Narodowe
Laboratorium
Technologii
Kwantowych

# *Prof. dr hab. Wojciech Gawlik*

*Opracowanie utworu pod tytułem:*

***"Pułapki atomowe" 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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# Atom traps
# – principles & realizations

**Wojciech Gawlik**

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FNP Fundacja na rzecz Nauki Polskiej

part I

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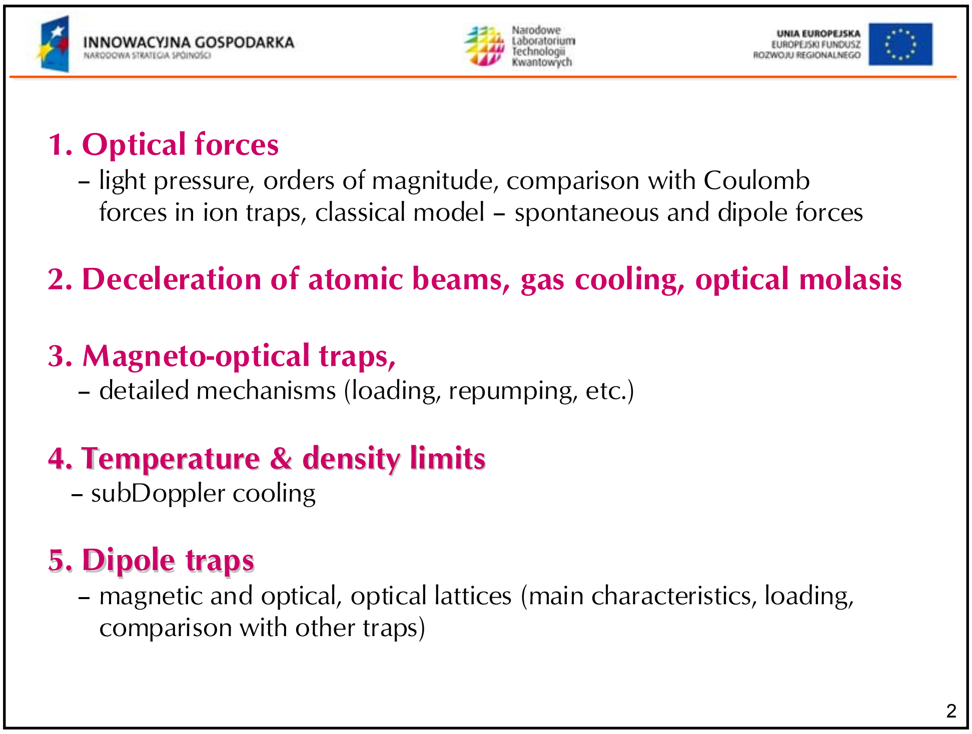

**1. Optical forces**
– light pressure, orders of magnitude, comparison with Coulomb forces in ion traps, classical model – spontaneous and dipole forces

**2. Deceleration of atomic beams, gas cooling, optical molasis**

**3. Magneto-optical traps,**
– detailed mechanisms (loading, repumping, etc.)

**4. Temperature & density limits**
– subDoppler cooling

**5. Dipole traps**
– magnetic and optical, optical lattices (main characteristics, loading, comparison with other traps)

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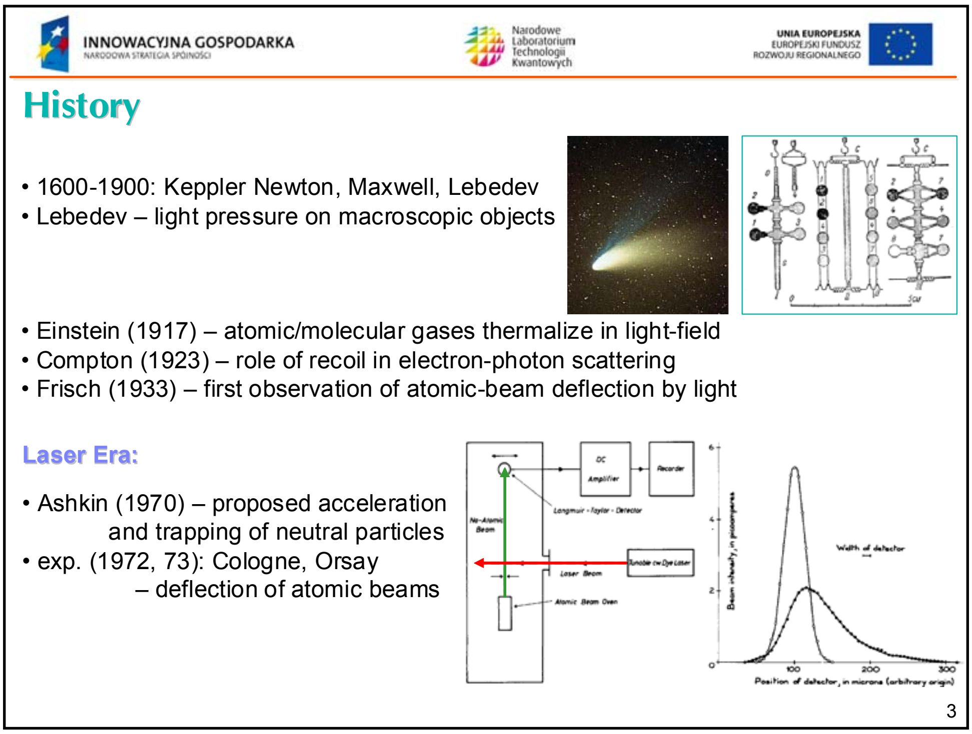
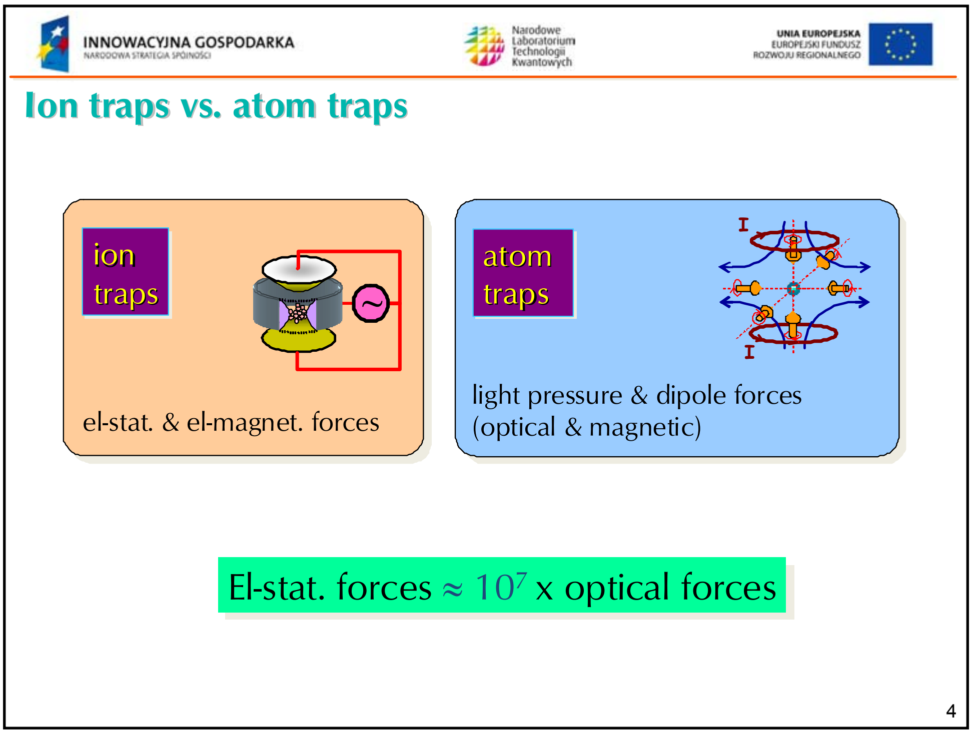


## History

- 1600-1900: Keppler Newton, Maxwell, Lebedev
- Lebedev – light pressure on macroscopic objects
- Einstein (1917) – atomic/molecular gases thermalize in light-field
- Compton (1923) – role of recoil in electron-photon scattering
- Frisch (1933) – first observation of atomic-beam deflection by light

**Laser Era:**

- Ashkin (1970) – proposed acceleration and trapping of neutral particles
- exp. (1972, 73): Cologne, Orsay – deflection of atomic beams



## Ion traps vs. atom traps

**ion traps**

el-stat. & el-magnet. forces

**atom traps**

light pressure & dipole forces
(optical & magnetic)

El-stat. forces ≈ $10^7$ x optical forces

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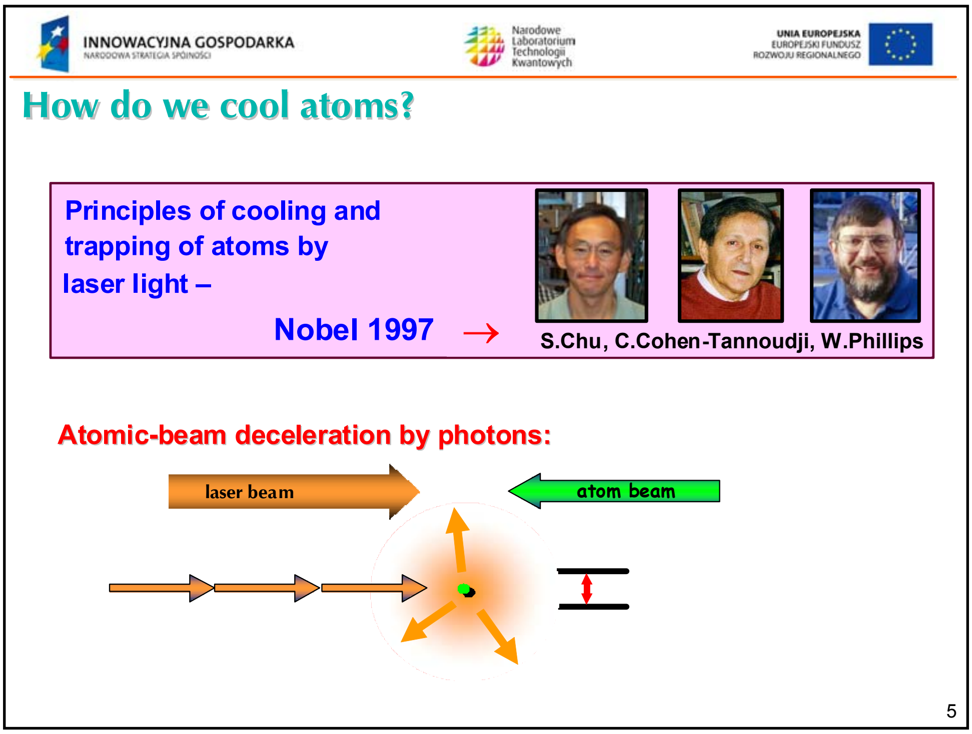


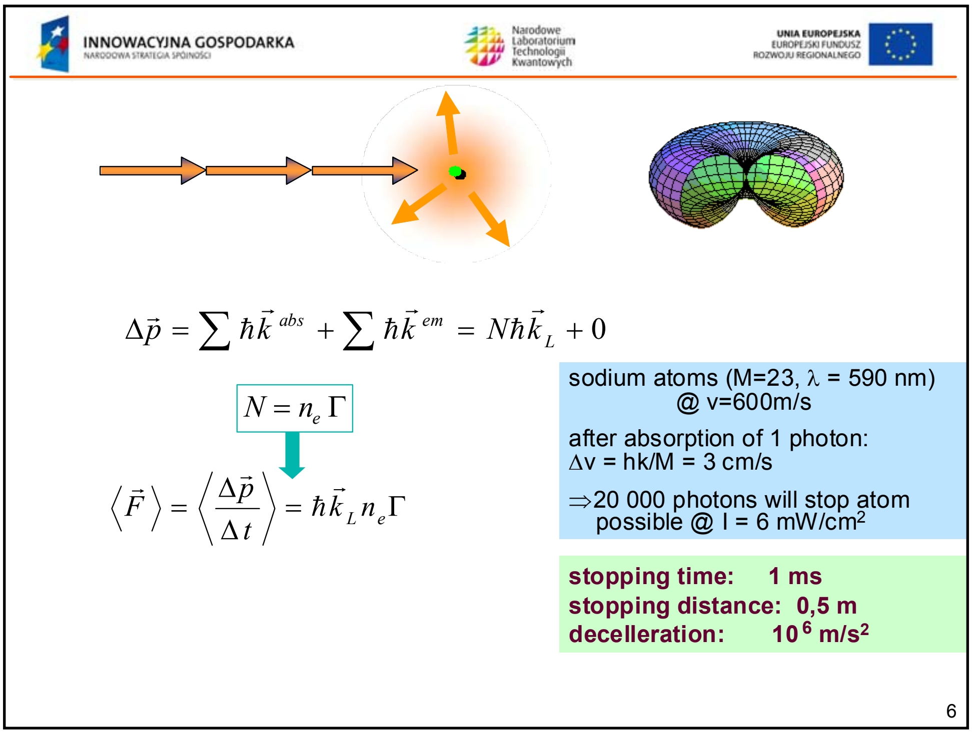
## How do we cool atoms?

