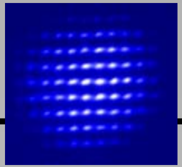


Cold Atoms
and
Laser Development for Spectroscopy on Trapped Highly Charged Ions

C. Ewen, M. Fraczek, J. Kruse, A. Lengwenus, J. Nes, M. Scherer, M. Schlosser, F. Steinebach, W. v. Drunen, M. Wagner, O. Wille, N. Herschbach, G. Birkl

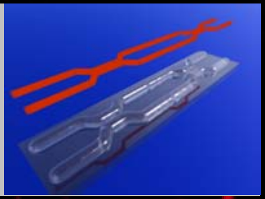
Institut für Angewandte Physik, Technische Universität Darmstadt

in collaboration with: - Institut für Quantenoptik, Universität Hannover
- GSI, Uni. Frankfurt, Uni Mainz, Imperial College, …

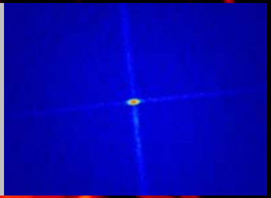
Funded by the DFG Focused Research Programs ‘Quantum Information Processing’ and ‘Interactions of Ultracold Atoms and Molecules’, BMBF Program ‘Hadron and Nuclear Physics’, the projects ‘ACQP’, ‘Atom Chips’, and ‘SCALA’ of the European Commission, and by ARDA/NSA/DTO/NIST

Project Overview

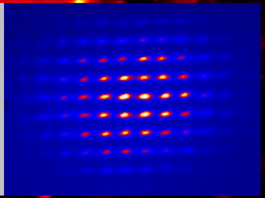
Integrated Atom Optics (ATOMICS)



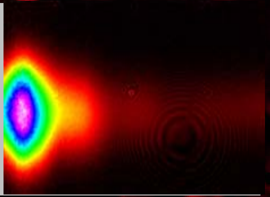
BEC in Optical Trapping Potentials



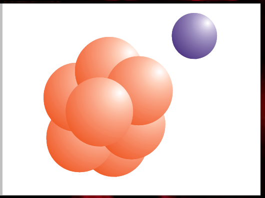
Quantum Information Processing with Atoms



Ultracold Collisions of Metastable Neon



Laser Spectroscopy on Trapped Highly Charged Ions



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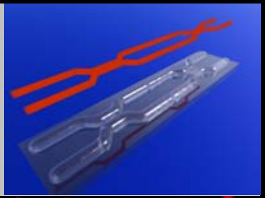
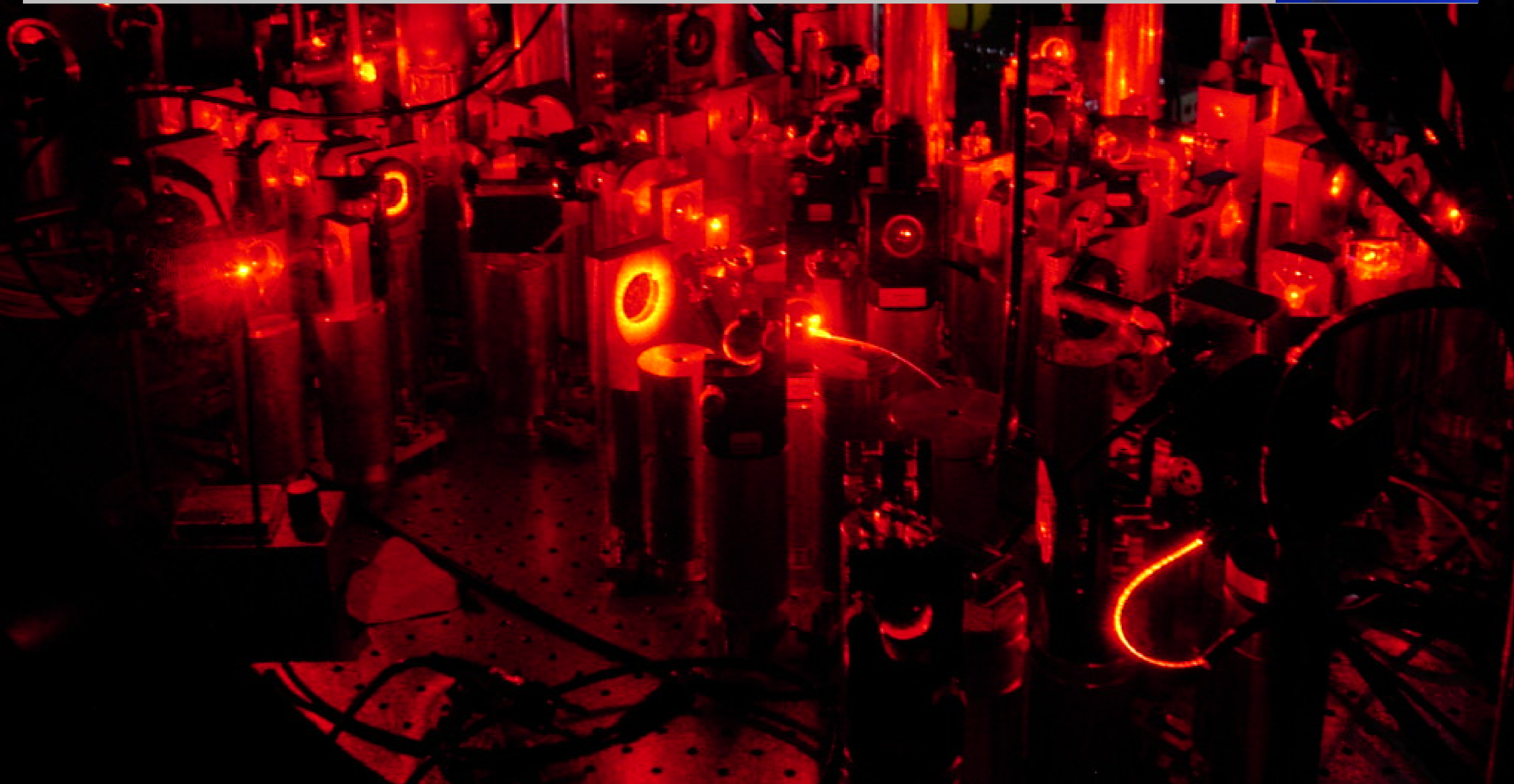
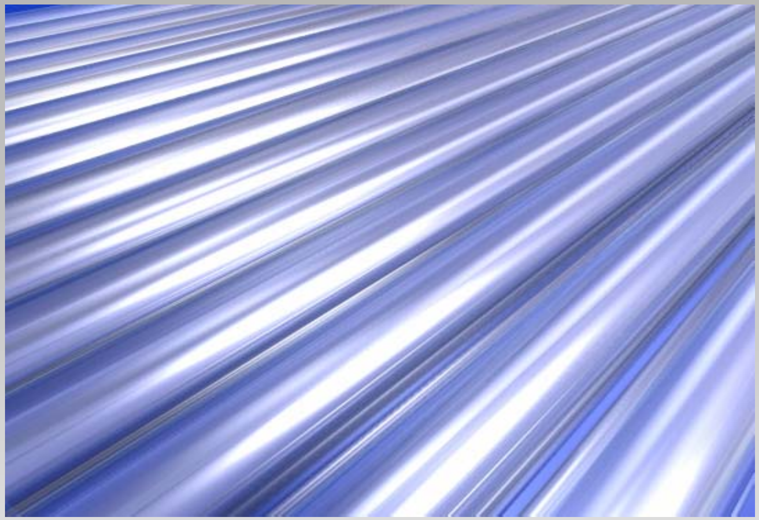


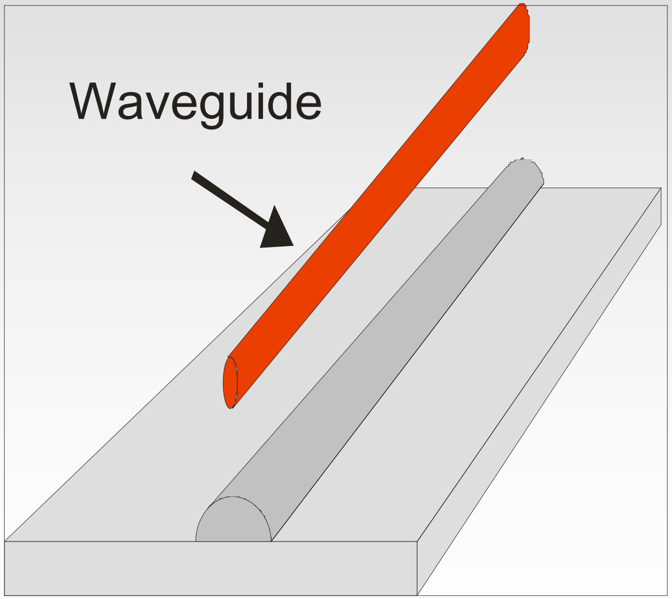


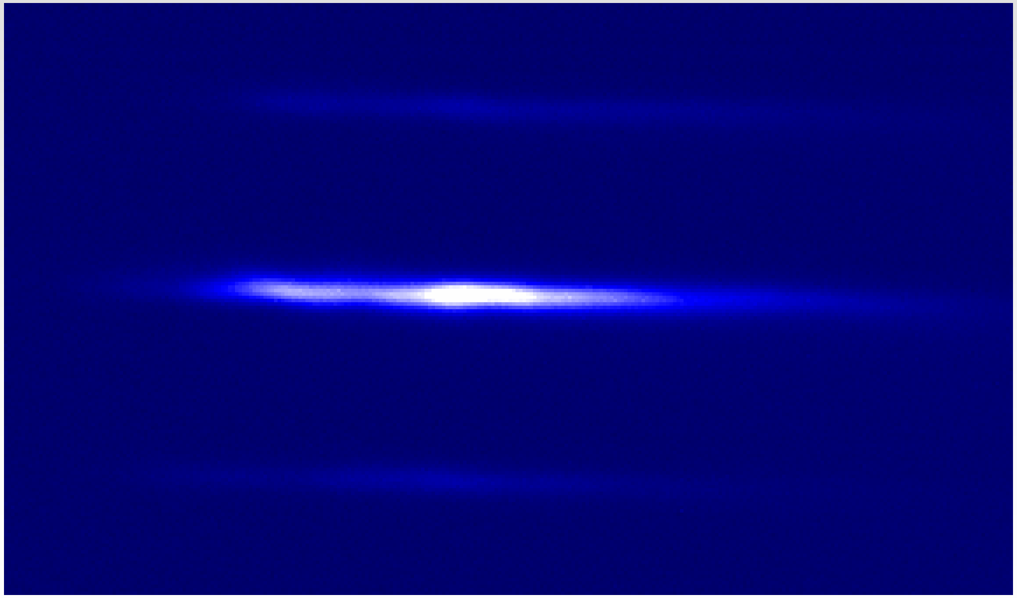
Micro-optical Lens Arrays:

Guiding of atoms along the linear potential minimum in the focus of a cylindrical lens

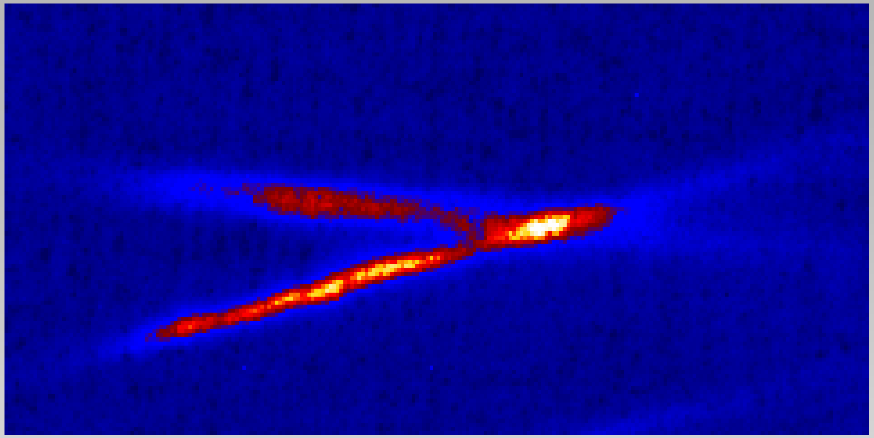
$\Rightarrow$ Waveguide for atoms similar to optical fibers

