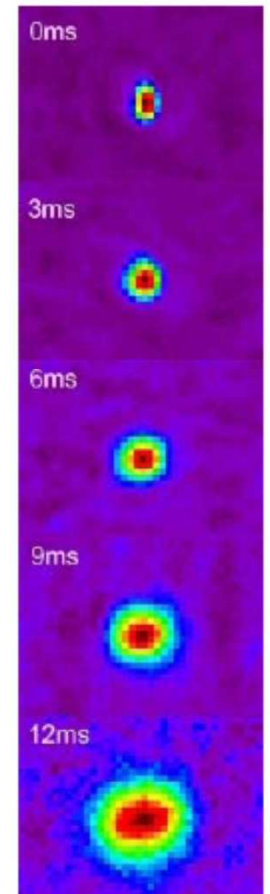
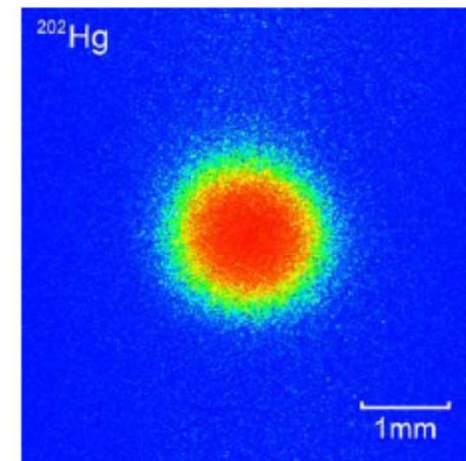
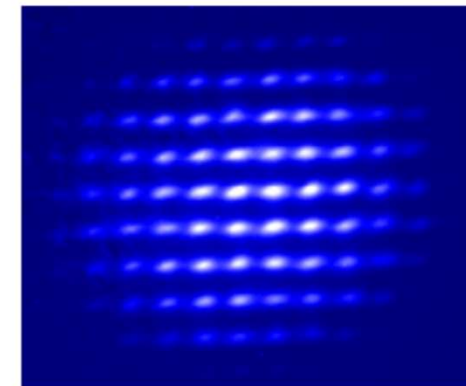
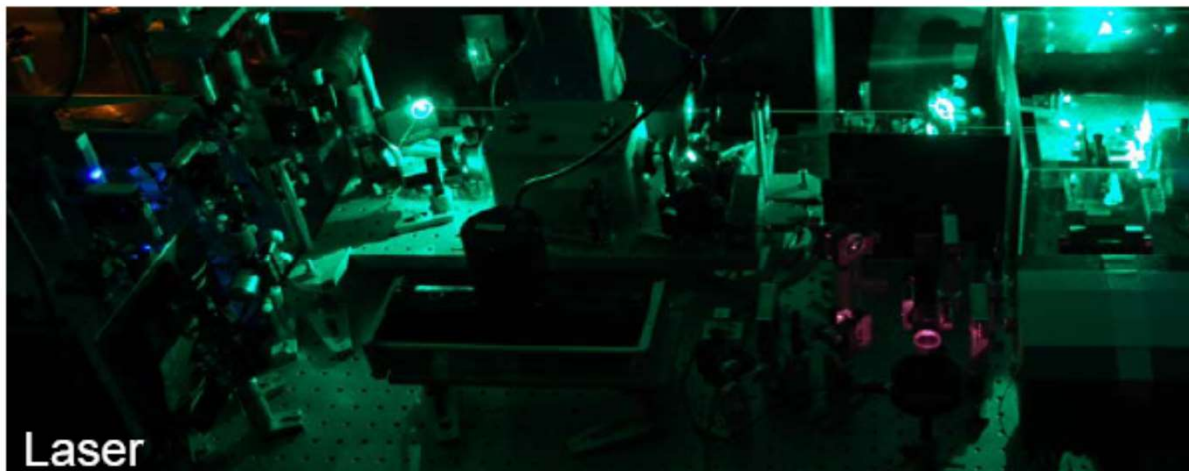


Attraktive Physik an der TU Darmstadt

Heute: Experimentelle Quantenoptik

Prof. Dr. Gerhard Birkl
Prof. Dr. Thomas Walther
Prof. Dr. Markus Gräfe

Institut für Angewandte Physik (IAP)



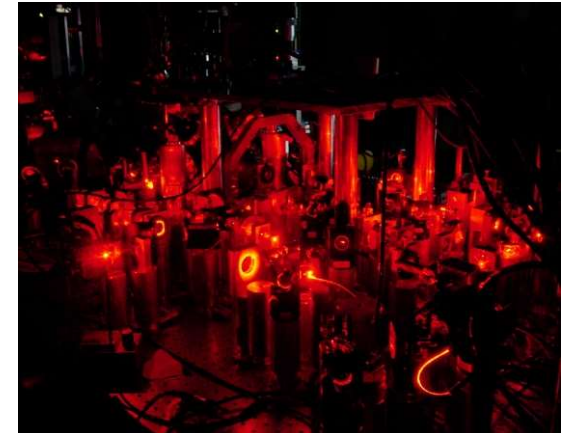
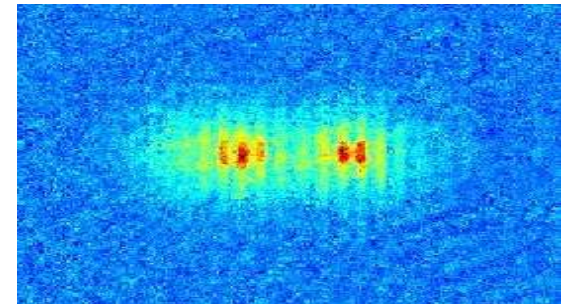
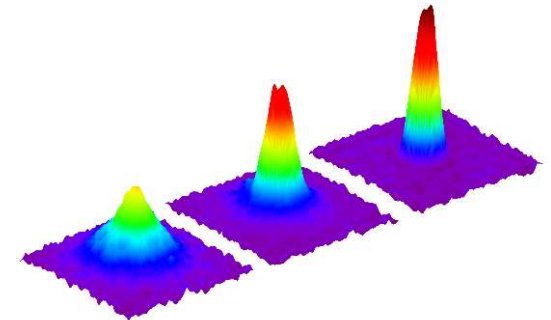
Experimentelle Quantenoptik (AG Birkl)

Atome - Photonen - Quanten

- Bose-Einstein-Kondensation
- Integrierte Atomoptik (ATOMTRONICS)
- Quanteninformation
- Laser-Spektroskopie hochgeladener Ionen

Gerhard Birkl

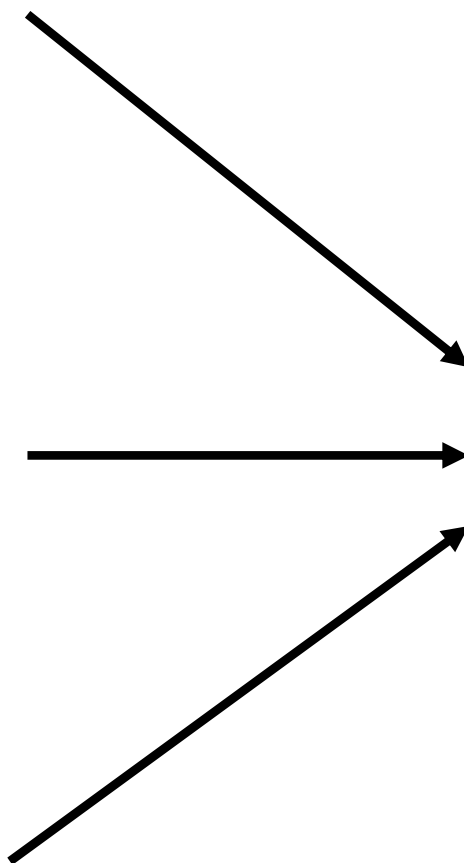
www.iap.tu-darmstadt.de/apq



Atoms as
Research Objects

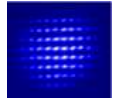
Quantum Optical
Methods for the
Control of Atoms

Quantum Physics as
Research Objective



**Quantum Physics
with Atoms
and Photons**

Projects, Group Members, and Co-Workers



ATOMTRONICS = Bose-Einstein-Condensation and Integrated Atom Optics

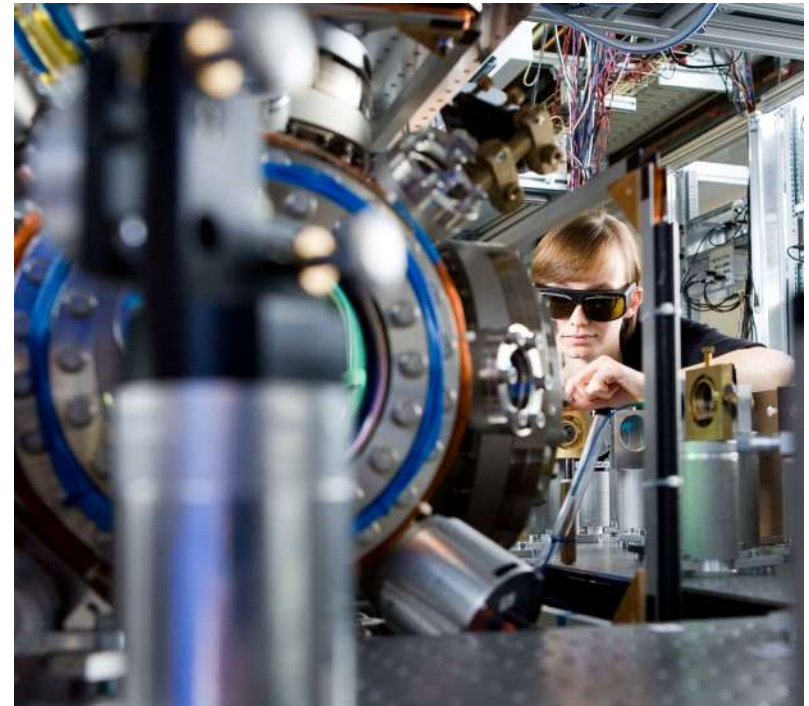
Dominik Pfeiffer, Ludwig Lind, Daniel Derr

Quantum Information Processing and Quantum Simulation with individual Atoms

Malte Schlosser, Dominik Schäffner, Tilman Preuschoff, Lars Pause, Tobias Schreiber, Fabian Lenz, Yannic Wolf

State-of-the-Art Electronics, Lasers, & Control Software for Quantum Optics Experiments