**Principles of cooling and trapping of atoms by laser light –**

**Nobel 1997** →

**S.Chu, C.Cohen-Tannoudji, W.Phillips**

**Atomic-beam deceleration by photons:**



$$\Delta\vec{p} = \sum \hbar\vec{k}^{\,abs} + \sum \hbar\vec{k}^{\,em} = N\hbar\vec{k}_L + 0$$

$$\boxed{N = n_e\Gamma}$$

$$\langle \vec{F} \rangle = \left\langle \frac{\Delta\vec{p}}{\Delta t} \right\rangle = \hbar\vec{k}_L n_e \Gamma$$

sodium atoms (M=23, $\lambda$ = 590 nm)
@ v=600m/s

after absorption of 1 photon:
$\Delta$v = hk/M = 3 cm/s

$\Rightarrow$20 000 photons will stop atom
possible @ I = 6 mW/cm$^2$

**stopping time: 1 ms**
**stopping distance: 0,5 m**
**decelleration: 10$^6$ m/s$^2$**

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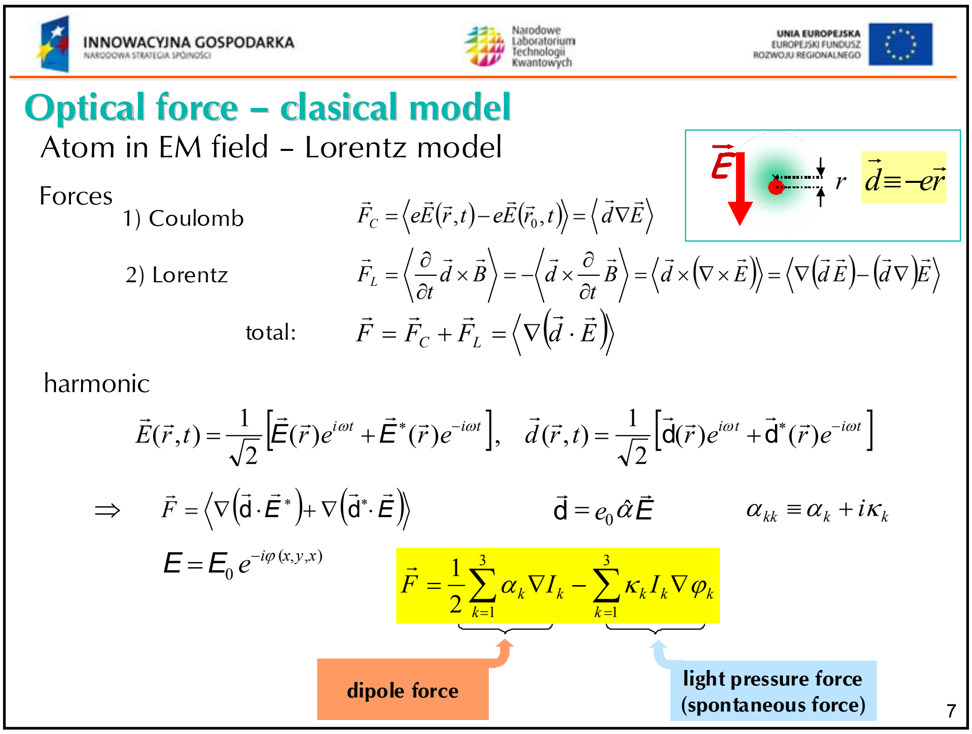


## Optical force – clasical model

Atom in EM field – Lorentz model

Forces

1) Coulomb $\vec{F}_C = \left\langle e\vec{E}(\vec{r},t) - e\vec{E}(\vec{r}_0,t) \right\rangle = \left\langle \vec{d}\nabla\vec{E} \right\rangle$

2) Lorentz $\vec{F}_L = \left\langle \frac{\partial}{\partial t}\vec{d}\times\vec{B} \right\rangle = -\left\langle \vec{d}\times\frac{\partial}{\partial t}\vec{B} \right\rangle = \left\langle \vec{d}\times\left(\nabla\times\vec{E}\right) \right\rangle = \left\langle \nabla\left(\vec{d}\,\vec{E}\right) - \left(\vec{d}\,\nabla\right)\vec{E} \right\rangle$

total: $\vec{F} = \vec{F}_C + \vec{F}_L = \left\langle \nabla\left(\vec{d}\cdot\vec{E}\right) \right\rangle$

harmonic

$$\vec{E}(\vec{r},t) = \frac{1}{\sqrt{2}}\left[\vec{E}(\vec{r})e^{i\omega t} + \vec{E}^*(\vec{r})e^{-i\omega t}\right], \quad \vec{d}(\vec{r},t) = \frac{1}{\sqrt{2}}\left[\vec{\mathrm{d}}(\vec{r})e^{i\omega t} + \vec{\mathrm{d}}^*(\vec{r})e^{-i\omega t}\right]$$

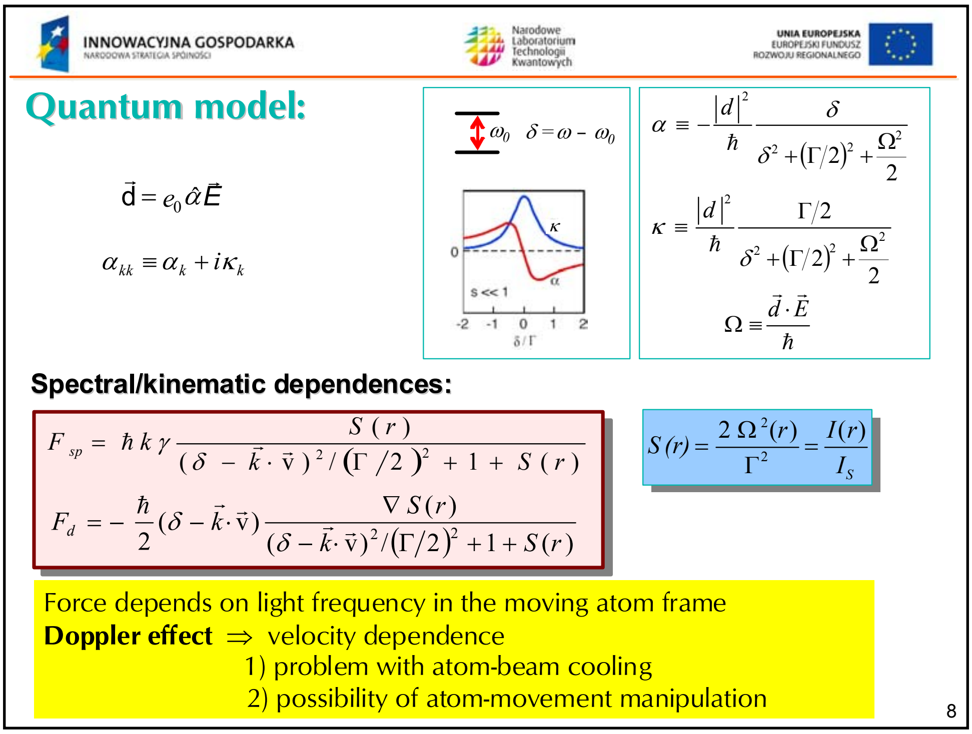
$$\Rightarrow \quad \vec{F} = \left\langle \nabla\left(\vec{\mathrm{d}}\cdot\vec{E}^*\right) + \nabla\left(\vec{\mathrm{d}}^*\cdot\vec{E}\right) \right\rangle \qquad \vec{\mathrm{d}} = e_0\hat{\alpha}\vec{E} \qquad \alpha_{kk} \equiv \alpha_k + i\kappa_k$$

$$E = E_0\, e^{-i\varphi(x,y,x)}$$

$$\vec{F} = \frac{1}{2}\underbrace{\sum_{k=1}^{3}\alpha_k \nabla I_k}_{} - \underbrace{\sum_{k=1}^{3}\kappa_k I_k \nabla\varphi_k}_{}$$

**dipole force**

**light pressure force (spontaneous force)**



## Quantum model:

$\delta = \omega - \omega_0$

$$\vec{\mathrm{d}} = e_0\hat{\alpha}\vec{E}$$

$$\alpha_{kk} \equiv \alpha_k + i\kappa_k$$

$$\alpha \equiv -\frac{|d|^2}{\hbar}\frac{\delta}{\delta^2 + (\Gamma/2)^2 + \frac{\Omega^2}{2}}$$

$$\kappa \equiv \frac{|d|^2}{\hbar}\frac{\Gamma/2}{\delta^2 + (\Gamma/2)^2 + \frac{\Omega^2}{2}}$$

$$\Omega \equiv \frac{\vec{d}\cdot\vec{E}}{\hbar}$$

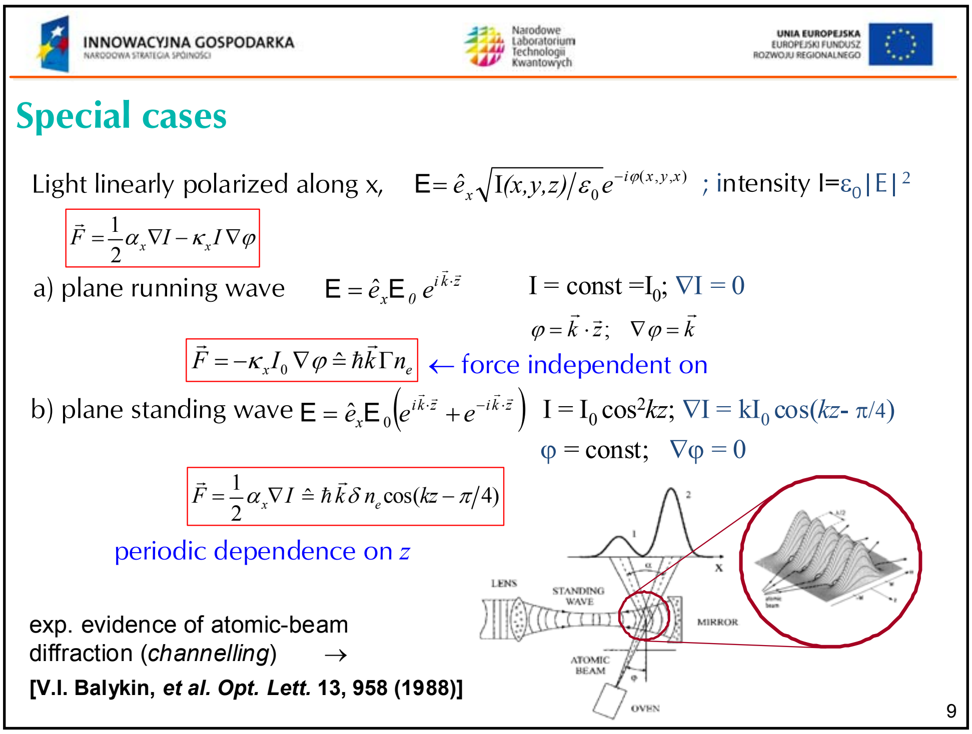
**Spectral/kinematic dependences:**

$$F_{sp} = \hbar k \gamma \frac{S(r)}{(\delta - \vec{k}\cdot\vec{\mathrm{v}})^2/(\Gamma/2)^2 + 1 + S(r)}$$

$$F_d = -\frac{\hbar}{2}(\delta - \vec{k}\cdot\vec{\mathrm{v}})\frac{\nabla S(r)}{(\delta - \vec{k}\cdot\vec{\mathrm{v}})^2/(\Gamma/2)^2 + 1 + S(r)}$$

$$S(r) = \frac{2\,\Omega^2(r)}{\Gamma^2} = \frac{I(r)}{I_S}$$

Force depends on light frequency in the moving atom frame
**Doppler effect** ⇒ velocity dependence
1) problem with atom-beam cooling
2) possibility of atom-movement manipulation



## Special cases

Light linearly polarized along x, $\mathrm{E}=\hat{e}_x\sqrt{\mathrm{I}(x,y,z)/\varepsilon_0}\,e^{-i\varphi(x,y,x)}$ ; intensity $\mathrm{I}=\varepsilon_0|\mathrm{E}|^2$

$$\boxed{\vec{F}=\frac{1}{2}\alpha_x\nabla I-\kappa_x I\,\nabla\varphi}$$

a) plane running wave $\mathrm{E}=\hat{e}_x\mathrm{E}_0\,e^{i\vec{k}\cdot\vec{z}}$ $\quad \mathrm{I}=\mathrm{const}=\mathrm{I}_0;\ \nabla\mathrm{I}=0$