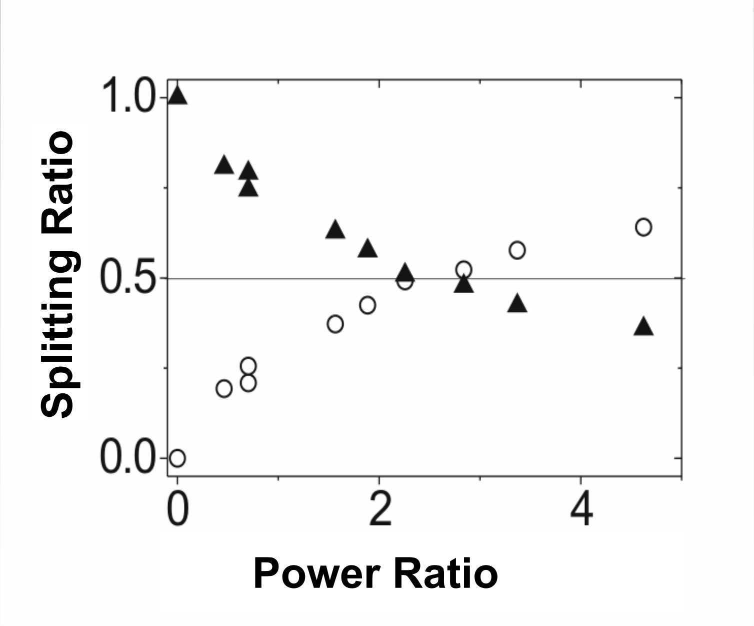


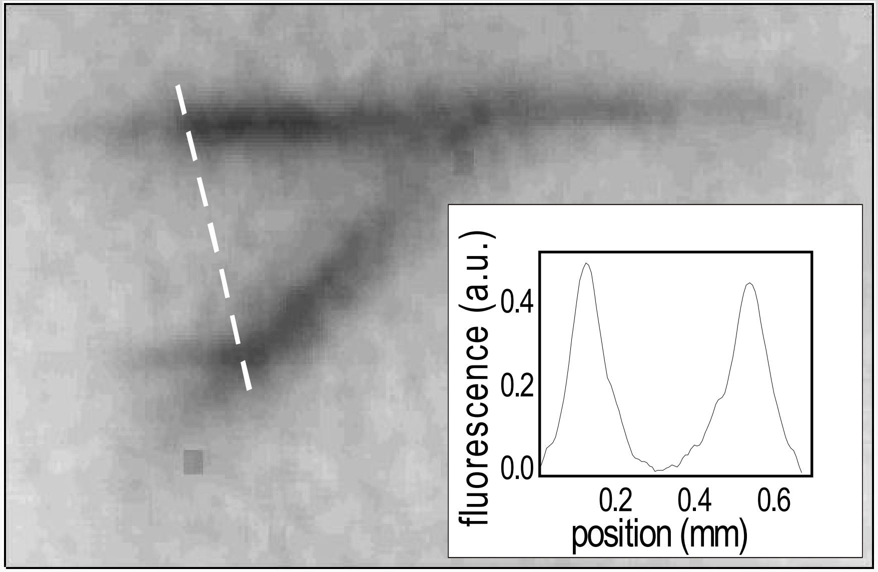




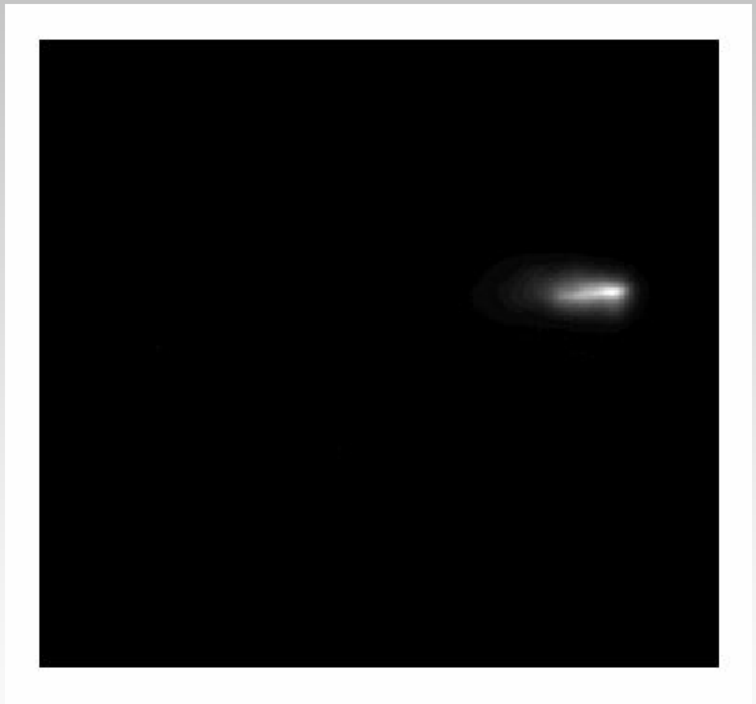
X-type beam splitter for atom samples based on the cylindrical micro-lenses

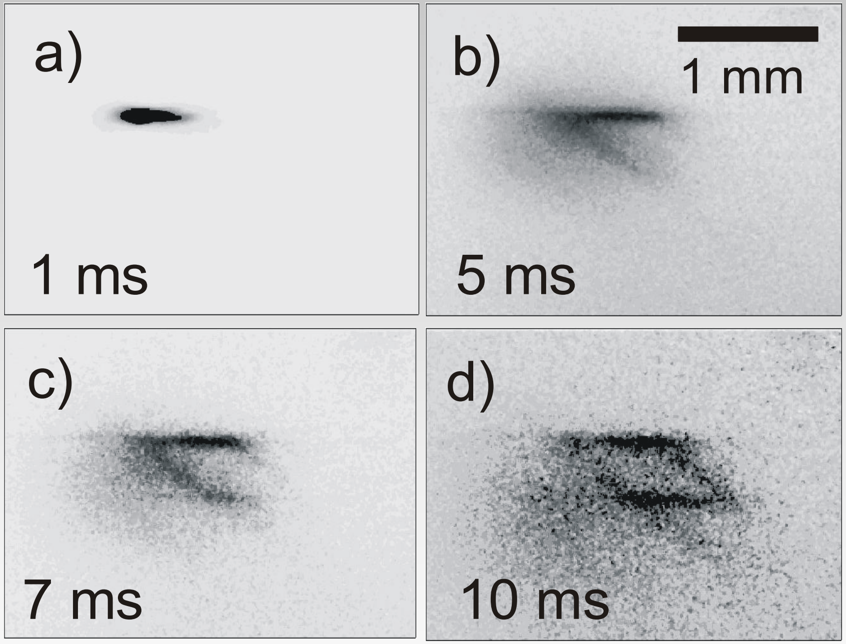






Experimental demonstration of structures for guided-atom interferometry based on optical micro-structures





R. Dumke, T. Müther, M. Volk, W. Ertmer und G. Birkl, PRL **89**, 220402 (2002)

Project Overview

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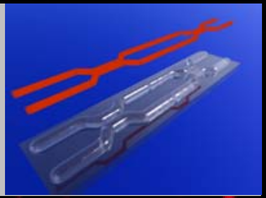
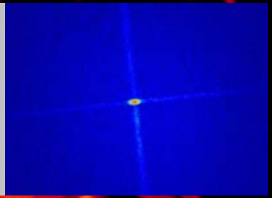
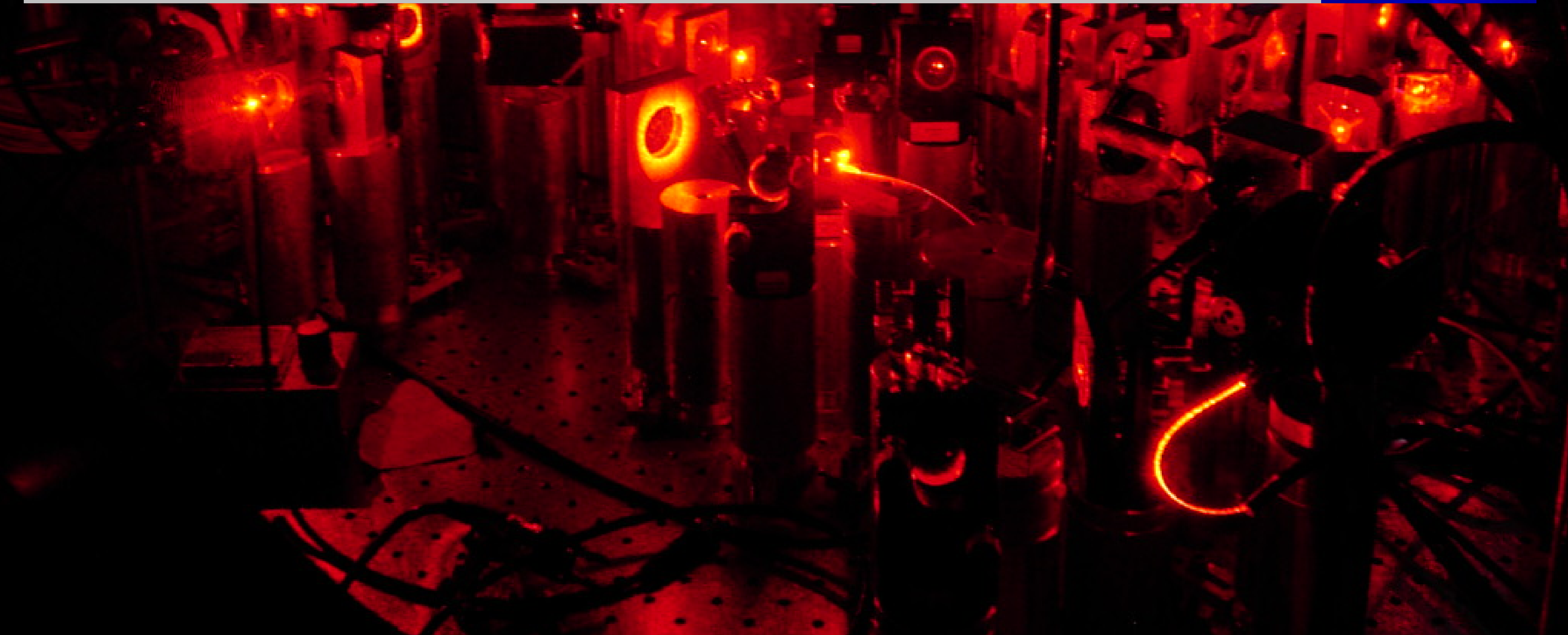
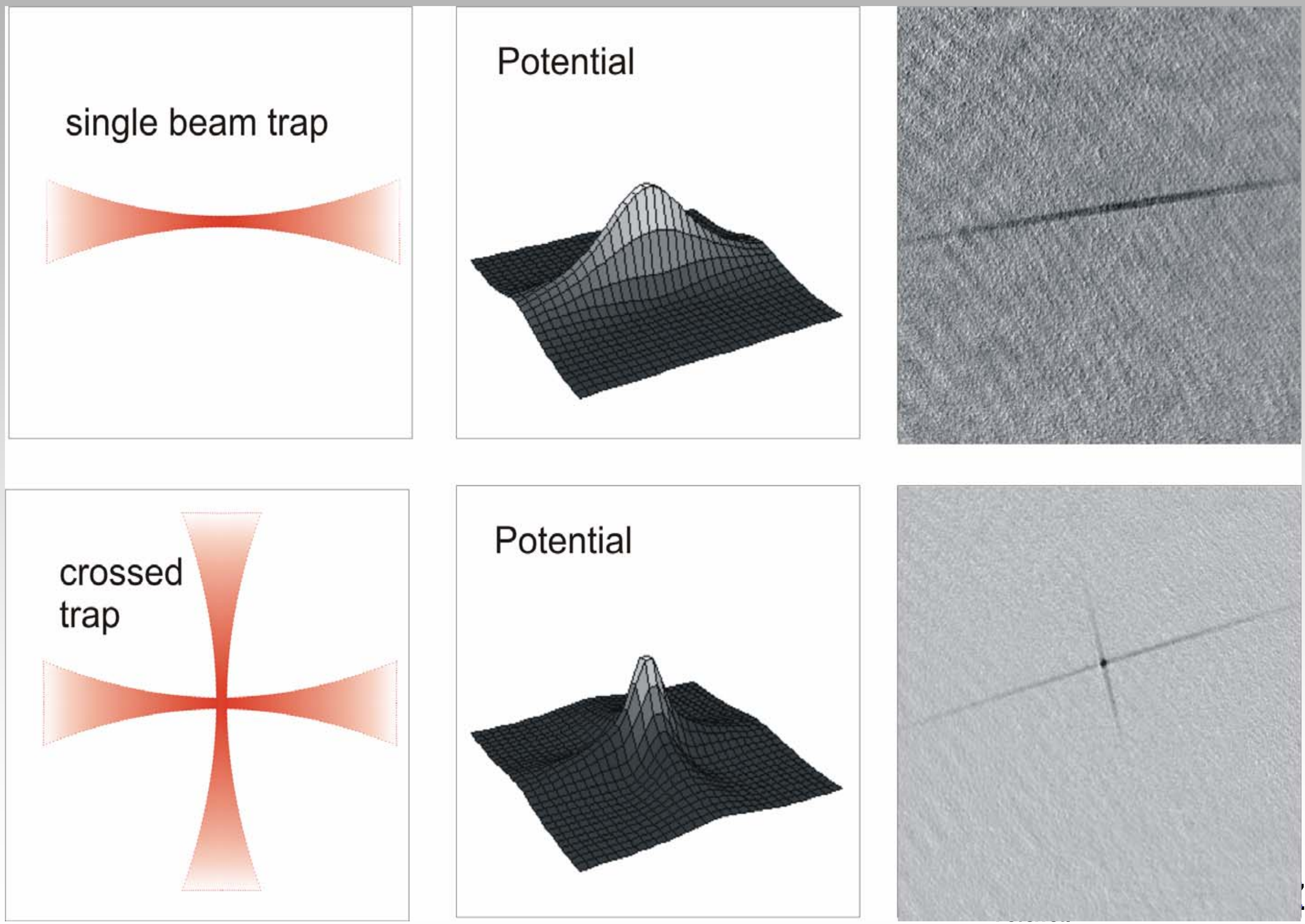


