Laser Cooling
of Thulium Atoms

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ФИАН

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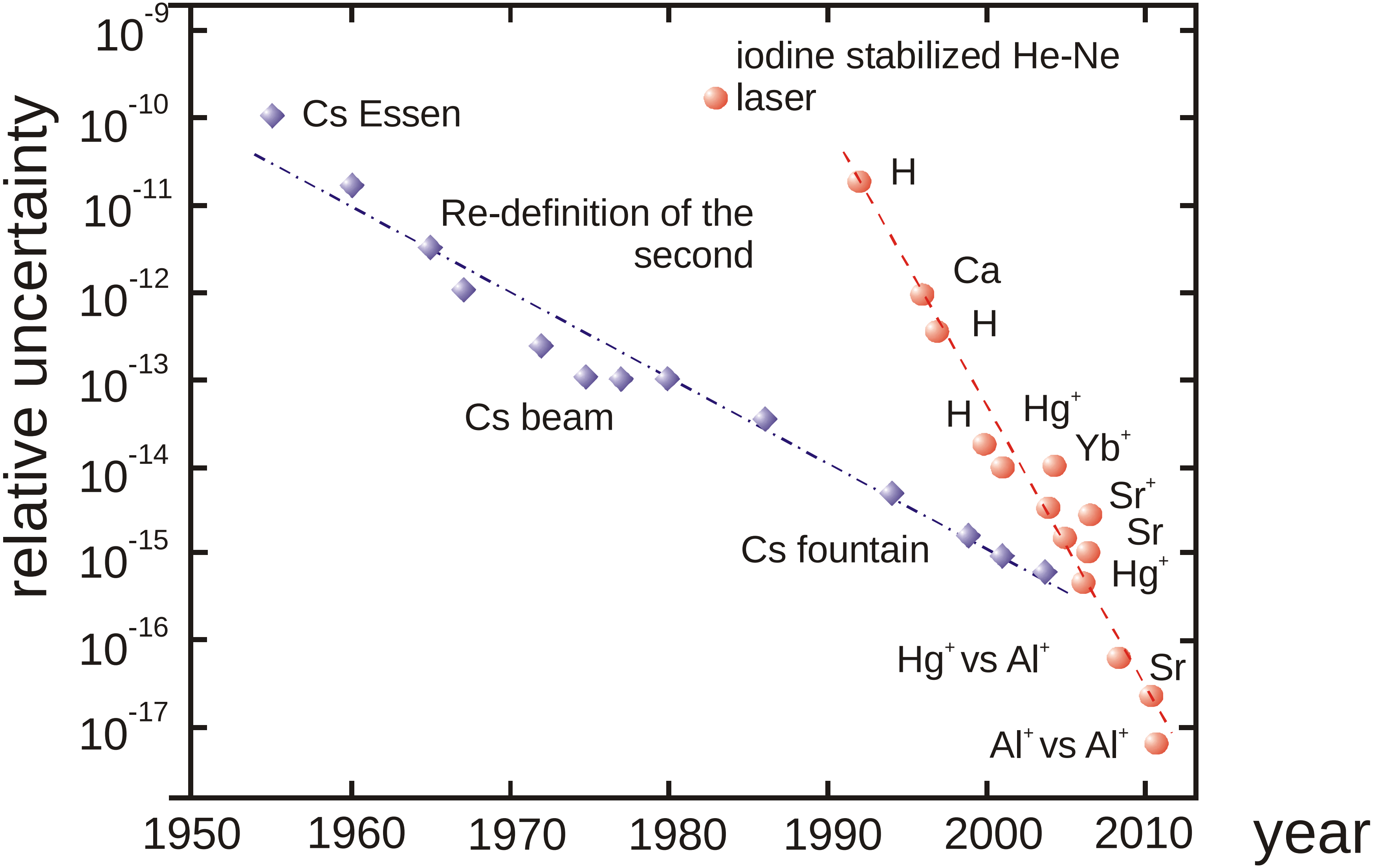
optical atomic clocks – a new era of clocks

Laboratory frequency measurements

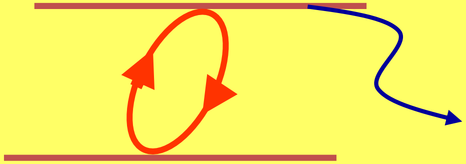


Laser cooling of Lanthanides

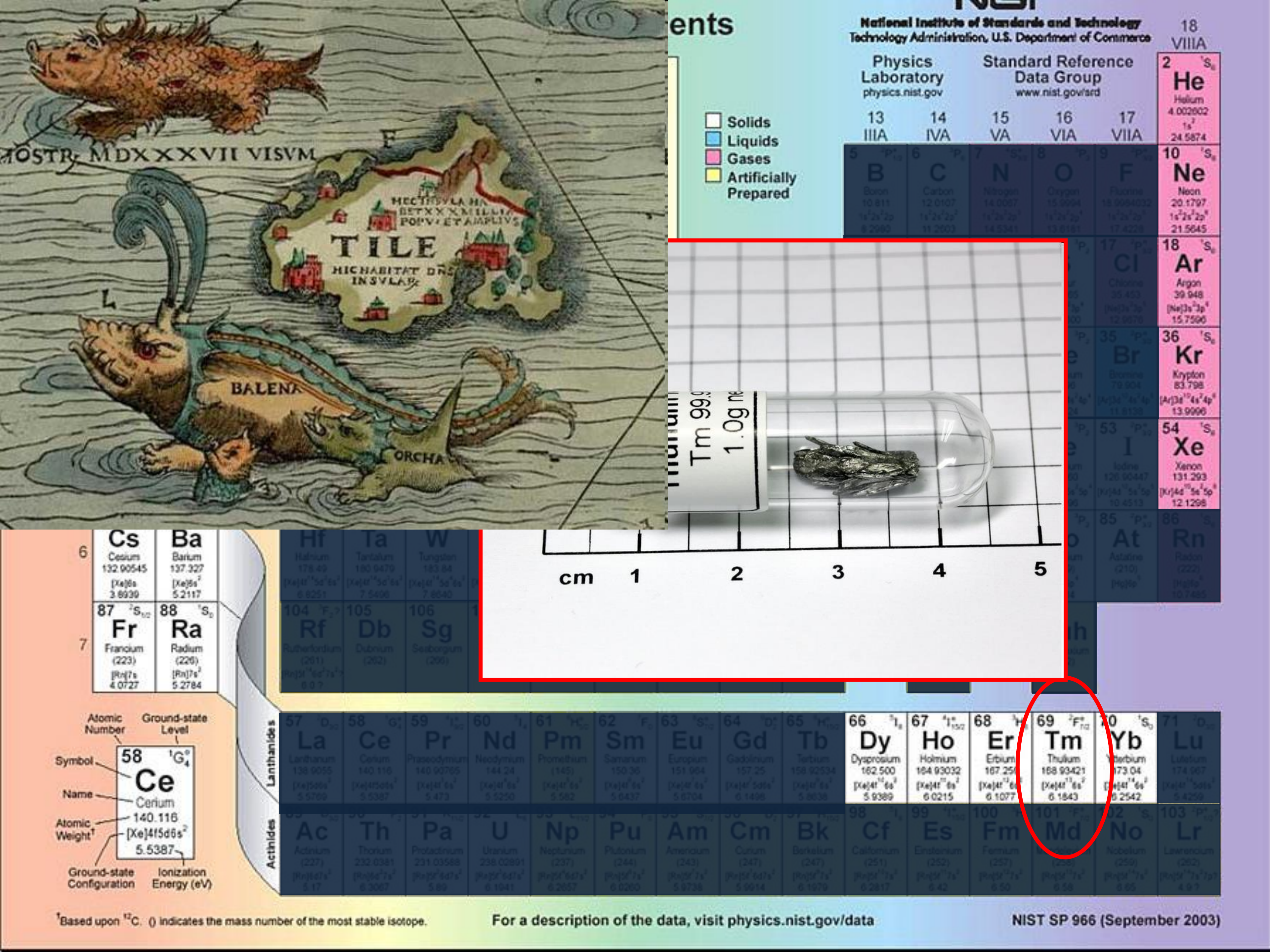
Electronic structure of lanthanides (Yb, Dy, Er, Tm) is similar to alkali-earth elements (Ca, Sr, Mg) due to a closed outer electronic *s*-shell.

Laser cooling of lanthanides is more challenging because of the absence of closed strong cooling transitions. All of strong transitions possess decay channels.

Requirements for an efficient laser cooling transition:



- strong rate $> 10^7$ s^{-1}
- cycled
- accessible for laser sources with a power of > 1 mW



ents

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data Group
www.nist.gov/srd

- ☐ Solids
- ☐ Liquids
- ☐ Gases
- ☐ Artificially Prepared

13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA

5 B | 6 C | 7 N | 8 O | 9 F

2 He Helium 4.002602 $1s^2$ 24.5874

10 Ne Neon 20.1797 $1s^22s^22p^6$ 21.5645

17 Cl

18 Ar Argon 39.948 $[Ne]3s^23p^6$ 15.7596

35 Br

36 Kr Krypton 83.798 $[Ar]3d^{10}4s^24p^6$ 13.9996

53 I

54 Xe Xenon 131.293 $[Kr]4d^{10}5s^25p^6$ 12.1298

85 At | 86 Rn

6 Cs Cesium 132.90545 $[Xe]6s$ 3.8939 | Ba Barium 137.327 $[Xe]6s^2$ 5.2117

Hf | Ta | W

7 87 Fr Francium (223) $[Rn]7s$ 4.0727 | 88 Ra Radium (226) $[Rn]7s^2$ 5.2784

104 Rf | 105 Db | 106 Sg

Lanthanides: 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 71 Lu

66 Dy Dysprosium 162.500 $[Xe]4f^{10}6s^2$ 5.9389

67 Ho Holmium 164.93032 $[Xe]4f^{11}6s^2$ 6.0215

68 Er Erbium 167.259 $[Xe]4f^{12}6s^2$ 6.1077

69 Tm Thulium 168.93421 $[Xe]4f^{13}6s^2$ 6.1843

70 Yb Ytterbium 173.04 $[Xe]4f^{14}6s^2$ 6.2542

Actinides: Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr

Atomic Number — Ground-state Level — Symbol — Name — Atomic Weight† — Ground-state Configuration — Ionization Energy (eV)

58 Ce Cerium 140.116 $[Xe]4f5d6s^2$ 5.5387

†Based upon ^{12}C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

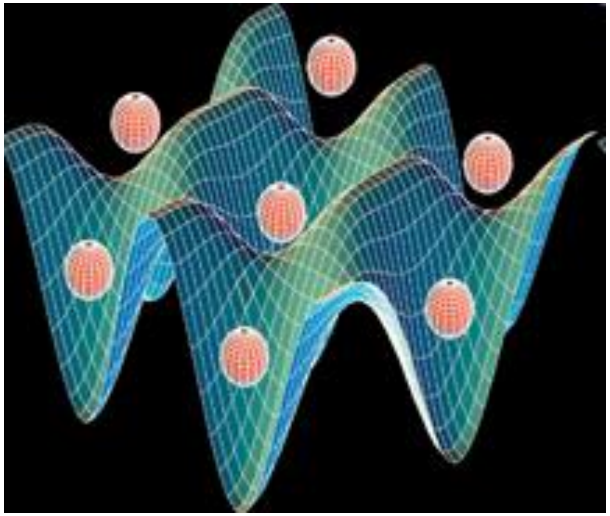
Applications

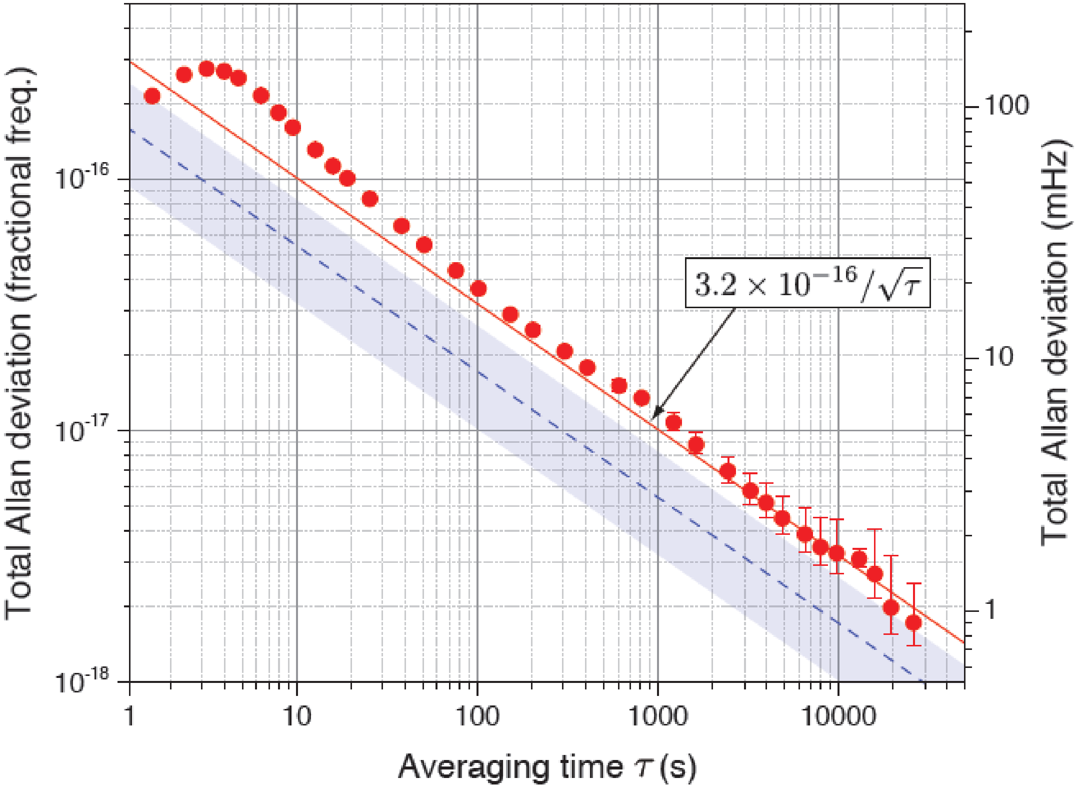
Very recently a significant progress in laser cooling and trapping of some lanthanides, including hollow-shell ones, is achieved. They are intensively studied and successfully implemented in

