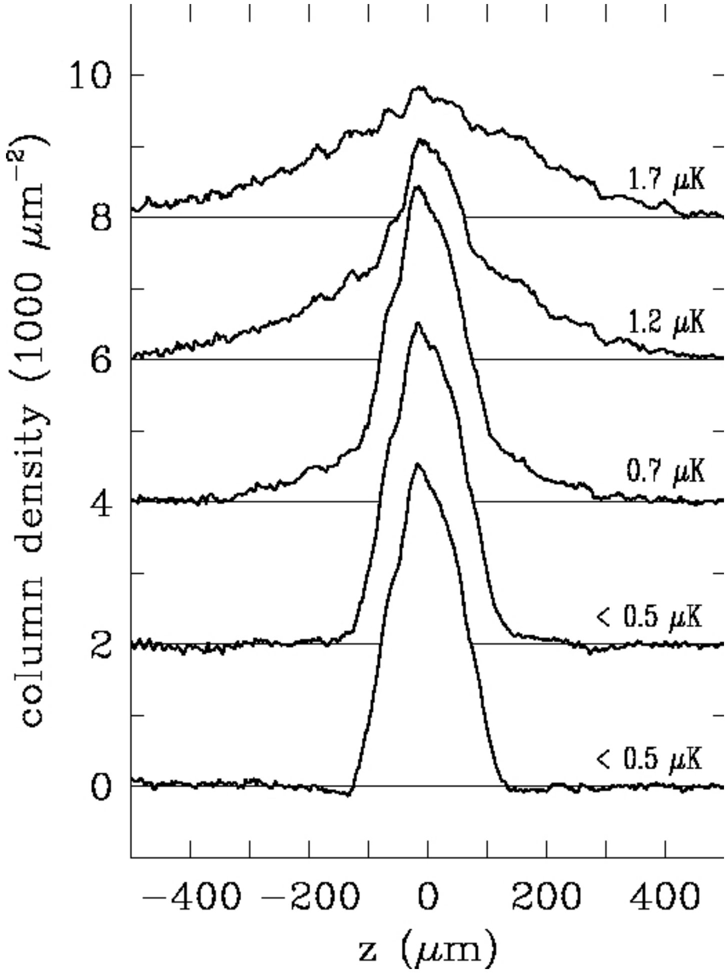
FIG. 1. (a) Experimental setup of the quadrupole coil pairs for the transport process. The magnetic trapping potential is moved over 33 cm around a 90° corner into an UHV vacuum region of a glass cell. (b) Contour plots, showing the absolute value of the magnetic field during different stages of the first half of the transport sequence.

Néhány tipikus paraméter:

	JILA Top csapda	MIT lóhere csapda
Anyag	^{87}RB	^{23}NA
BEC T_c	170 nK	2 μK
N_0	10^5	10^8
ω_z	$2\pi * 208$ Hz	$2\pi * 18$ Hz
$\omega_\perp$	$2\pi * 74$ Hz	$2\pi * 320$ Hz
d_z	1,25 μm	1,7 μm
$d_\perp$	0,74 μm	7,0 μm

Megjegyzés: $\omega=(D/m)^{1/2}$; $d=(h/(2\pi m\omega))^{1/2}$

Sűrűségprofil (MIT)



„Hőmérő" a csapdázott gázoknál: a termális és kondenzátum alakját ismerve a sűrűségprofilból a hőmérséklet meghatározható

A leghidegebb megmért hőmérséklet BEC-cel:

Forrás (MIT): Journal of Physics: Csonference Series 19 (2005) 139-145

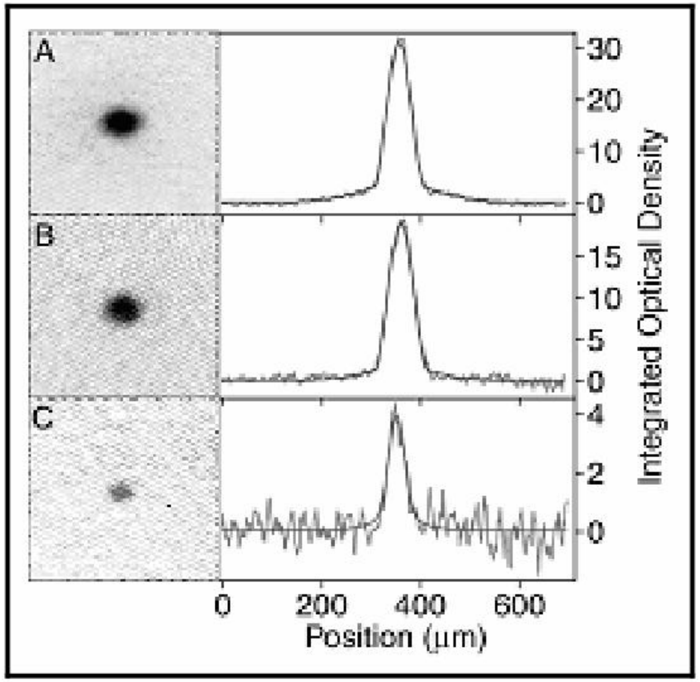
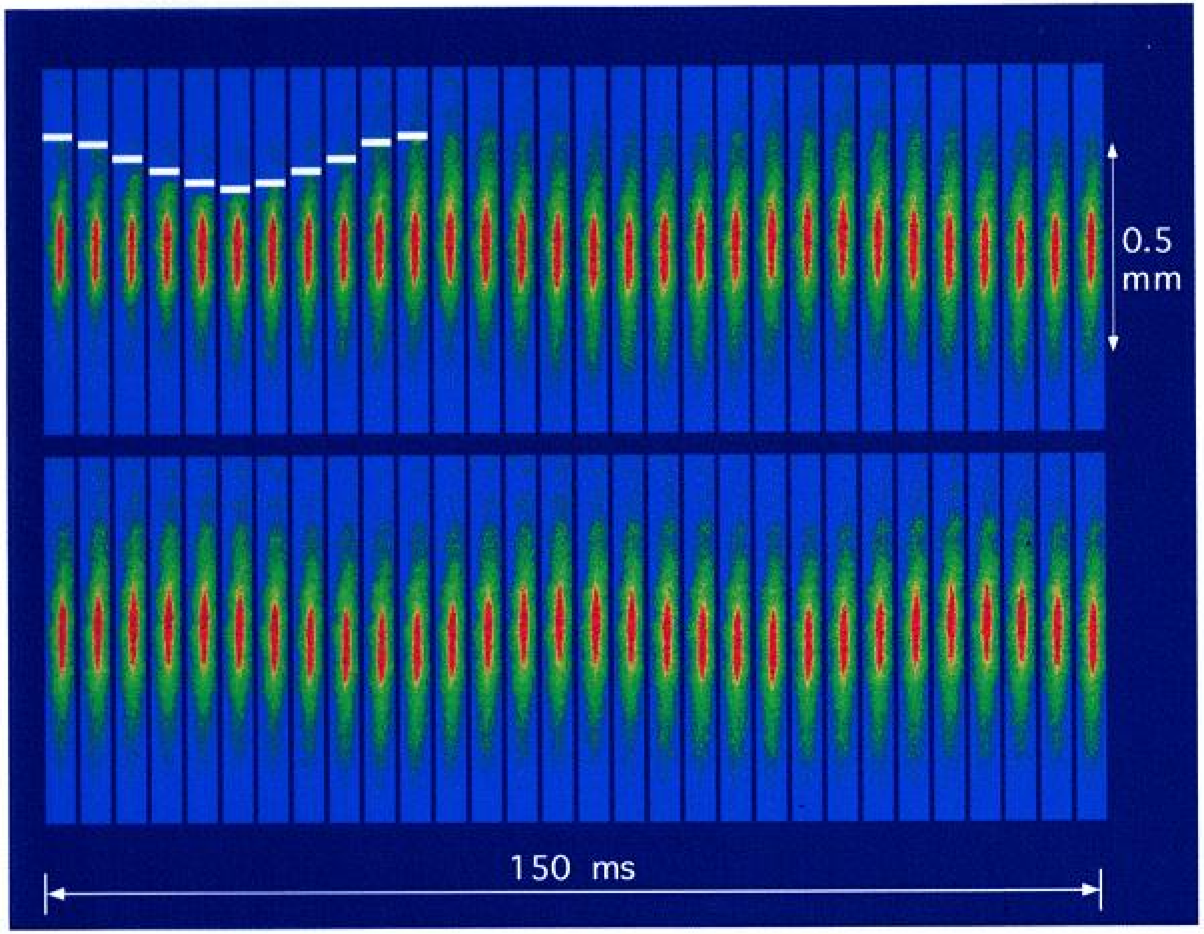