BEC in Optical Trapping Potentials

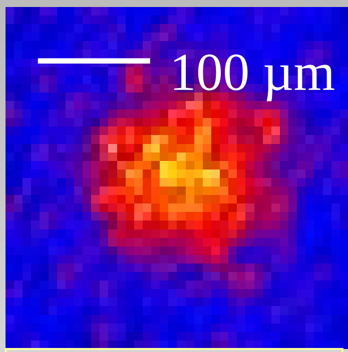




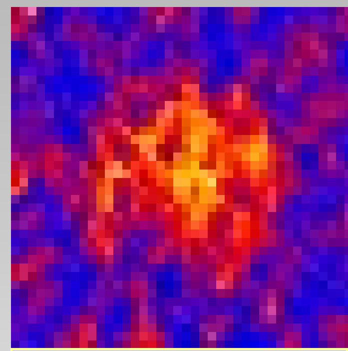
Trap Geometries



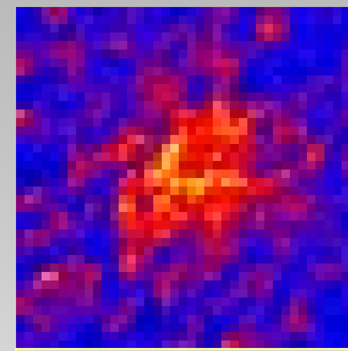
Measurement of density and temperature (TOF 10 ms)



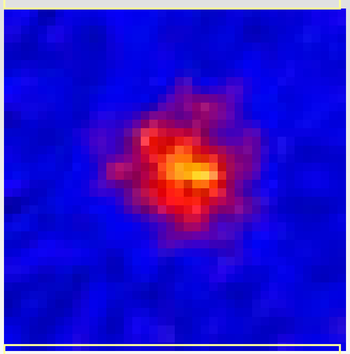
P = 210 mW
T < 400 nK



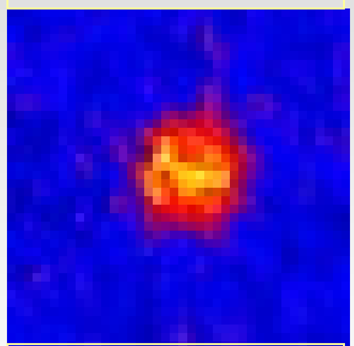
P = 185 mW
T ≤ 240 nK



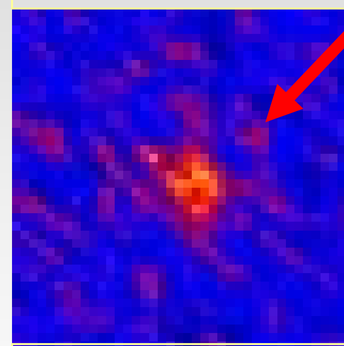
P = 170 mW
T ≤ 260 nK



P = 155 mW
T ≤ 140 nK



P = 140 mW
T ≤ 160 nK



P = 110 mW
T ≤ 100 nK

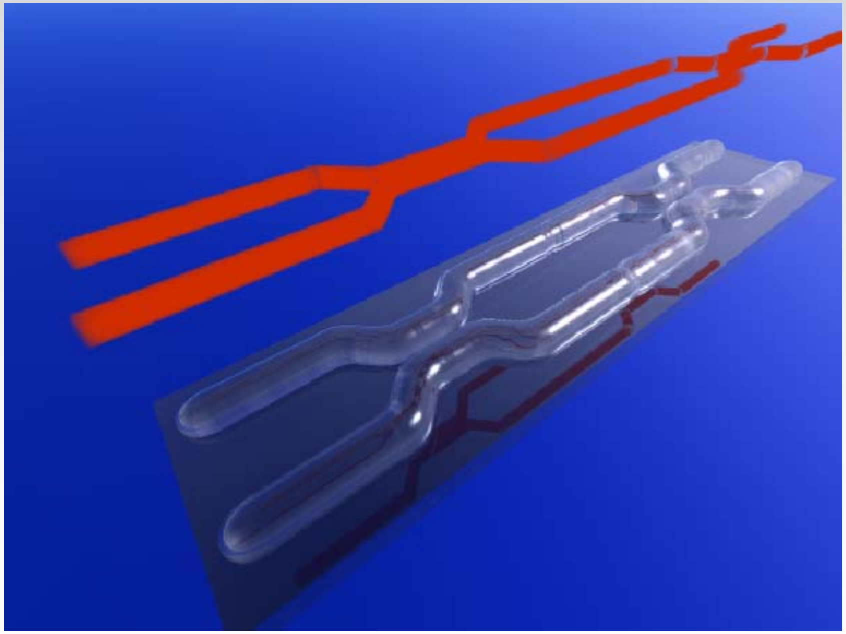
Uncertainty: T±30 nK

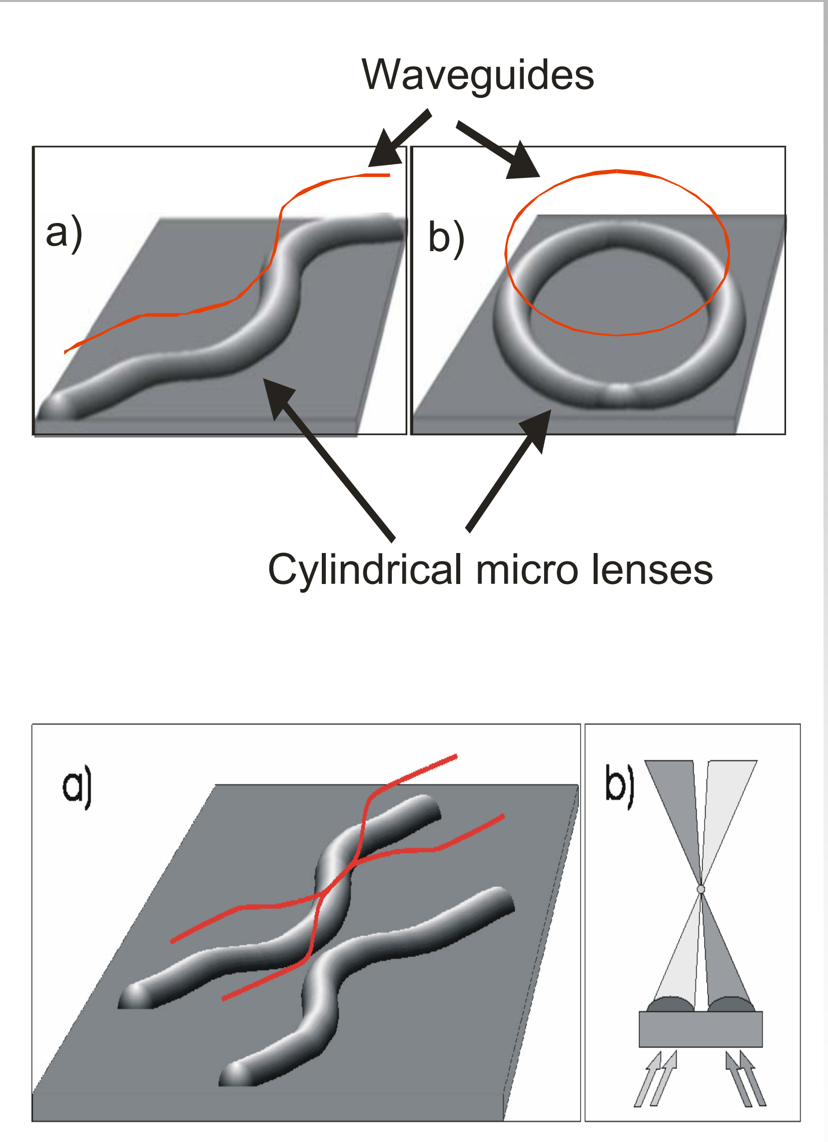
Phase-space density 0.1 - 1

(large uncertainties due to small structures at resolution limit)

Matter wave optics in optimized and complex micro- and nano-structures

- Compact atom interferometer geometries as quantum sensors
- Resonator for atomic matter waves





Project Overview

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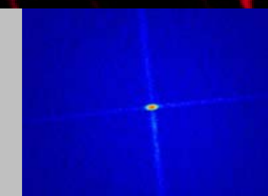
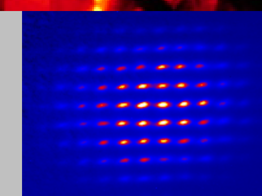
BEC in Optical Trapping Potentials



Quantum Information Processing with Atoms



- **Unit of Classical Information:**

‚Bit‘: ‚0‘ or ‚1‘, e.g. current state

- **Unit of Quantum Information:**

‚Qubit‘: $|0\rangle$ and/or $|1\rangle$, e.g internal states of atoms

$$|\boldsymbol{qubit}\rangle = \alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$$

- **Deutsch, Shor, Grover et. al.:** Quantum algorithms can perform specific tasks (significantly) faster than classical algorithms
  Example: Shor algorithsm for factoring large numbers.

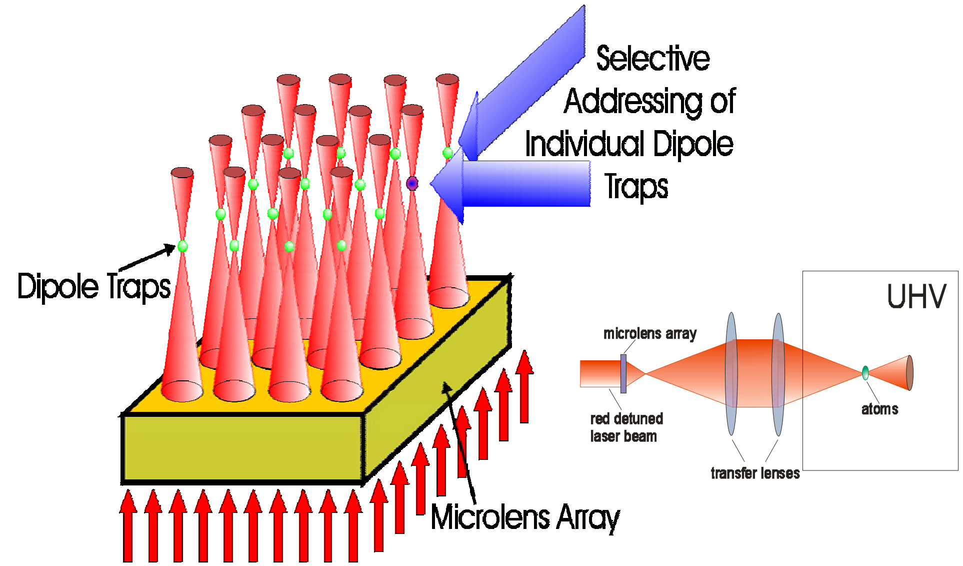
- **Investigation of Fundamental Aspects of Quantum Physics**

Multiple realization of dipole traps by focusing a (far) red-detuned laser beam with a microlens array

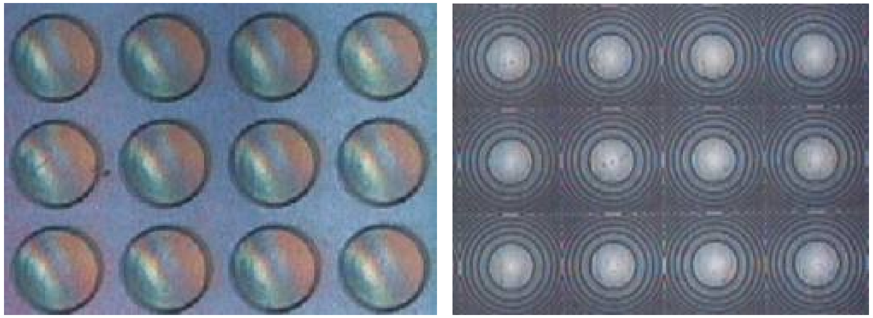
Very tight foci due to high numerical aperture possible