- **precision spectroscopy and optical frequency metrology**

- **study of interactions in quantum regime, study of quantum gases**

Ytterbium optical lattice clock are unprecedentedly stable



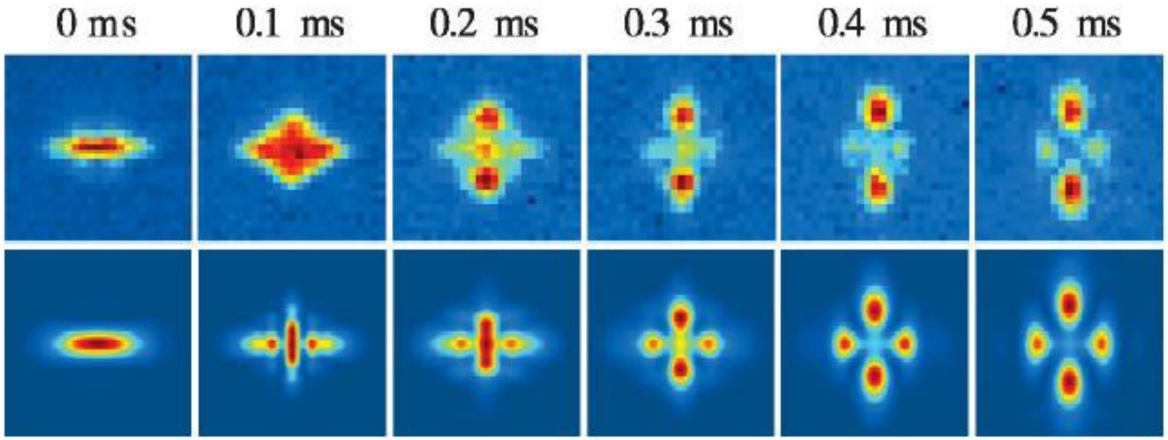


Comparison of two identical Yb clocks is performed at NIST, 2013 in the group of Andrew Ludlow

N. Hinkley at al., arXiv:1305.5869v1

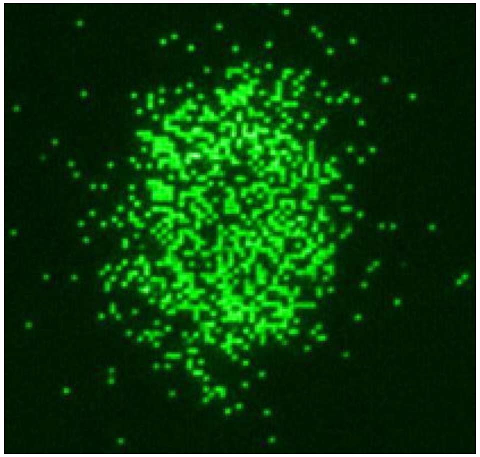
Magnetic gases

Cr:
dipole-dipole
interactions



T. Lahaye,et al., [Phys Rev Lett.](#) 080401 (2008)

Optical
lattice+microscope for
degenerate gases?



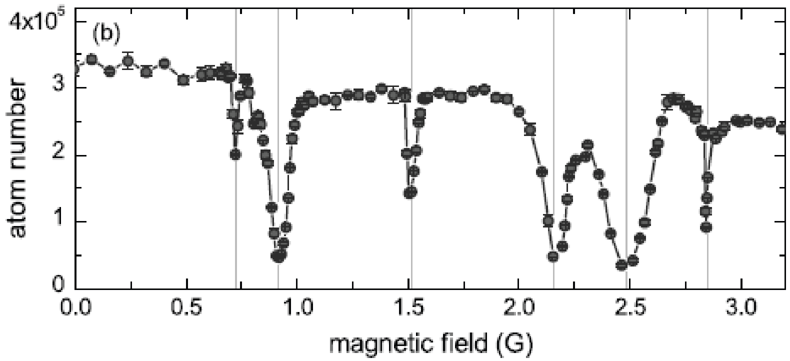
Rb

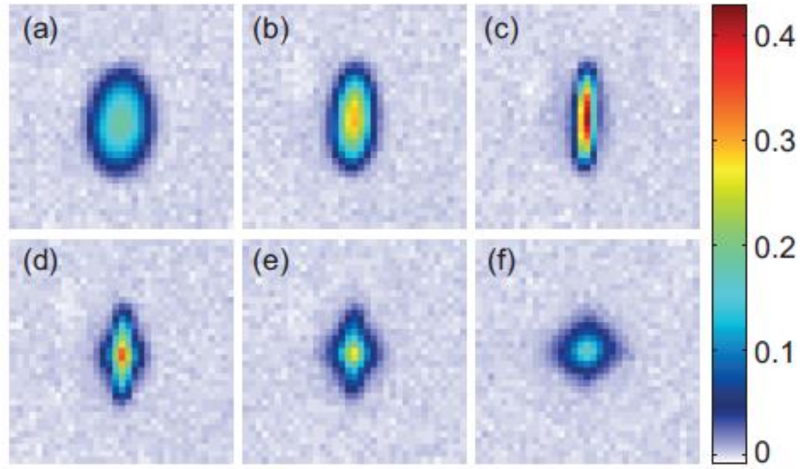
W. S. Bakr, J. I. Gillen, A. Peng, S. Foelling, M. Greiner
[Nature 462, 74-77 (2009)](#)

Hollow-shell Lanthanides

Vacancies in the hollow 4*f*-shell (e.g. Er, Dy, Tm) provide big magnetic moment in the ground state.

Feshbach resonance in Er



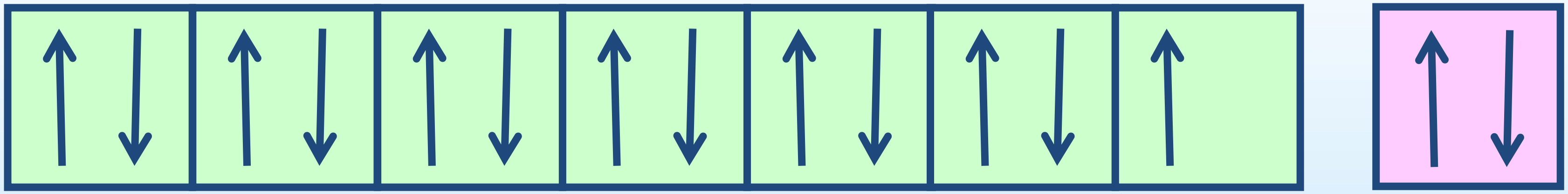


Magnetic moment of Dy equals $10\ \mu_B$, of Er – $6\mu_B$. Strong dipole-dipole interactions between ground state atoms. Dipole-interacting condensates and quantum simulators.

M. Lu, N.Q. Burdick, S.H. Youn, and B.L. Lev Phys. Rev. Lett. 107 190401 (2011)
K. Aikawa et al. Phys. Rev. Lett. 108 210401 (2012)

Thulium electronic structure

Tm: $4f^{13}$ $6s^2$



- one vacancy in the $4f$ shell
- relatively simple level structure
- fine splitting of the ground state

$$\mu_{ground} = 4\mu_B$$

shell	*s*	*p*	*d*	*f*
L	0	1	2	3

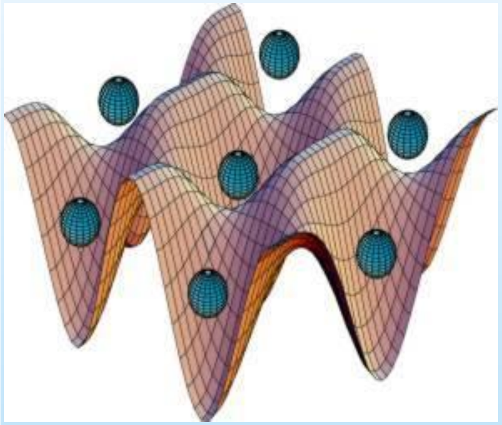
$$L = 3$$

$$S = 1/2$$

Large J causes large magnetic moments of the ground state

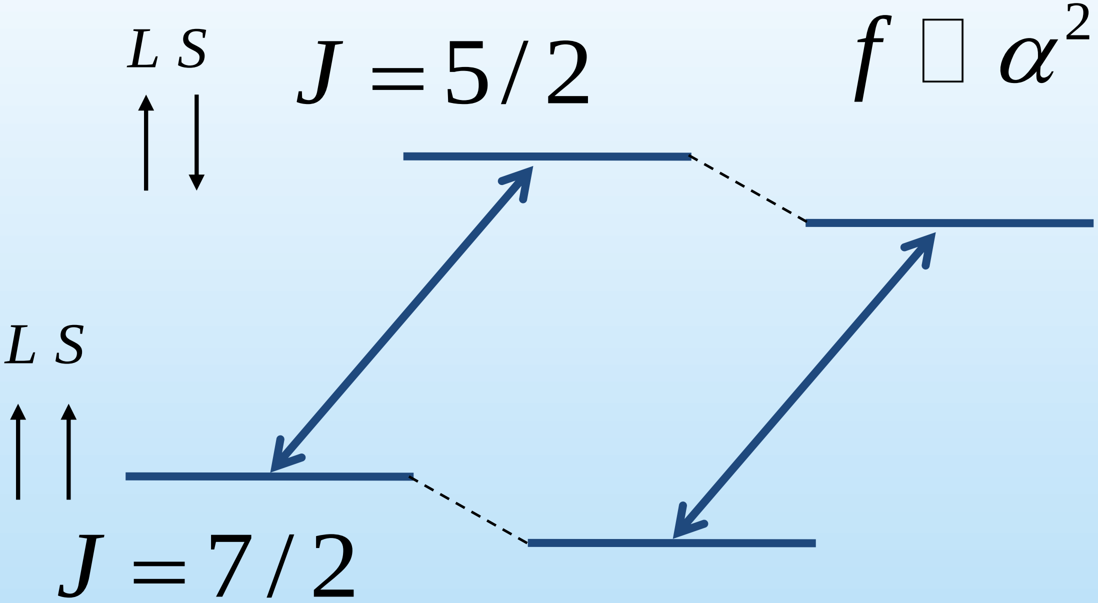
Similar polarizabilities of the ground-state fine structure components

Optical lattice



M1 transition λ = 1.14 μm, γ ~ 1 Hz

$f \sim \alpha^2 Ry$



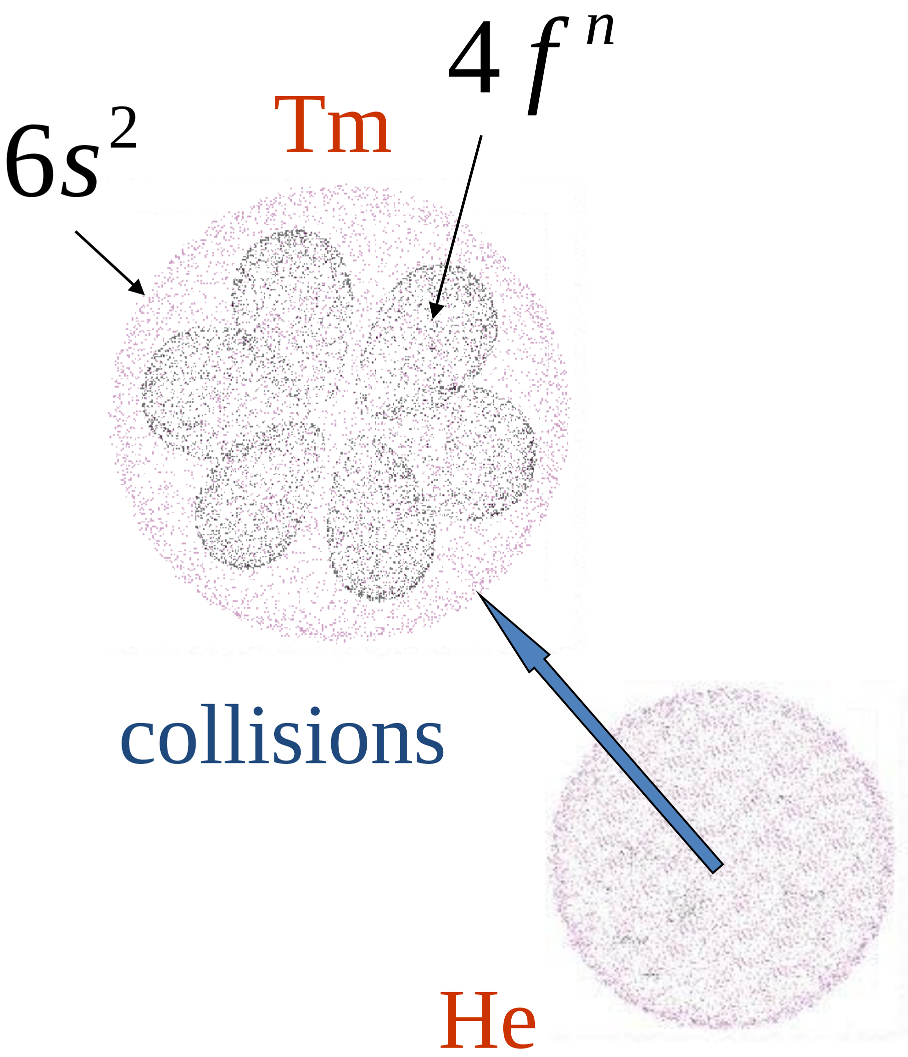
$L\ S$ $\uparrow\downarrow$ $J = 5/2$

$L\ S$ $\uparrow\uparrow$ $J = 7/2$

(V.D. Ovsyannikov, 2010)

To what extent the transition frequency remains unperturbed? Calculations needed!