Figure 6. Picokelvin temperature thermometry. Partially condensed atomic vapors confined in the gravito-magnetic trap with (A) 28,000, (B) 16,000, and (C) 2,500 atoms. The one-dimensional cross sections were obtained by integrating the two-dimensional absorption images of the trapped clouds along the y-axis. Bimodal fits yielded temperatures of (A) 1.05 ± 0.08 nK, (B) 780 ± 50 pK, and (C) 450 ± 80 pK, where the uncertainty is due to the fit of an individual image. The field of view for the absorption images is 460 μm x 460 μm.

Gerjesztések keltése (MIT)



Egy hasonló jelenség (csak kicsit durvább!)

Gerjesztések hengerszimmetrikus csapdában (MIT)

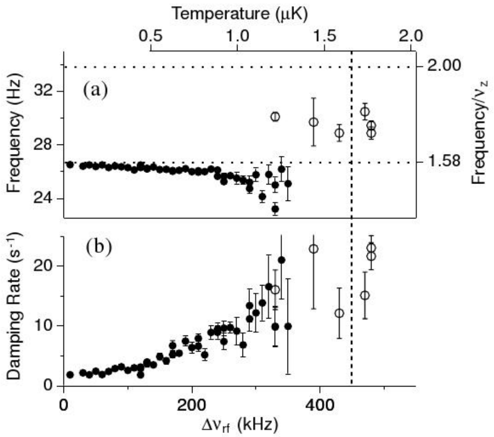


FIG. 2. Temperature dependent frequency and damping rates of $m = 0$ quadrupolar collective modes. Points show measurements for oscillations of the thermal cloud (open circles) and condensate (closed circles). The free-particle limit of $2\nu_z$ and the zero-temperature condensate oscillation limit of $1.580\nu_z$ are indicated. The vertical dashed line marks the observed transition temperature. The temperature axis is based on a linear fit to the data in (b), and is determined only for $T > 0.5$ μK, where temperature could be measured.