Sufficiently low rate of sponta-neous emission

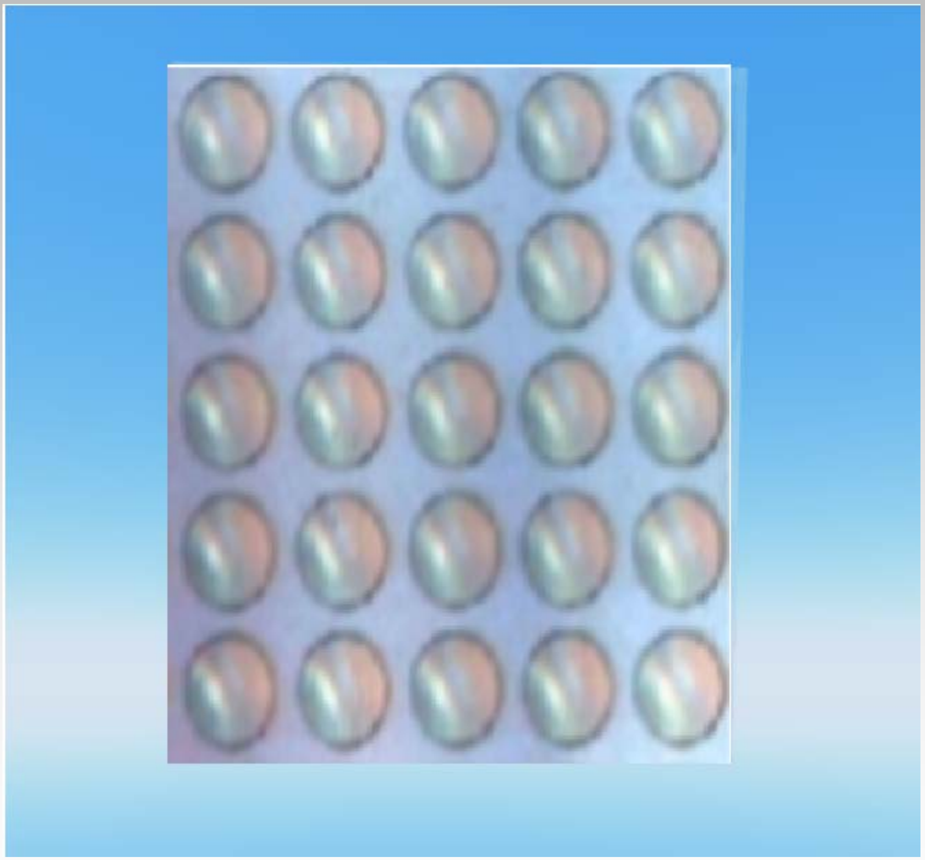
Individual dipole traps can be selectively addressed due to large separation of the microlenses (typically 125 µm)



Refraktive und diffraktive Mikrolinsen



Atoms in far detuned dipole trap arrays can serve as a two-dimensional register for qubits:



R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, G. Birkl, and W. Ertmer, Phys. Rev. Lett. **89**, 097903 (2002).

Atoms in far detuned dipole trap arrays can serve as a two-dimensional register for qubits:

Number of traps > 80

Parameter for dipole trap array:

P = 1 mW per Trap

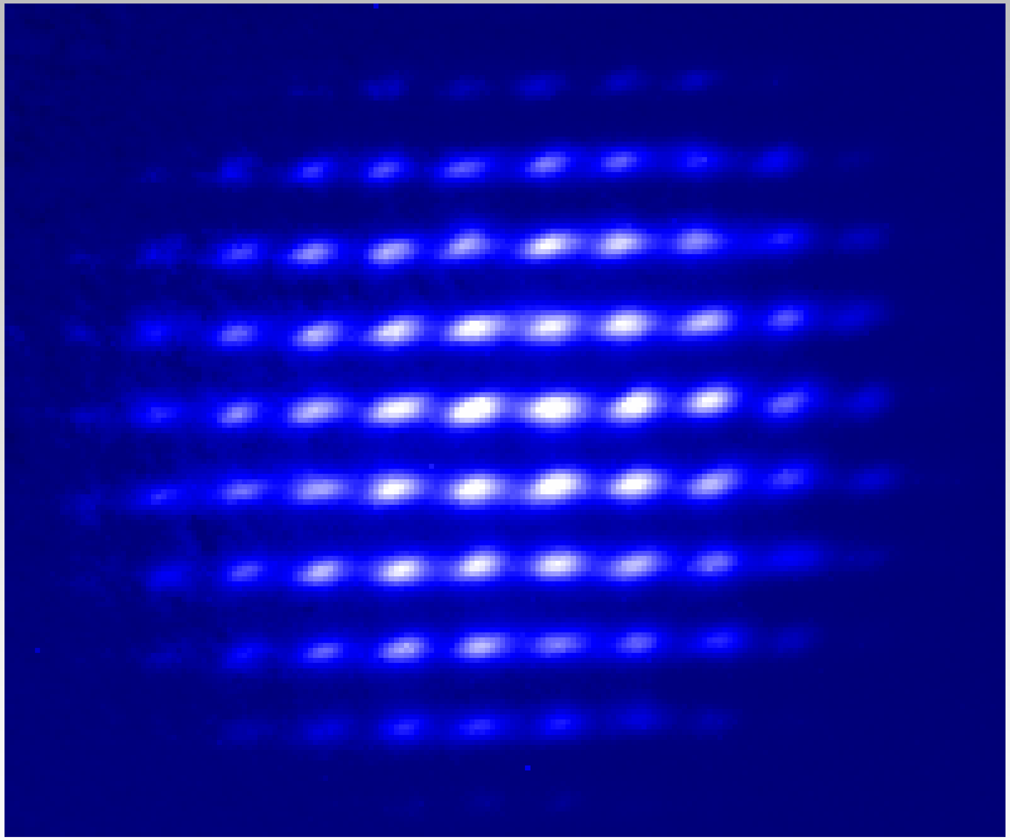
Trap size w_0=7µm

Trap depth 1 mK

Temperature 20 µK

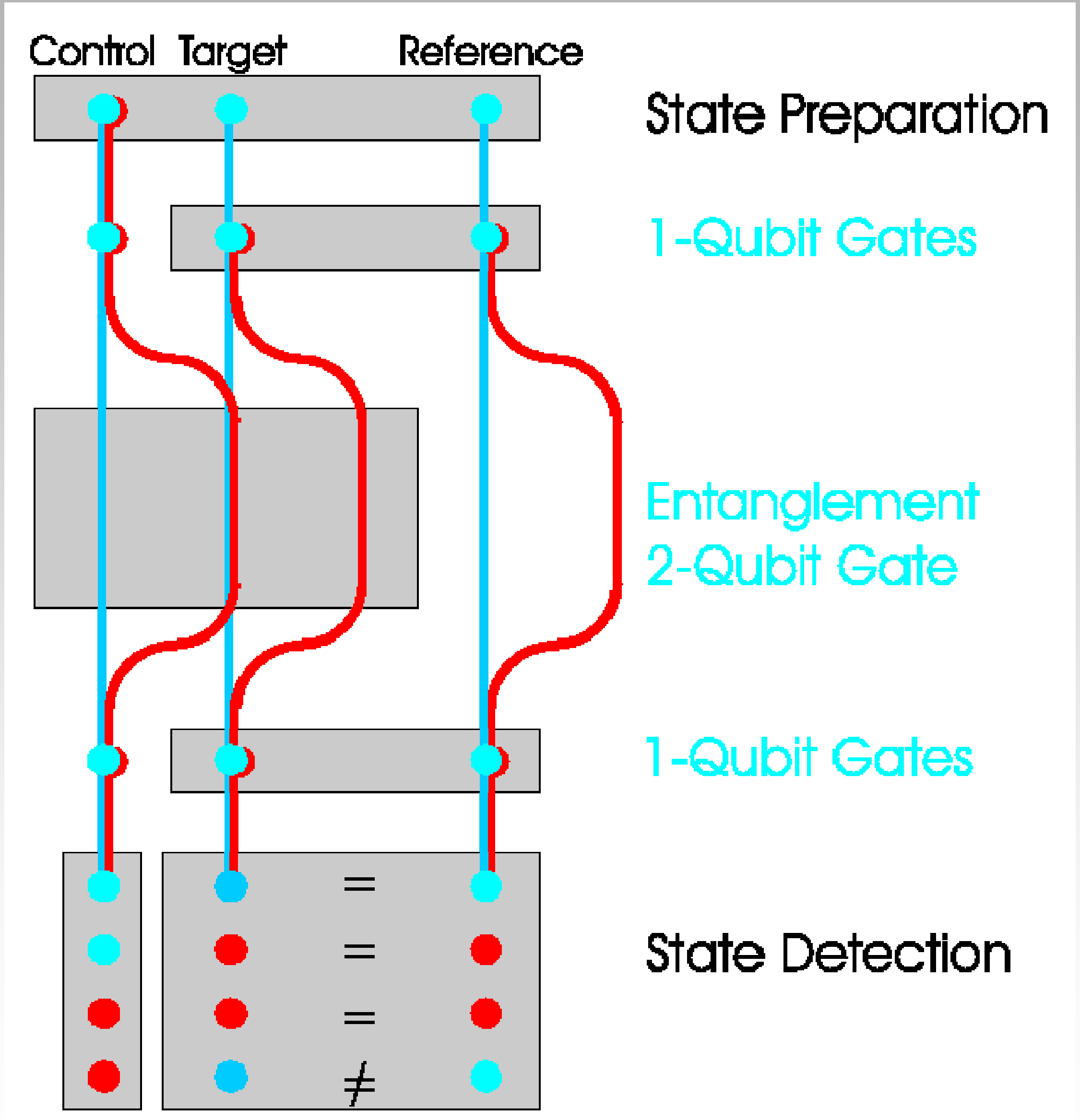
Atoms per trap 100-1000

Lifetime up to 2 s
(depending on detuning)

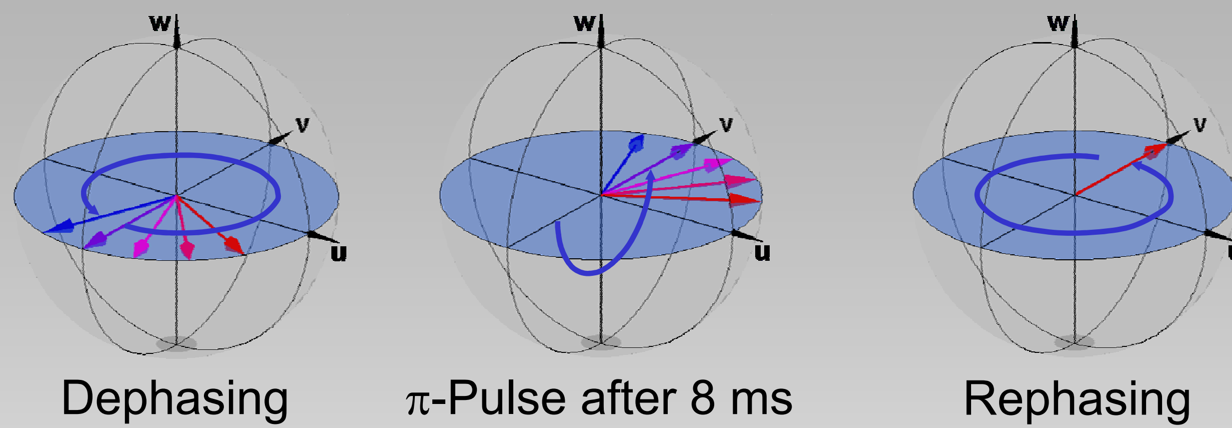


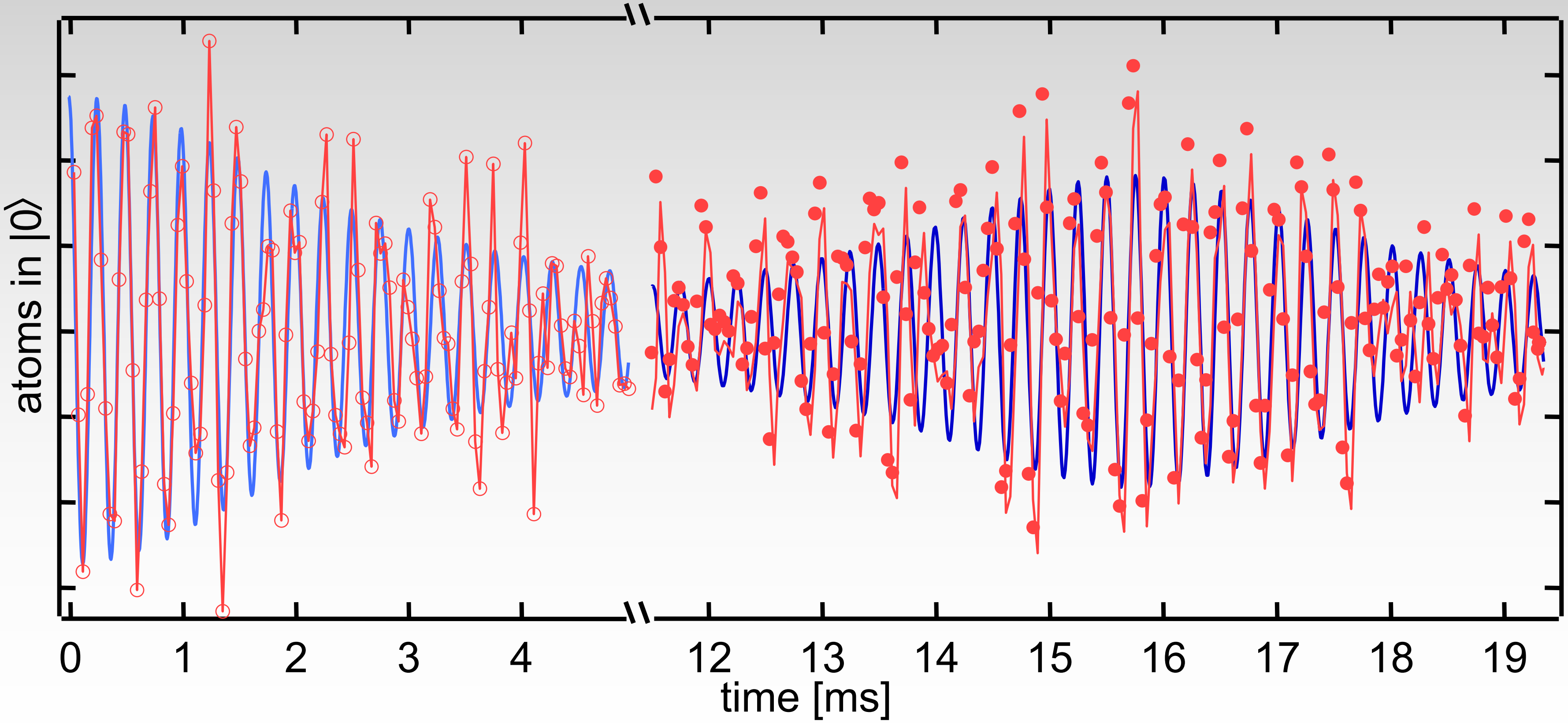
R. Dumke, M. Volk, T. Müther, F.B.J. Buchkremer, G. Birkl, and W. Ertmer, Phys. Rev. Lett. **89**, 097903 (2002).