Shielding of the $4f$ shell levels



- Because of the closed $6s^2$ shell, the inner shells are shielded to the external perturbations.

- The shileding was first demonstrated experimentally by E.B. Alexandrov in 1983

- J. Doyle at al. measured for He-Tm collisions (Nature, 2004)

$$\sigma_{in}/\sigma_{el} = 4\times10^{-5}$$

- For Tm-Tm collisions in specific magnetic state the shielding disappears (PRA, 2010)

E.B.Aleksandrov et al., Opt. Spektrosk., 54, 3, (1983)
C.I. Hancox et al. Nature 431, 281 (2004)
C.B.Connolly et al., Phys. Rev. A 81, 010702 (2010)

The M1 transition in Tm atom

Spectroscopy on the ground state sublevels in lanthanides
is not yet performed

Thulium: λ = **1.14 μm,** γ ~ **1 Hz**

- suppression of the external electric fields perturbations

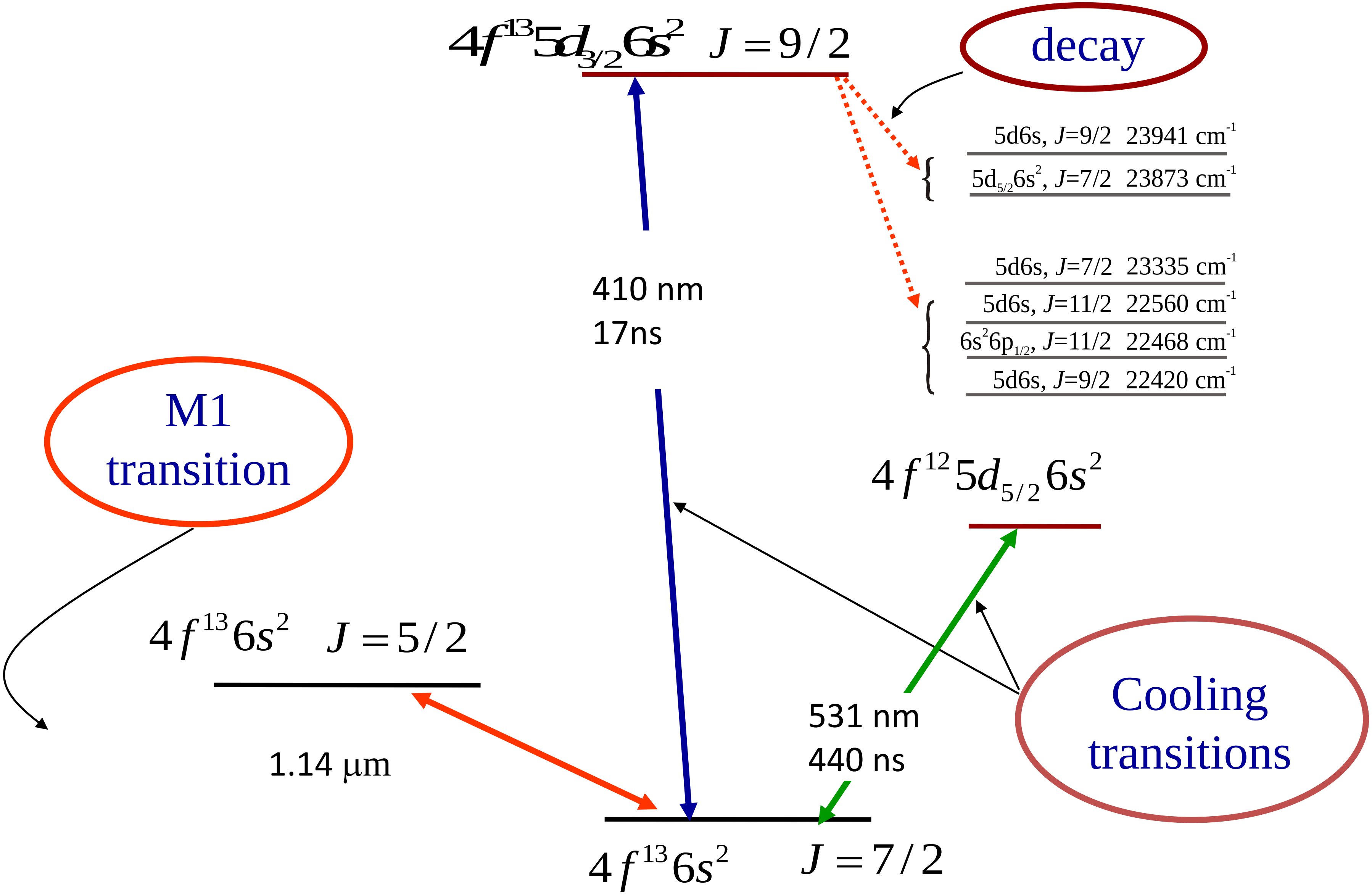
- small black-body shift

- loading in the optical lattice with small perturbation of the clock transition

- strong α-dependency $f \,\square\, \alpha^2 Ry$

Laser cooling of Thulium

Cooling transitions in Tm



$4f^{13}5d_{3/2}6s^2$ $J=9/2$

decay

5d6s, J=9/2 23941 cm^{-1}

$5d_{5/2}6s^2$, J=7/2 23873 cm^{-1}

5d6s, J=7/2 23335 cm^{-1}

5d6s, J=11/2 22560 cm^{-1}

$6s^2 6p_{1/2}$, J=11/2 22468 cm^{-1}

5d6s, J=9/2 22420 cm^{-1}

410 nm
17ns

M1 transition

$4f^{12}5d_{5/2}6s^2$

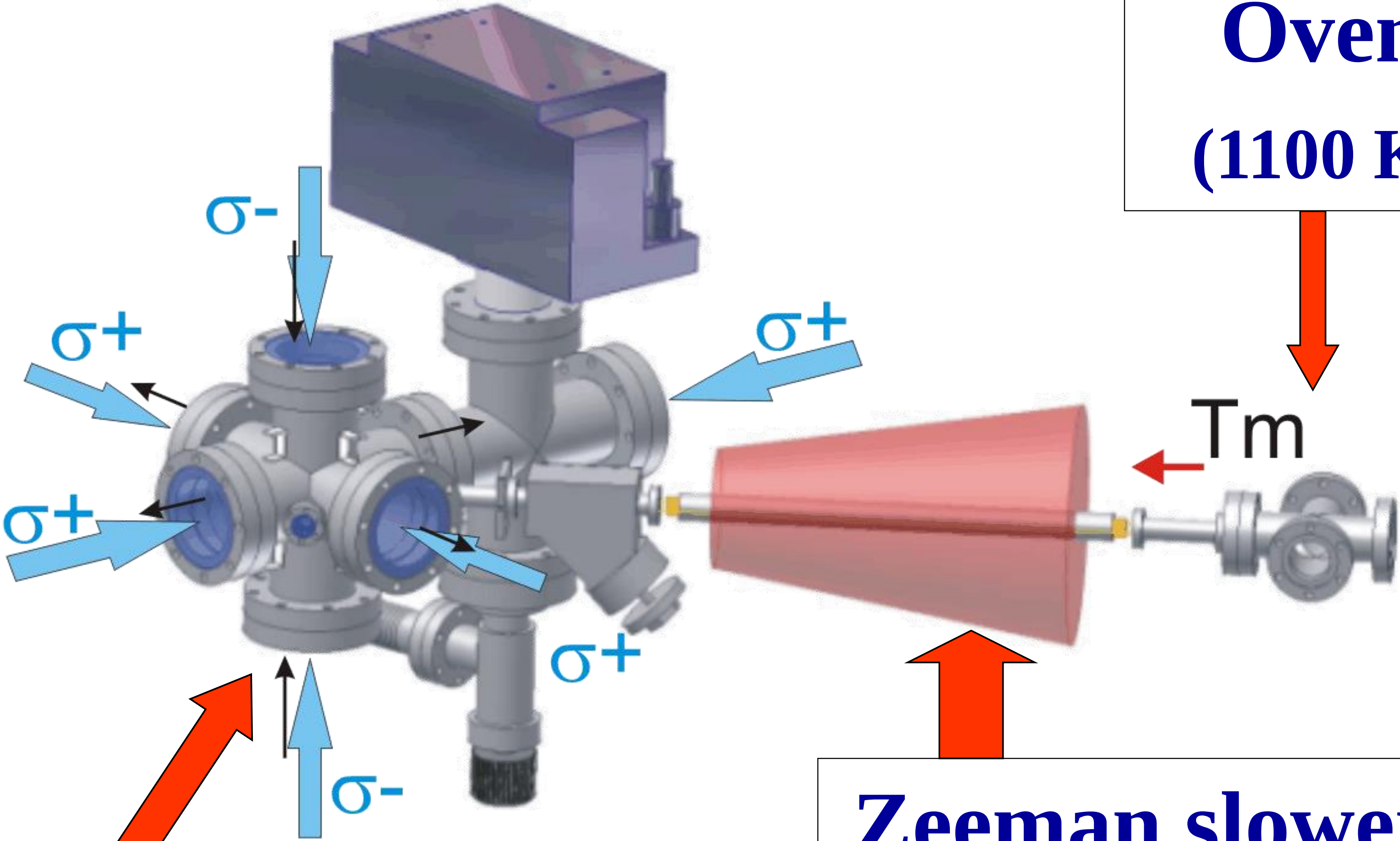
$4f^{13}6s^2$ $J=5/2$

1.14 μm

531 nm
440 ns

Cooling transitions

$4f^{13}6s^2$ $J=7/2$



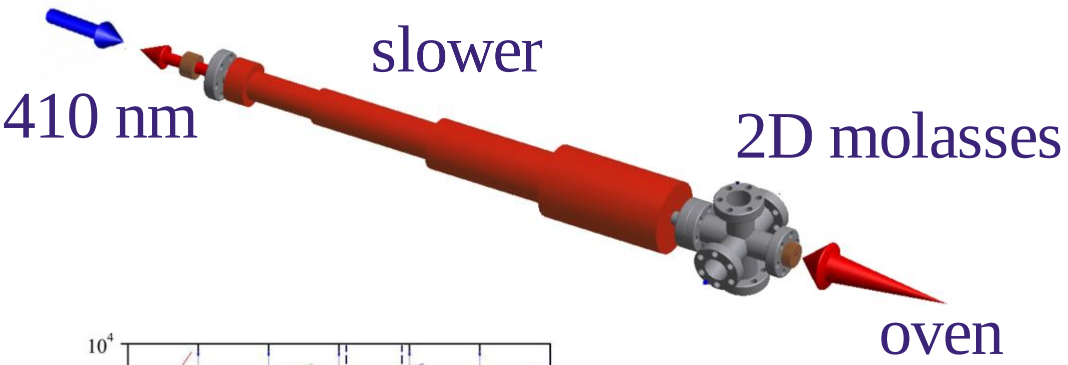
Oven

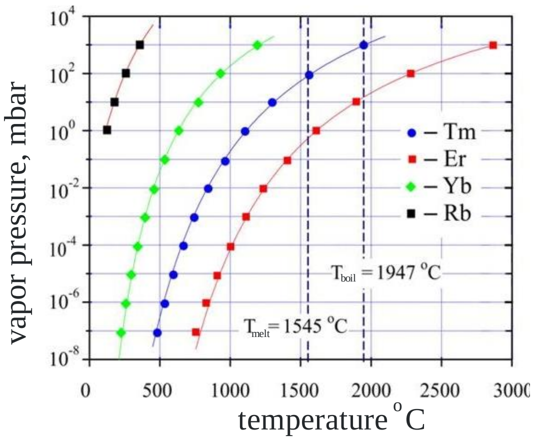
(1100 K)