prediction of $1.580\nu_z$ [9]. The slight difference between

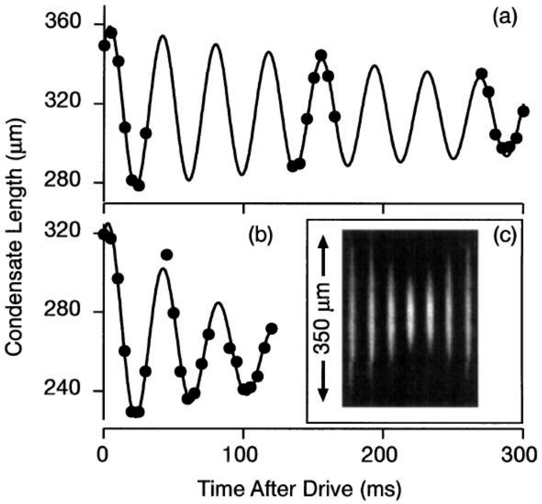
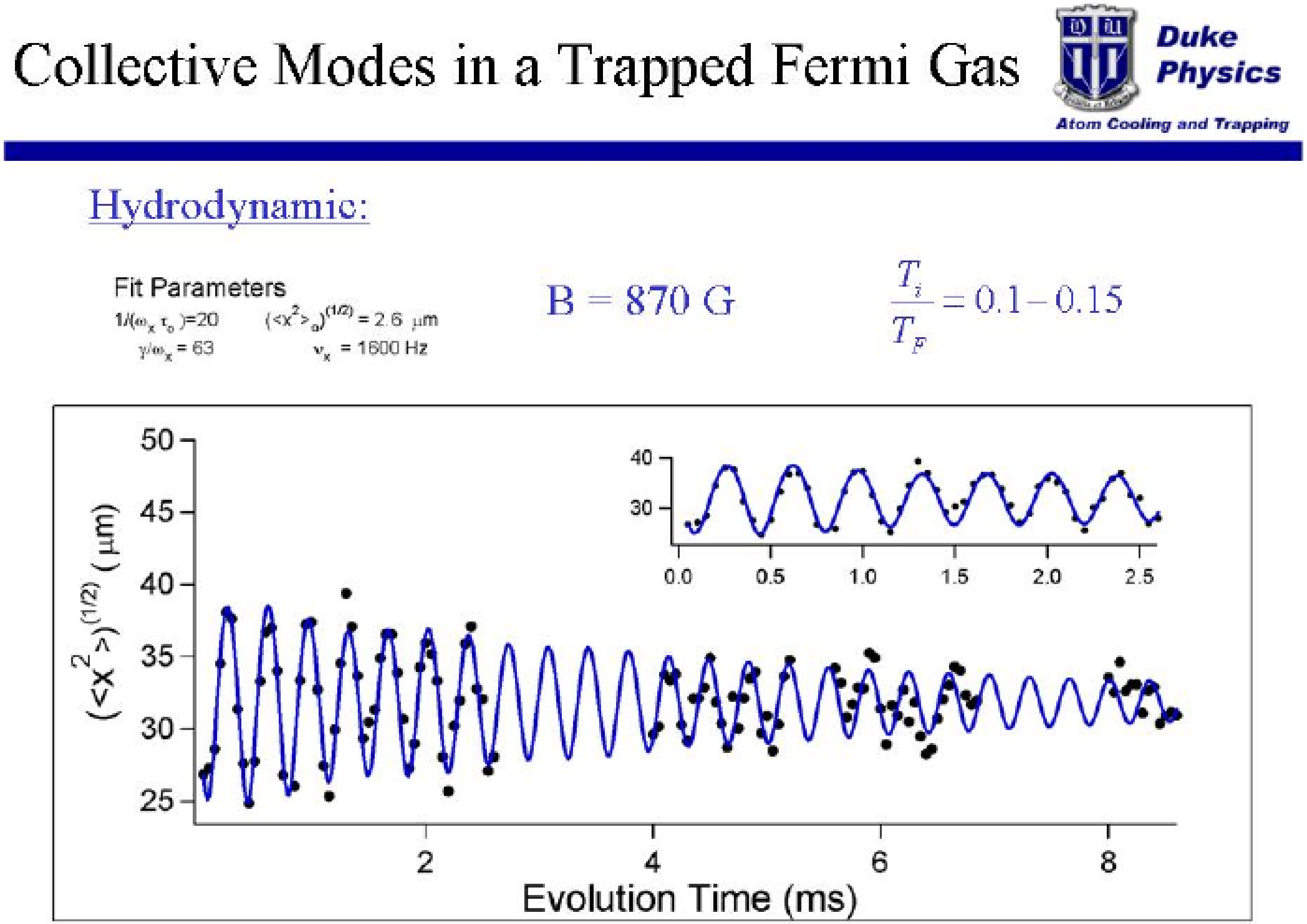


FIG. 3. Quadrupolar condensate oscillations. Axial condensate lengths determined from fits to phase-contrast images are shown for (a) low and (b) high temperature. (a) $\Delta\nu_{\mathrm{rf}} =$ 30 kHz and $T < 0.5$ μK; (b) $\Delta\nu_{\mathrm{rf}} = 250$ kHz and $T =$ 0.95 μK. Lines are fits to a damped sinusoidal oscillation with a downward slope to account for heating. (c) *In situ* images, taken at 5 ms intervals, show large-amplitude oscillations of a low-temperature Bose-Einstein condensate. Final data were evaluated for oscillation amplitudes of about 10%.