Patrick Baus, Tilman Preuschoff, Lars Pause



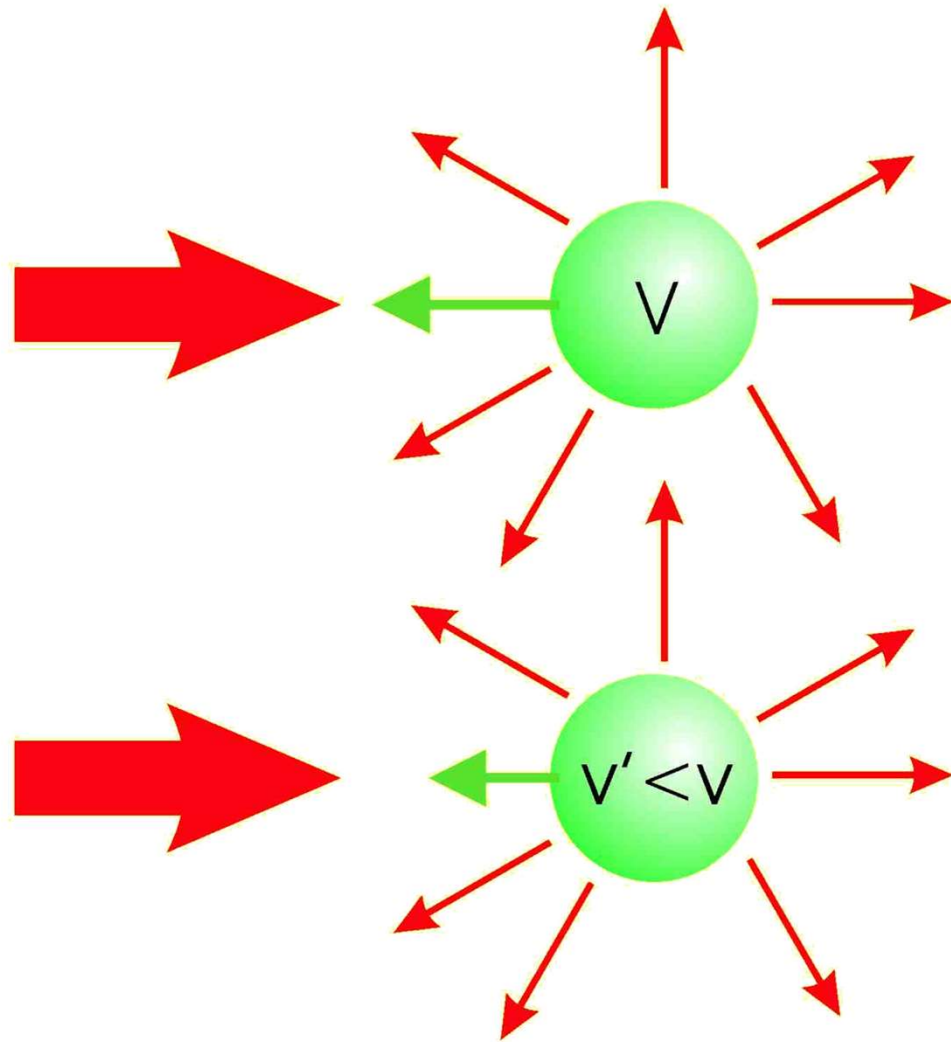
Laser Spectroscopy with Highly Charged Ions (@GSI/FAIR)

Patrick Baus, Jeffrey Klimes, Kanika Kanika, Manuel Vogel, Wolfgang Quint, and the **SPECTRAP** and **ARTEMIS** collaborations

Collaborations

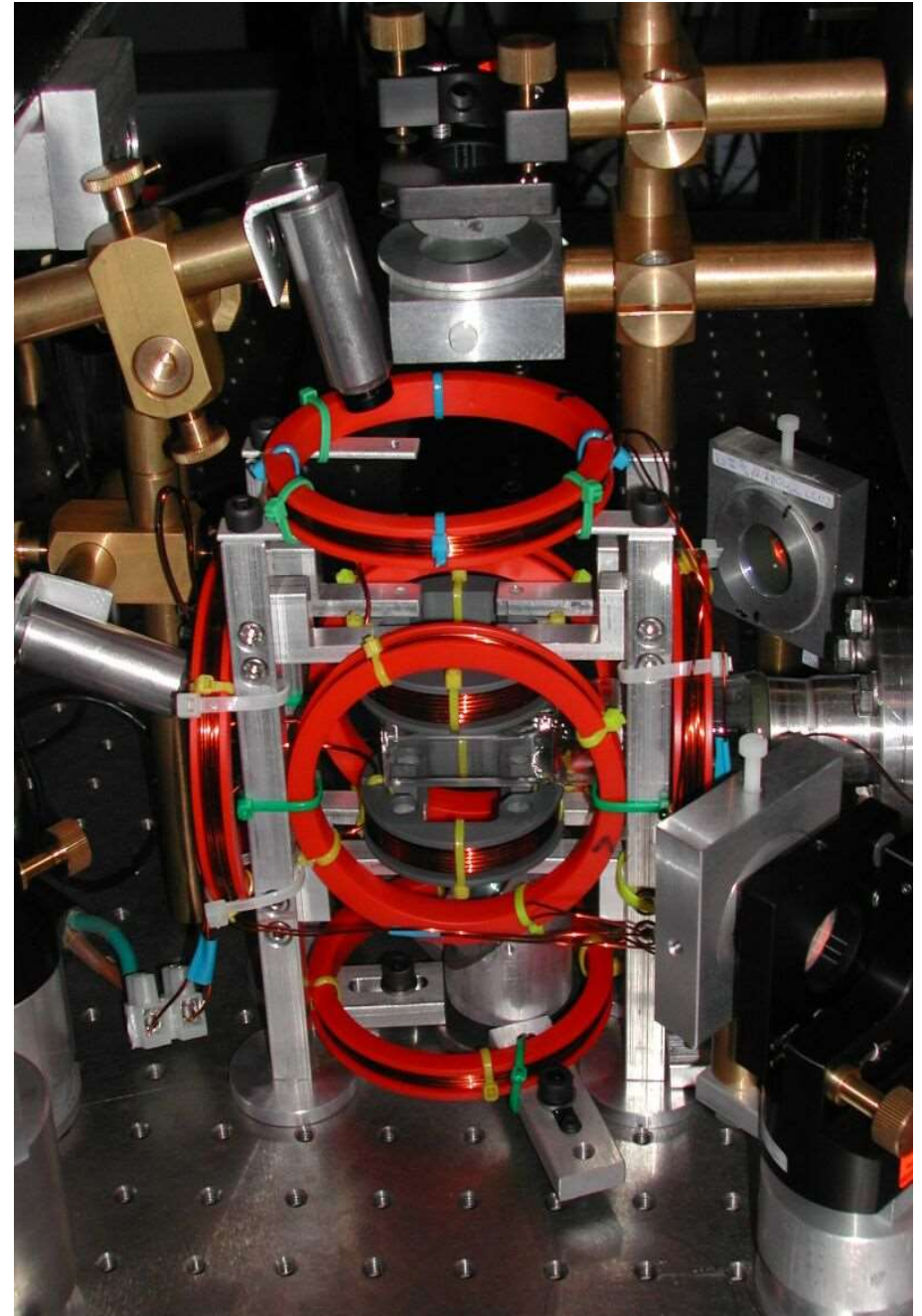
Jordi Mompart, Anna Sanpera, Veronica Ahufinger, Alex Turpin, Maciej Lewenstein (Barcelona)
R. Dumke (NTU), Th. Stöhlker (Uni Jena und GSI), Bill Phillips (NIST), K. Helmerson (Monash)

Dissipative: Spontaneous Scattering

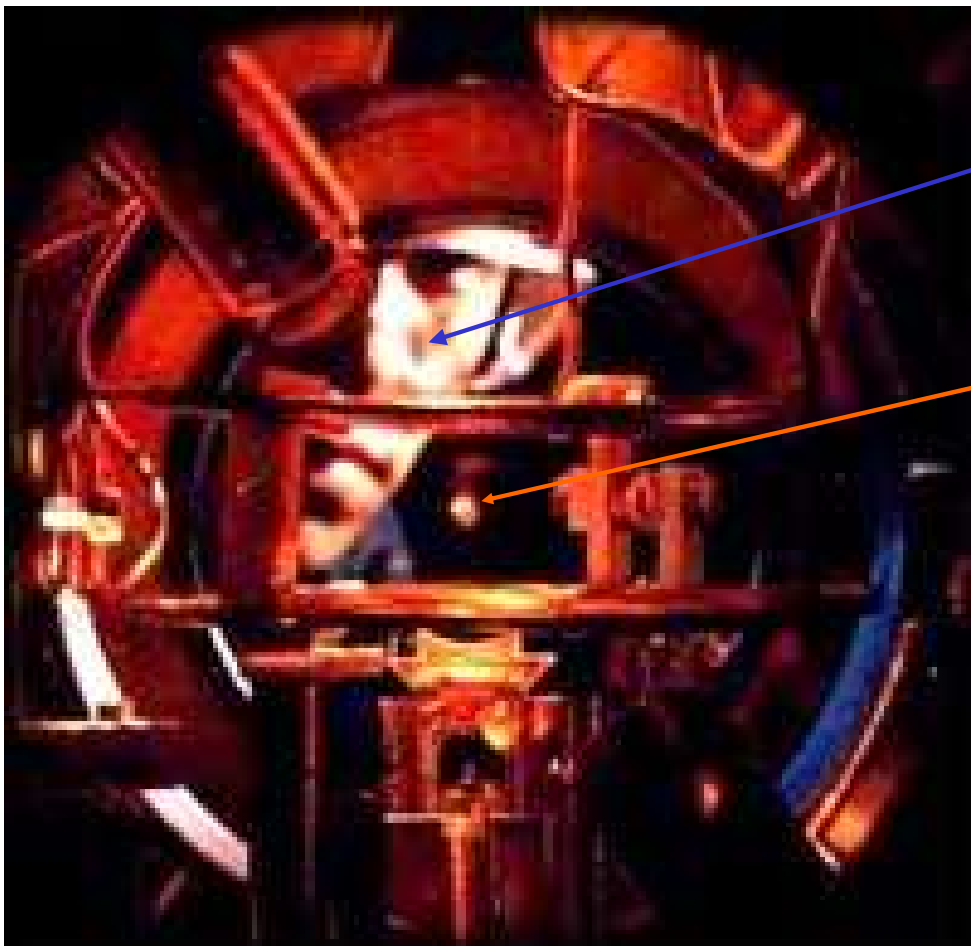


Laser Cooling

Preparation and Readout



Fangen von Atomen mit Laserlicht: Magneto-optische Falle (MOT)



Kris Helmerson

$T > 300 \text{ K}$

Natrium Atome

$T = 200 \mu\text{K}$

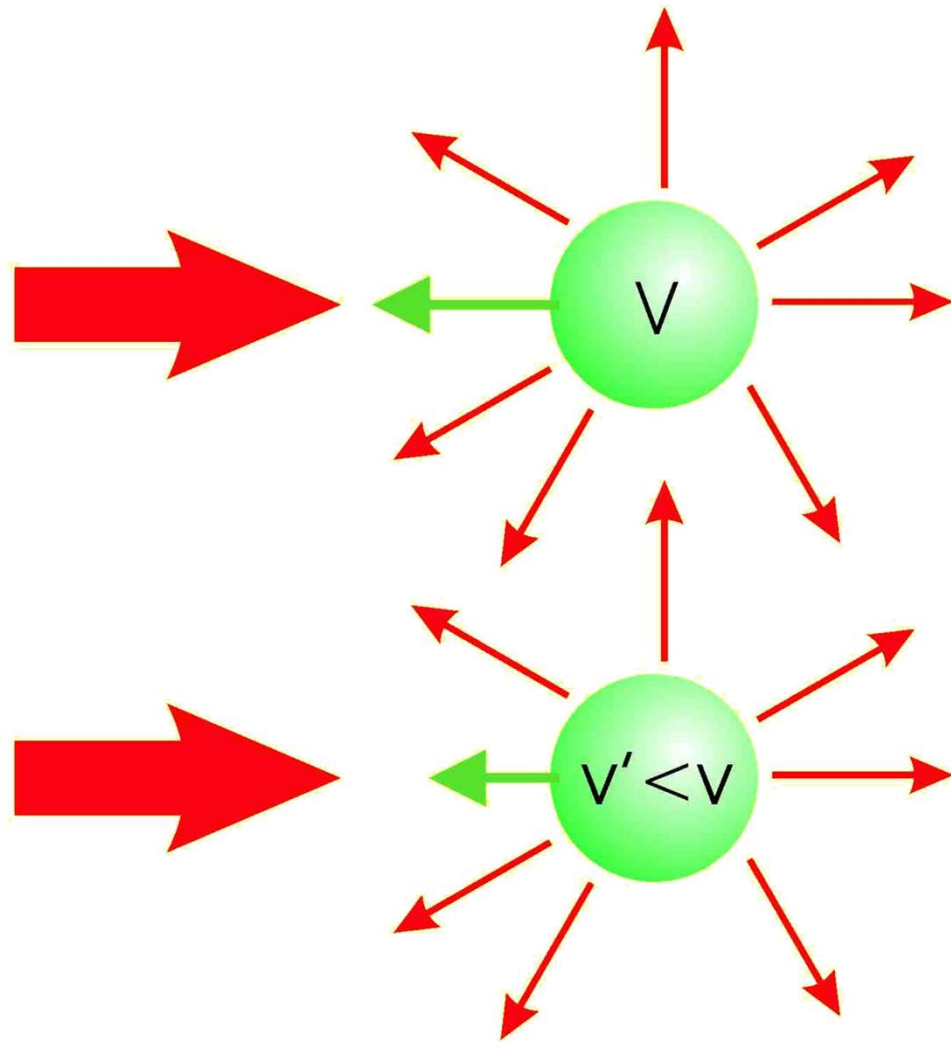
**Niedrigste Temperatur
durch Laserkühlung**