Zeeman slower

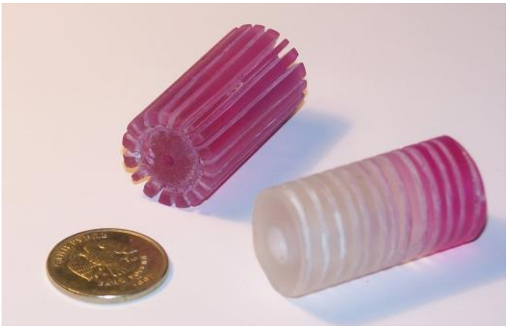
MOT chamber

Zeeman slowing





Oven design



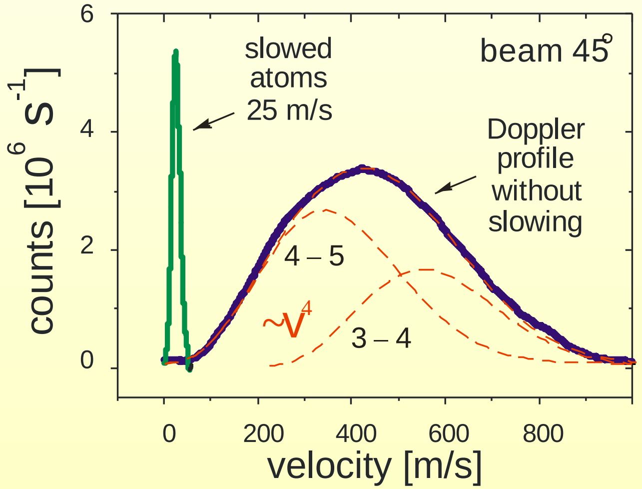
Slower operation

initial beam ~ **10^9 at/s**

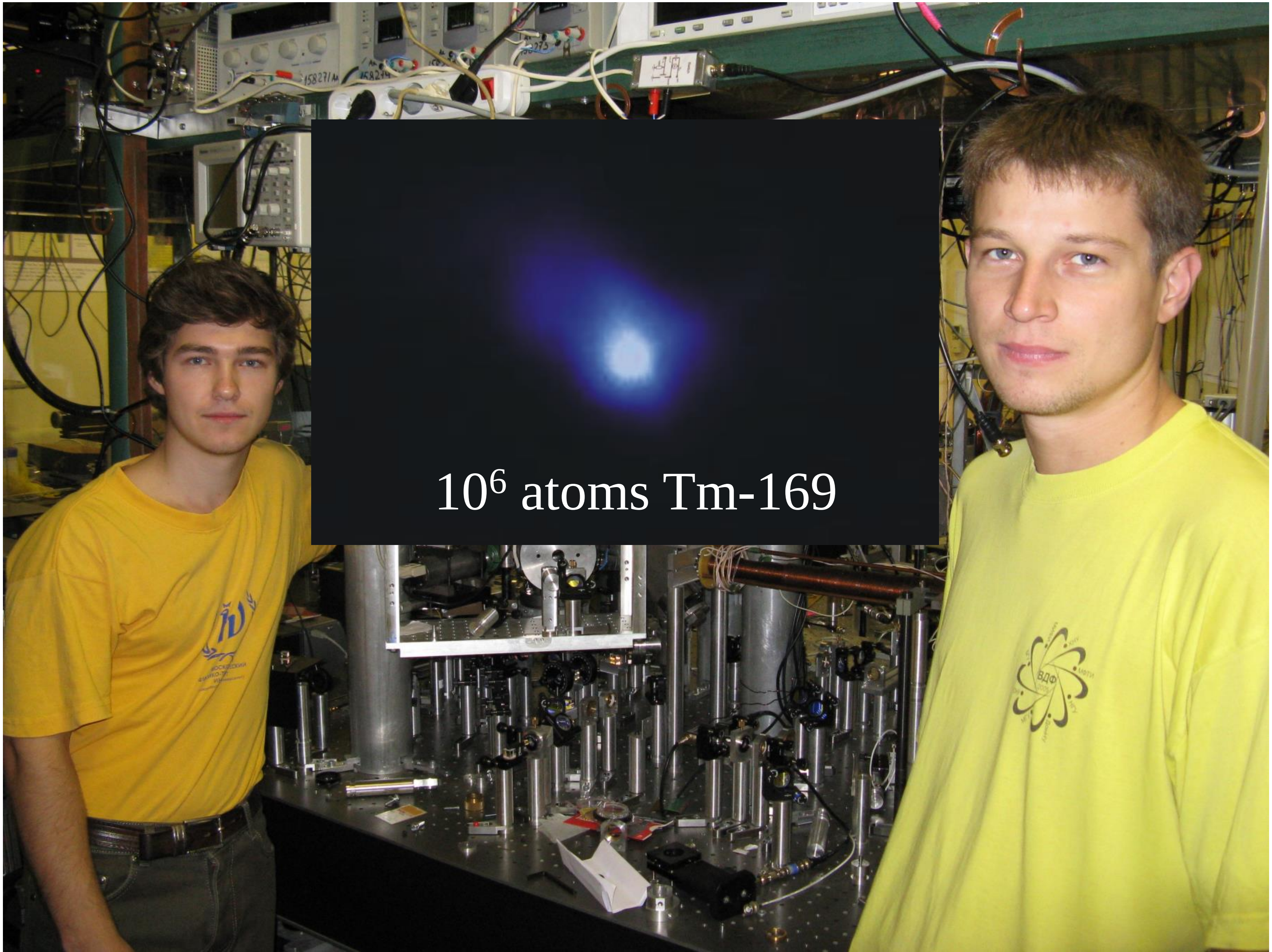
slowing **1% atoms**

beam size **1 cm^2**

flux (typ) **10^7 at/s cm^2**

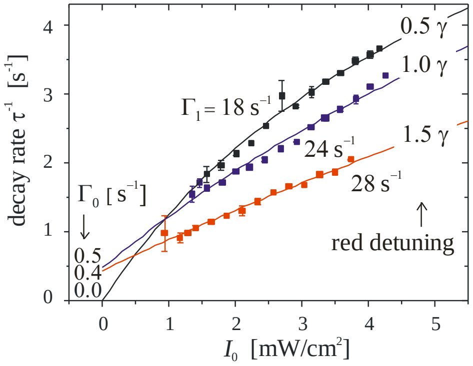


Magneto-optical trap (2010)



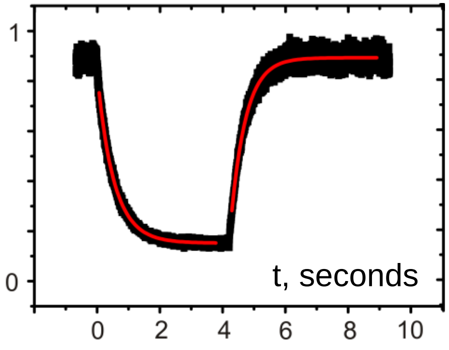
10^6 atoms Tm-169

- The life time of Tm atoms in the MOT



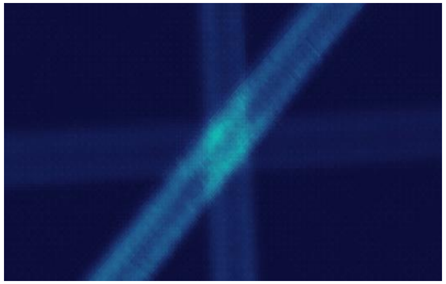
$$\Gamma_1 = 22(6)\ s^{-1}$$

- Binary collisions in the MOT



$$\sigma = 3(2)\cdot 10^{-10}\ \frac{cm^3}{s}$$

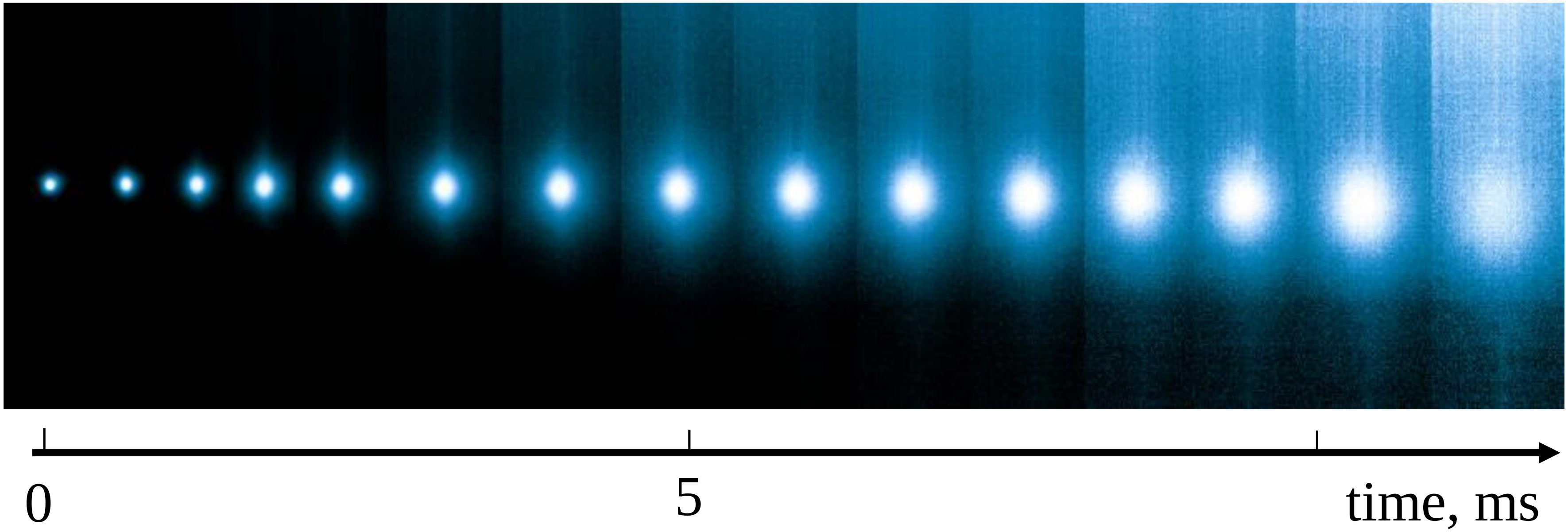
- “Dark” MOT implemented



5 times more atoms

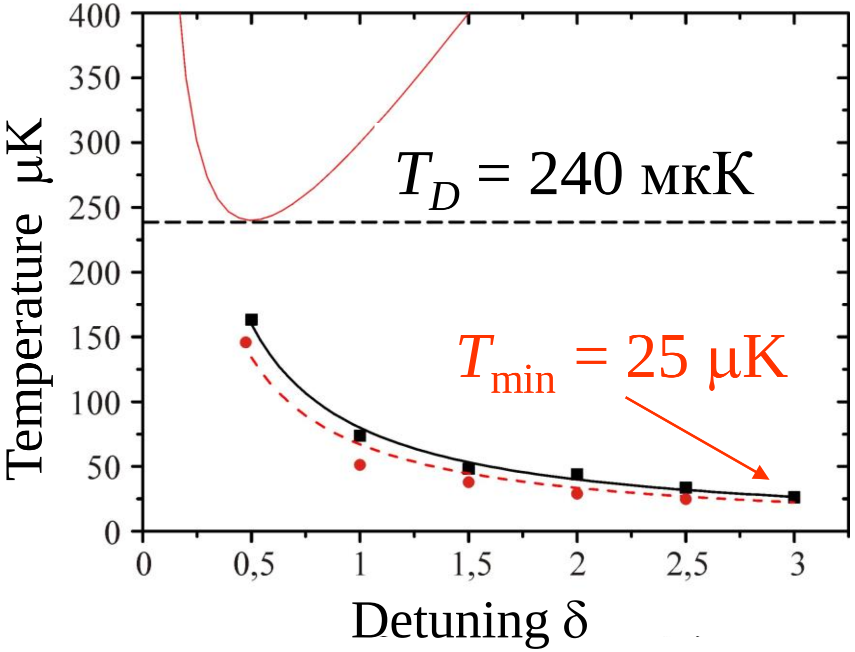
- Temperature of atoms

Temperature measurements



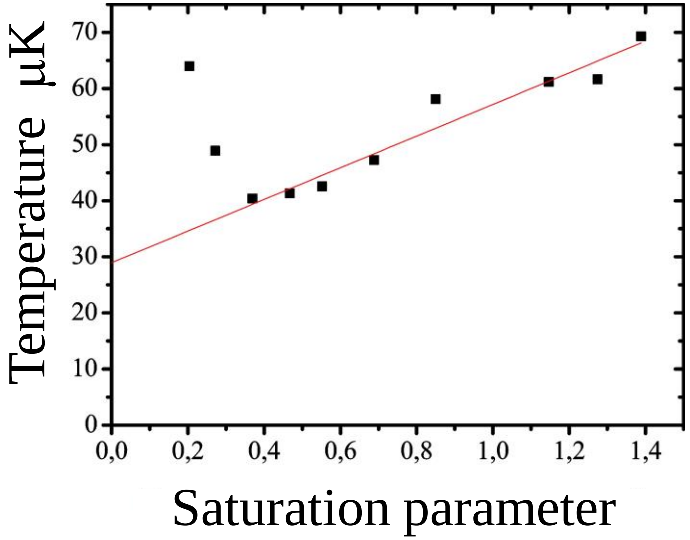
Ballistic expansion of the atomic cloud to measure temperature

Temperature in Tm MOT



$$T_D = 240\mu K$$

$$T_{\min} = 25\mu K$$



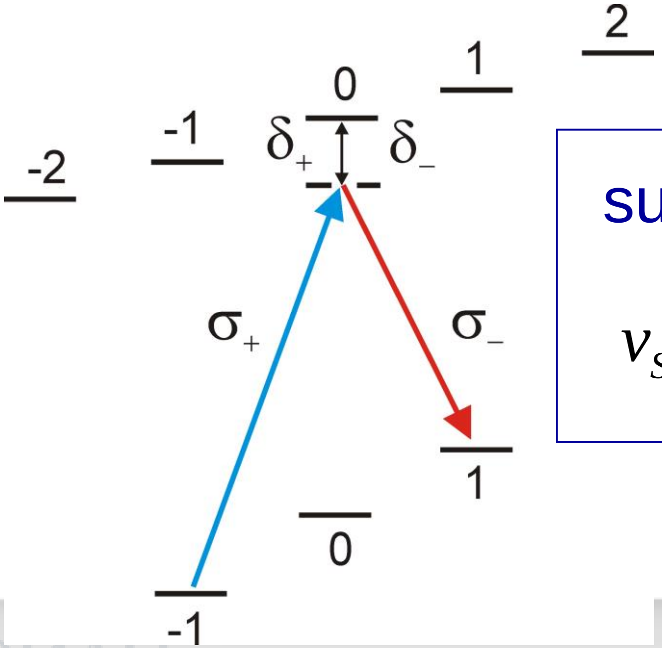
$$\boxed{T \propto \frac{I}{\delta \cdot F}}$$

Magnetic field

Due to specific level structure of Tm atom (degeneracy of the Landé g-factors) sub-Doppler mechanism **IS EFFICIENT** even in the presence of magnetic field