$\varphi=\vec{k}\cdot\vec{z};\quad \nabla\varphi=\vec{k}$

$$\boxed{\vec{F}=-\kappa_x I_0\,\nabla\varphi\triangleq\hbar\vec{k}\Gamma n_e}$$ ← force independent on

b) plane standing wave $\mathrm{E}=\hat{e}_x\mathrm{E}_0\left(e^{i\vec{k}\cdot\vec{z}}+e^{-i\vec{k}\cdot\vec{z}}\right)$ $\quad \mathrm{I}=\mathrm{I}_0\cos^2 kz;\ \nabla\mathrm{I}=k\mathrm{I}_0\cos(kz-\pi/4)$

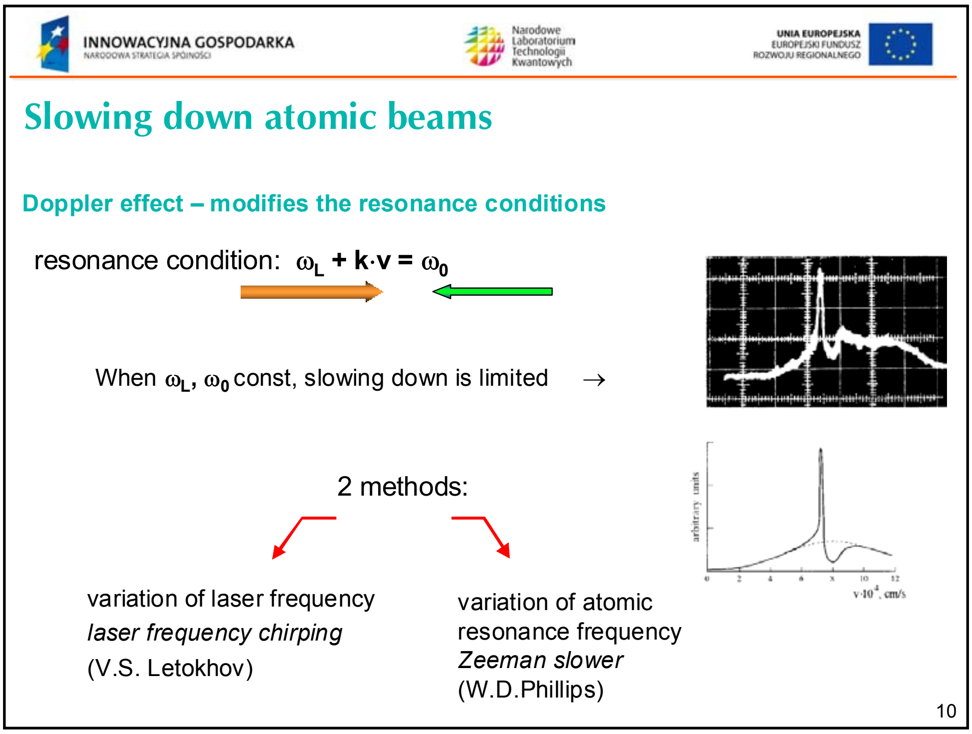
$\varphi=\mathrm{const};\quad \nabla\varphi=0$

$$\boxed{\vec{F}=\frac{1}{2}\alpha_x\nabla I\triangleq\hbar\vec{k}\delta\,n_e\cos(kz-\pi/4)}$$

periodic dependence on *z*

exp. evidence of atomic-beam diffraction (*channelling*) →

**[V.I. Balykin, *et al. Opt. Lett.* 13, 958 (1988)]**



## Slowing down atomic beams

**Doppler effect – modifies the resonance conditions**

resonance condition: $\omega_L+\mathbf{k}\cdot\mathbf{v}=\omega_0$

→ ←

When $\omega_L$, $\omega_0$ const, slowing down is limited →

2 methods:

↙ ↘

variation of laser frequency
*laser frequency chirping*
(V.S. Letokhov)

variation of atomic resonance frequency
*Zeeman slower*
(W.D.Phillips)

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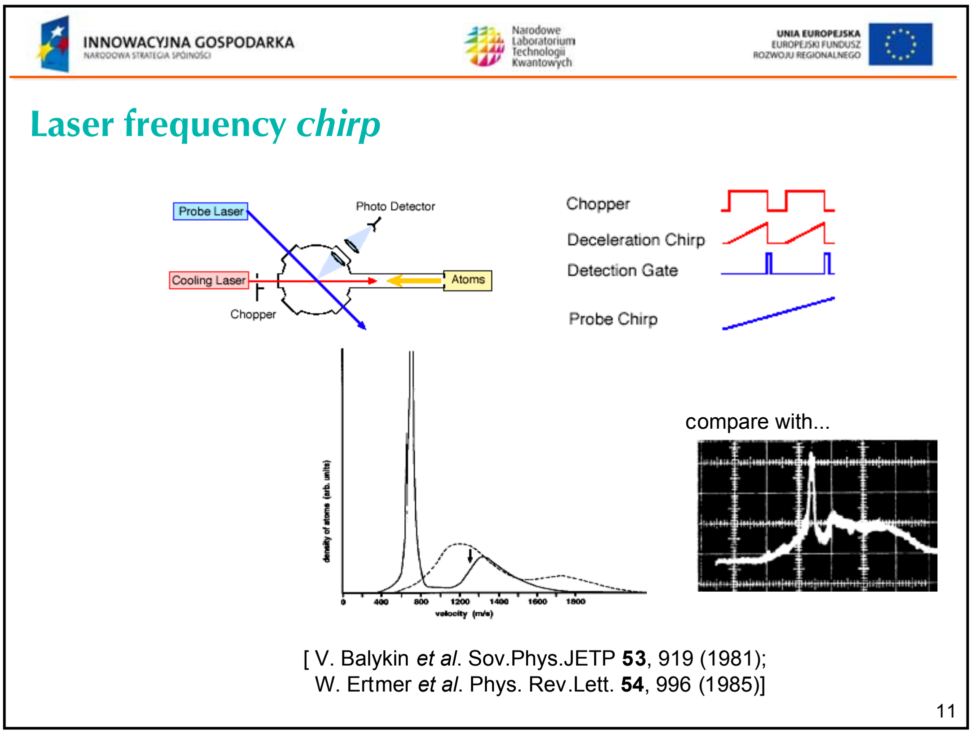

## Laser frequency *chirp*

compare with...

[ V. Balykin *et al*. Sov.Phys.JETP **53**, 919 (1981);
W. Ertmer *et al*. Phys. Rev.Lett. **54**, 996 (1985)]

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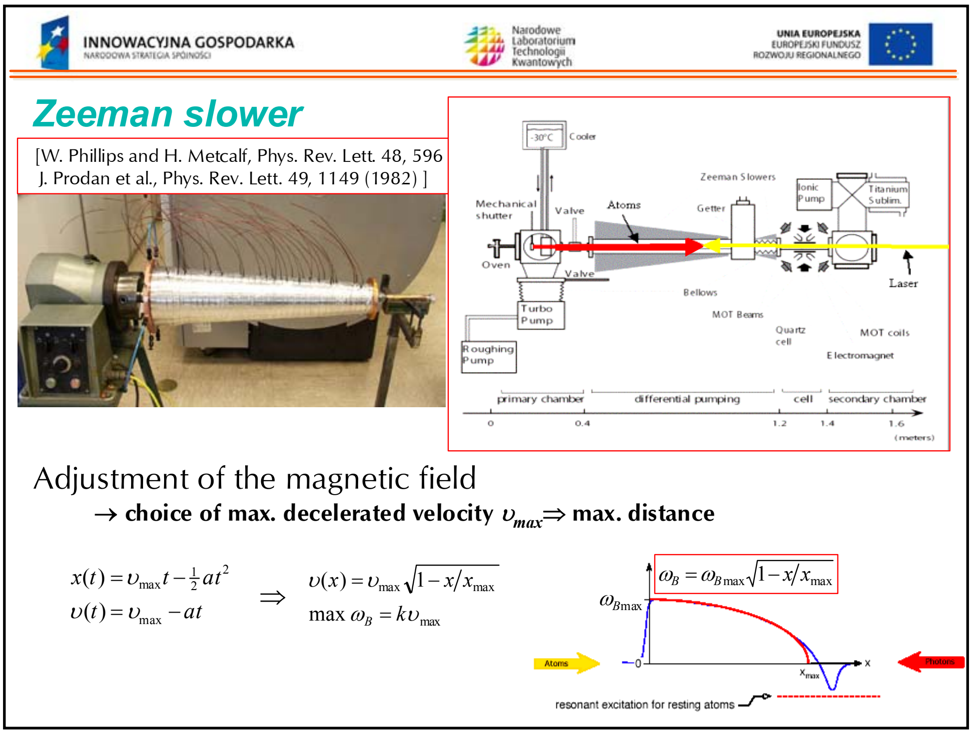


## *Zeeman slower*

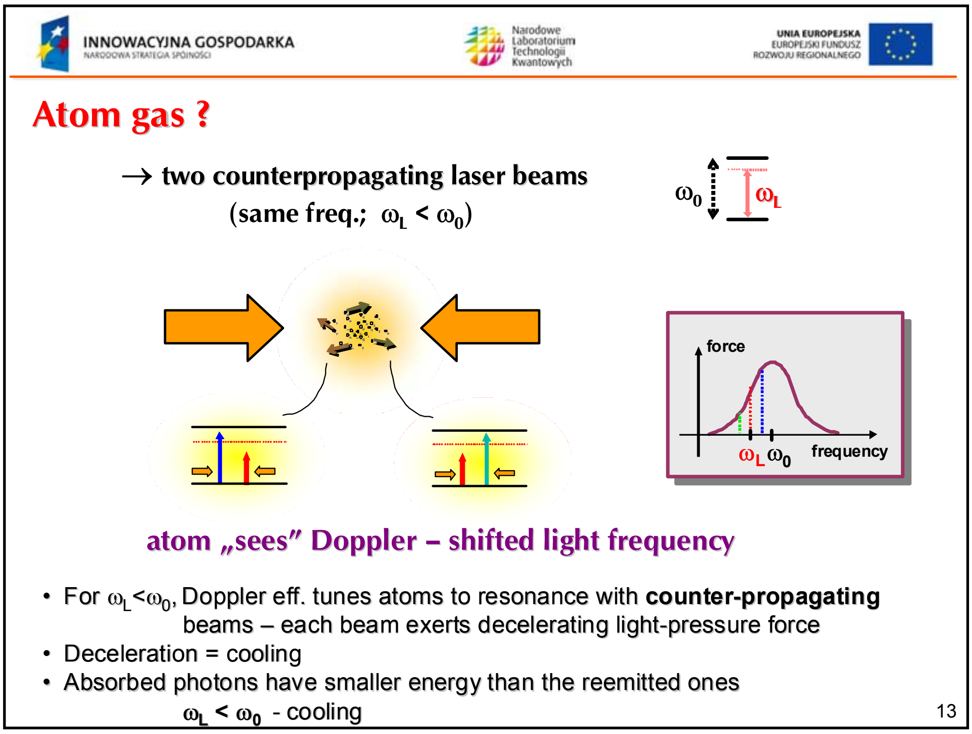
[W. Phillips and H. Metcalf, Phys. Rev. Lett. 48, 596
J. Prodan et al., Phys. Rev. Lett. 49, 1149 (1982) ]