Forrás: Physical Review Letters **81,** 500 (1998)

Csapdázott fermionok rezgései (Duke-egyetem):



Collective Modes in a Trapped Fermi Gas

Duke Physics
Atom Cooling and Trapping

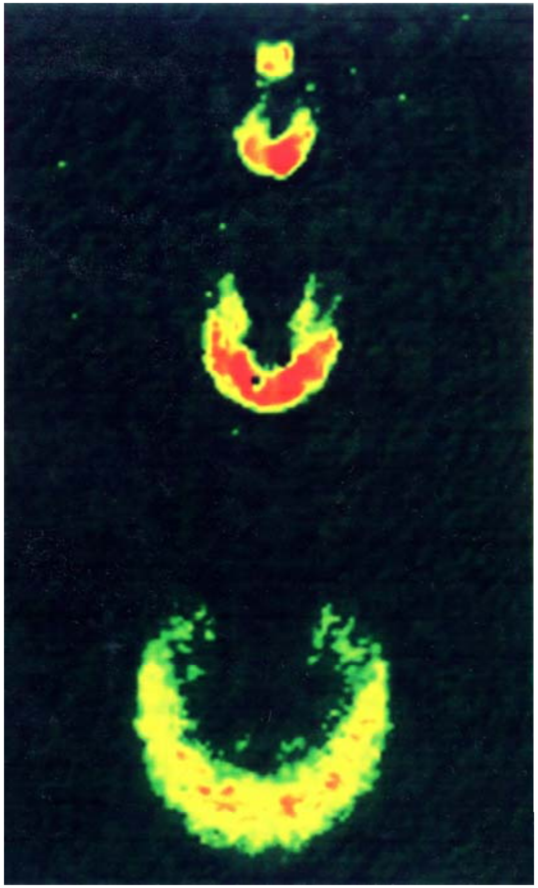
Hydrodynamic:

Fit Parameters
$1/(\omega_x \tau_0)=20$ $(\langle x^2\rangle_0)^{(1/2)} = 2.6\ \mu m$
$\gamma/\omega_x = 63$ $\nu_x = 1600$ Hz