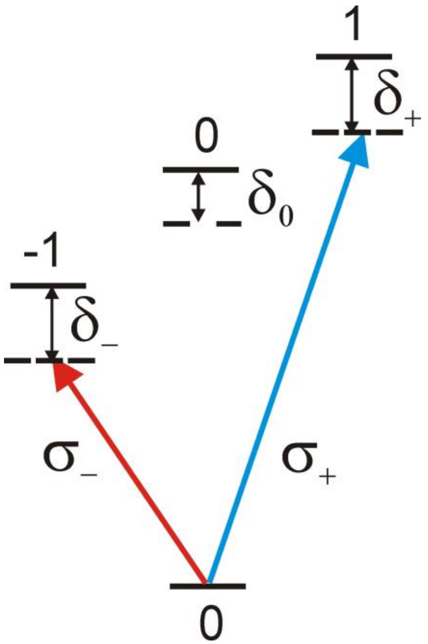
Doppler:

$$v_D = g_e \frac{\mu_B B}{\hbar k}$$

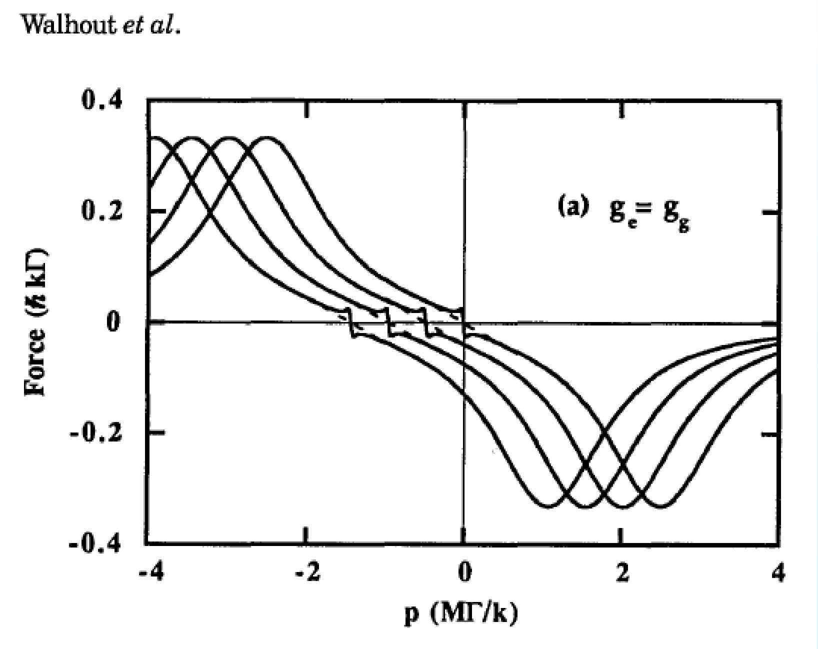


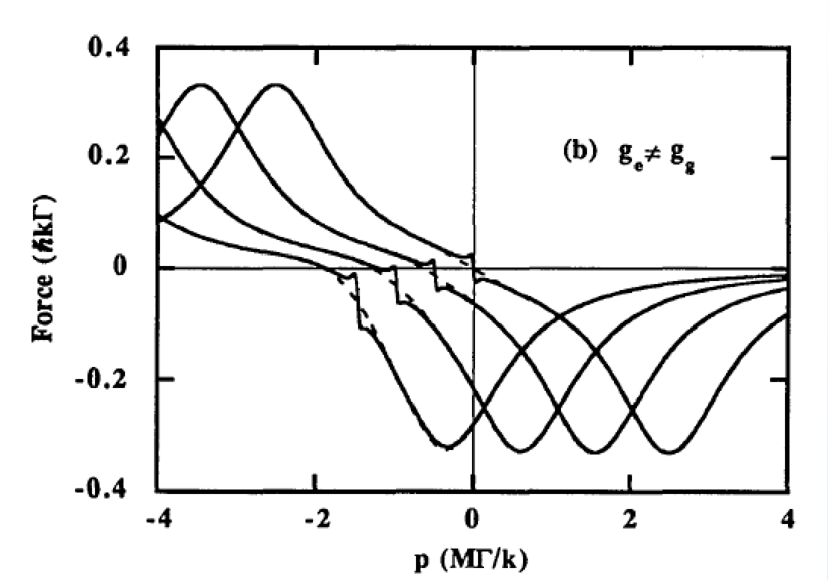
sub-Doppler

$$v_S = g_g \frac{\mu_B B}{\hbar k}$$



Role of Landé *g*-factors





Tm: $g_g = 1.14$, $g_e = 1.12$

(2% difference)

Rb: $g_g = 1/2$, $g_e = 2/3$

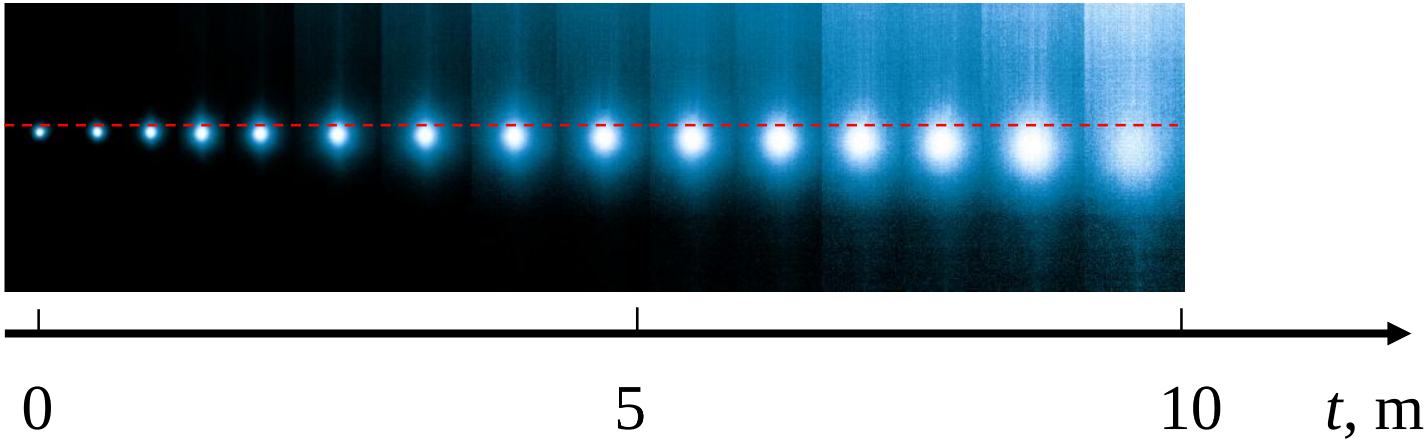
(30% difference)

M. Walhout, J. Dalibard, S.L.Rolston, and W.D. Phillips, J. Opt.Soc. Am. ***9****, 1997 (1992)*

Magnetic trap for Tm

MOT

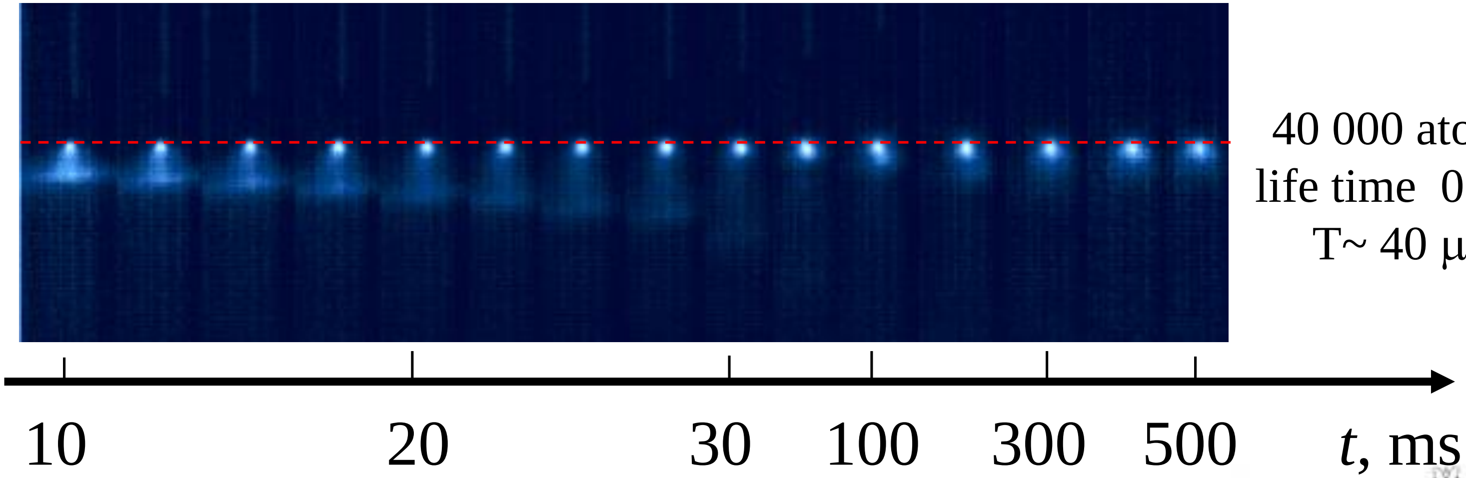
$\nabla B = 0$



MT

$\nabla B \neq 0$

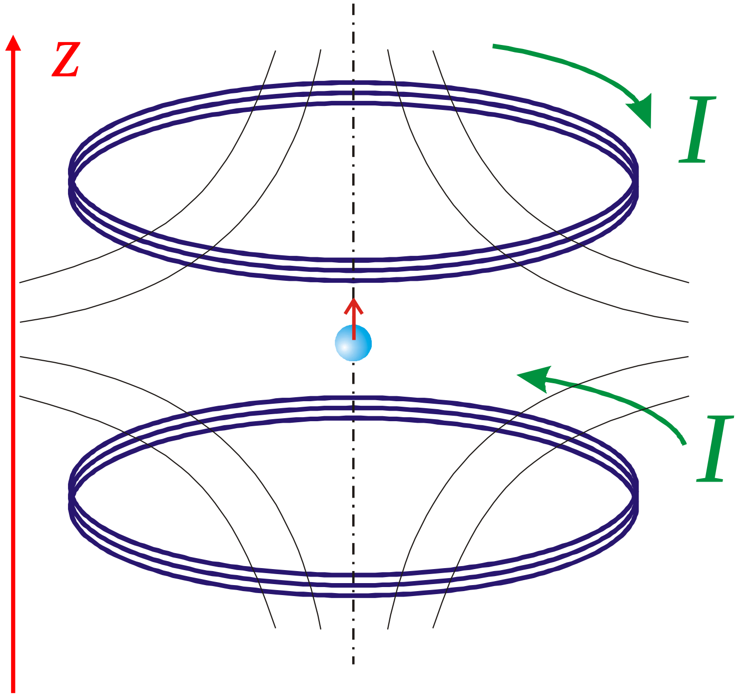
20 G/cm



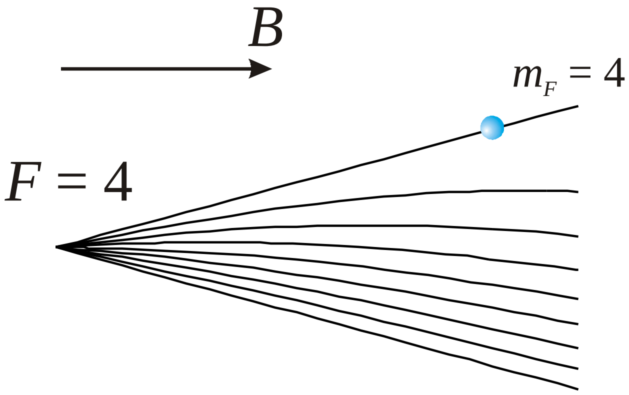
40 000 atoms,
life time 0.5-1s,
T~ 40 μK

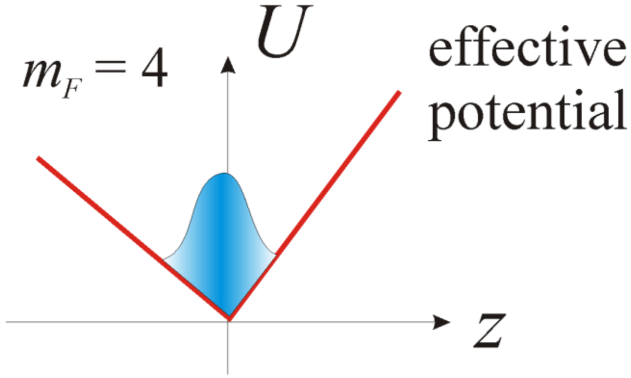
Magnetic trap

(in presence of gravitation)