Adjustment of the magnetic field

→ **choice of max. decelerated velocity $\upsilon_{max}$ ⇒ max. distance**

$$x(t) = \upsilon_{\max} t - \tfrac{1}{2} a t^2 \qquad \upsilon(t) = \upsilon_{\max} - at \quad \Rightarrow \quad \upsilon(x) = \upsilon_{\max}\sqrt{1 - x/x_{\max}} \qquad \max\ \omega_B = k\upsilon_{\max}$$

$$\boxed{\omega_B = \omega_{B\max}\sqrt{1 - x/x_{\max}}}$$

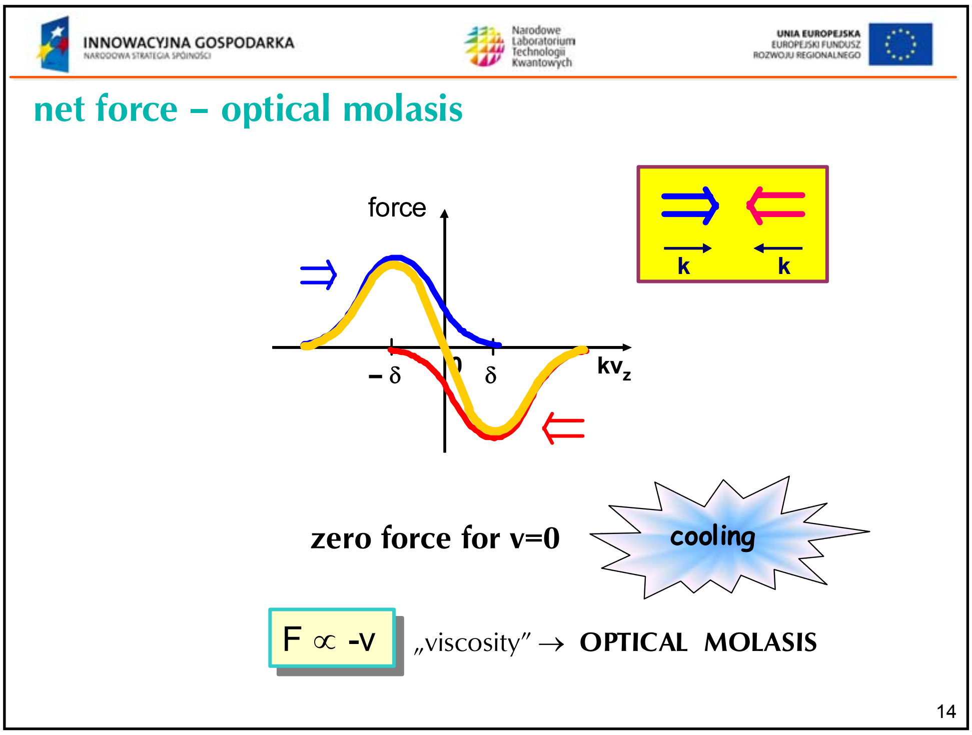


## Atom gas ?

→ two counterpropagating laser beams
(same freq.; $\omega_L < \omega_0$)

**atom „sees" Doppler – shifted light frequency**

- For $\omega_L < \omega_0$, Doppler eff. tunes atoms to resonance with **counter-propagating** beams – each beam exerts decelerating light-pressure force
- Deceleration = cooling
- Absorbed photons have smaller energy than the reemitted ones
  $\omega_L < \omega_0$ - cooling



## net force – optical molasis

zero force for v=0

$F \propto -v$ „viscosity" → OPTICAL MOLASIS

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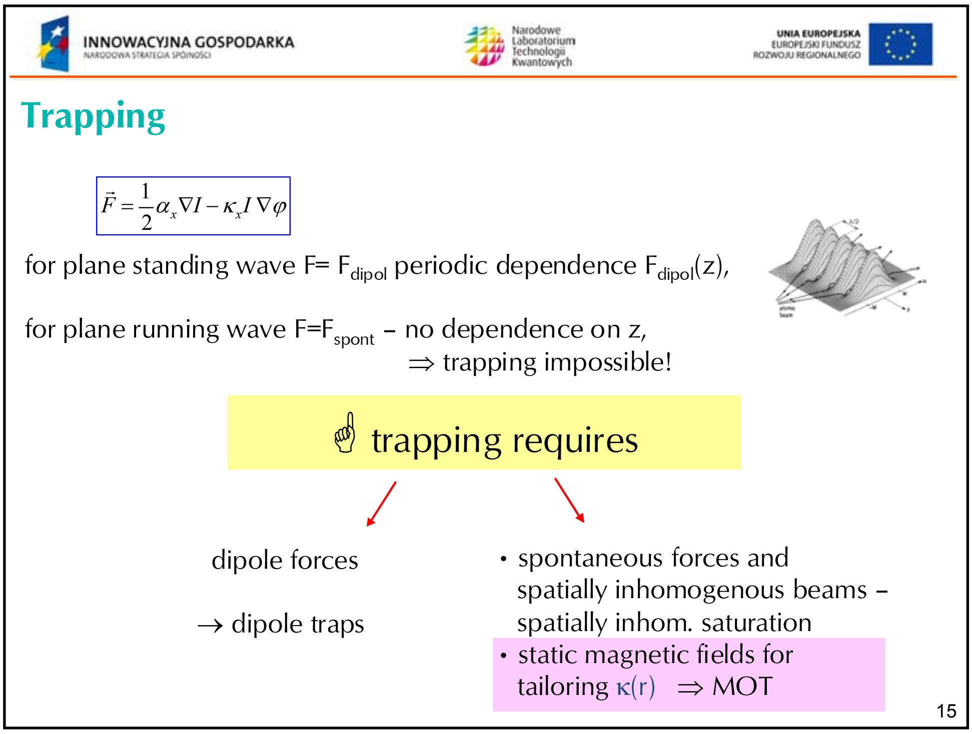


## Trapping

$$\boxed{\vec{F} = \frac{1}{2}\alpha_x \nabla I - \kappa_x I \nabla \varphi}$$

for plane standing wave F= $F_{dipol}$ periodic dependence $F_{dipol}(z)$,

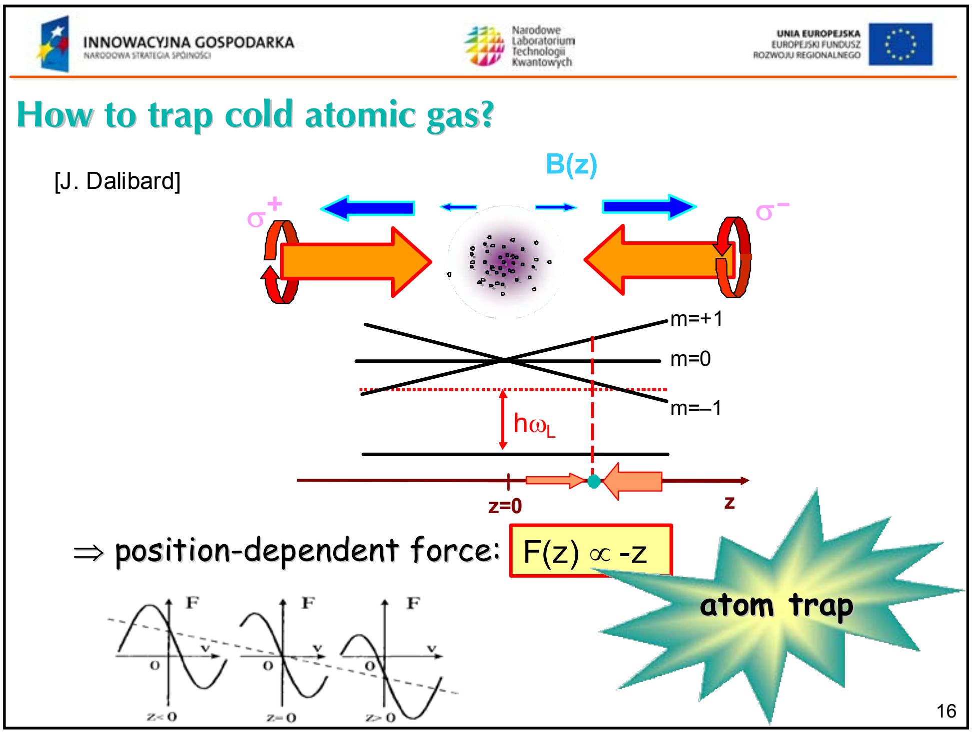
for plane running wave F=$F_{spont}$ – no dependence on z,
⇒ trapping impossible!

☝ trapping requires

dipole forces

→ dipole traps

- spontaneous forces and spatially inhomogenous beams – spatially inhom. saturation
- static magnetic fields for tailoring κ(r) ⇒ MOT



## How to trap cold atomic gas?

[J. Dalibard]

⇒ position-dependent force: $\boxed{F(z) \propto -z}$

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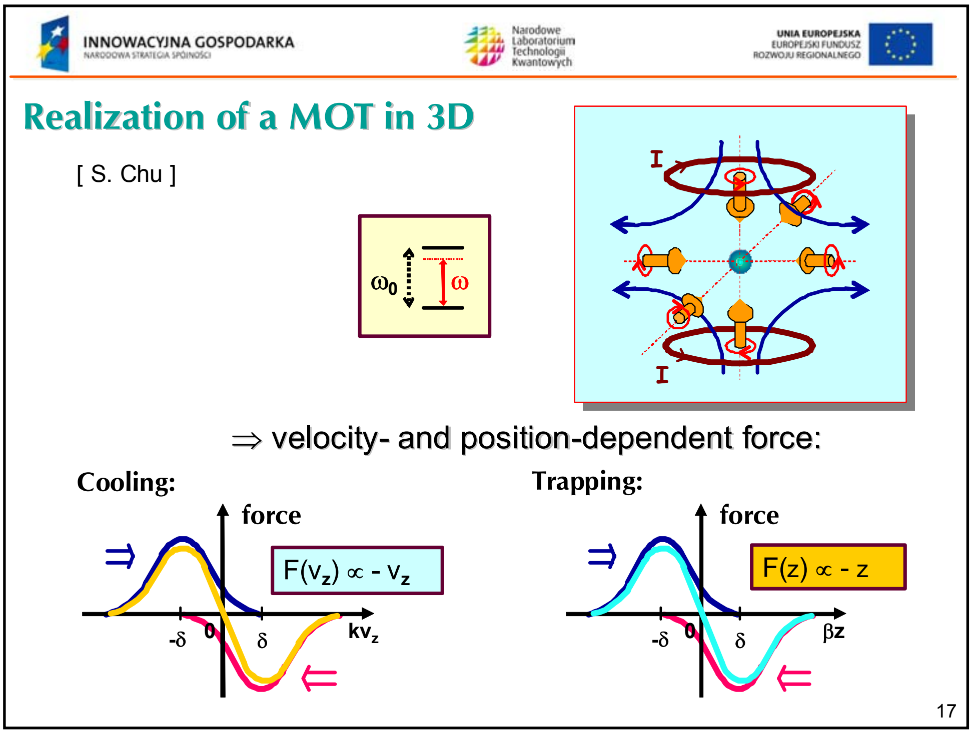


## Realization of a MOT in 3D

[ S. Chu ]

$\Rightarrow$ velocity- and position-dependent force:

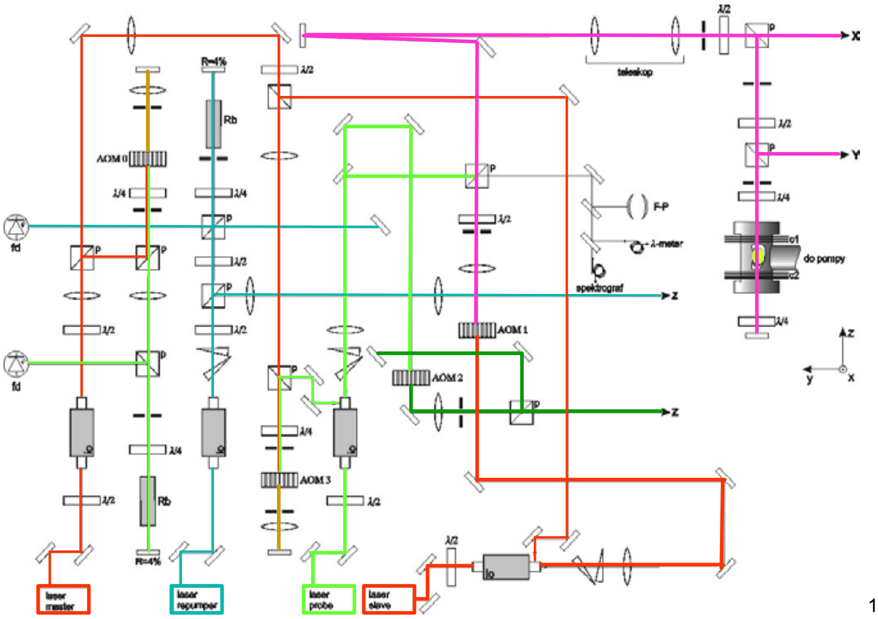
**Cooling:**

$F(v_z) \propto - v_z$

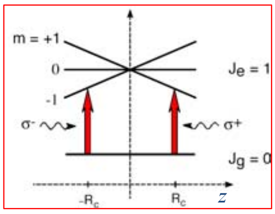
**Trapping:**

$F(z) \propto - z$

## Real traps



## Doppler theory of a MOT



(1D, beam interference neglected)

notation: $\omega_{\pm} = \omega_0 \pm \omega_B(z)$

$$\frac{F}{m} = \left[n_{+1}(\delta + k\upsilon_z + gz) - n_{-1}(\delta - k\upsilon_z - gz)\right]\frac{\hbar k\Gamma}{m} \hat{=} \beta\upsilon_z + \omega_T^2 z$$