- State preparation and detection of single atoms
- 1-qubit gates based on coherent Raman transitions
- 2-qubit gates based on collisional phase shift (and others)
- Interferometric test of entanglement and qubit interaction

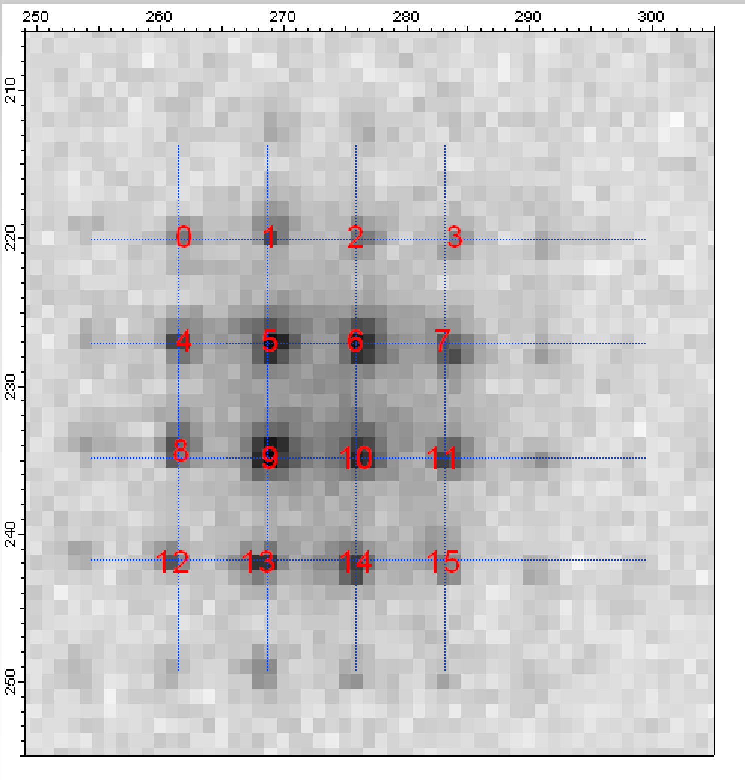


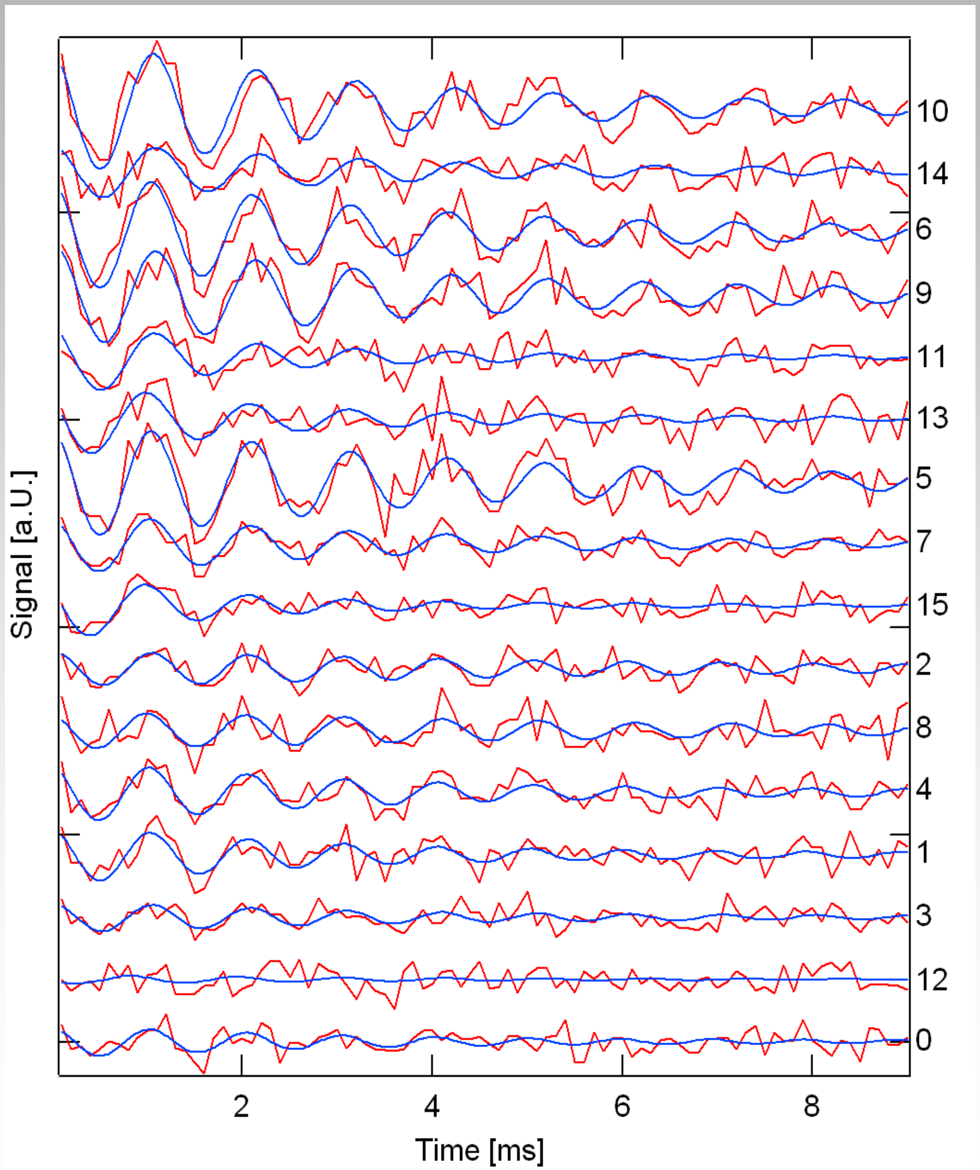
Coherent Qubit Rotation (Ramsey- and Spin-Echo)



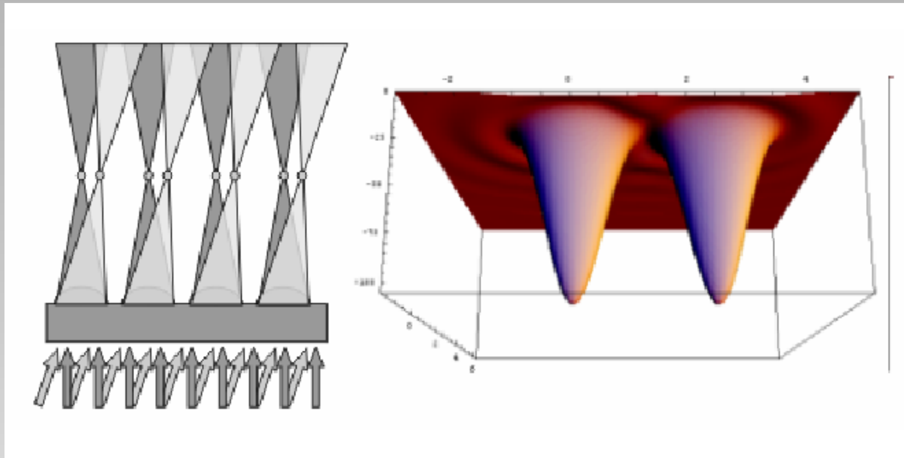


Simultaneous Ramsey Measurements in 16 different dipole traps



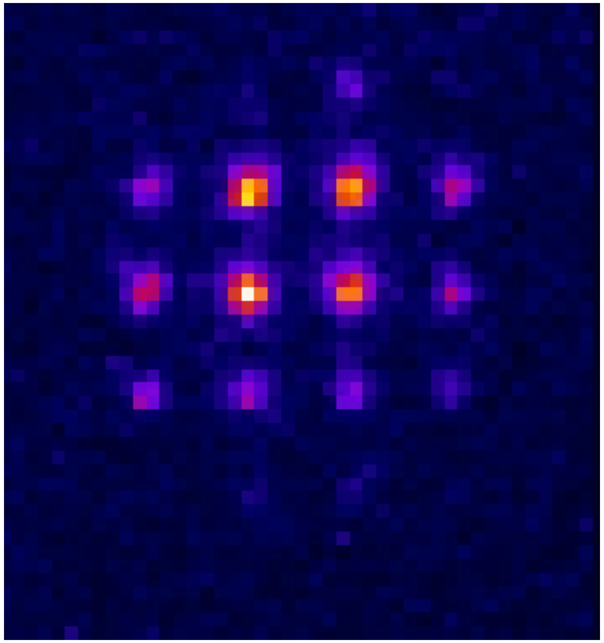


Efficient operation of quantum gates requires strong (state selective) interaction of qubits



Control of trap separation:

- Use of two independant microlens arrays
- Irradiation of one microlens array by two laser beams with variable angle
- Minimum distances are 0 or range down to about 2µm for sep. traps.
- State-selective transport of qubits



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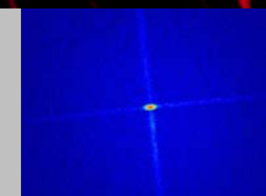

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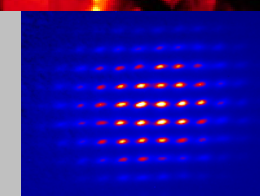
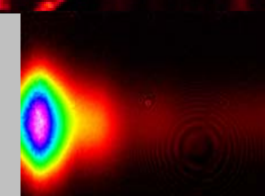


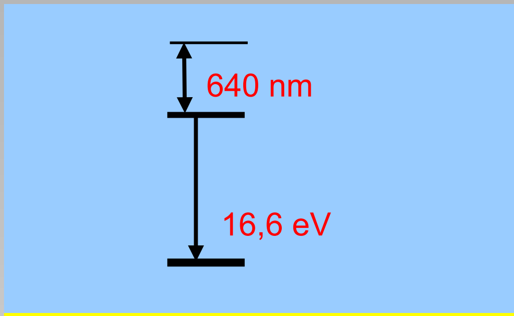
Ultracold Collisions of Metastable Neon



Metastable Neon: from Atomic Physics to BEC

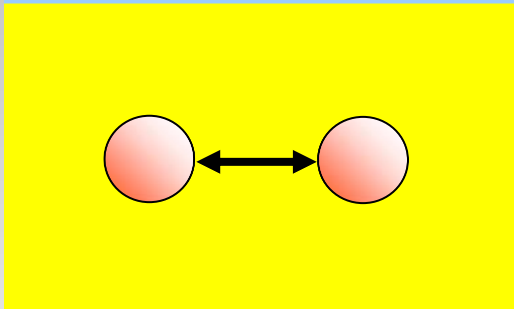
Atomic physics

- Lifetime of the metastable state ?
  Previous measurement: 22s



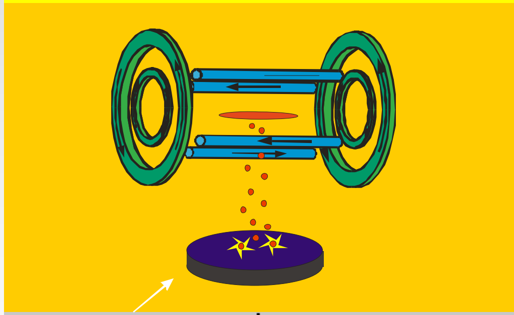
Collision physics

- Rates of elastic and inelastic collisions
- Suppression of Penning-Ionization by spin-polarization: 10^4 ?