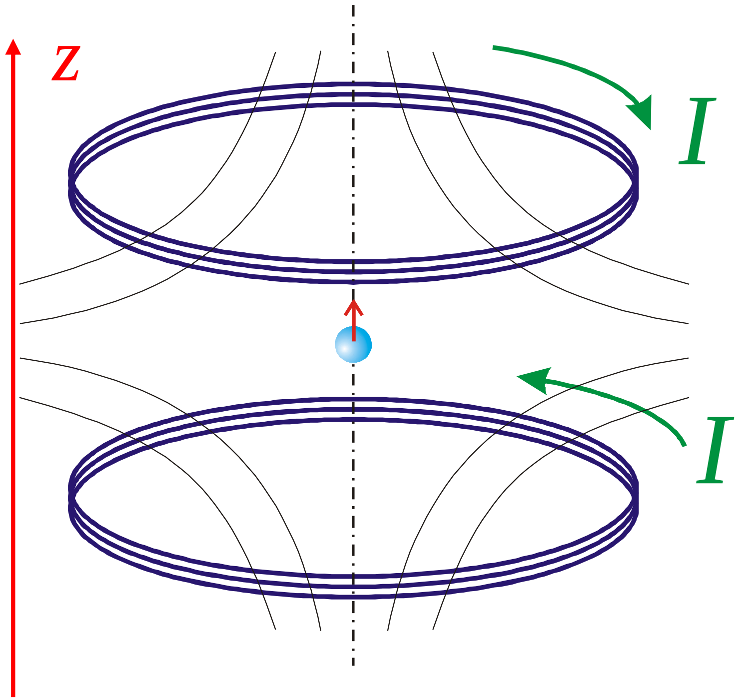
$$\Delta E = -\vec{\mu}\vec{B}$$



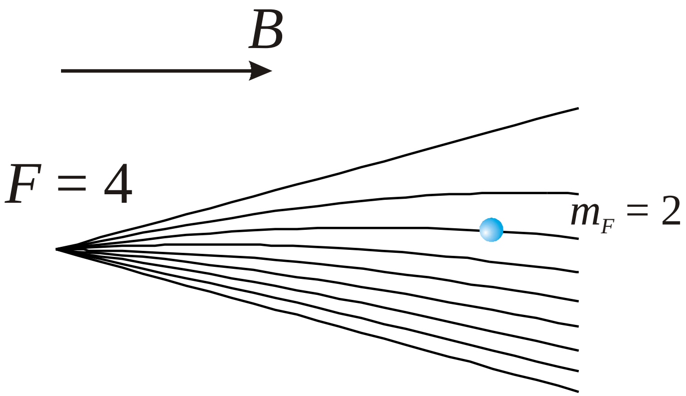


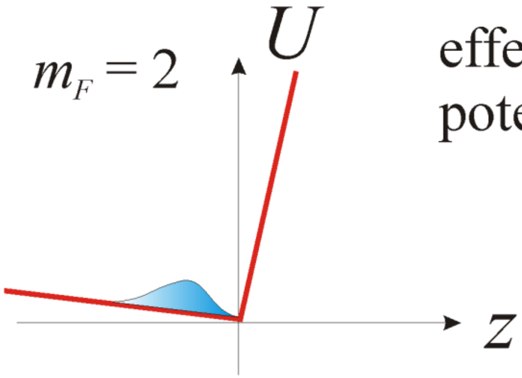
Magnetic trap

(in presence of gravitation)



$$\Delta E = -\vec{\mu}\vec{B}$$

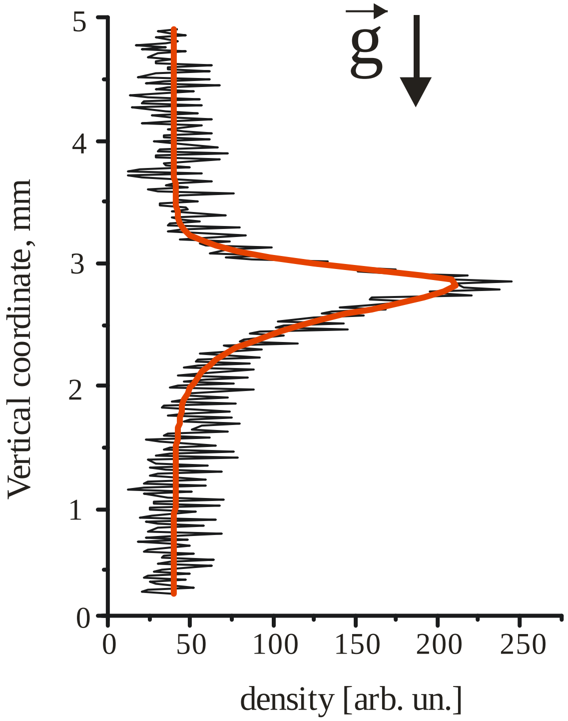


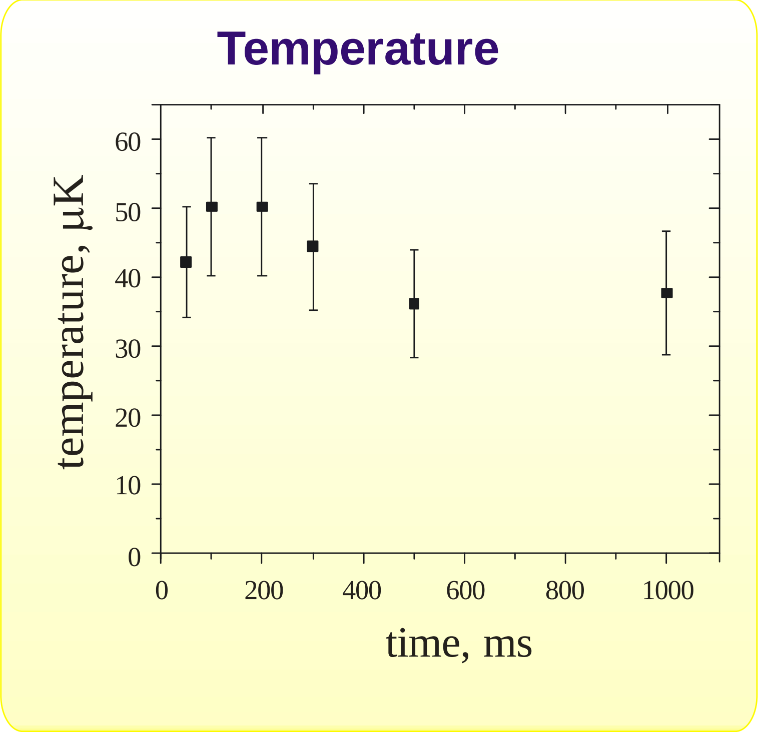


effective potential

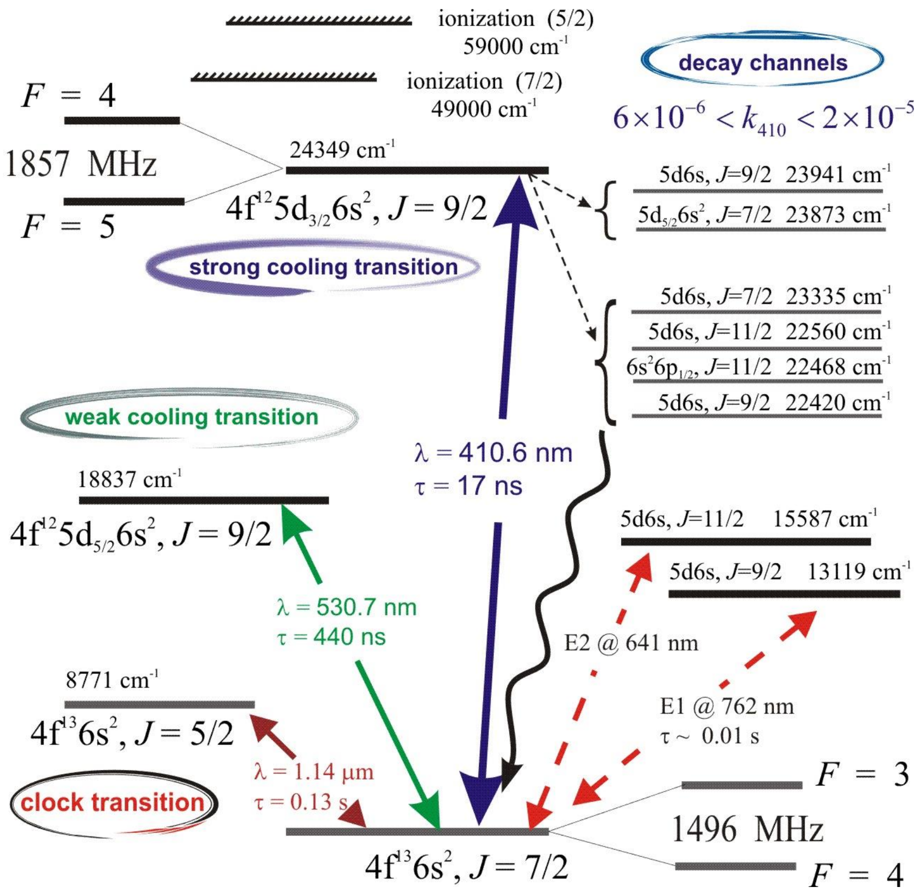
Magnetic trap profile

Only atoms in m_F=+2,3,4 states are trapped





Second stage cooling



First stage cooling at 410 nm
T_D=240 μK

Second stage cooling at 530.7 nm
T_D=9 μK

Frequency-doubled laser diode radiation is used

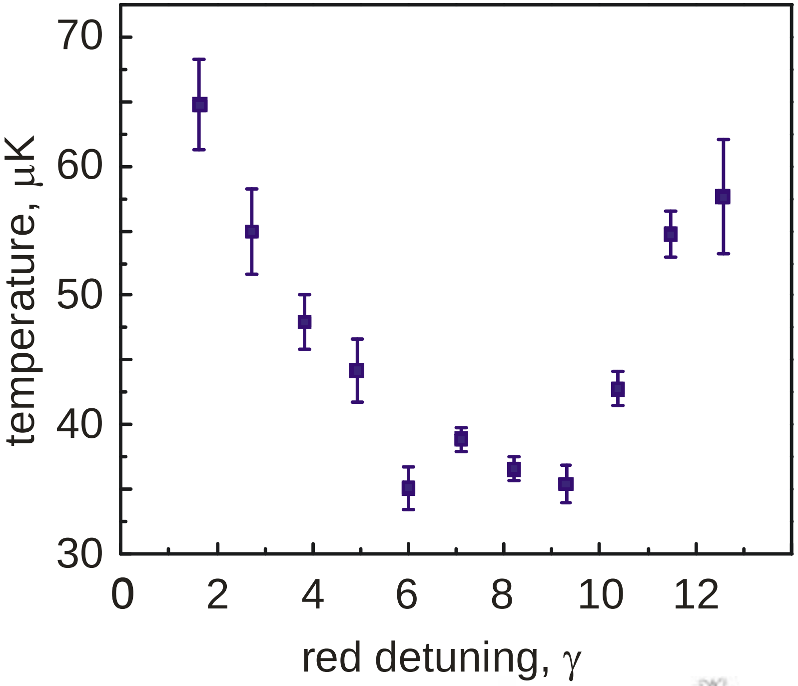
Second stage cooling

- Efficient cooling recapture directly from Zeeman slower

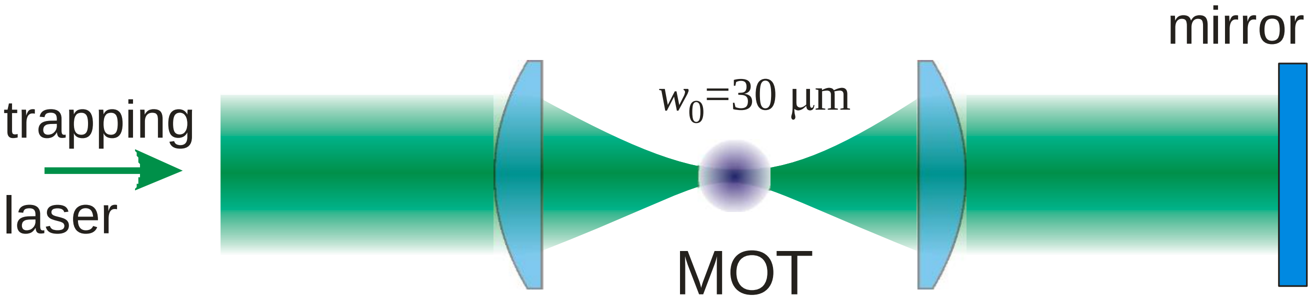
- Number of atoms similar to blue MOT due to Zeeman slower design

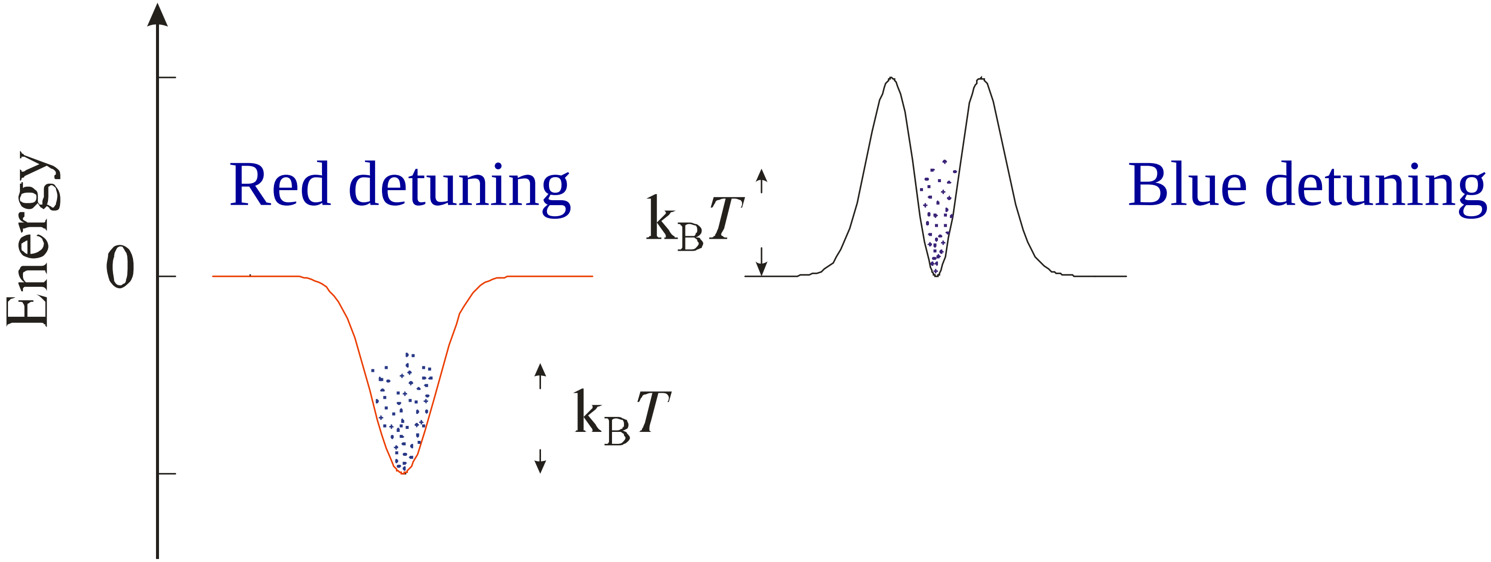
- Recapture efficiency from blue MOT 100%