$T = 1 \mu\text{K}$

NIST

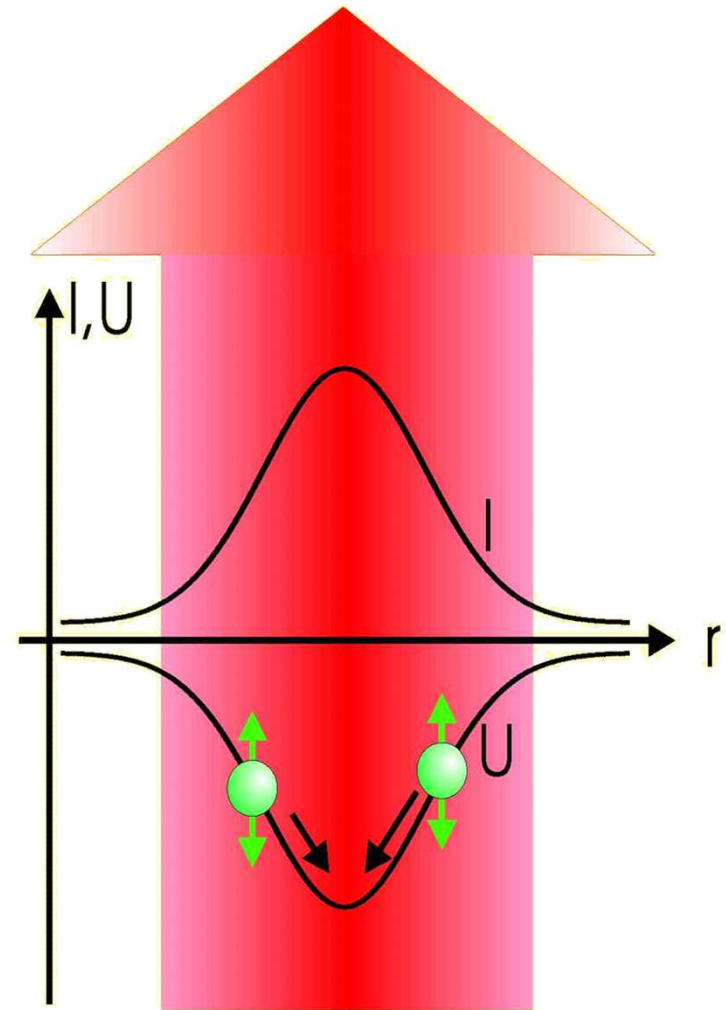
Optical Control of Atoms

Dissipative: Spontaneous Scattering



Laser Cooling
Preparation and Readout

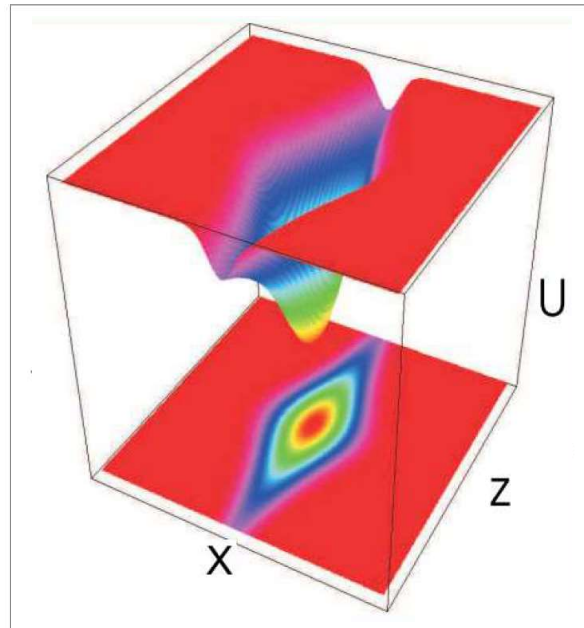
Conservative: Dipole Force



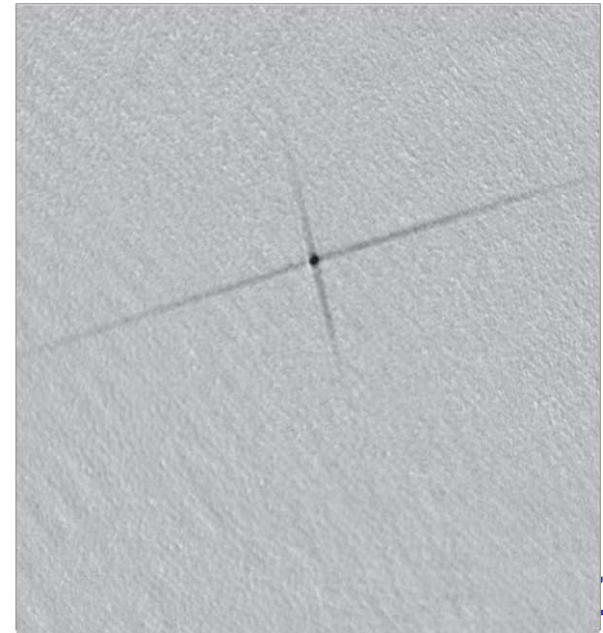
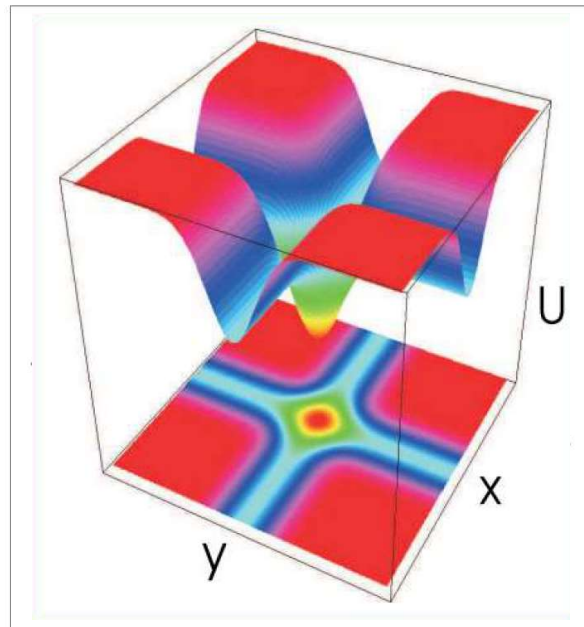
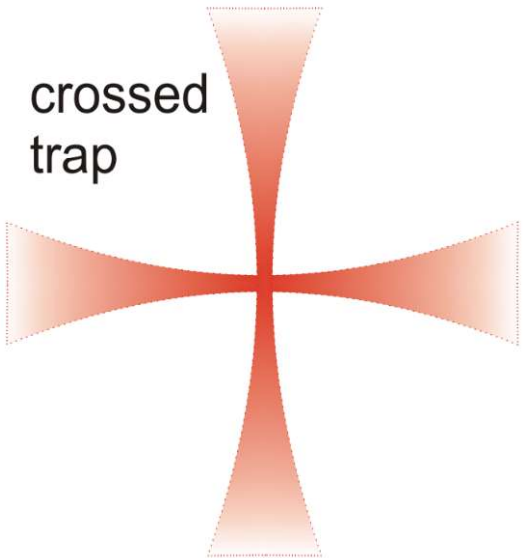
Dipole Traps

Trap Geometries

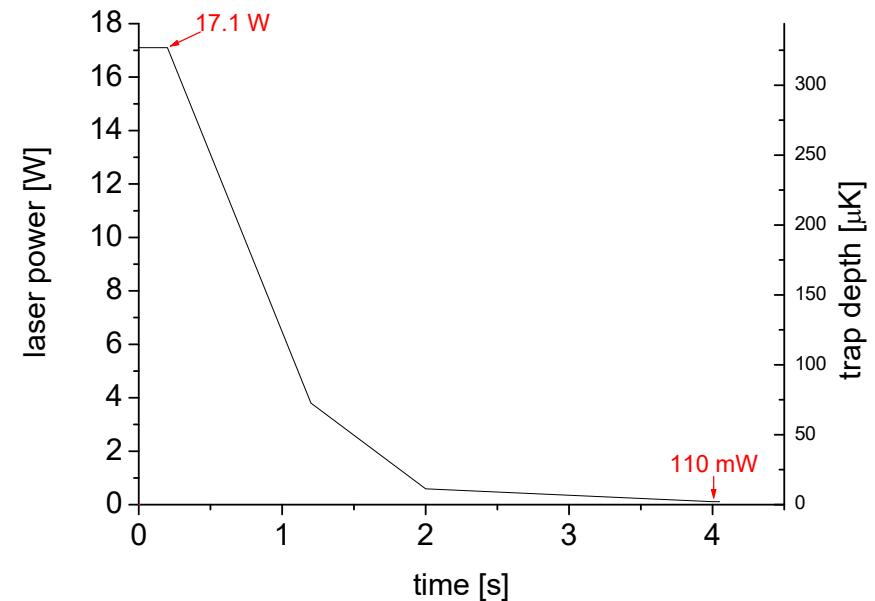
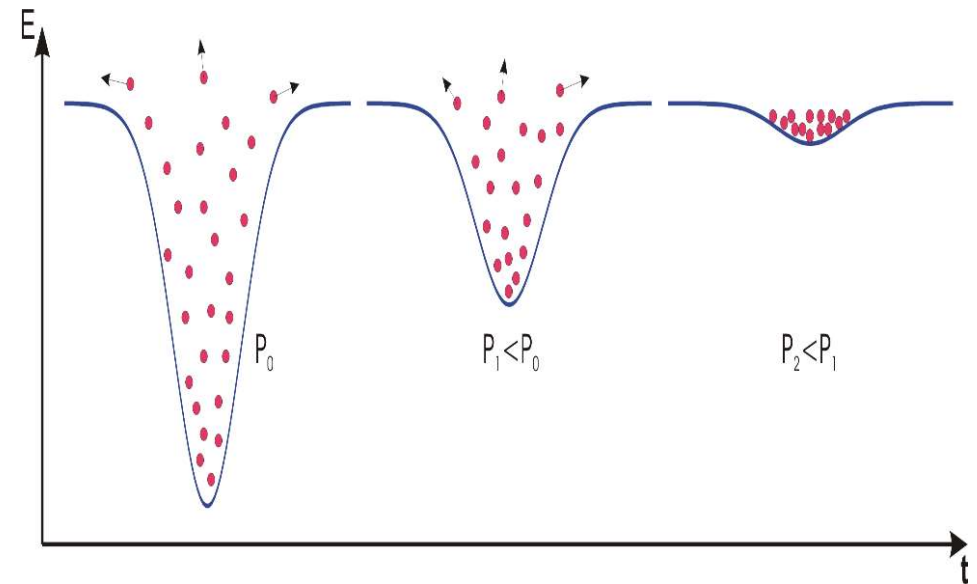
single beam trap