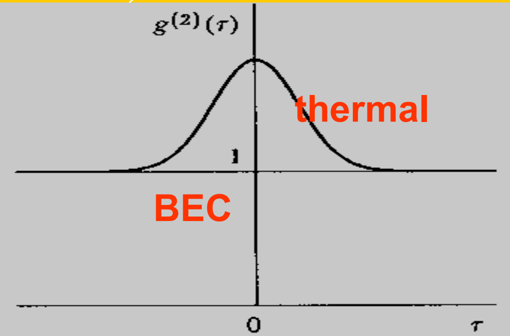
Electronic Detection

- Direct, highly efficient detection of Ne* and Ne^+
- Real-time detection of ions
- Spatially resolved detection of atoms



Bose-Einstein-Condensation

- Investigation of collective excitations
- Measurement of higher order correlation functions



Lifetime of the $^3P_2$ ($3s[3/2]_2$) state

One-body decay in the MOT due to:

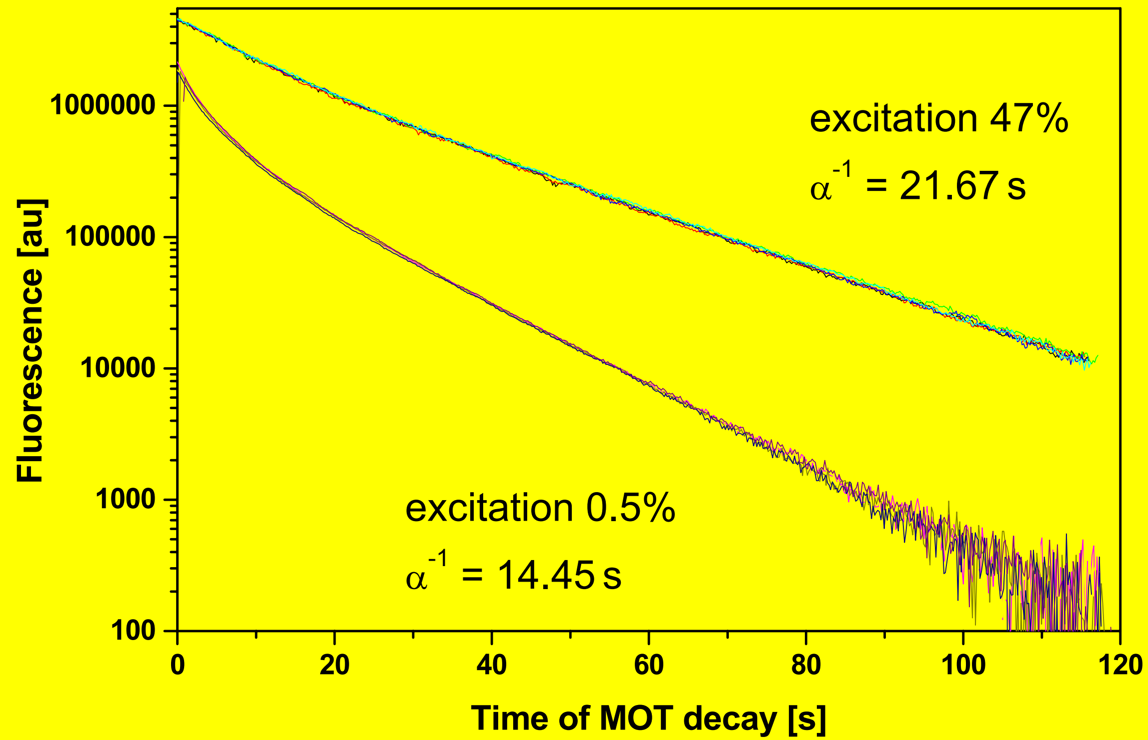
- Finite lifetime of $^3P_2$-state
- Background gas collisions
- Residual loss processes

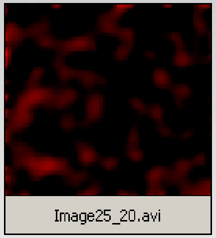
Exponential decay (p=0): $\dot{N} = -\tau_2^{-1}(1-\pi)N$

Limits:

$\pi \approx 0$: $\frac{\dot{N}}{N} = \tau_2^{-1}$

$\pi \approx 0.5$: $\frac{\dot{N}}{N} = (2\tau_2)^{-1}$





Final Value:

τ_2 **= 14.73(14) s**

M. Zinner, P. Spoden, T. Kraemer, G. Birkl, and W. Ertmer, Phys. Rev. A 67, 010501R (2003)

Determination of Scattering Length

- Compare theory curves of $\sigma_{rel}(a,T)$ for different values of a with experimental data

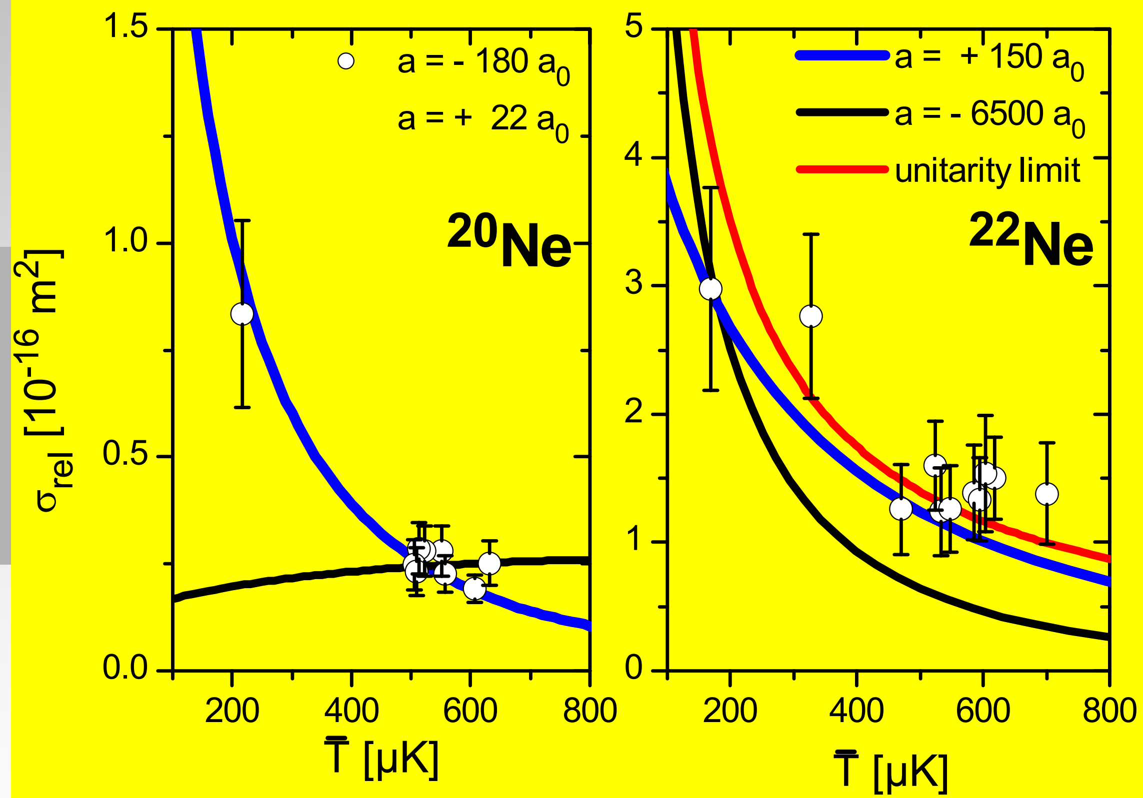
- Scattering length:

$$^{20}\mathrm{Ne}: a = -180^{+40}_{-40} a_0$$

$$^{22}\mathrm{Ne}: a = +150^{+80}_{-50} a_0$$

P. Spoden et al.,

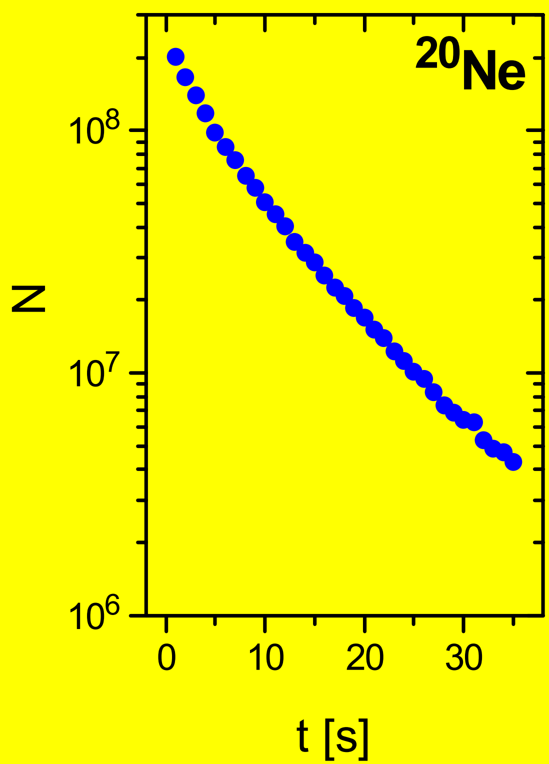
PRL 94, 223201 (2005)

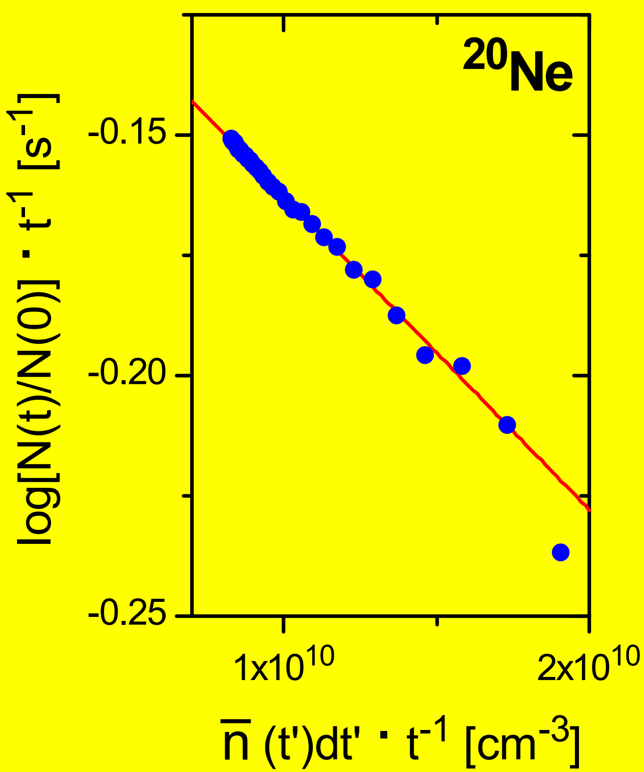


Analysis:

$$\dot{N} = -\alpha N - \beta \frac{N^2}{V_{eff}} \quad \rightarrow \quad \frac{1}{t}\log\frac{N(t)}{N(0)} = -\alpha - \beta\left(\frac{1}{t}\int_o^t dt'\,\overline{n}(t')\right)$$

heating !





P. Spoden et al., PRL 94, 223201 (2005)

^{20}Ne

β_{pol} = 6.5(18) 10^{-12} cm^3 s^{-1}

Suppression: 38(16)

^{22}Ne

β_{pol} = 12(3) 10^{-12} cm^3 s^{-1}

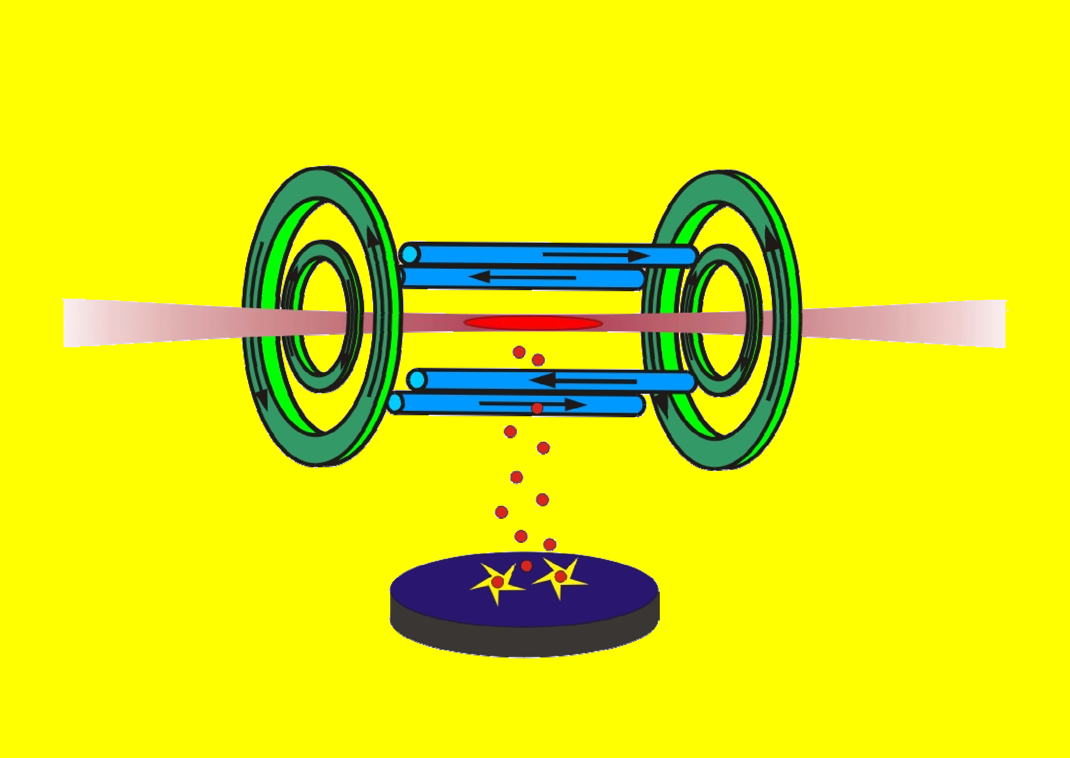
Suppression: 7(5)