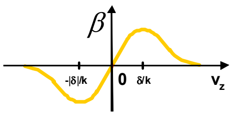
damping constant/viscosity coefficient

trap frequency

$$\beta = 16\omega_{rec}\Omega^2 \frac{\delta}{\left(\delta^2 + (\Gamma/2)^2 + \Omega^2/2\right)^2}$$

$$\omega_T^2 = \beta\frac{g}{k} \quad g = \frac{\partial\omega_B}{\partial z}$$

$$\omega_{rec} = \frac{\hbar\omega^2}{2mc^2}$$



- maximal damping $\beta_{\max} \cong -\frac{1}{2}\hbar k^2 \;@\; \Omega = \delta,\ \delta = \Gamma/2$

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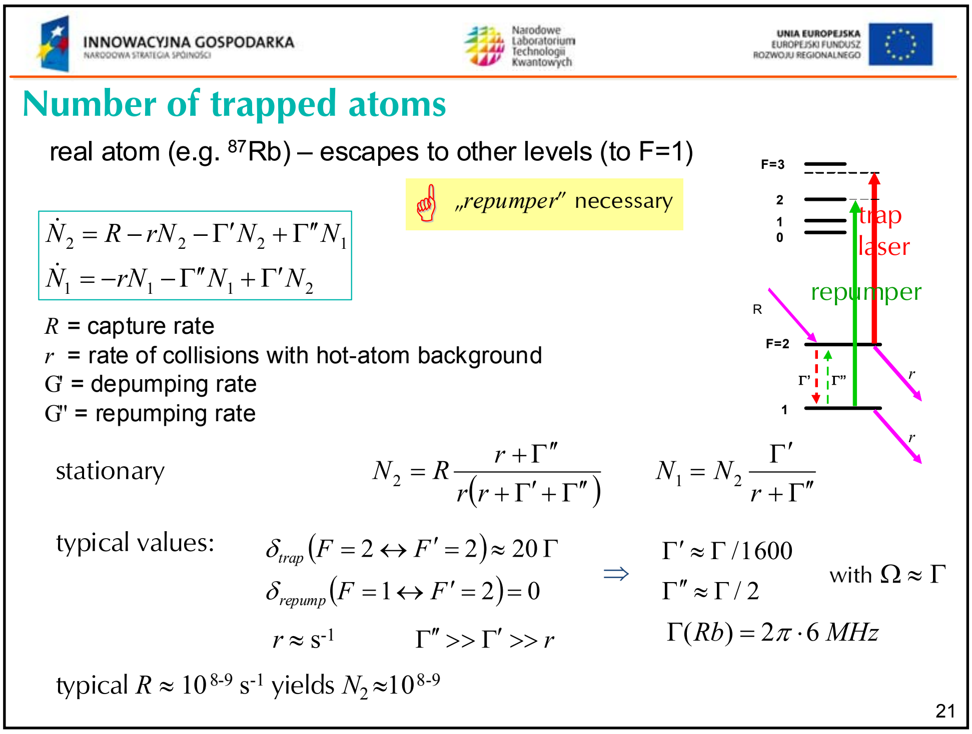


## Number of trapped atoms

real atom (e.g. $^{87}$Rb) – escapes to other levels (to F=1)

☝ *„repumper”* necessary

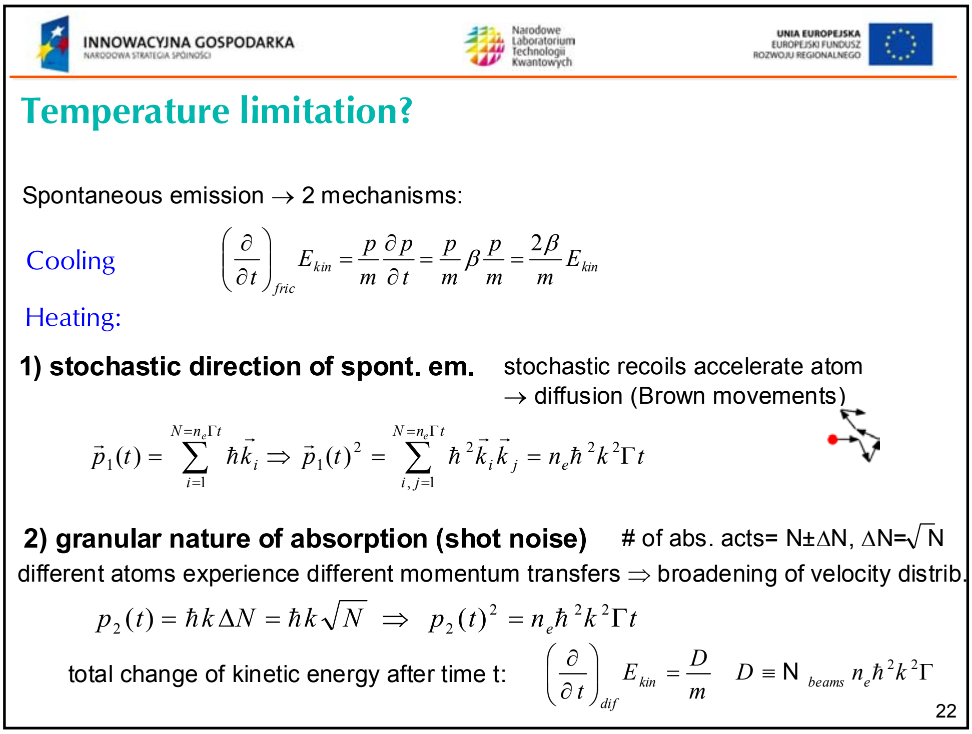
$$\dot{N}_2 = R - rN_2 - \Gamma' N_2 + \Gamma'' N_1$$
$$\dot{N}_1 = -rN_1 - \Gamma'' N_1 + \Gamma' N_2$$

$R$ = capture rate
$r$ = rate of collisions with hot-atom background
G' = depumping rate
G'' = repumping rate

stationary $$N_2 = R\frac{r+\Gamma''}{r(r+\Gamma'+\Gamma'')} \qquad N_1 = N_2\frac{\Gamma'}{r+\Gamma''}$$

typical values:
$$\delta_{trap}(F=2 \leftrightarrow F'=2) \approx 20\,\Gamma \qquad \Gamma' \approx \Gamma/1600$$
$$\delta_{repump}(F=1 \leftrightarrow F'=2) = 0 \quad \Rightarrow \quad \Gamma'' \approx \Gamma/2 \qquad \text{with } \Omega \approx \Gamma$$
$$r \approx \mathrm{s}^{-1} \qquad \Gamma'' >> \Gamma' >> r \qquad \Gamma(Rb) = 2\pi \cdot 6\ MHz$$

typical $R \approx 10^{8\text{-}9}\ \mathrm{s}^{-1}$ yields $N_2 \approx 10^{8\text{-}9}$



## Temperature limitation?

Spontaneous emission → 2 mechanisms:

Cooling $$\left(\frac{\partial}{\partial t}\right)_{fric} E_{kin} = \frac{p}{m}\frac{\partial p}{\partial t} = \frac{p}{m}\beta\frac{p}{m} = \frac{2\beta}{m}E_{kin}$$

Heating:

**1) stochastic direction of spont. em.** stochastic recoils accelerate atom
→ diffusion (Brown movements)

$$\vec{p}_1(t) = \sum_{i=1}^{N=n_e\Gamma t} \hbar\vec{k}_i \Rightarrow \vec{p}_1(t)^2 = \sum_{i,j=1}^{N=n_e\Gamma t} \hbar^2\vec{k}_i\vec{k}_j = n_e\hbar^2k^2\Gamma t$$

**2) granular nature of absorption (shot noise)** # of abs. acts= N±ΔN, ΔN=$\sqrt{N}$
different atoms experience different momentum transfers ⇒ broadening of velocity distrib.

$$p_2(t) = \hbar k\Delta N = \hbar k\sqrt{N} \Rightarrow p_2(t)^2 = n_e\hbar^2k^2\Gamma t$$

total change of kinetic energy after time t: $$\left(\frac{\partial}{\partial t}\right)_{dif} E_{kin} = \frac{D}{m} \qquad D \equiv \mathrm{N}_{beams}\, n_e\hbar^2k^2\Gamma$$

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## Doppler temperature

equlibrium cooling – heating:

$$\left(\frac{\partial}{\partial t}\right)_{dif} E_{kin} + \left(\frac{\partial}{\partial t}\right)_{fric} E_{kin} = 0 \Rightarrow \quad \overline{E}_{kin} = \frac{D}{2\beta} \quad \Rightarrow$$

$$\boxed{k_B T = \frac{D}{k} = -\frac{\mathrm{N}}{4d}\frac{\delta^2 + \left(\frac{\Gamma}{2}\right)^2 + \left(\frac{\Omega}{2}\right)^2}{|\delta|\Gamma}\hbar\Gamma} \quad \boxed{\approx -\frac{\mathrm{N}\hbar\Gamma}{4d}\left(\delta + \delta^{-1}\right)}$$

($d$ – # of degrees of freedom)

minimum @ $|\delta| = \frac{\Gamma}{2}\sqrt{1+2\left(\frac{\Omega}{\Gamma}\right)^2} \Rightarrow k_B T_{\min} = \frac{\mathrm{N}}{4d}\sqrt{1+2\left(\frac{\Omega}{\Gamma}\right)^2}\hbar\Gamma$

for 6 beams, 3 deg. of freedom, with $\Omega \to 0$ : $k_B T_{\min} \to \hbar\frac{\Gamma}{2}$ $\boxed{T_D = \frac{\hbar\Gamma}{2k_B}}$

(Na: 240 μK, Rb: 140 μK)

☝ the model includes neither light interference & polarization nor real atomic structure

## Atomic density limitation ?

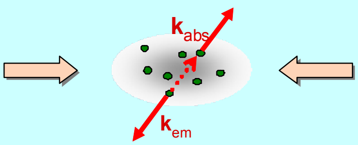
**2 limiting regimes of a MOT:**

1. Constant volume regime @ small density ρ $\rho = \rho_0 e^{-\frac{m\omega_v^2}{2k_B T}r^2}$

⇒ atomic cloud radius @ 1/e $R_e = \sqrt{\frac{2k_B T}{m\omega_v^2}}$

- independent on N
- density $\rho_0 \propto$ N

when N grows, ρ, ☞ **radiation trapping**



2. Constant density regime

- atomic density = const, independent on N,
- cloud size $R_e \propto$ N

$$\boxed{\rho_{0,\max} \approx \frac{k}{I_L\sigma_L(\sigma_R - \sigma_L)}}$$

$\rho_{\max} \approx 10^{11\text{-}12}$ at/cm$^3$

$T_d = T\,(1 + ?s\,n^{2/3}N^{1/3})$.