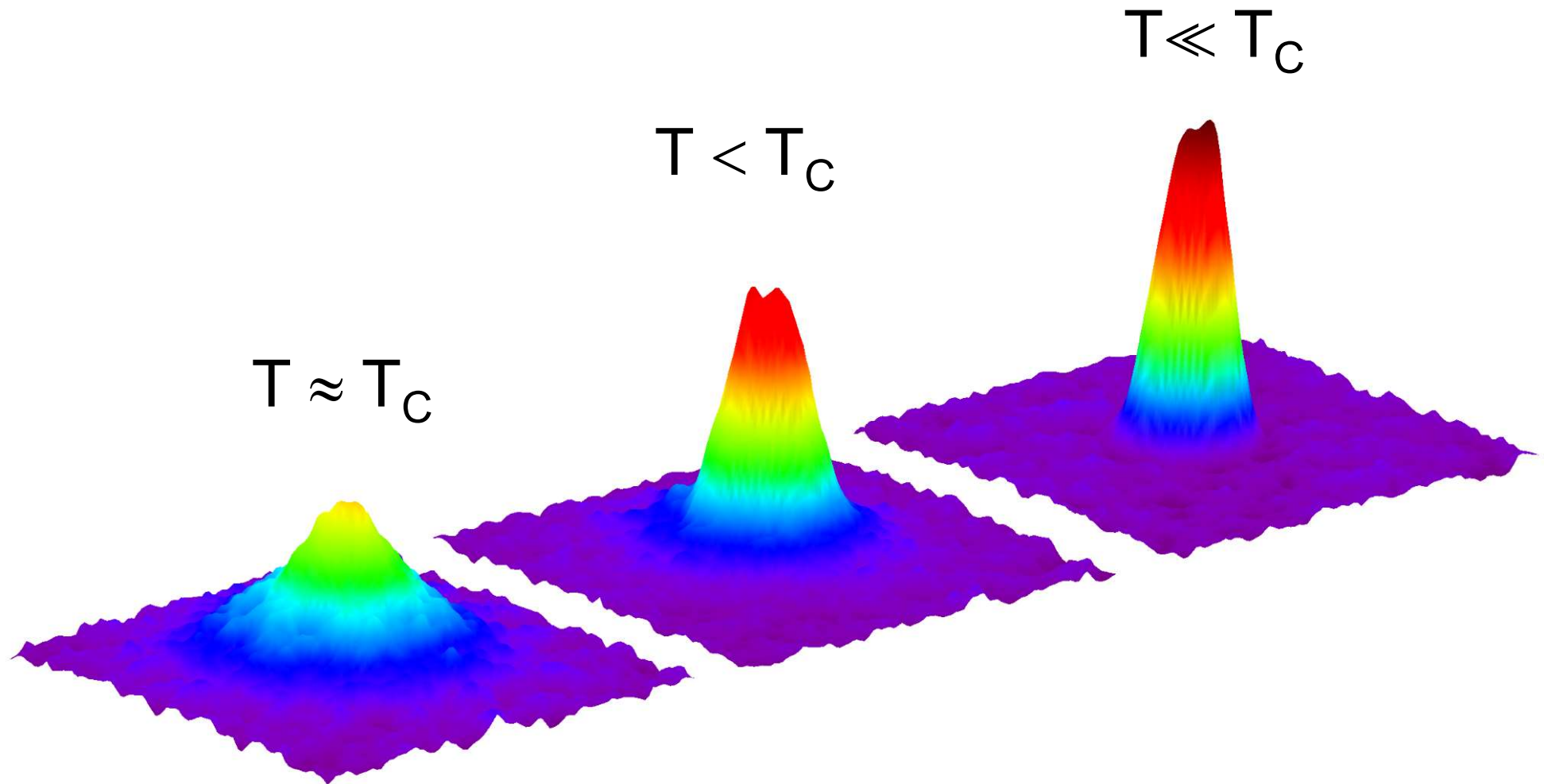


crossed trap

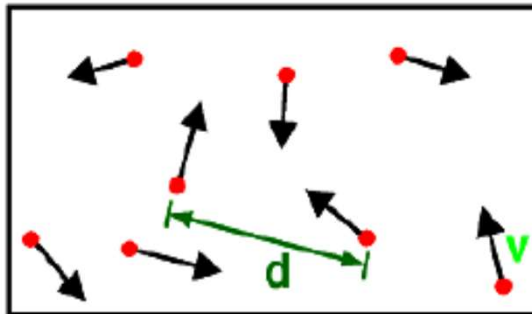


- start conditions:
 $5 \cdot 10^4 - 2 \cdot 10^5$ atoms in dipole trap @ 40 mK
- self-evaporation (~100 ms)
- three linear evaporation ramps (~500-3000 ms):
 - independent optimisation of the ramp durations
- time-of-flight (TOF) absorption images

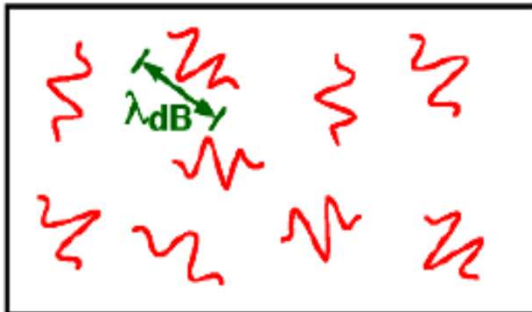




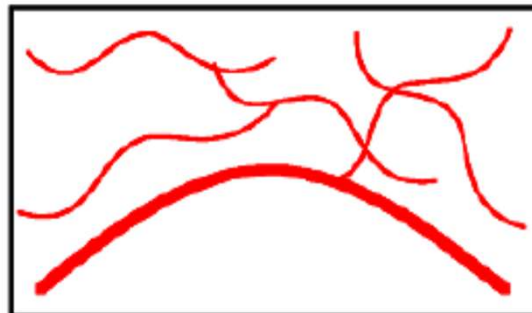
Bose-Einstein Condensation



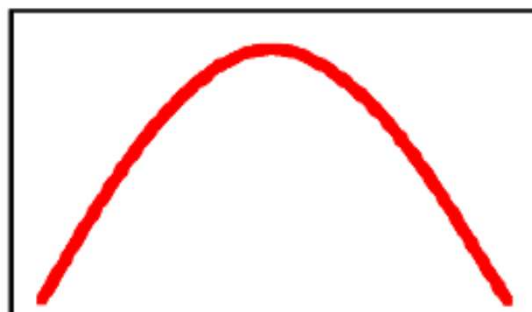
High
Temperature T :
thermal velocity v
density d^{-3}
"Billiard balls"



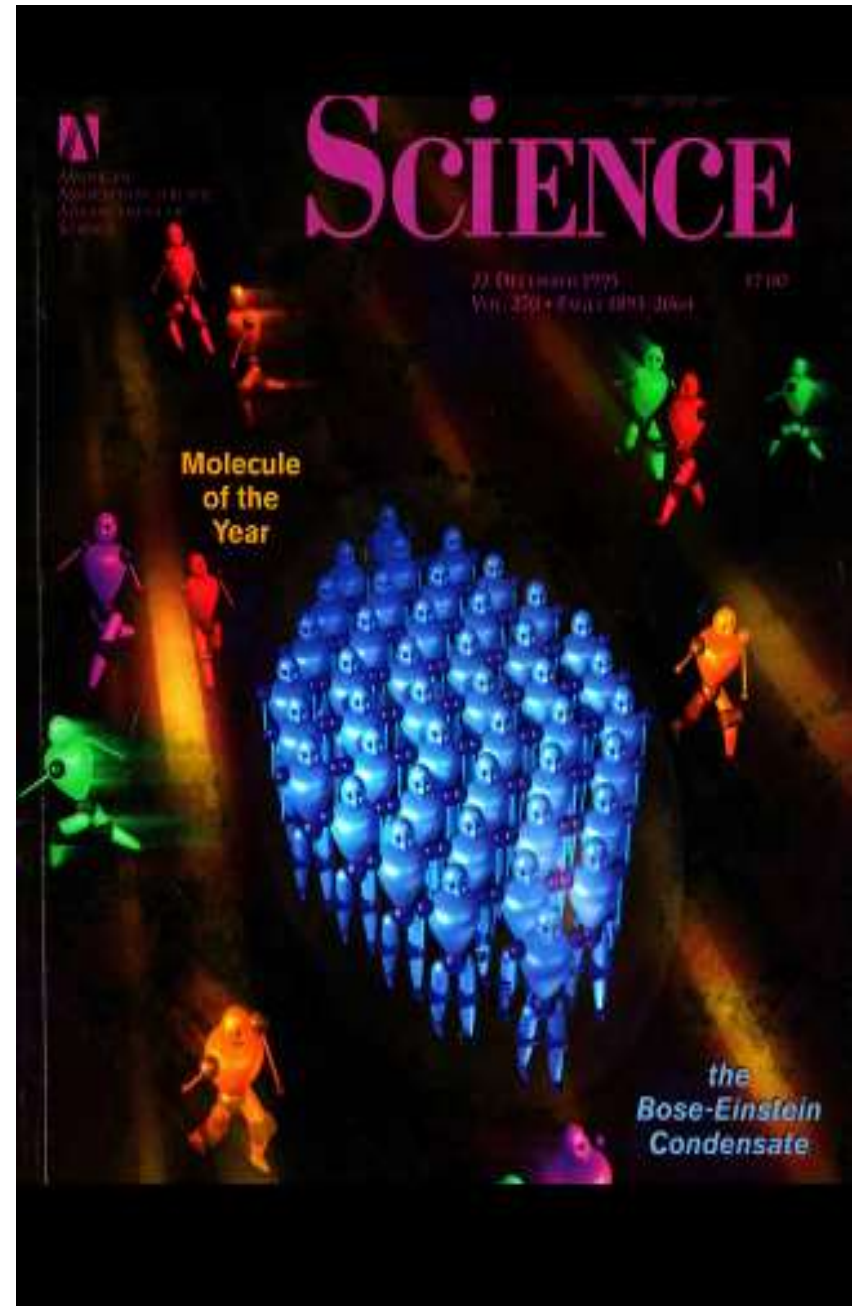
Low
Temperature T :
De Broglie wavelength
 $\lambda_{dB} = h/mv \propto T^{-1/2}$
"Wave packets"



$T = T_{crit}$:
Bose-Einstein
Condensation
 $\lambda_{dB} \approx d$
"Matter wave overlap"