- To reach lower temperatures we need to narrow the diode laser line width (lower than 100 kHz)

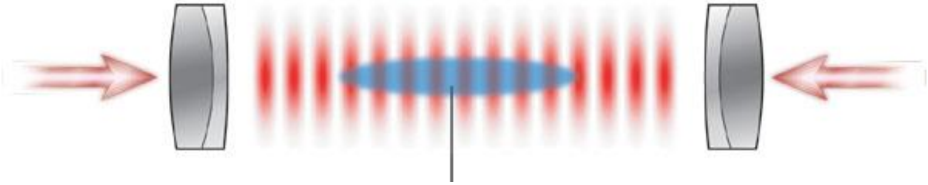


Optical trapping

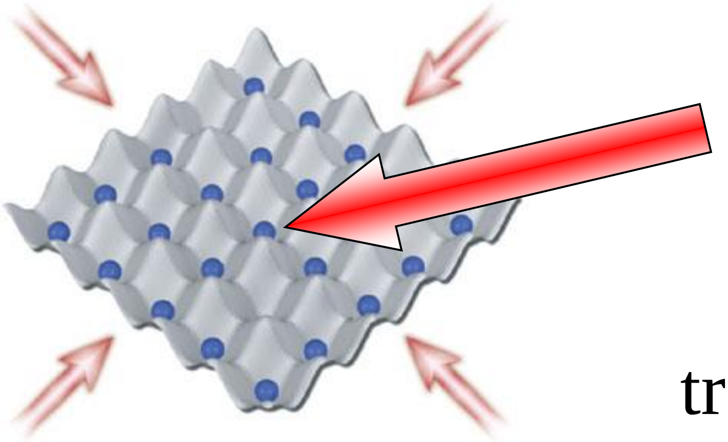




Spectroscopy of Tm clock transition in the optical lattice



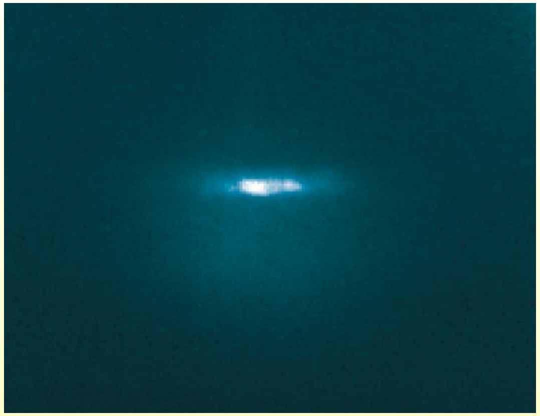
Dipole optical trap with a standing wave



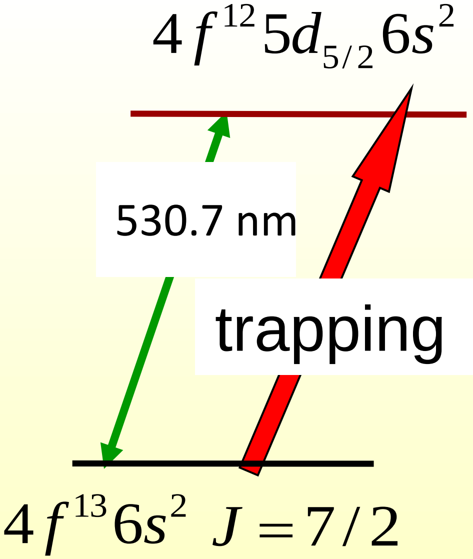
stabilized 1.14 μm

Excitation of the clock transition in trapped atoms

One trapping beam



530.660 nm



$4f^{12}5d_{5/2}6s^2$

530.7 nm

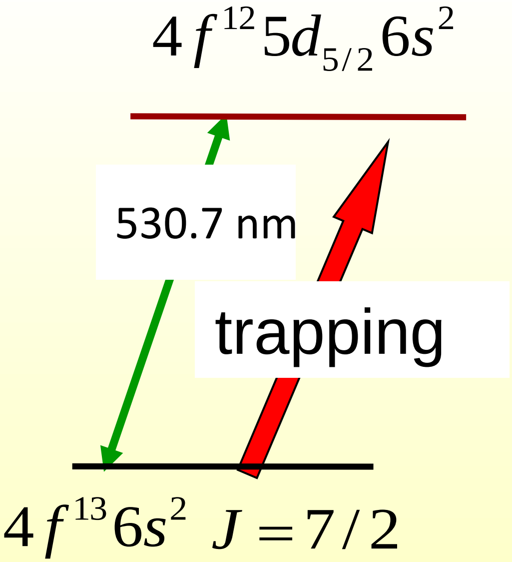
trapping

$4f^{13}6s^2\ J=7/2$

- Loading from MOT at 100 mK
- Laser Verdi G-12 blue detuned!
- Optical trap depth 1 mK
- Strong blue transitions mainly contribute to the polarizability
- About 1% of atoms is recaptured

Optical lattice

532.0 nm



$4f^{12}5d_{5/2}6s^2$

530.7 nm

trapping

$4f^{13}6s^2\ J=7/2$

- Loading from MOT at 100 mK
- Laser Verdi V-8 red detuned!
- Optical trap depth 1 mK
- Optical trapping is more efficient for red detuning
- Trapping depends on polarization => lattice effect!

Intermediate conclusions

- Tm atoms are trapped in an optical lattice and prepared for spectroscopy of clock transition at 1.14 μm

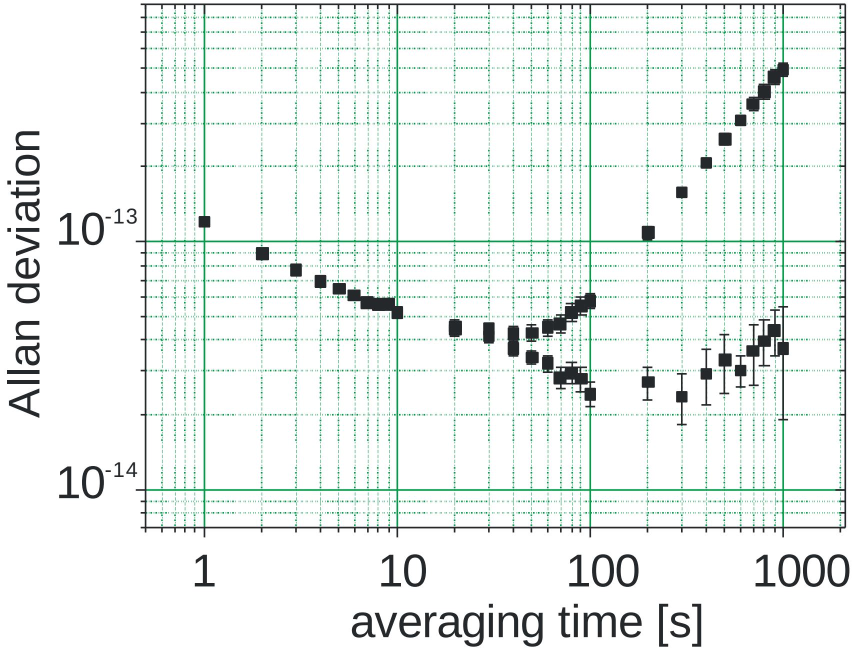
- Temperature of atoms is still too high for efficient recapture into the shallow lattice => further cooling is necessary

- Narrow line lasers for second stage cooling (530.7 nm) and studying of metrological transition (1.14 μm)

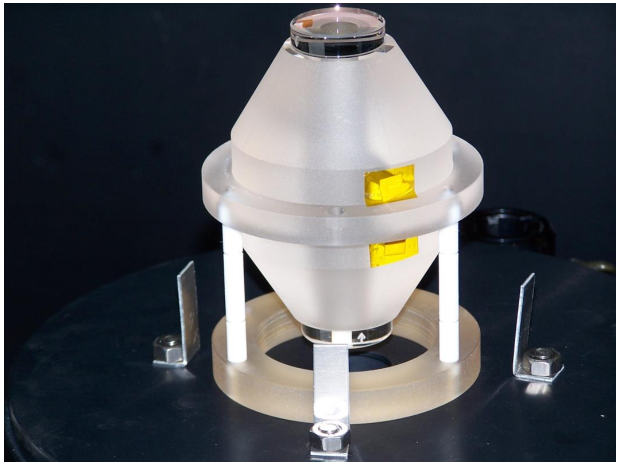
- Increasing of the number of atoms

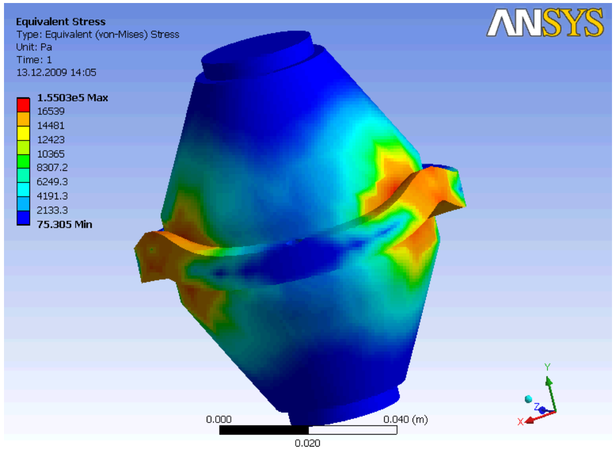
Stabilized laser systems at Lebedev Institute

Vertical cavity F=60000



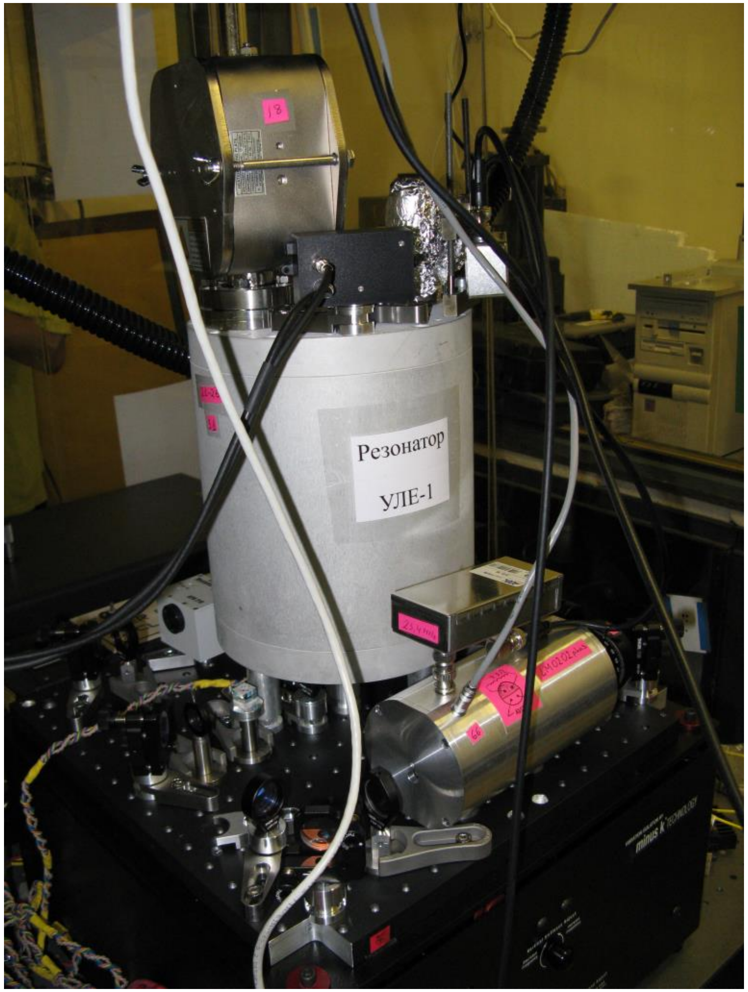
Comparison of two systems designed for 698 nm