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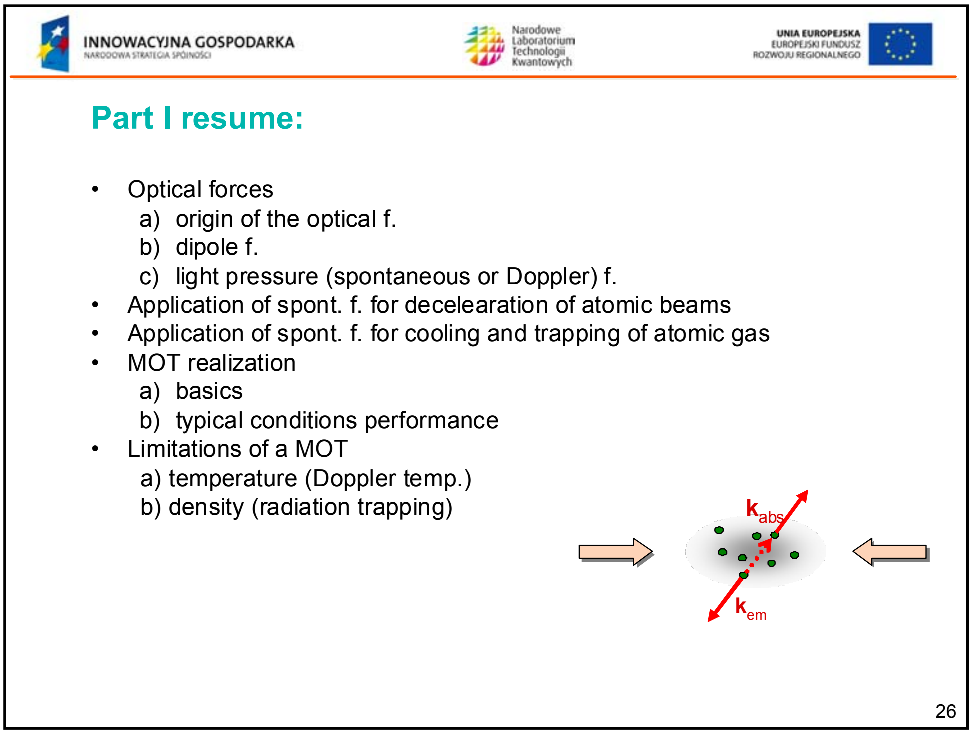
Projekt współfinansowany ze środków Europejskiego Funduszu Rozwoju Regionalnego w ramach Programu Operacjnego Innowacyjna Gospodarka

# Atom traps
## – principles & realizations

**Wojciech Gawlik**

part II

www.if.uj.edu.pl/ZF



## Part I resume:

- Optical forces
  - a) origin of the optical f.
  - b) dipole f.
  - c) light pressure (spontaneous or Doppler) f.
- Application of spont. f. for decelearation of atomic beams
- Application of spont. f. for cooling and trapping of atomic gas
- MOT realization
  - a) basics
  - b) typical conditions performance
- Limitations of a MOT
  - a) temperature (Doppler temp.)
  - b) density (radiation trapping)

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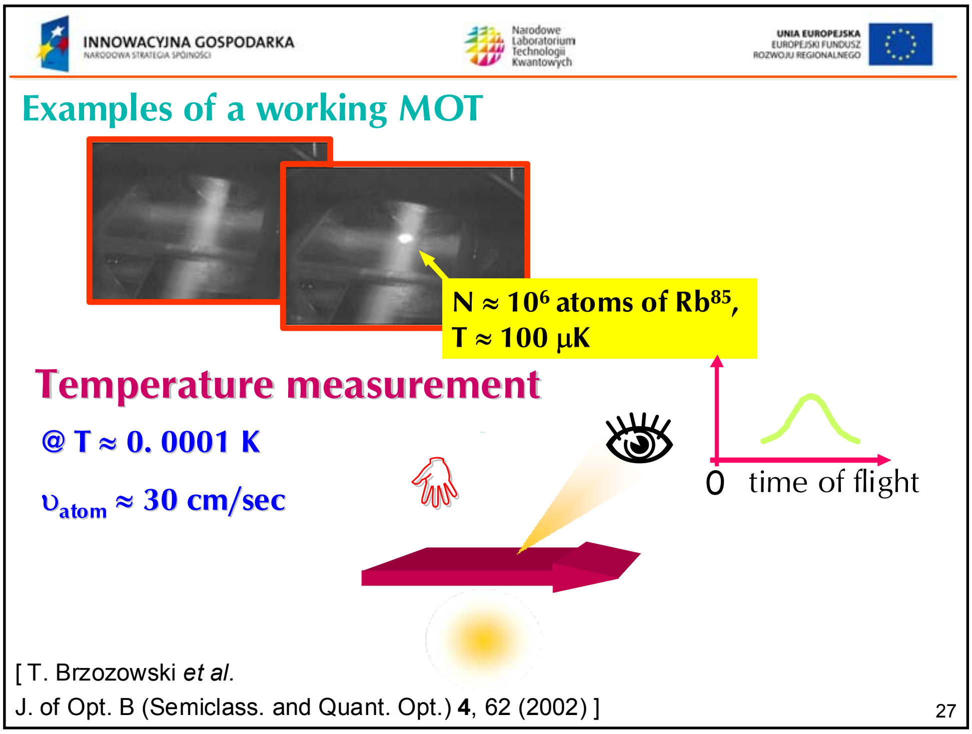


## Examples of a working MOT

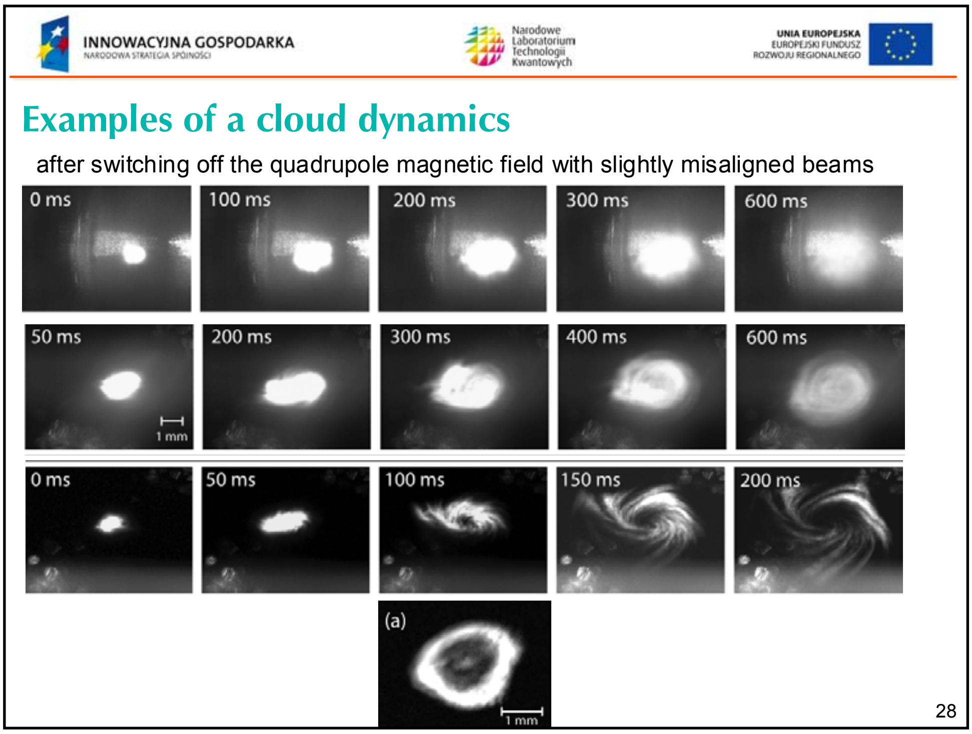
**$N \approx 10^6$ atoms of $Rb^{85}$,**
**$T \approx 100\ \mu K$**

## Temperature measurement

**@ $T \approx 0.\ 0001$ K**

**$\upsilon_{atom} \approx 30$ cm/sec**

[ T. Brzozowski *et al.*
J. of Opt. B (Semiclass. and Quant. Opt.) **4**, 62 (2002) ]



## Examples of a cloud dynamics

after switching off the quadrupole magnetic field with slightly misaligned beams

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## Example application – our route to BEC

Magneto-optical trapping in MOT1

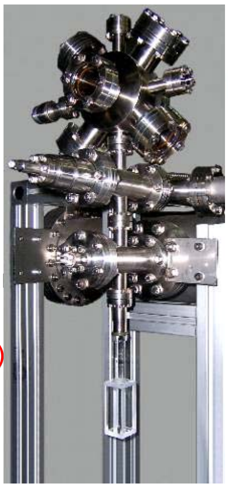
T ≈ 300 μK, N ≈ $10^8 – 10^9$

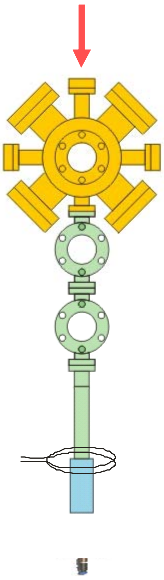
Transfer to MT,
collection in MOT2

diff. pumping ($10^{-9}$ mbar →$10^{-11}$ mba

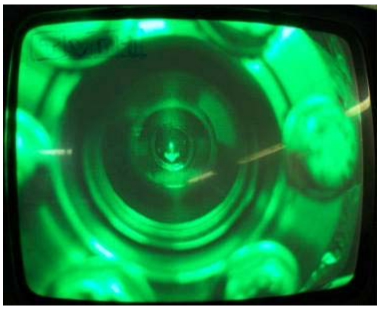
Magnetic trapping (magnetic dipole trap)

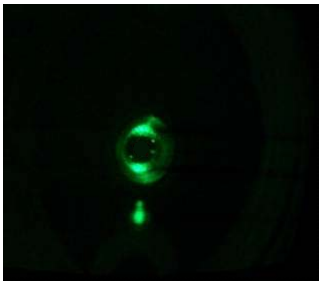
evaporation of the hottest atoms,
colisional thermalization
T ≈ 100 nK, N ≈ $10^5$ - $10^6$





## Transfer of cold atoms





- why?

upper MOT:
many atoms – vacum $10^{-9}$ mbar
lower MOT:
vacum < $10^{-11}$ mbar

- how?

light pressure force
– pushing beam

- problems?

geometry of differential pumping
(distance ~0,5 m, cappilary ? 5 mm, L12 cm)

atoms blown out from the top MOT
are recaptured in the lower one

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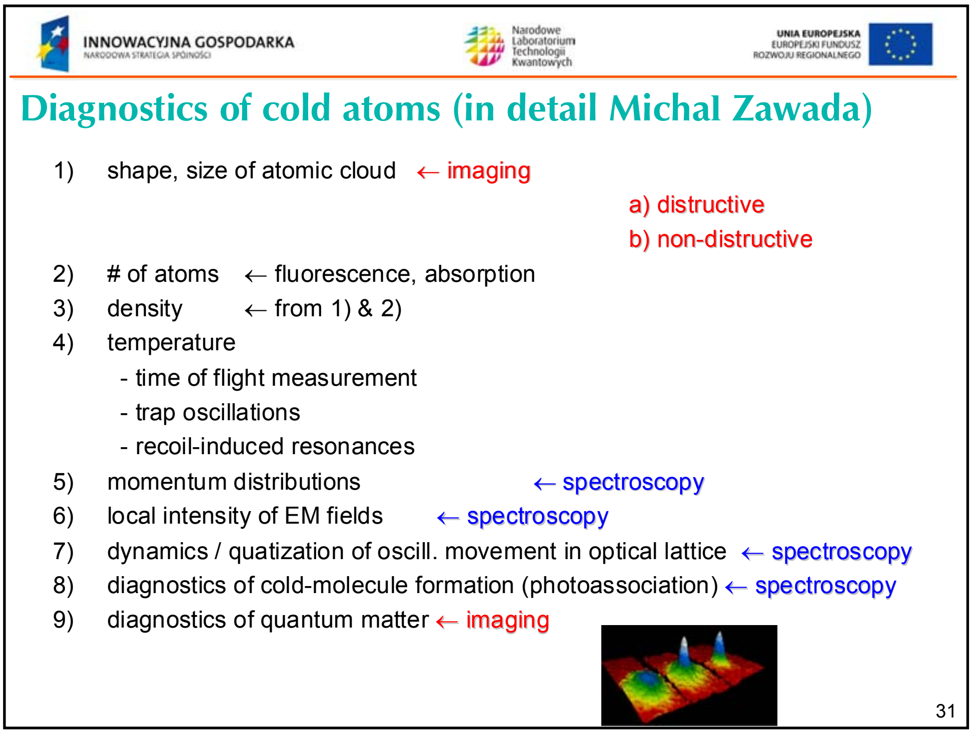
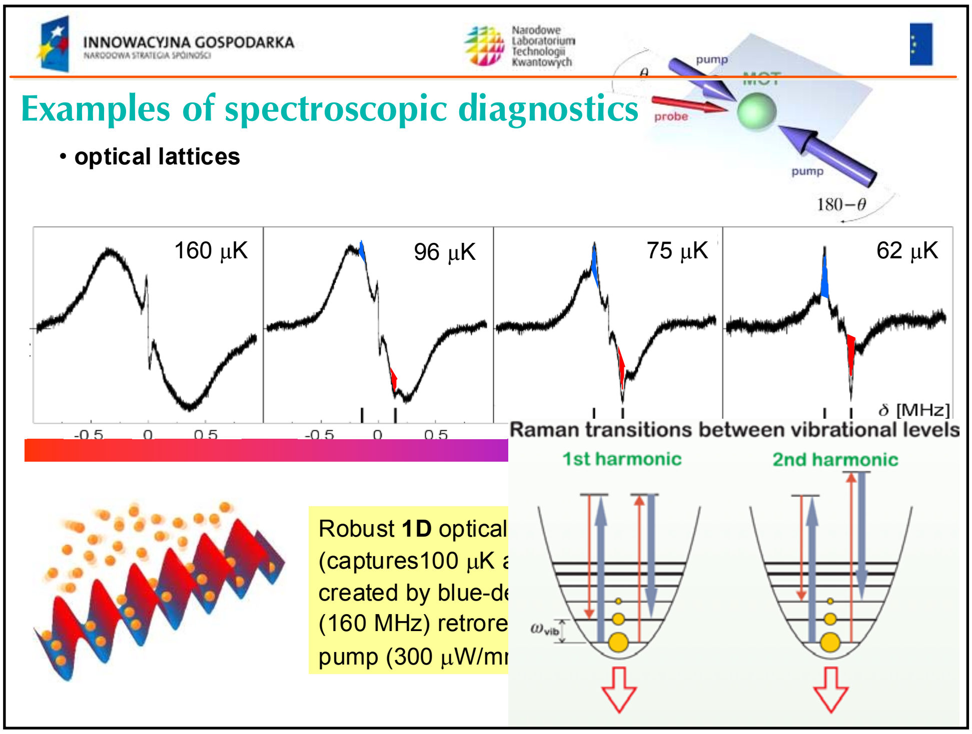