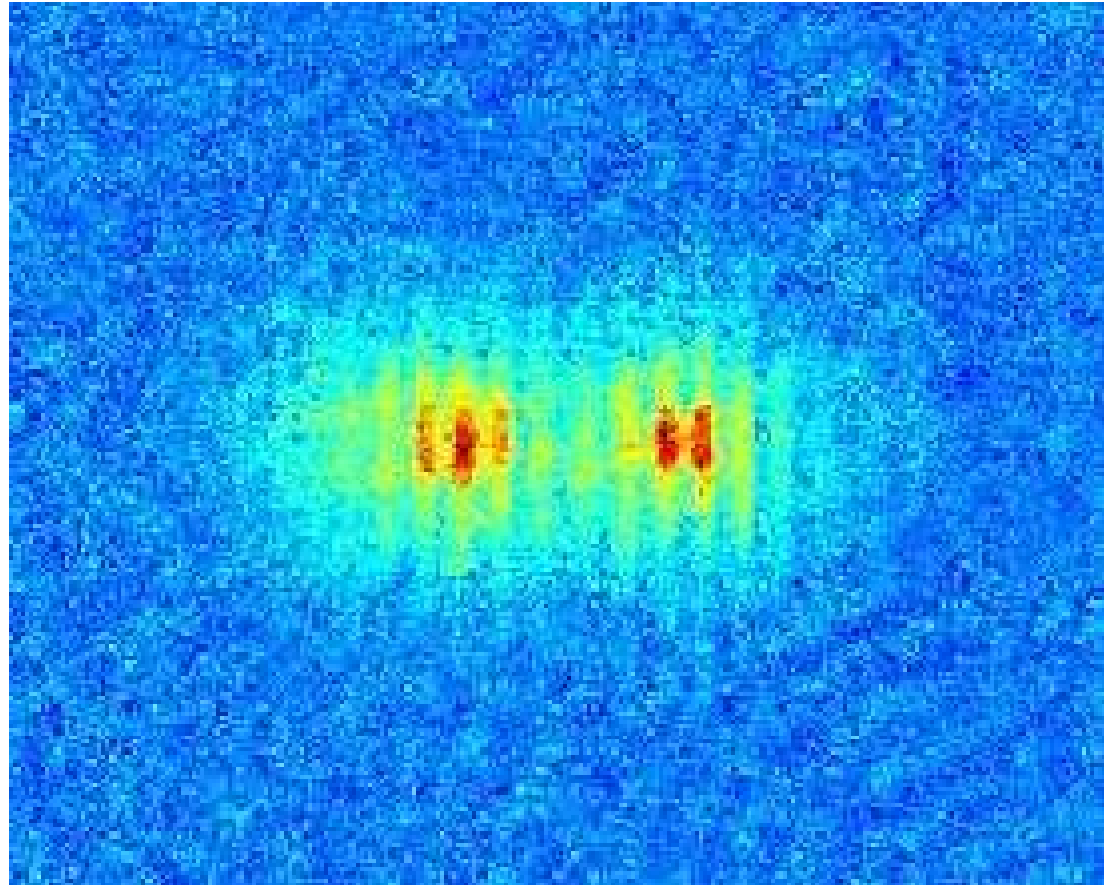
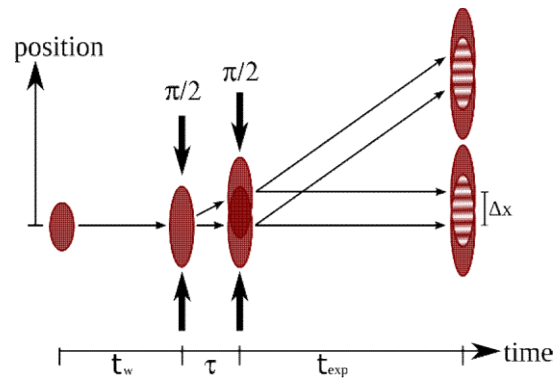


$T = 0$:
Pure Bose
condensate
"Giant matter wave"



Interference of two Bose-Einstein Condensation

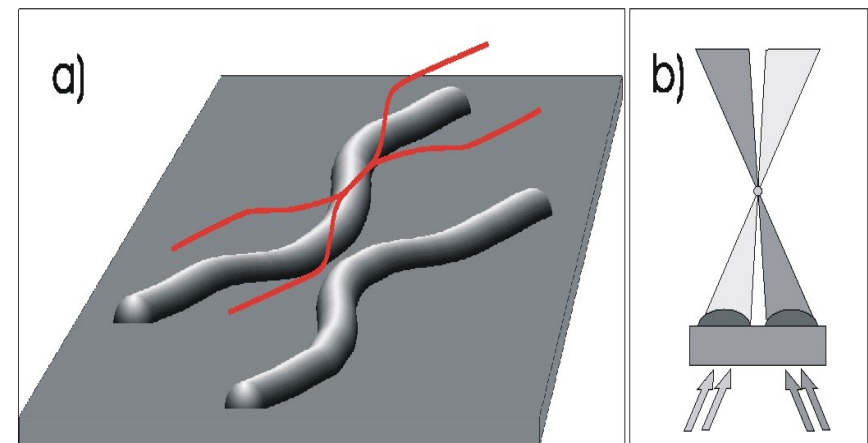
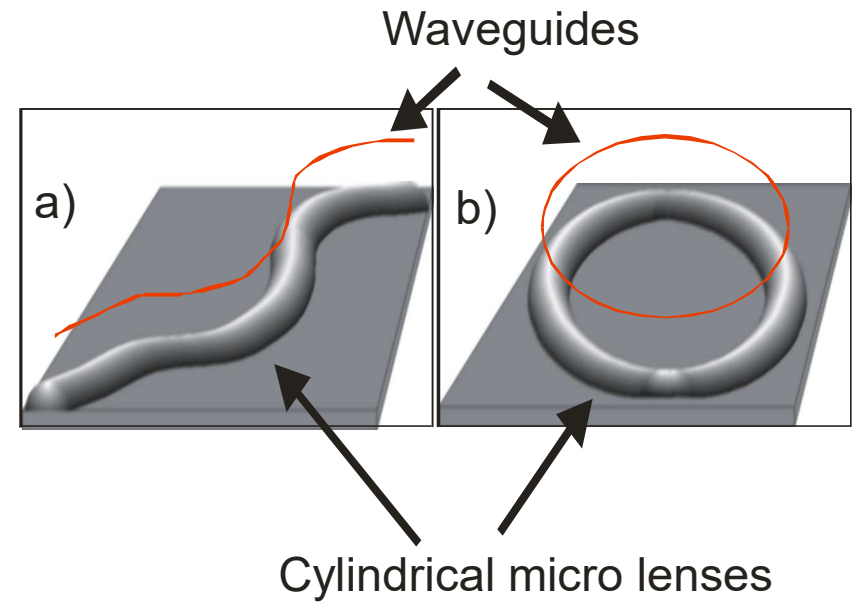
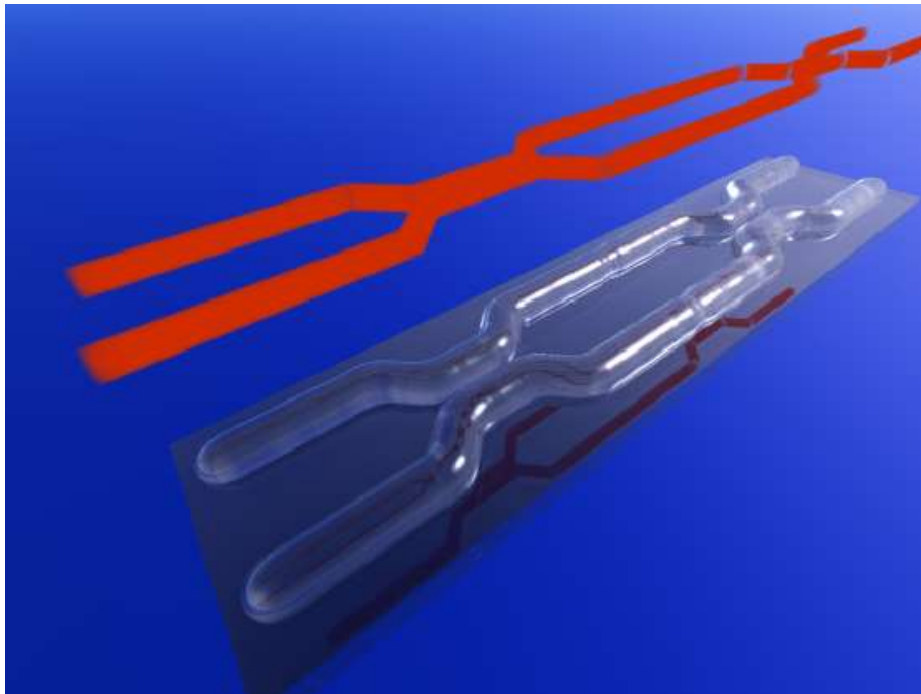
Two superimposed BECs show interference.



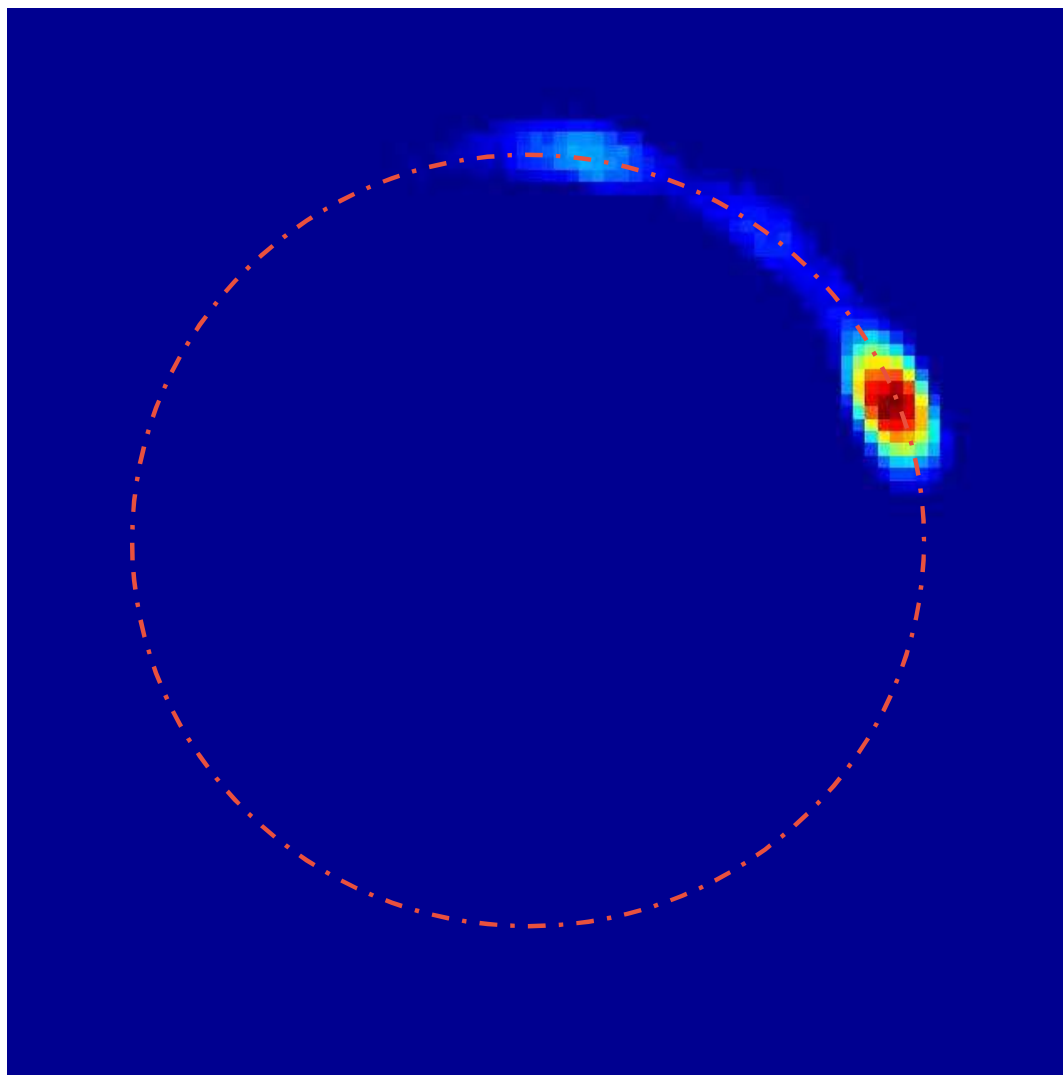
Bose-Einstein condensates behave like waves.