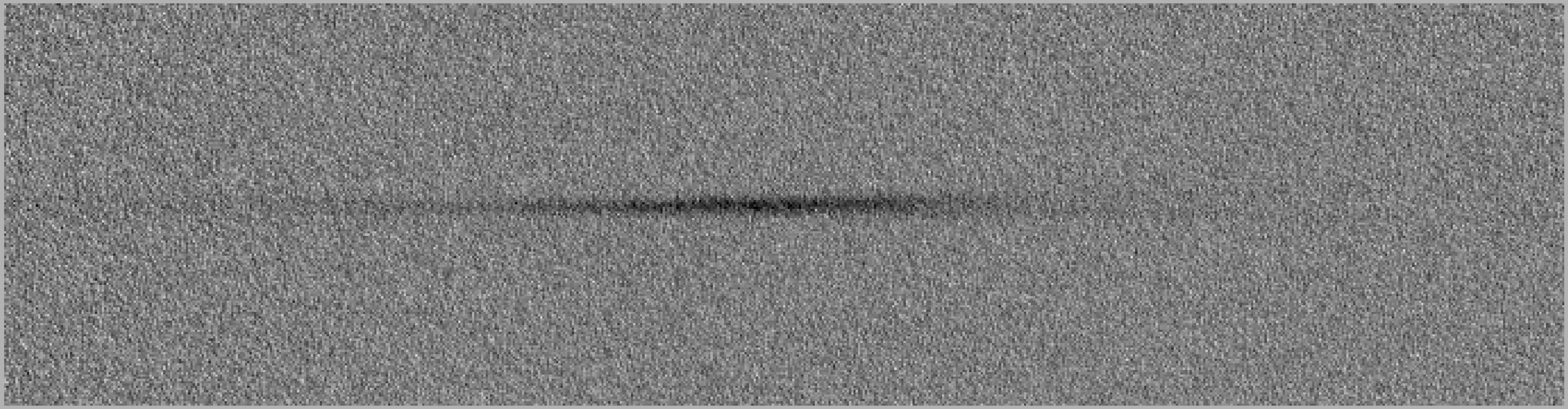
Trap parameters:

- Fiber laser: λ = 1065nm, P=40 W
- Waist of ~50 μm
- Beams cross at an angle of 3°
- Loading from magnetic trap or MOT

Detection:

- Absorption imaging, MCP

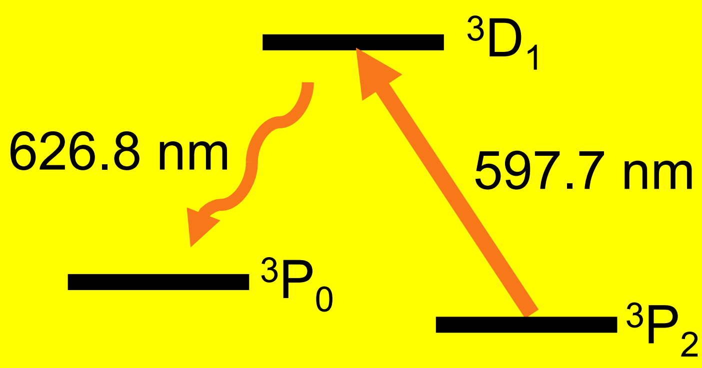


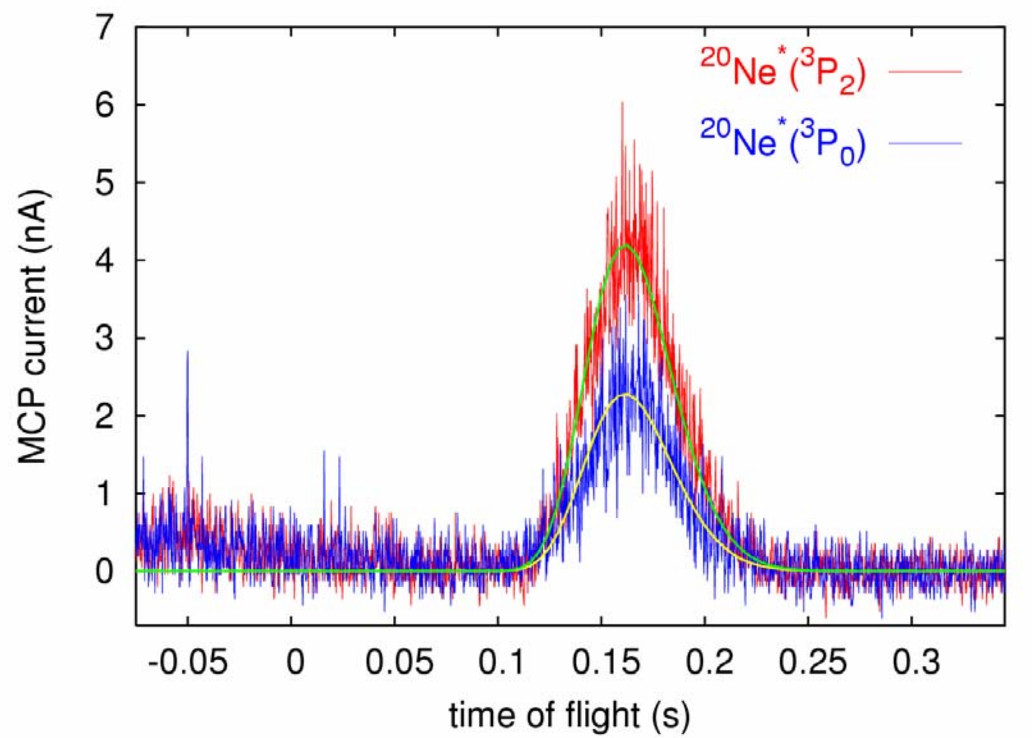


Loading of $^3P_0$ metastable neon

Method:

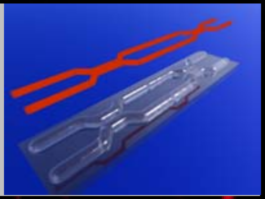
- Load $^3P_2$ atoms from MOT
- Apply laser pulse resonant with the $^3P_2 \rightarrow {}^3D_1$ transition at 598 nm while the trap laser is shortly switched off
- Half of the atoms are transferred to the $^3P_0$ metastable state, the other half decays to the ground state via $^1P_1$ emitting easily detectable UV-photons
- Atoms in the $^3P_0$ metastable state are detected as time-of-flight signal on a MCP after turning off the dipole trap
- Using absorption imaging we can confirm that no atoms remain in the $^3P_2$ state



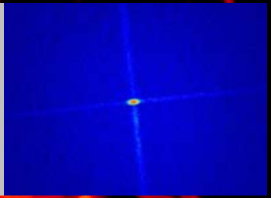


Project Overview

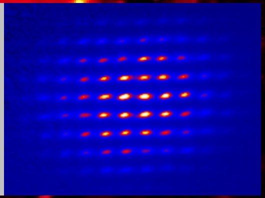
Integrated Atom Optics (ATOMICS)



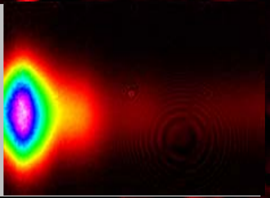
BEC in Optical Trapping Potentials



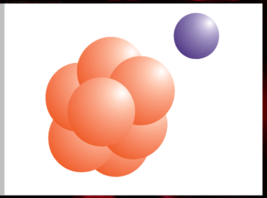
Quantum Information Processing with Atoms



Ultracold Collisions of Metastable Neon



Laser Spectroscopy on Trapped Highly Charged Ions



Laser Spectroscopy at RETRAP and HITRAP

Fine Structure Measurements

- Ca^{15+} λ=250nm
- As^{19+} λ=244nm

Hyperfine Structure Measurements

- $^{207}Pb^{+}$ λ=710nm

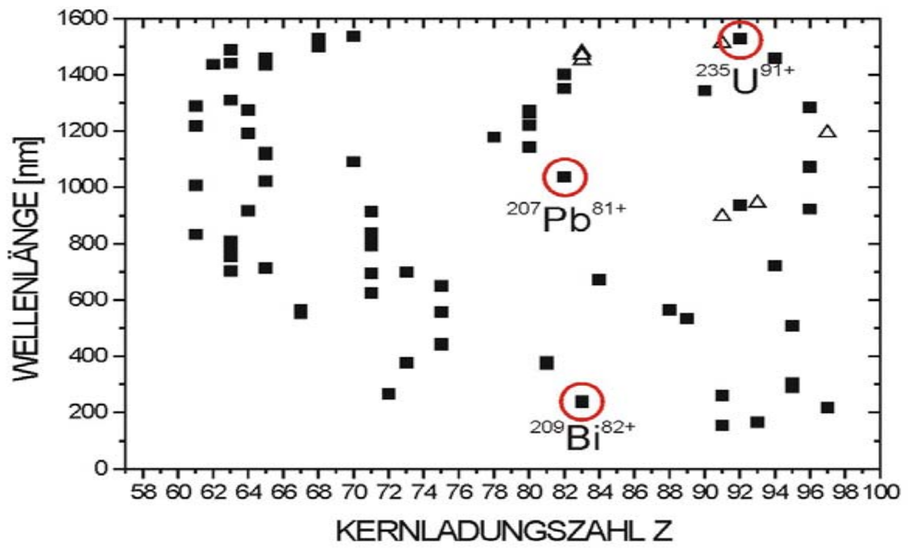
H-like Ions

- $^{209}Bi^{82+}$ λ= 239nm
- $^{207}Pb^{81+}$ λ=973nm
- $^{235}U^{91+}$ λ=1528nm

➔ **Highly Flexible Laser System needed !**

element	ion	type	λ (nm)	t (ms)	I	μ (μ_N)
lead	$^{207}Pb^{81+}$	H-like	973	45	1/2	0.59
bismuth	$^{209}Bi^{82+}$	H-like	239	0.38	9/2	4.11
	$^{209}Bi^{80+}$	Li-like	1469	87		
protactinium	$^{231}Pa^{90+}$	H-like	262	0.64	3/2	2.01
	$^{231}Pa^{88+}$	Li-like	1511	123		
lead [12]	$^{207}Pb^{+}$	$P_{3/2}$ - $P_{1/2}$	710	41	1/2	0.59
chlorine [13]	$^{35}Cl^{+}$	$^3P_2$ - $^1D_2$	858	n.n.	3/2	0.82
		$^3P_1$ - $^1D_2$	913	n.n.		
argon [14]	$^{37}Ar^{2+}$	$^3P_2$ - $^1D_2$	714	n.n.	7/2	1.3
		$^3P_1$ - $^1D_2$	775	n.n.		

D.F.A. Winters et al., Can. J. Phys.