## Diagnostics of cold atoms (in detail Michal Zawada)

1) shape, size of atomic cloud ← imaging
   a) distructive
   b) non-distructive
2) # of atoms ← fluorescence, absorption
3) density ← from 1) & 2)
4) temperature
   - time of flight measurement
   - trap oscillations
   - recoil-induced resonances
5) momentum distributions ← spectroscopy
6) local intensity of EM fields ← spectroscopy
7) dynamics / quatization of oscill. movement in optical lattice ← spectroscopy
8) diagnostics of cold-molecule formation (photoassociation) ← spectroscopy
9) diagnostics of quantum matter ← imaging



## Examples of spectroscopic diagnostics

- **optical lattices**

Robust **1D** optical
(captures100 μK a
created by blue-de
(160 MHz) retrore
pump (300 μW/mr

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# Optical forces:

$$\vec{\mathbf{F}} = -\nabla \mathbf{V} = \left| \mathbf{V} = -\vec{\mathbf{E}} \cdot \vec{\mathbf{D}} \right| = \sum \mathbf{d}_i \nabla \mathbf{E}_i(\vec{\mathbf{r}})$$

$$\vec{\mathbf{d}} = Tr(\rho_{at}\vec{\mathbf{D}}) \qquad \mathbf{E}(\mathbf{r}, \mathbf{t}) = \mathcal{E}(\mathbf{r})\,\hat{\mathbf{e}}(\mathbf{r})\,e^{-i[\omega t - \Phi(\mathbf{r})]} + \mathbf{C.C.}$$

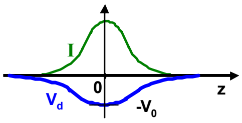
$\nabla\Phi(\mathbf{r}) \rightarrow \mathbf{F}_{\mathbf{sp}}$ – spontaneous, dissipative forces (light pressure)

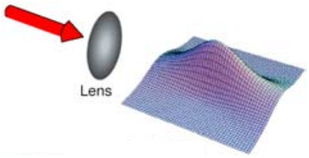
$\nabla\, \mathrm{E}(\mathbf{r}) \rightarrow \mathbf{F}_{\mathbf{d}}$ – dipole, reactive

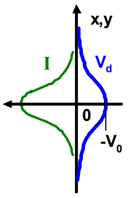
$\nabla\, \hat{\mathbf{e}}(\mathbf{r}) \rightarrow$ polarization gradient

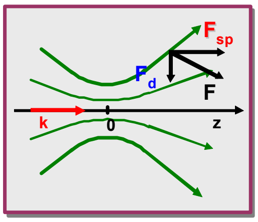
light pressure forces – occur with plane waves,

dipole forces – require inhomogeneous light field









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# Dipole forces – classical picture

$\omega < \omega_0$, ($\delta < 0$) – induced atomic dipole moment oscillates in phase with the field
$\Rightarrow$ atom attracted to the field maximum
(electrostriction with classical dielectric, $\varepsilon > 1$)

$\omega > \omega_0$, ($\delta > 0$) – induced atomic dipole moment lags 180° behind the field
$\Rightarrow$ atom expelled from the field maximum
(no analogy to electrostriction – no classical dielectric with $\varepsilon < 1$)

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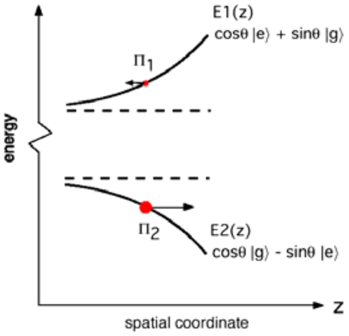
## Dipole forces – quantum picture

- atomic energy levels are modified by EM field
- the modifications depend on local field intensity



force = $n_1 \nabla E_1(z) + n_2 \nabla E_2(z) = -\nabla U$

$$U(z) = \frac{\hbar\delta}{2} ln(1 + S(z))$$

$$S(z) = \frac{1}{2} \frac{\Omega^2}{\delta^2 + (\Gamma/2)^2}$$

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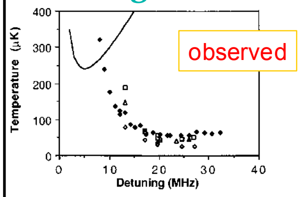
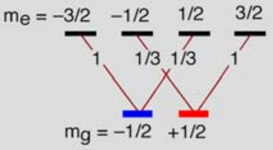
## Cooling below Doppler limit (sub-Doppler cooling)

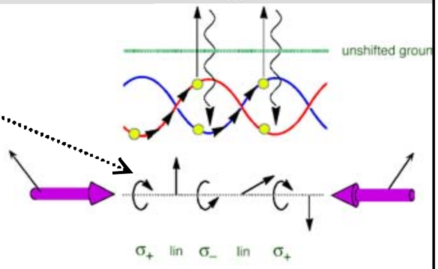


Interpretation:

model atom with $J_g$=1/2, $J_e$=3/2,
2 bems linearly polarized lin⊥lin,
red detuned ($\delta$ <0)



- Interference ? resulting light polarization position-dependent



- Selection rules ⇒
→state couplings polarization dependent
→*light-shifts* polarization dependent
→opt. pumping polarization dependent

- Spatial correlation between *light-shifts* & optical pumping;
  opt. pump. populates most shifted Zeeman sublevels

Sysiphus cooling, polarization gradient cooling

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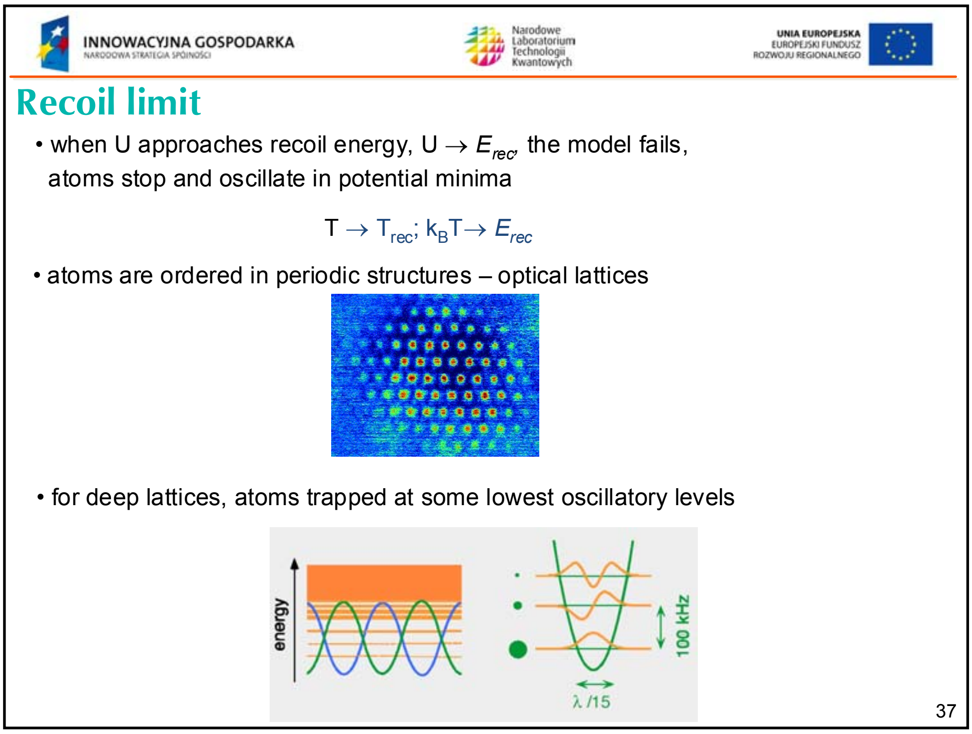
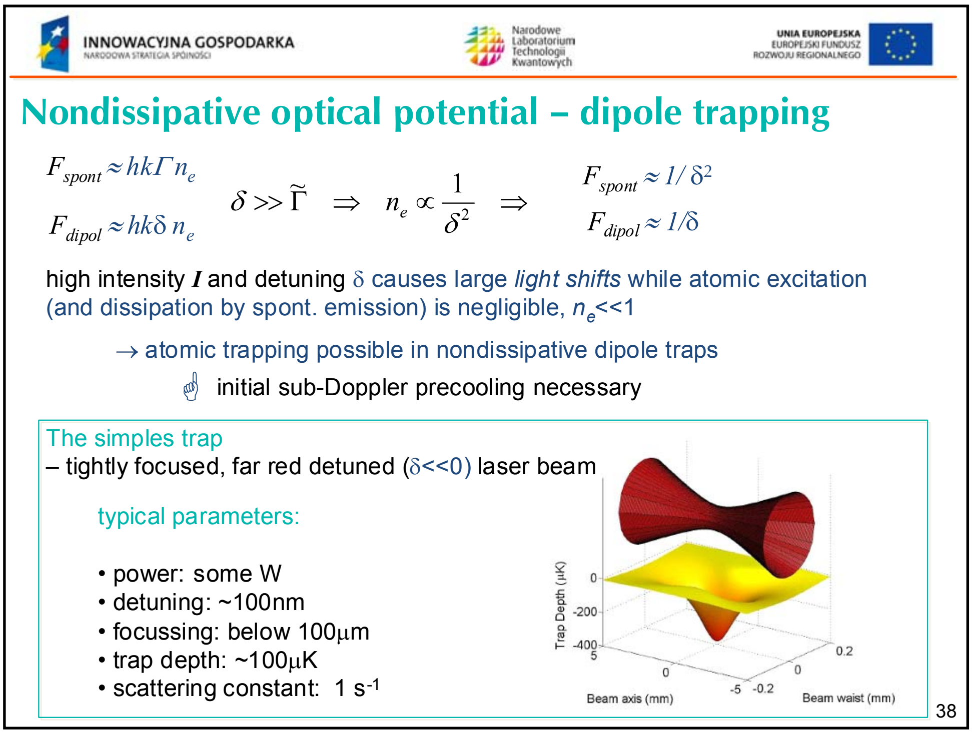


## Recoil limit

- when U approaches recoil energy, U → $E_{rec}$, the model fails, atoms stop and oscillate in potential minima

$$T \rightarrow T_{rec};\ k_B T \rightarrow E_{rec}$$

- atoms are ordered in periodic structures – optical lattices
- for deep lattices, atoms trapped at some lowest oscillatory levels



## Nondissipative optical potential – dipole trapping

$$F_{spont} \approx hk\Gamma n_e \qquad \delta >> \tilde{\Gamma} \;\Rightarrow\; n_e \propto \frac{1}{\delta^2} \;\Rightarrow\; F_{spont} \approx 1/\delta^2$$

$$F_{dipol} \approx hk\delta\, n_e \qquad\qquad\qquad\qquad F_{dipol} \approx 1/\delta$$

high intensity ***I*** and detuning δ causes large *light shifts* while atomic excitation (and dissipation by spont. emission) is negligible, $n_e$<<1

→ atomic trapping possible in nondissipative dipole traps

☝ initial sub-Doppler precooling necessary

The simples trap
– tightly focused, far red detuned (δ<<0) laser beam

typical parameters:

- power: some W
- detuning: ~100nm
- focussing: below 100μm
- trap depth: ~100μK
- scattering constant: 1 $s^{-1}$