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

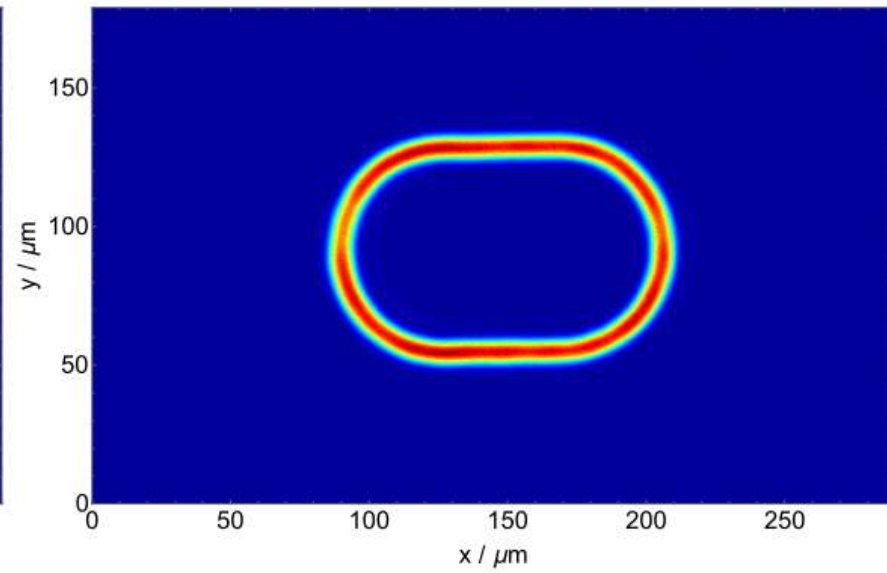
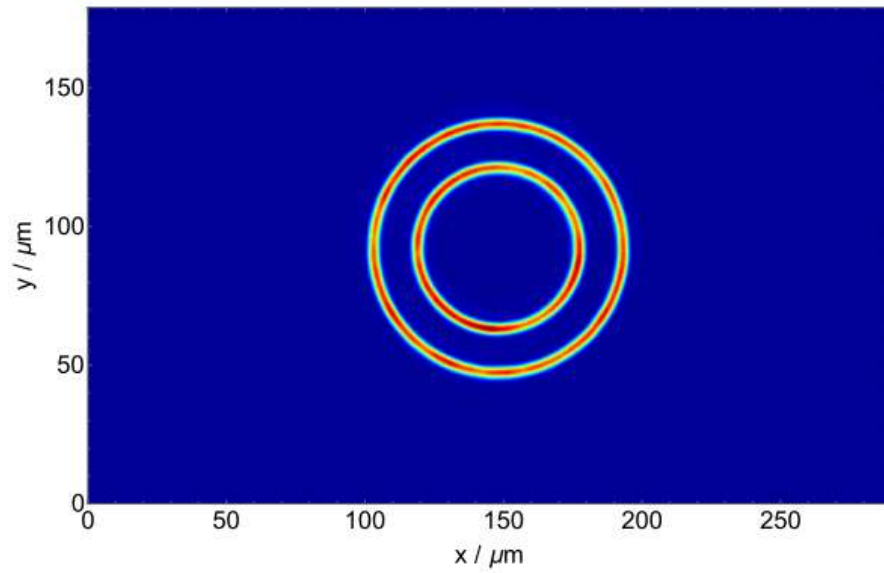
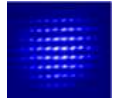
- Compact atom interferometer geometries as quantum sensors
- Resonator for atomic matter waves



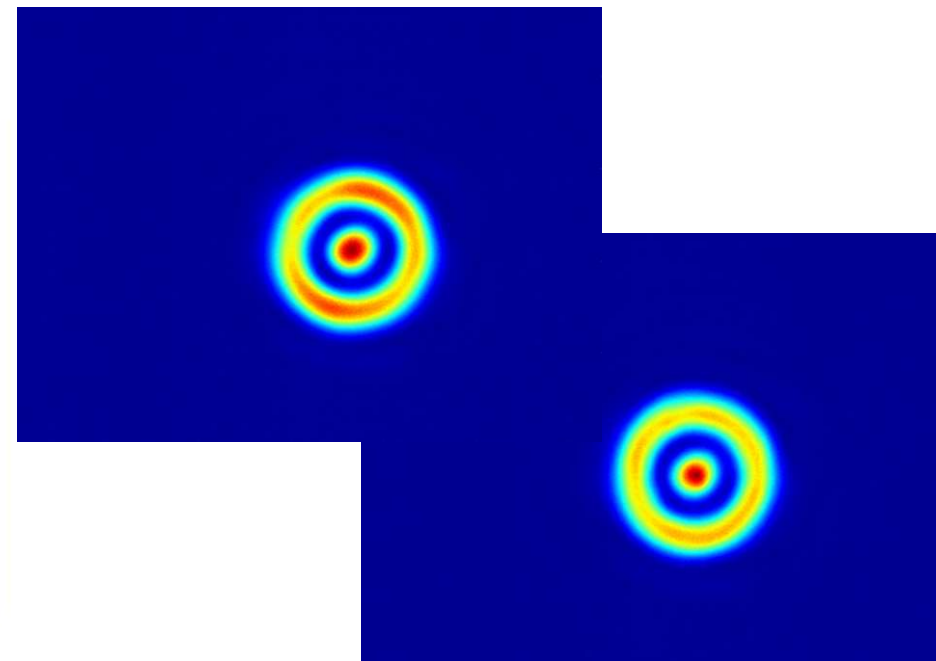
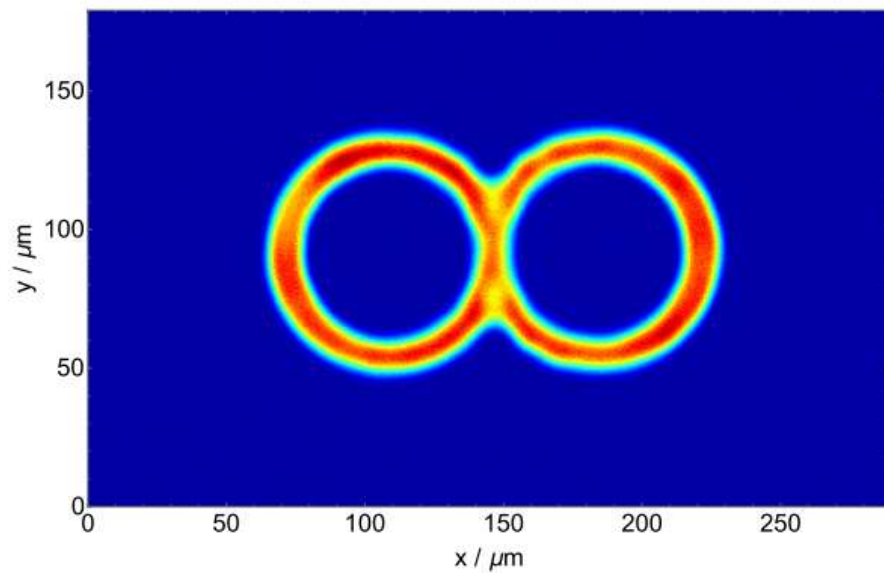
Bose-Einstein Condensate in a Storage Ring



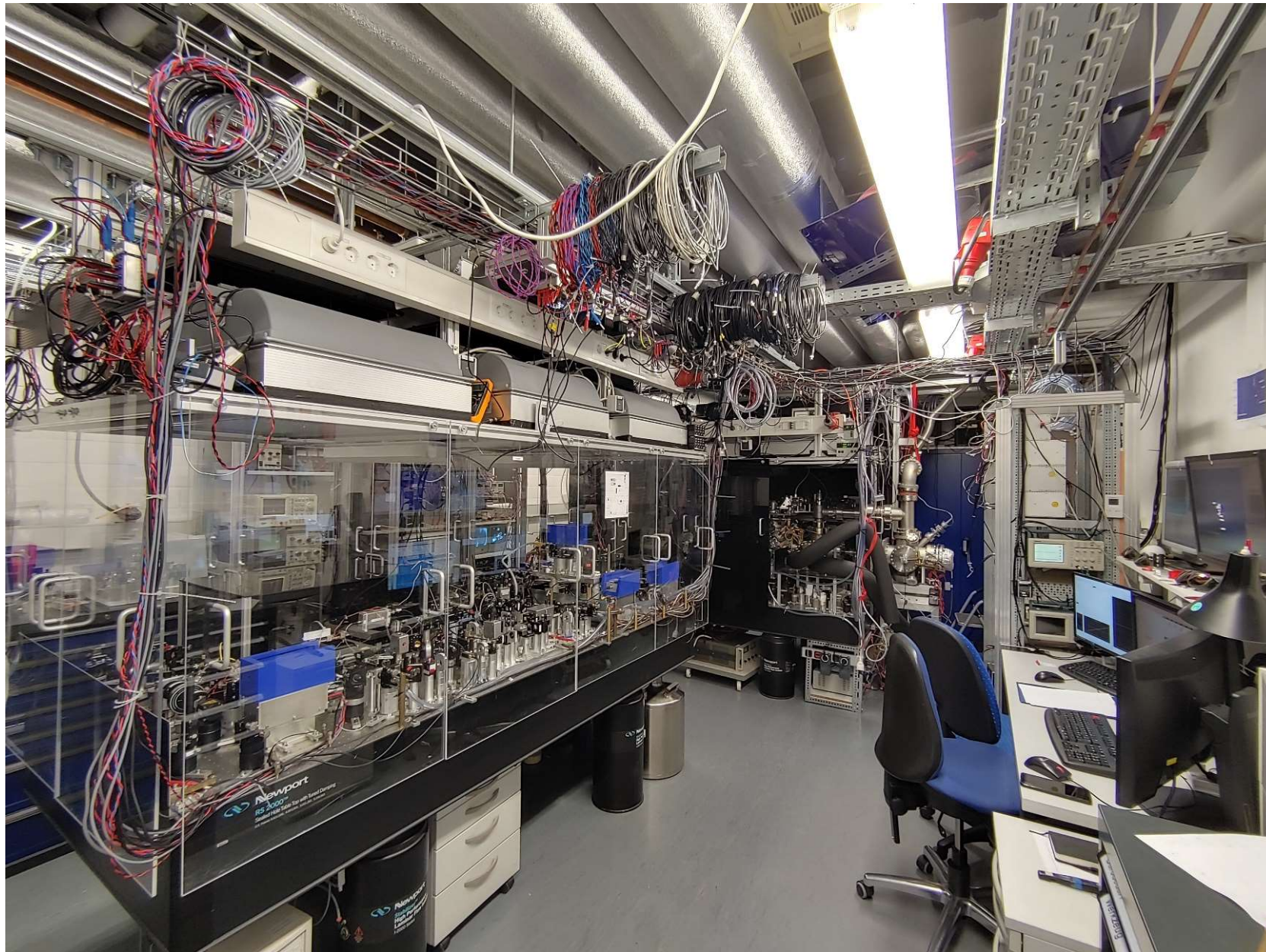
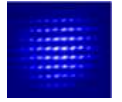
DMD-based Dipole Potentials for Integrated Atom Optics



c)