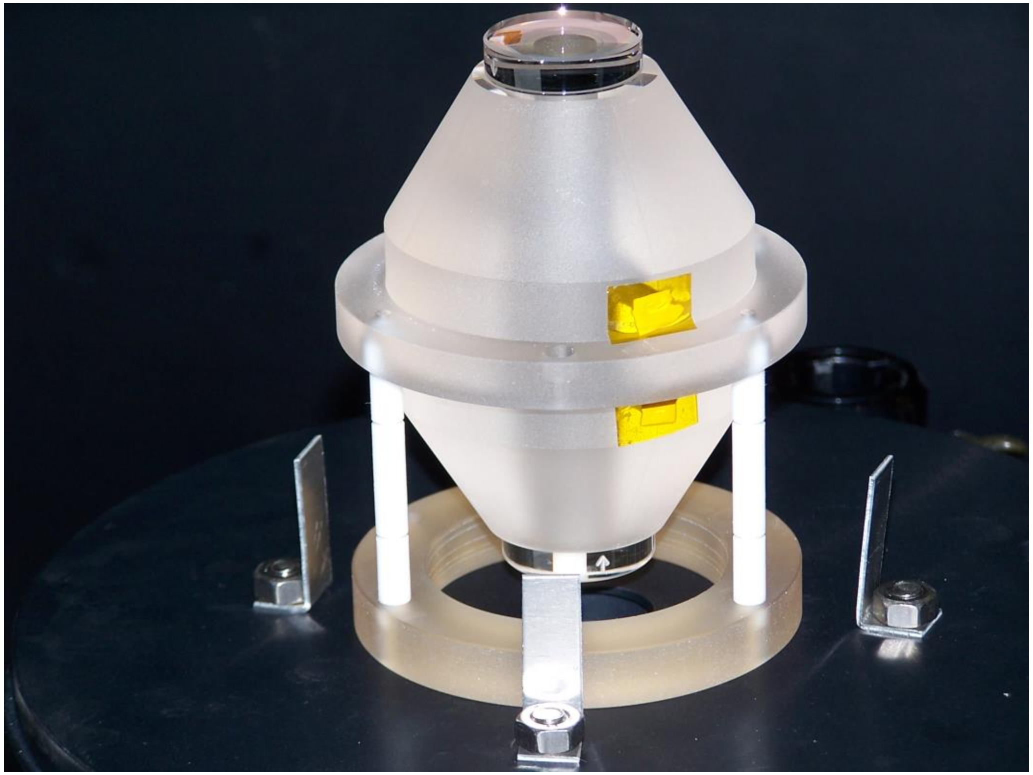


Laser systems for optical clocks at Lebedev Institute

Transportable setup



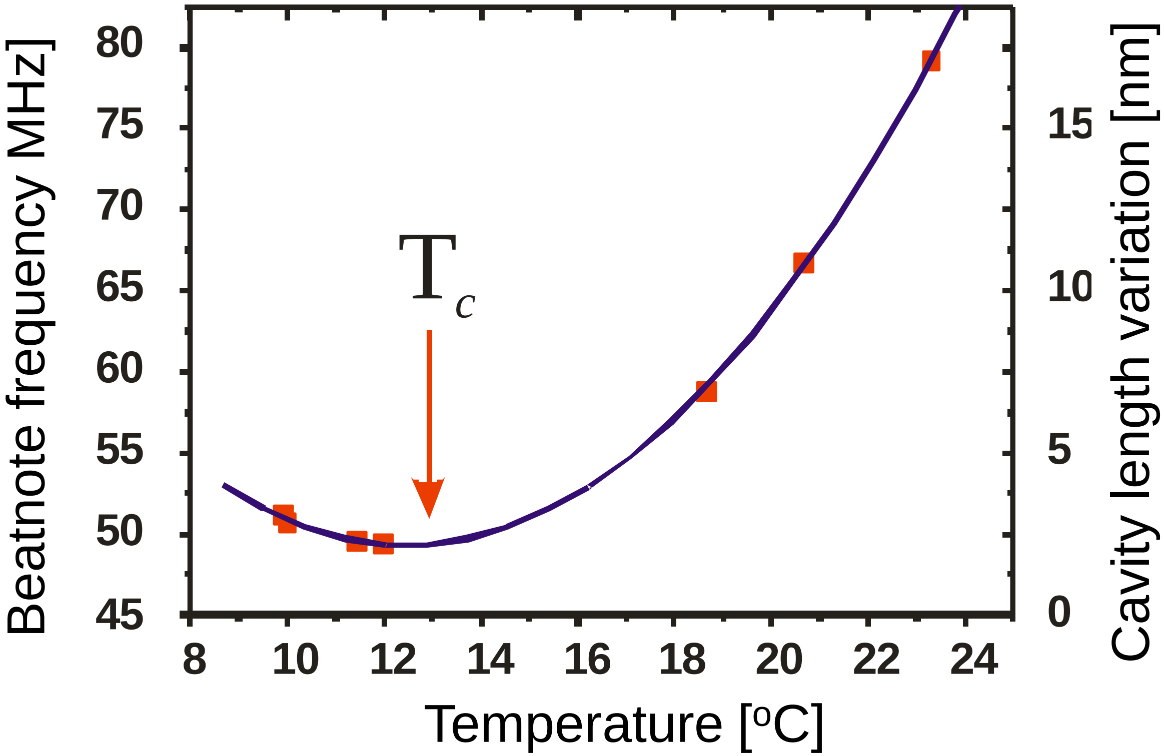
Vertical cavity



Compensation of temperature fluctuations

ULE thermal expansion coefficient

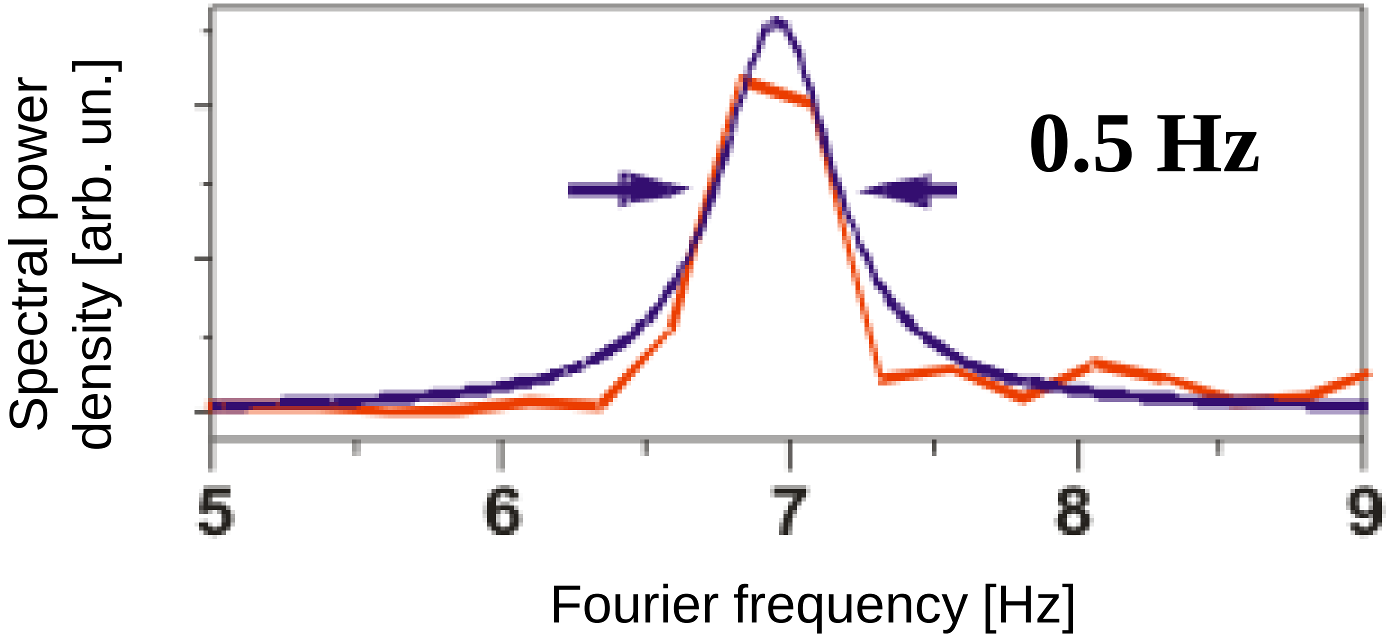
$$\delta l/l \;\square\; 10^{-9}(T-T_c)^2$$



Spectral line width

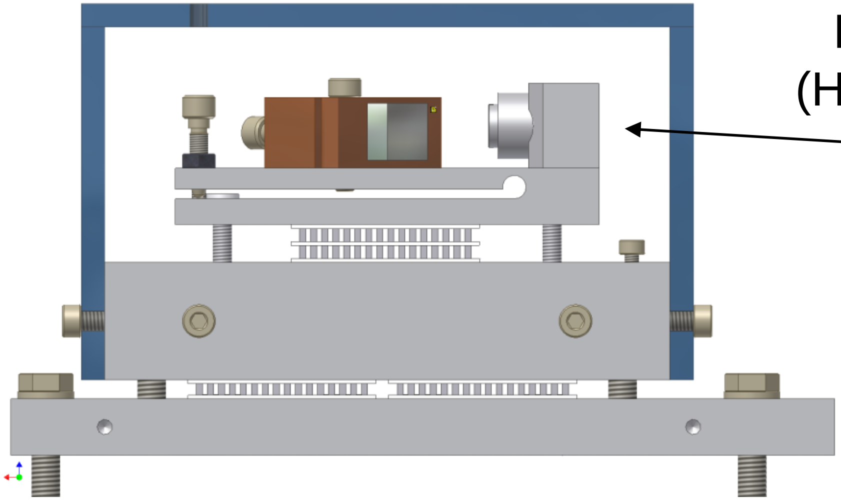
Beatnote between two independent cavities

(972 nm, for hydrogen spectroscopy)



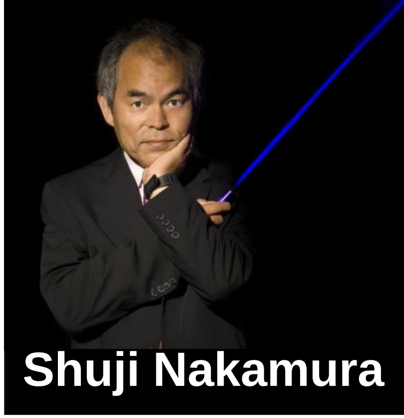
J. Alnis, A. Matveev, N. Kolachevsky, Th. Udem, and T. W. Hänsch, Phys. Rev. A 77, 053809 (2008)

GaN diode lasers @ 410.6 nm



Diode PHR-803T
(HD-DVD, Blue-Ray)

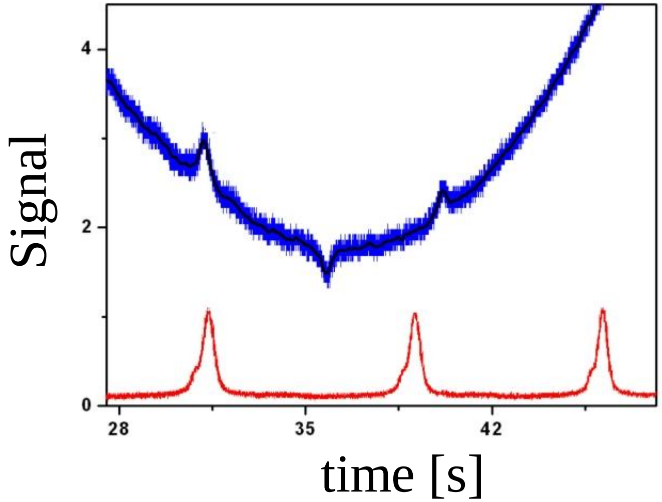
+70 ^{o}C

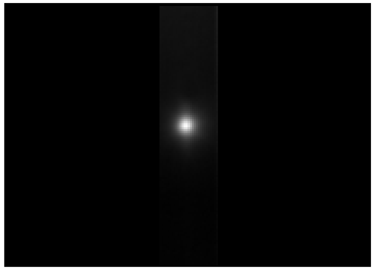


Shuji Nakamura

Fraction of power in a single frequency >95%

Saturation absorption signal in Tm

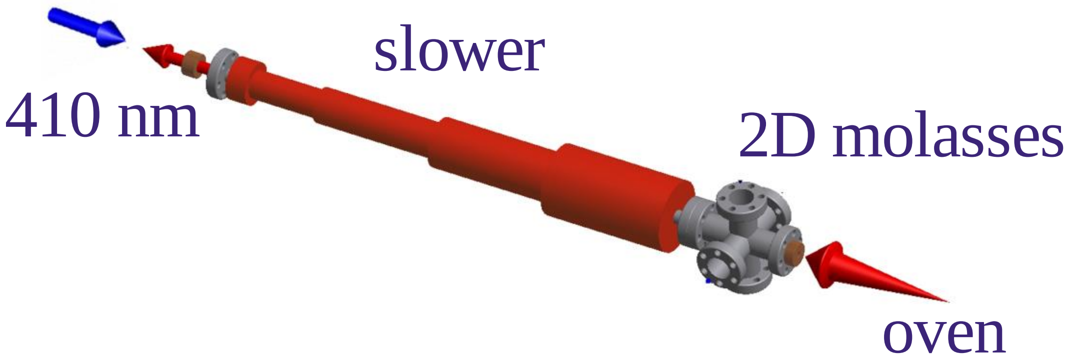


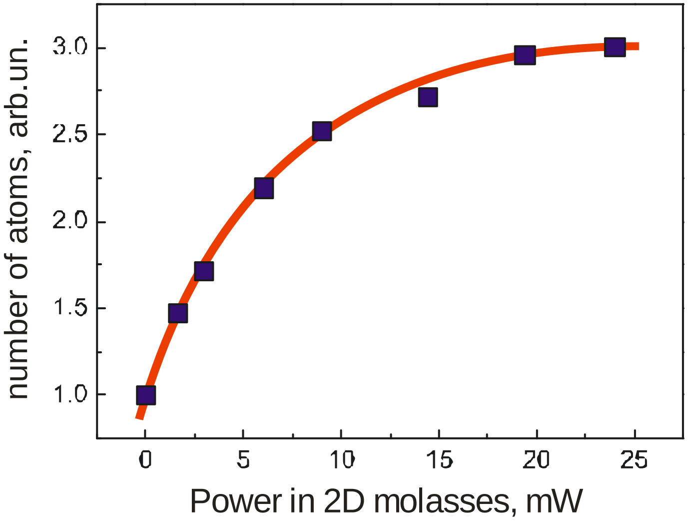


Tm cloud trapped by diode laser radiation

Injection locking gives up to 150 mW @ 410.6 nm

2D molasses for Tm beam collimation





up to threefold increase in the number of atoms in the MOT

- Slave diode SF-BW512P

- Max power 500 mW
- Central wavelength:
  405 nm @ 25° C
  410 nm @ 70° C
- Seed power < 1 mW
- Output power 120 mW

Thank you for attention!

ФИАН

Cooling transitions in Tm