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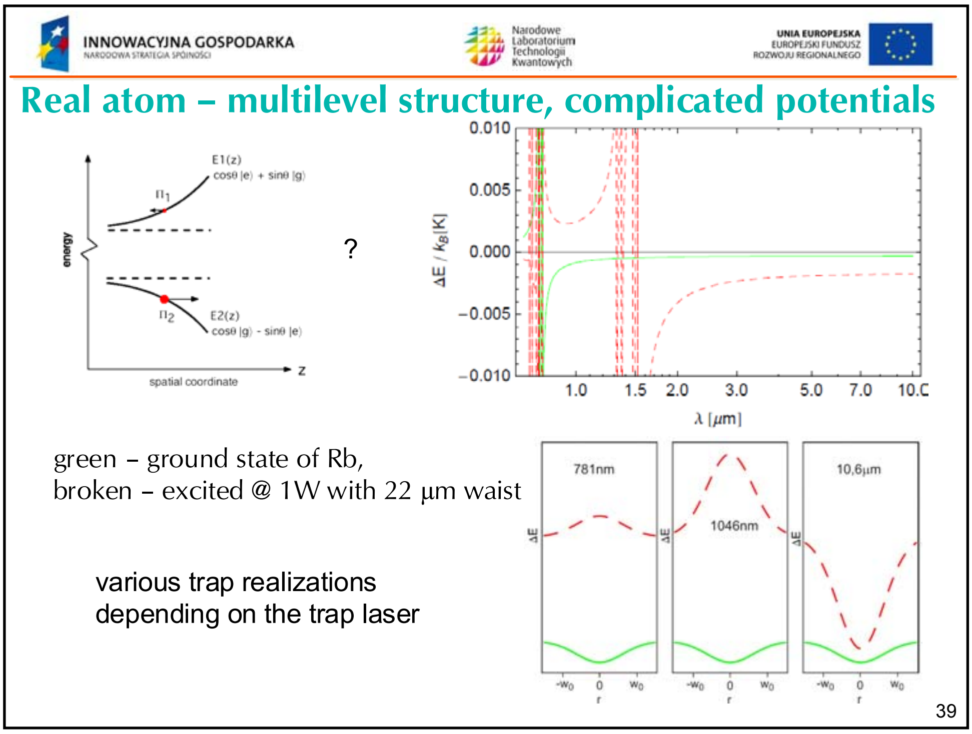
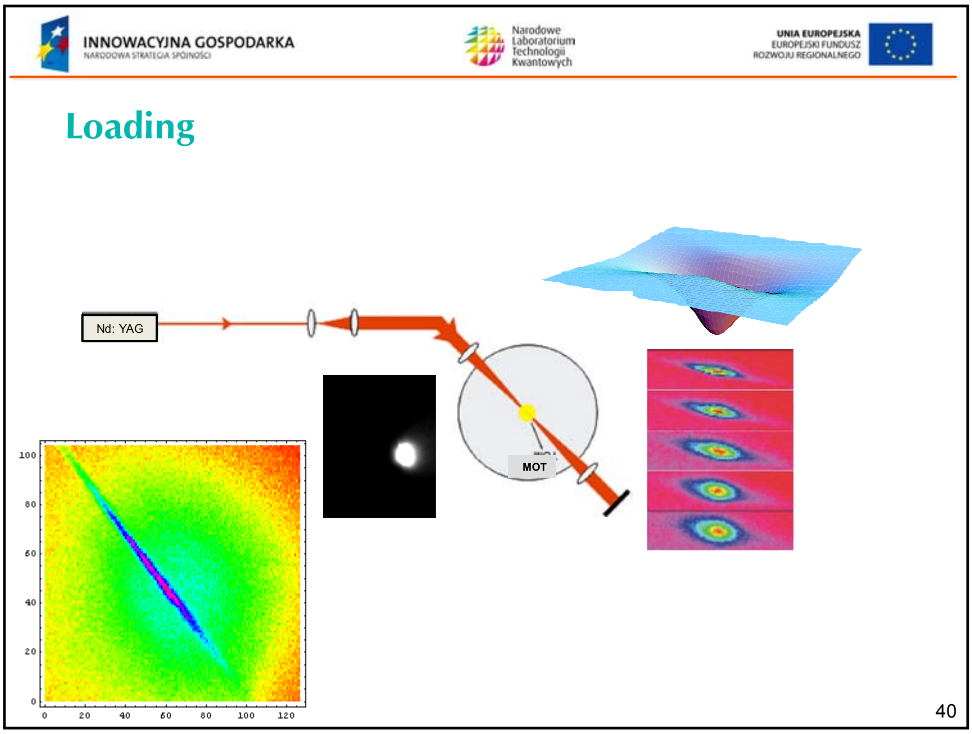


## Real atom – multilevel structure, complicated potentials

?

green – ground state of Rb,
broken – excited @ 1W with 22 μm waist

various trap realizations
depending on the trap laser



## Loading

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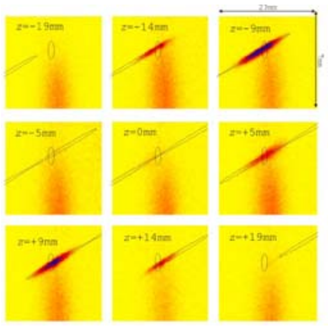
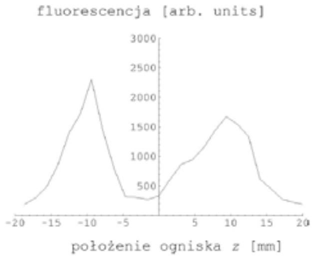
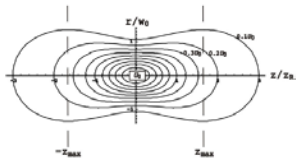
## Loading problems

a) geometry
b) cooling







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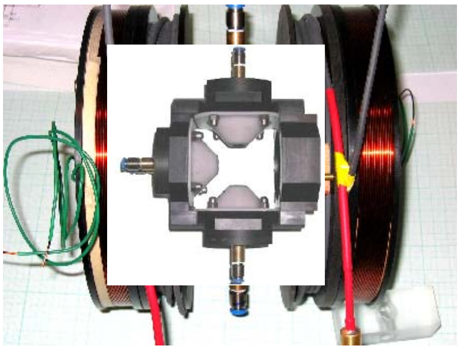
## Magnetic trap



- Heart of the MT– set of conical coils
  (two → quadrupole field, third = Ioffe coil – Majorana losses!).
- Along axis of the Ioffe coil – two offset coils (Helmholtz).
- Typical current 40A → water cooling

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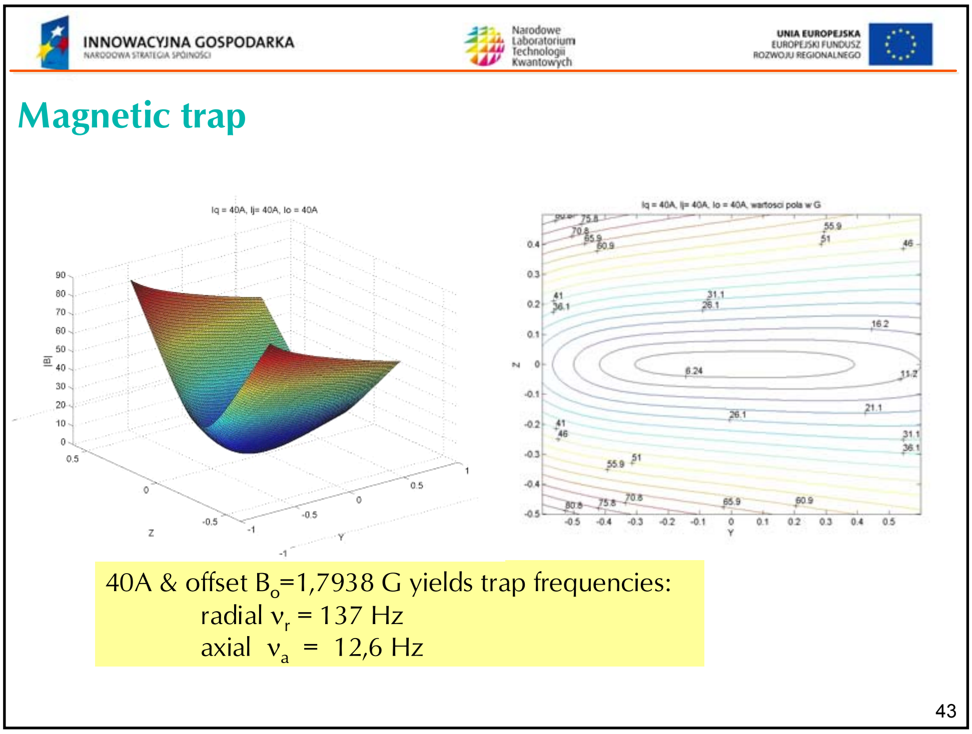
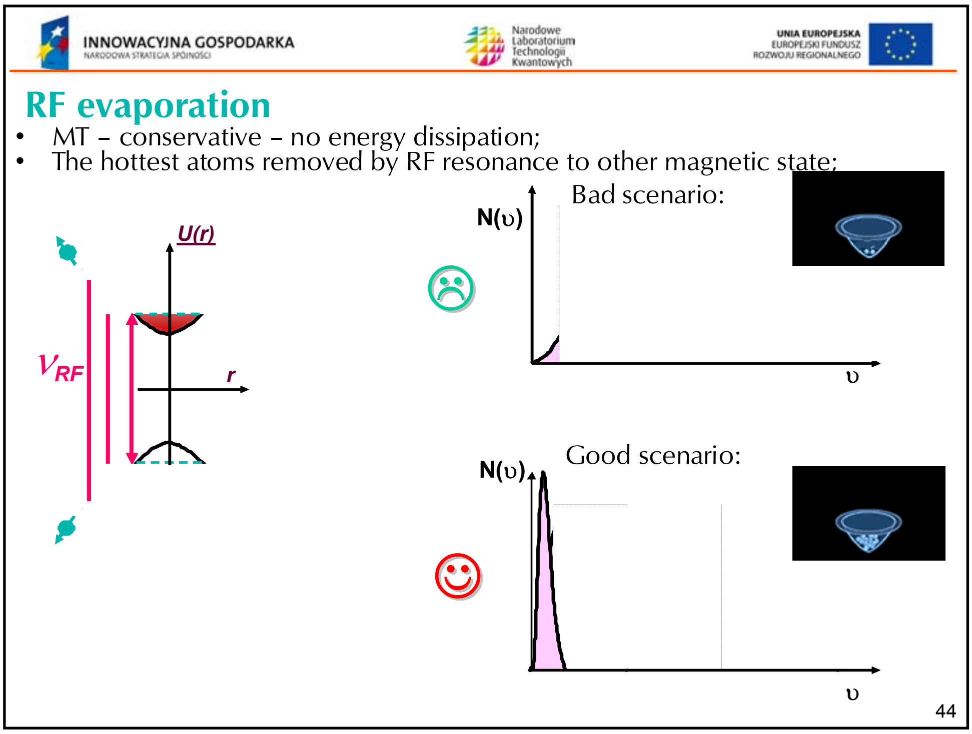


## Magnetic trap

40A & offset $B_o$=1,7938 G yields trap frequencies:
radial $\nu_r$ = 137 Hz
axial $\nu_a$ = 12,6 Hz



## RF evaporation

- MT – conservative – no energy dissipation;
- The hottest atoms removed by RF resonance to other magnetic state;

Bad scenario:

Good scenario:

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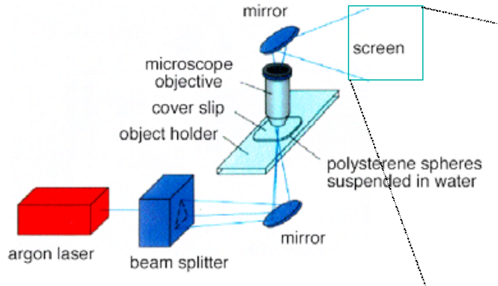
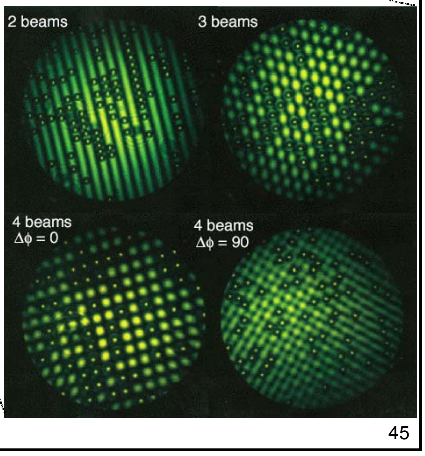
## Dipole trapping of classical (macro) objects

4 μm polysterene beads in water [M. Burns et al., Science **249**, 749 (1990)]





- beads pulled into high-intensity region (interference pattern) (green Ar$^+$laser beam is red-detuned from UV polystyrene absorption line)
- room-temp. (water cooling) sufficient for trapping
- green Ar$^+$ laser light visible due to Rayleigh scattering on water molecules

Other important examples – *optical tweezers*

## Dipole traps – resume:

- less effficient than MOTs – need MOT for loading
- no temp. limit – perfect for BEC
- conservative character – extra cooling mechanism necessary
  – evaporation!
- optical – insensitive to magnetic states but not trivial evaporation
- magnetic – only specific m-state trapped (J?0)

**cool down….**

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