$B = 870$ G

$\frac{T_i}{T_F} = 0.1 - 0.15$

Atomlézerek



MIT

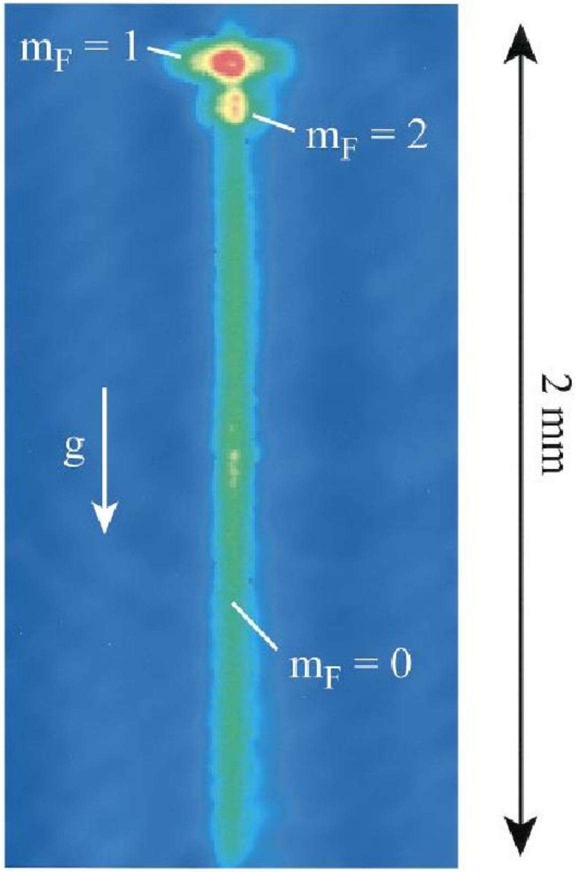
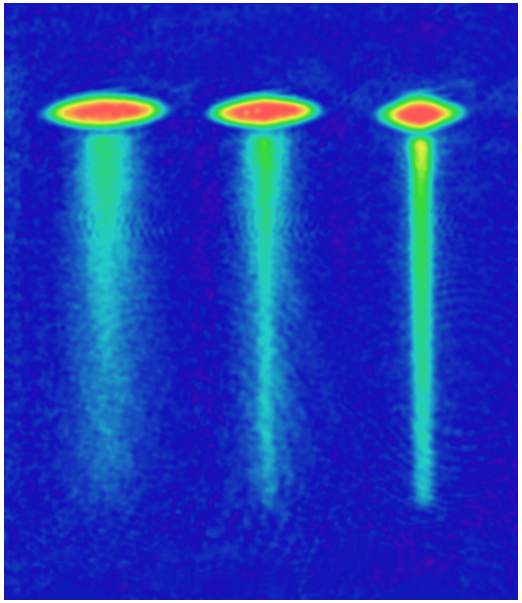


FIG. 1(color). Atom laser output: A collimated atomic beam is derived from a Bose-Einstein condensate over a 15 ms period of continuous output coupling. A fraction of condensed atoms has remained in the magnetically trapped $|F = 2, m_F = 2\rangle$ and $|F = 2, m_F = 1\rangle$ state. The magnetic trap has its weakly confining axis in the horizontal direction.

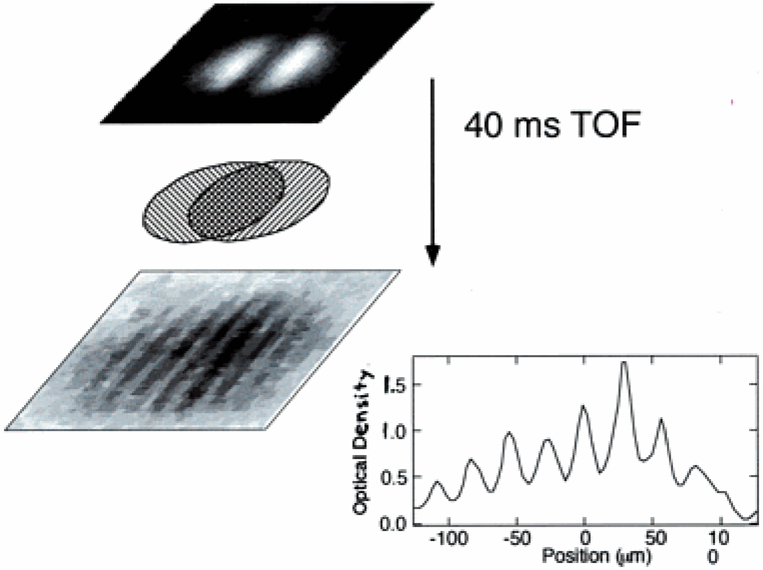


München

Az atomlézer valóban koherens nyalábot bocsát ki: Interferenciára képes a két elvágott darab!

(W. Ketterle mérése)

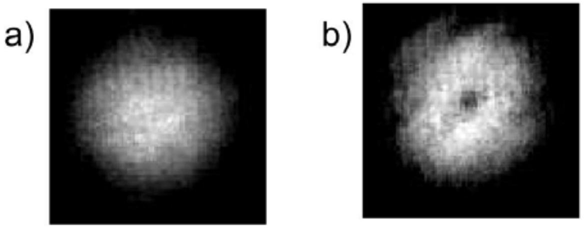
Reminder: The atom laser indeed produces coherent beams



Fringe spacings of 25 μm !