Laser System for 1,5 micron range

Commercial Laser System available (NEW FOCUS)

TLB-6300 Tunable Lasers

- *New wavelength ranges from 630 to 2 µm*
- *Cavity design eliminates mode-hops*
- *Smooth, linear, mode-hop-free tuning*

1470–1545 nm	1415–1480 nm	1520–1570 nm
4 mW	3 mW	20 mW
10 mW	8 mW	20 mW
20 nm/s	20 nm/s	20 nm/s
0.02 nm	0.02 nm	0.02 nm
0.1 nm	0.1 nm	0.1 nm
30 GHz (0.23 nm)	30 GHz (0.24 nm)	30 GHz (0.24 nm)
2 kHz	2 kHz	2 kHz
100 MHz	100 MHz	100 MHz
<300 kHz	<300 kHz	<300 kHz
TLB-6326	TLB-6327	TLB-6328

Laser System for UV and 1000 nm range

Tuning Range of Titanium:Sapphire System:

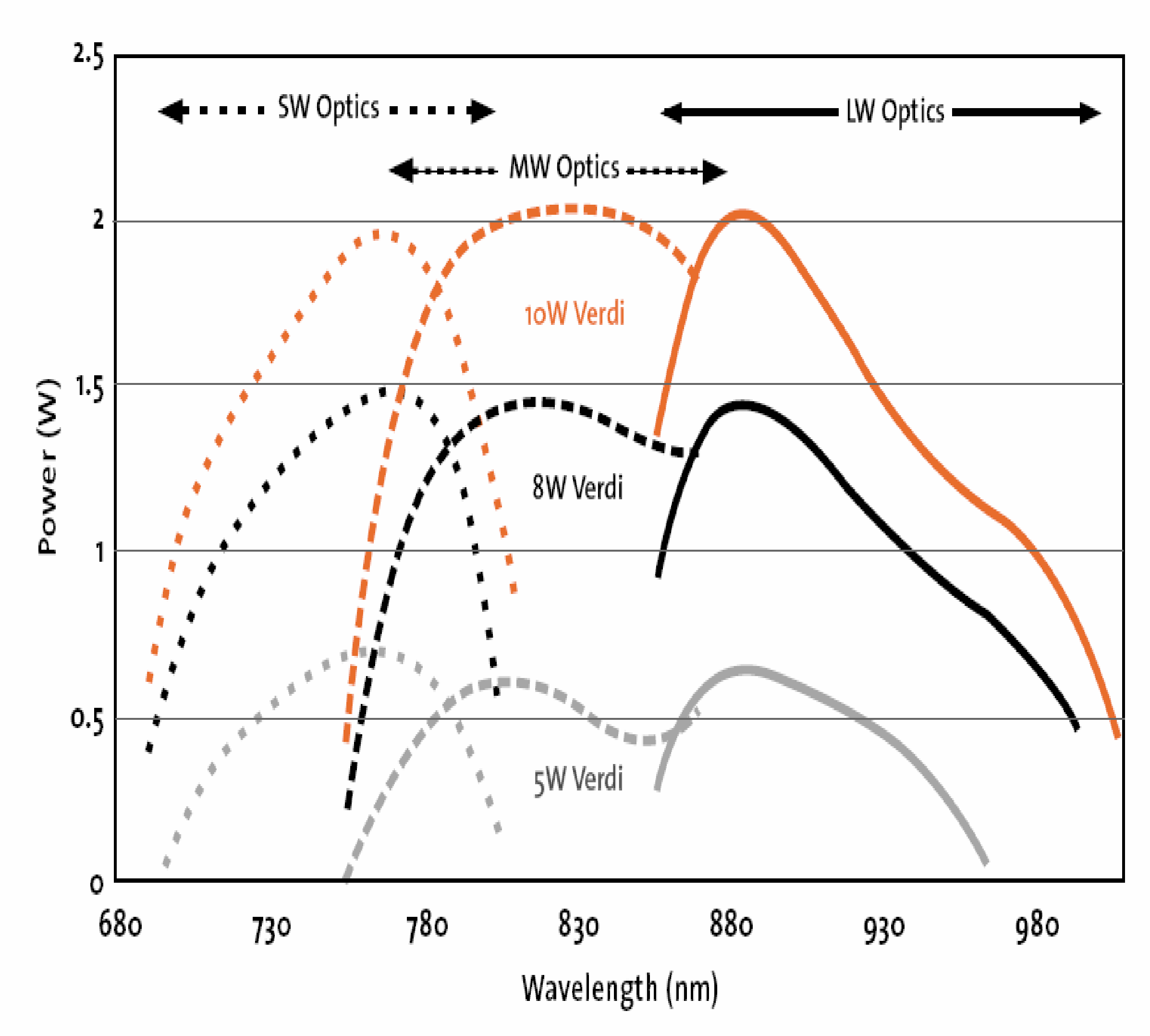
λ = 700nm to 1000nm

Standard Approach for Creation of UV-Radiation:

- Fourth Harmonic Generation in two successive frequency doubling cavities

- Fundamental:
  λ = 956 to λ = 1000 nm

- Expected Power:
  1mW to 5 mW



Alternative Approach for Creation of UV-Radiation:

- Third Harmonic Generation in two successive enhance-ment cavities

- Fundamental: λ = 717 to λ = 750 nm

- Advantage: Operation of Ti:Sa close to maximum of output power

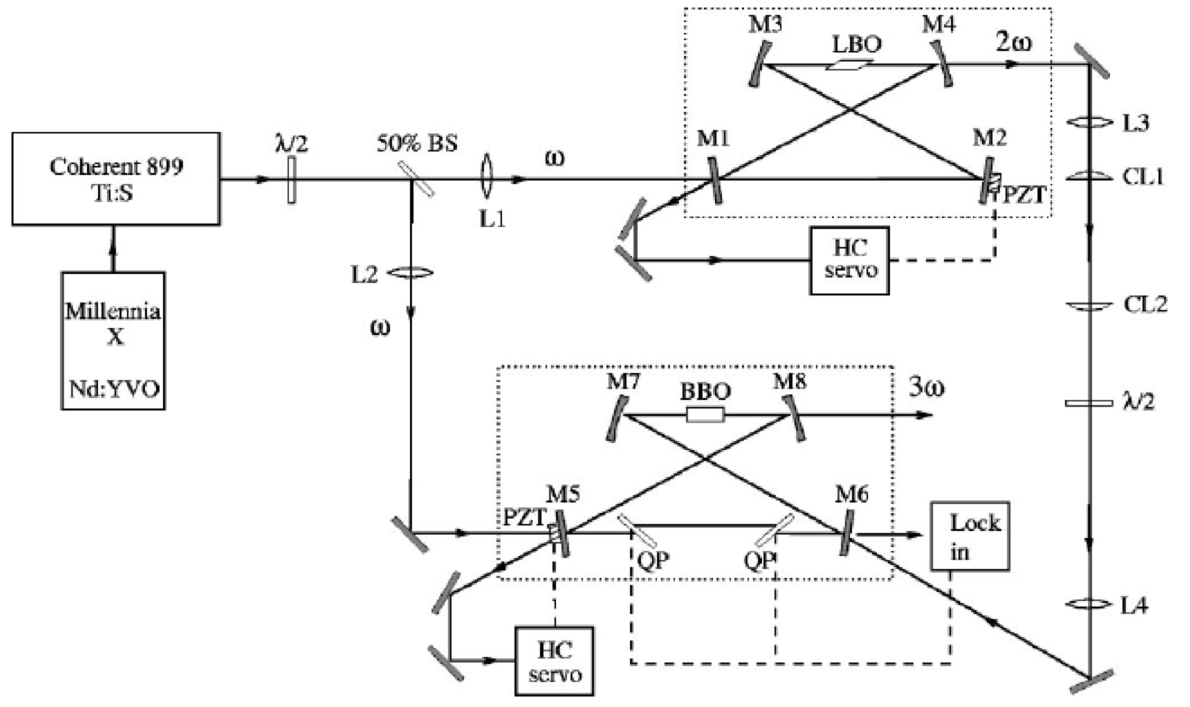


FIG. 1. Schematic of the setup for generation of the third harmonic of a Ti:S laser. BS: beamsplitter, QP: quartz plate, PZT: piezo, L: mode-matching lens, CL: cylindrical lens, M: mirror, and HC: Hänsch–Couillaud locking setup.

Reference: J. Mes, E.J. van Duijn, R. Zinkstok, S. Witte, W. Hogervorst, 'Third harmonic generation of a contineous-wave Ti:Sapphire laser in external resonant cavities', Appl. Phys. Lett. **82**, 4423 (2003)

Laser System for UV range

Results at Amsterdam:

- Wavelength:
  λ = 272 (λ = 817 nm/3)

- Pump Power: 10 W

- Output Power:
  - up to 175 mW achieved
  - at 900 mW Ti:Sa Power:
    50 mW at 272nm

- Extension to 240 nm expected

- Quality and optical properties (absorption of UV) might reduce conversion efficiency.

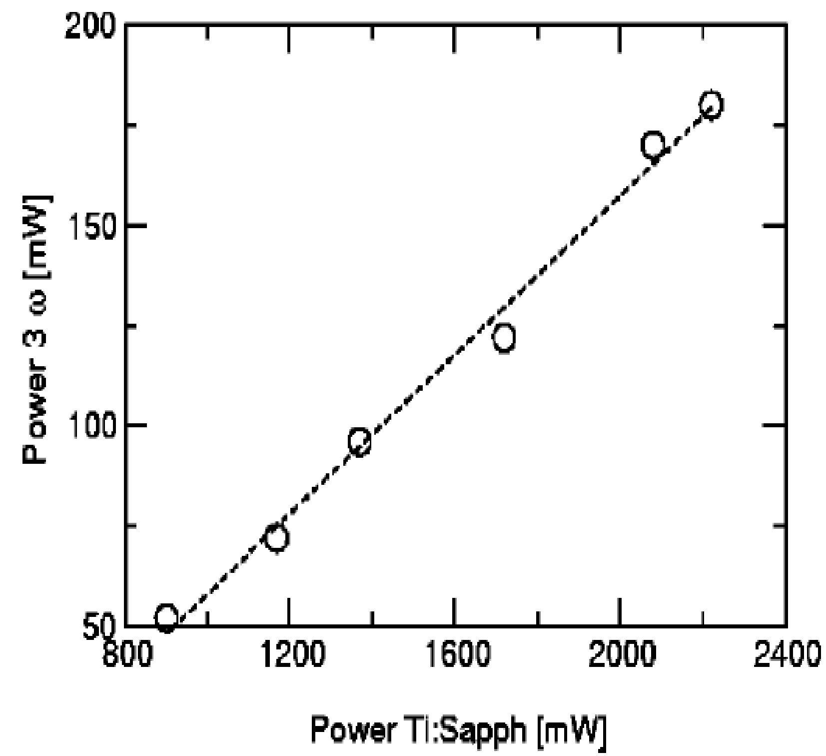


FIG. 3. Output power of the third harmonic as function of Ti:S power.

Reference: J. Mes, E.J. van Duijn, R. Zinkstok, S. Witte, W. Hogervorst, 'Third harmonic generation of a contineous-wave Ti:Sapphire laser in external resonant cavities', Appl. Phys. Lett. **82**, 4423 (2003)

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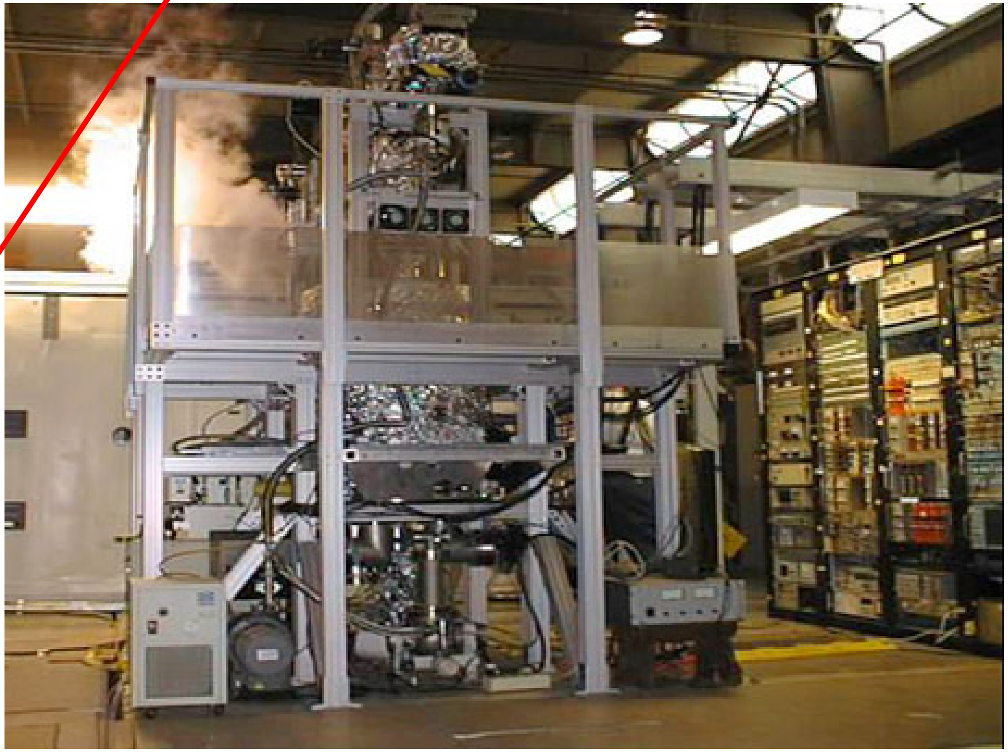
WE WILL FIND OUT !!



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Summary

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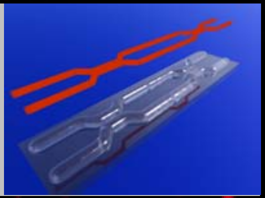

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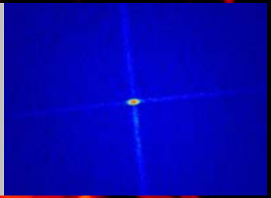

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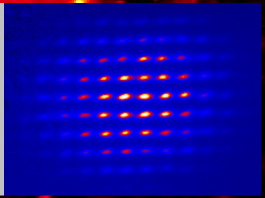

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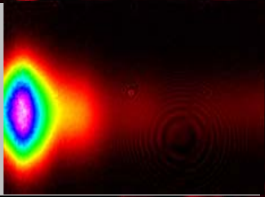

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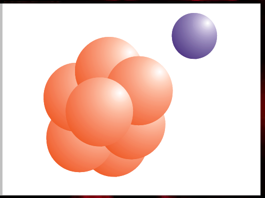

For more information: www.iap.physik.tu-darmstadt.de/apq