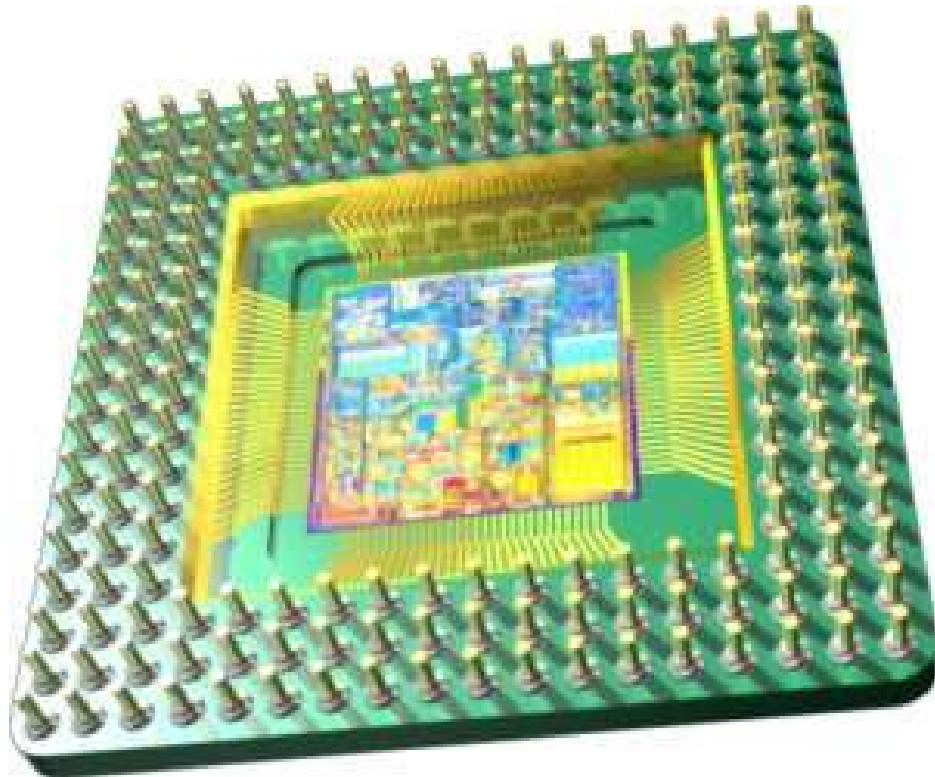


ATOMTRONICS – Lab Visit



Towards Quantum Computing and Quantum Information Processing

Using the characteristics of quantum mechanics gives rise to completely new ways for information processing



Physik November 2005
4. Jahrgang
Journal
www.physik-journal.de



Schwerpunkt Quanteninformation
Industrieforschung im Wandel
DPG-Praktikumsbörse

Φ Deutsche Physikalische Gesellschaft

The cover features three small images. The top-left image shows a quantum device, possibly a superconducting qubit, mounted on a metal base with various wires and connections. The top-right image is a close-up of a quantum circuit, showing a series of gates and qubits on a chip. The bottom-right image shows a grid of red laser spots, likely representing a quantum state or a measurement result.

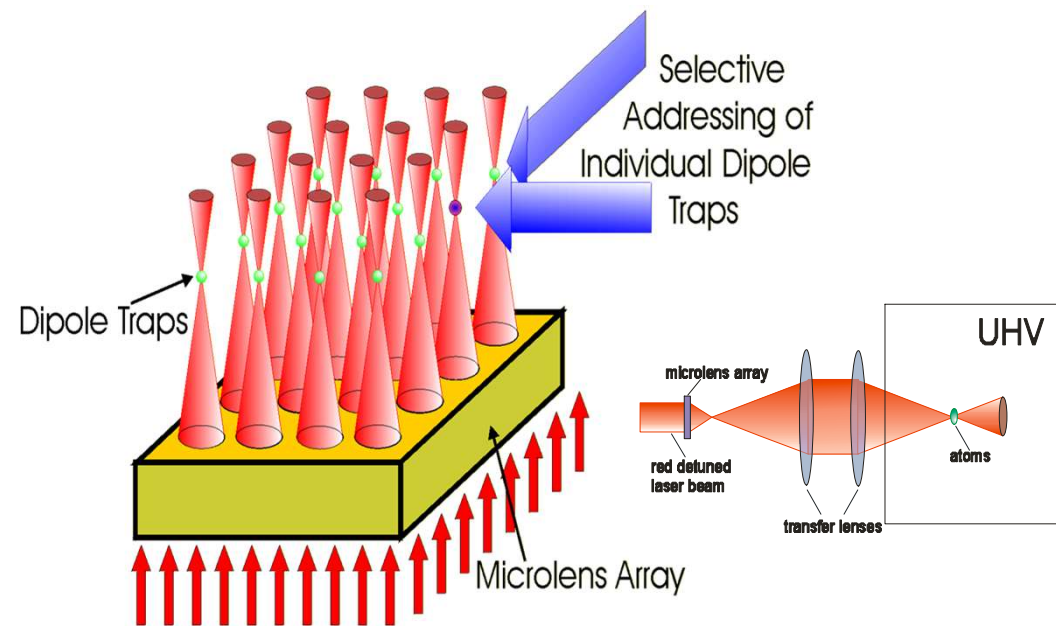
Scalable Register for Atomic Qubits

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

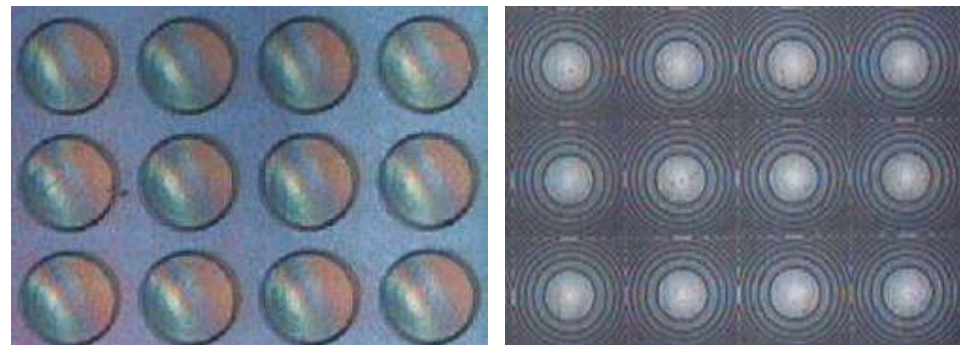
Very tight foci due to high numerical aperture possible

Sufficiently low rate of spontaneous emission

Individual dipole traps can be selectively addressed due to large separation of the microlenses (typically $125\ \mu\text{m}$)



Refraktive und diffraktive Mikrolinsen



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

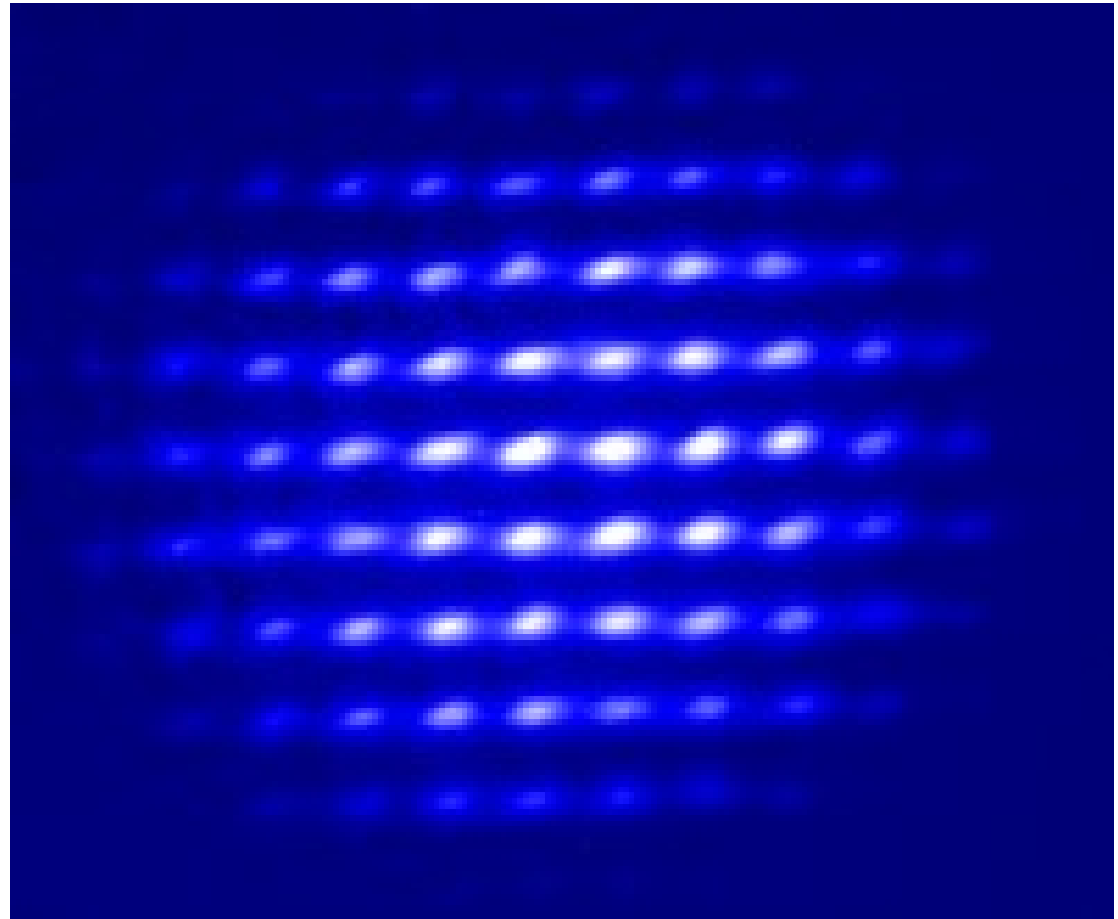
Trap size $w_0 = 7\mu\text{m}$

Trap depth 1 mK

Temperature $20\ \mu\text{K}$

Atoms per trap 100-1000

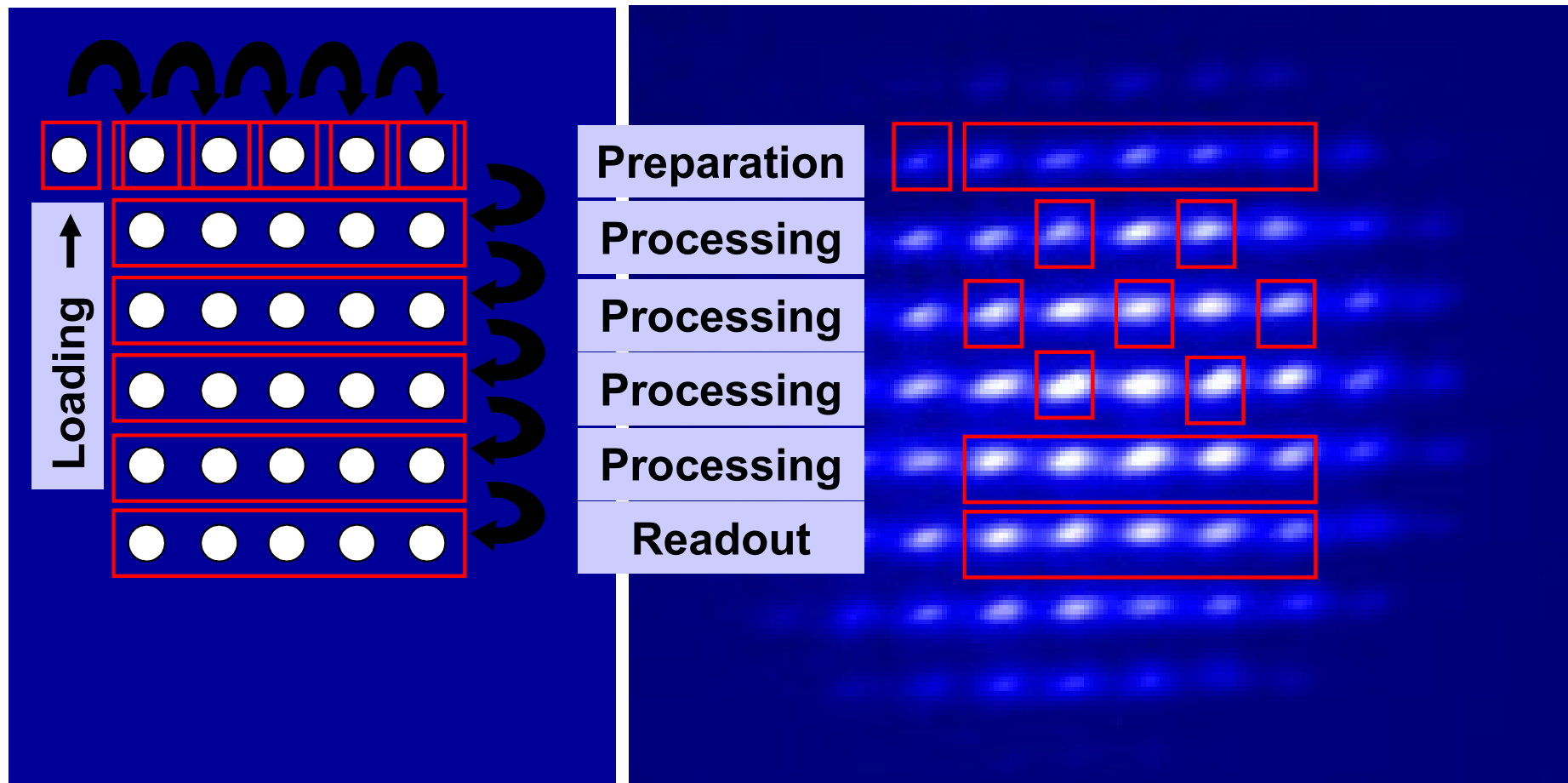
Lifetime up to 2 s
(depending on detuning)