Örvények (vortexek) keltése

Figure 2: A cigar-shaped atomic cloud confined in an axisymmetric magnetic trap is stirred by a far-detuned laser beam. The laser beam propagates along the long axis of the cigar (z), and it creates a dipole potential which is anisotropic in the xy plane. This anisotropy rotates around the z axis at the angular frequency Ω.



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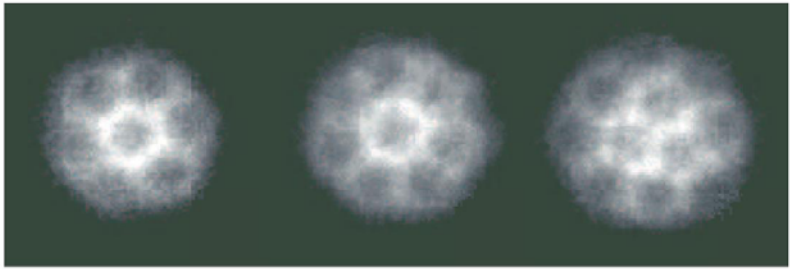
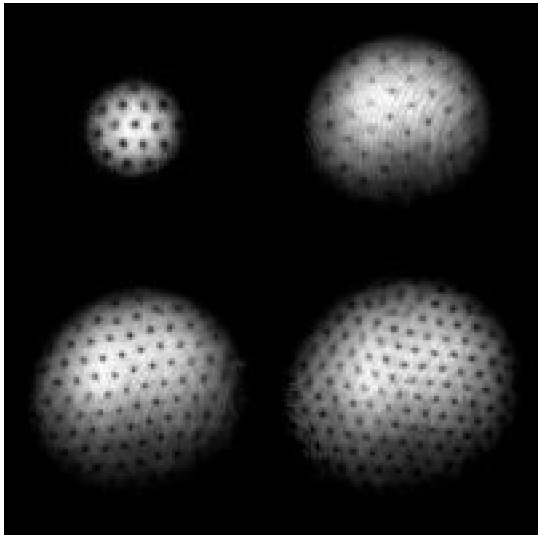
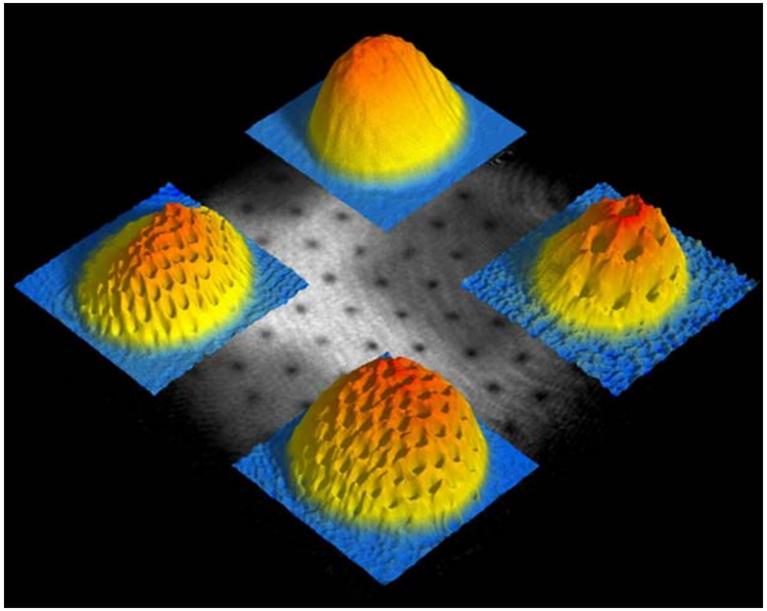


Figure 5: Arrays of vortices in a Bose-Einstein condensate stirred by a laser beam (after a 27 ms time-of-flight). These pictures have been obtained with a magnetic trap less stiff than for the pictures of Fig. 4 (ω_t $2\pi = 169$ Hz).

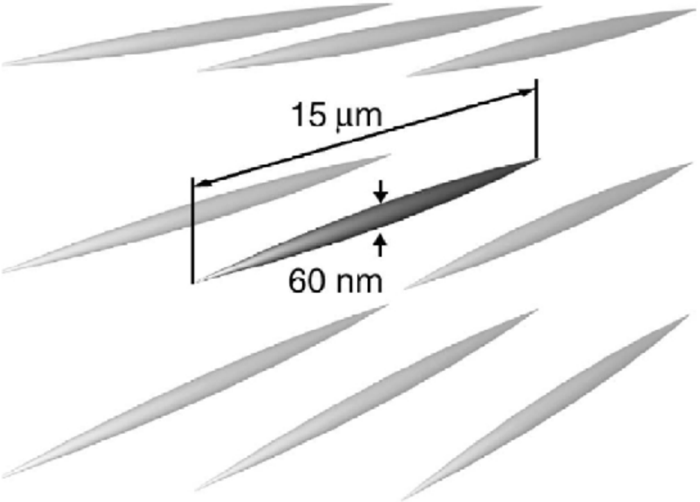
ENS (cond-mat/0004037)

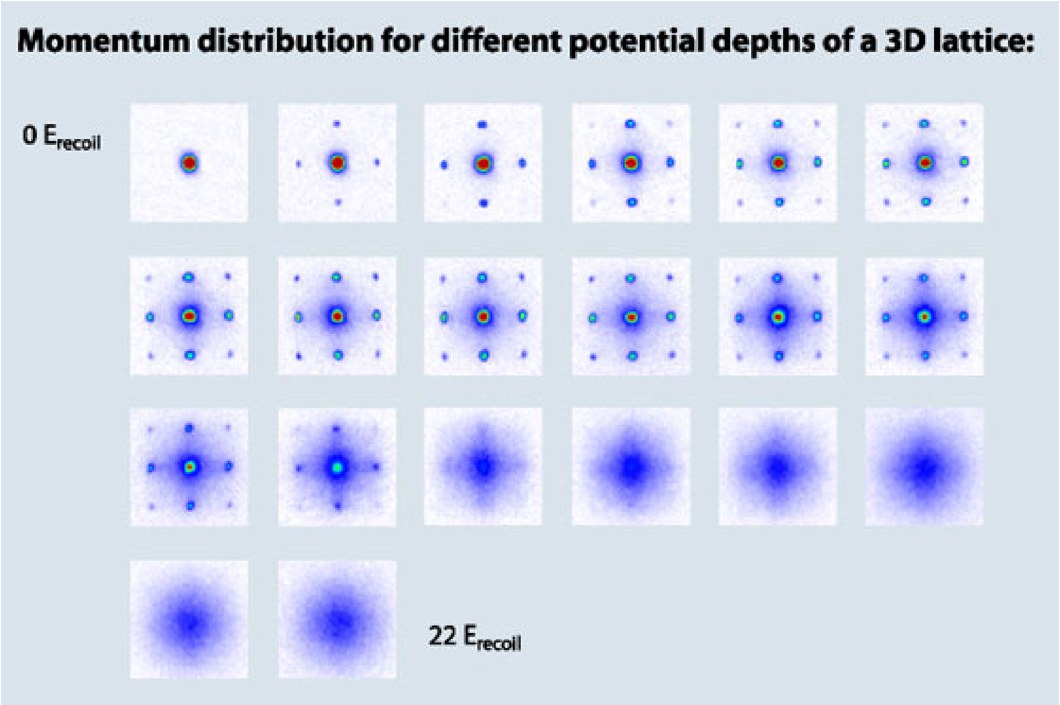




MIT (cua.mit.edu/ketterle_group/Nice_pics.htm)

Atomok periódikus potenciálban:





Szuperfolyékony-Mott szigetelő átmenet

(Nature 415, 39 (2002))

Köszönöm a figyelmet!