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

Complex Architectures for a Quantum Processor

Complex processor architecture based on quantum shift register with spatially separated loading and processing units



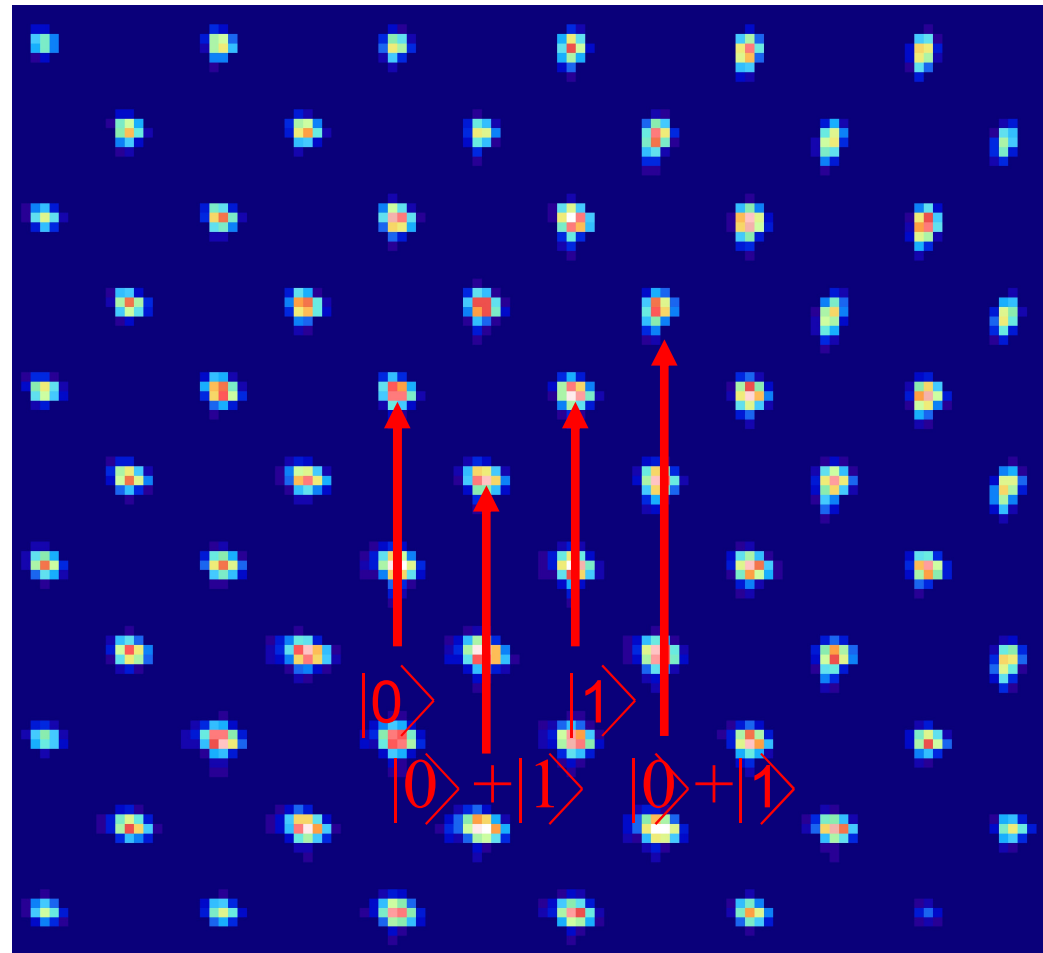
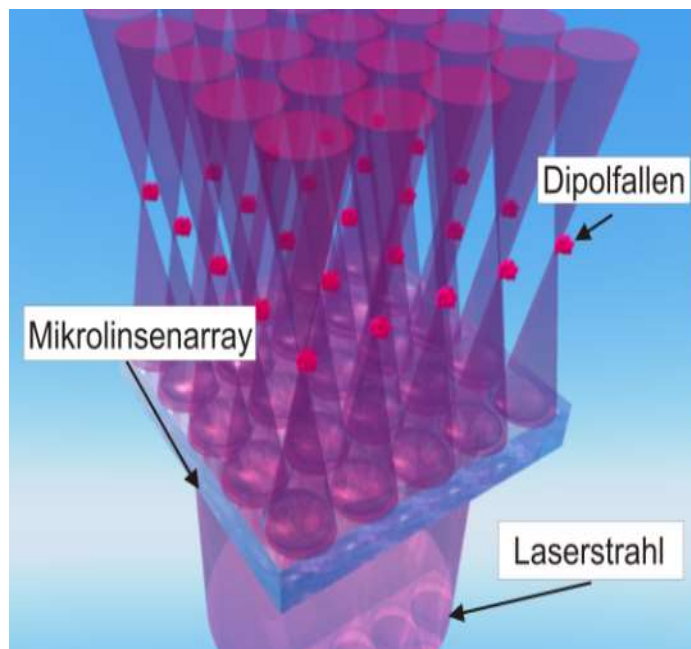
Two-Dimensional Register for Quantum States

Multiple realisation of individually controllable **quantum systems** serve as random access memory for **quantum bits**

Goal: Quanten Computer

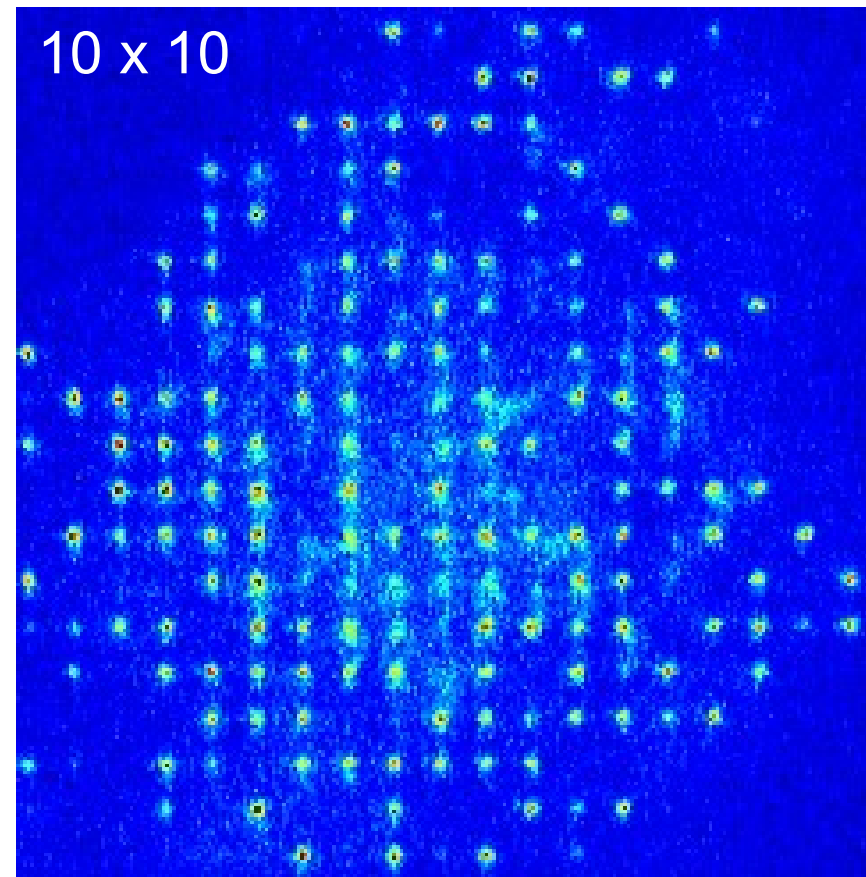
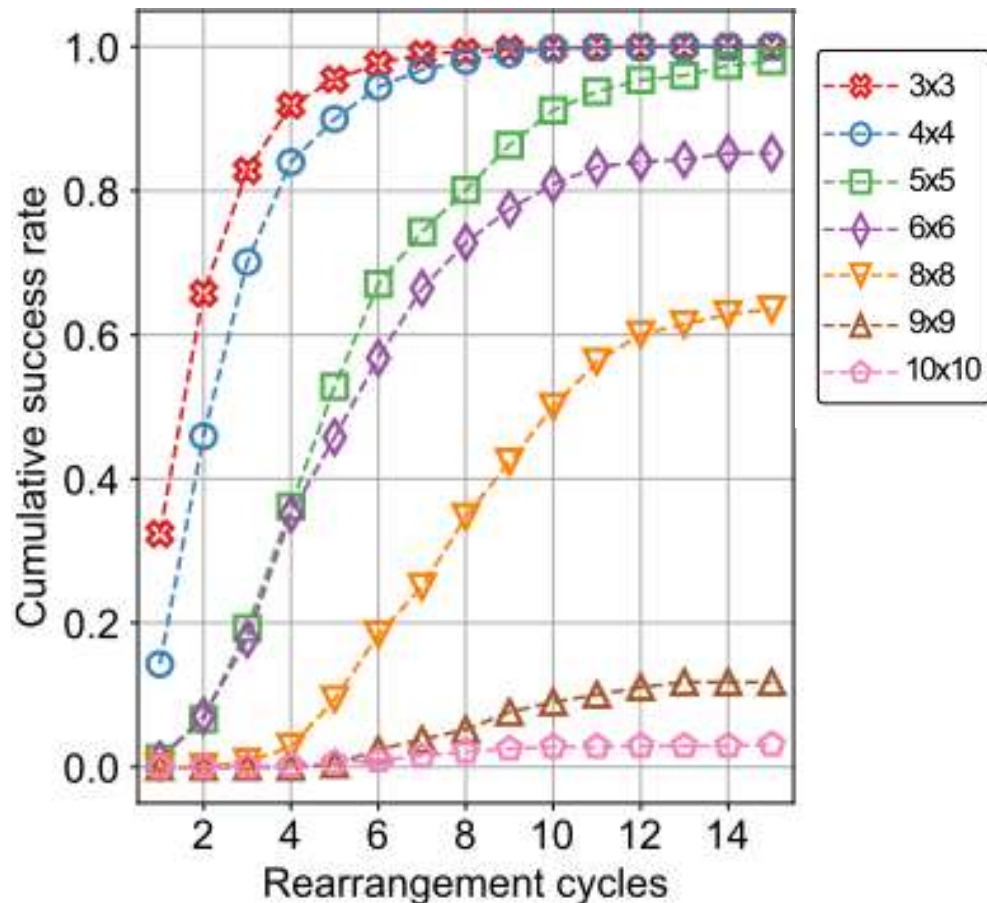
Example: Quantum Memory

Addressing of each memory site is possible.

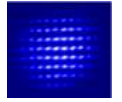


Defect-Free Large-Scale Single Atom Clusters

- Deterministic assembly of defect-free target structures
- Atom rearrangement using real time feedback loop
- Enhanced success rate via multiple rearrangement cycles
- Extended lifetime and repeated re-creation of target structure

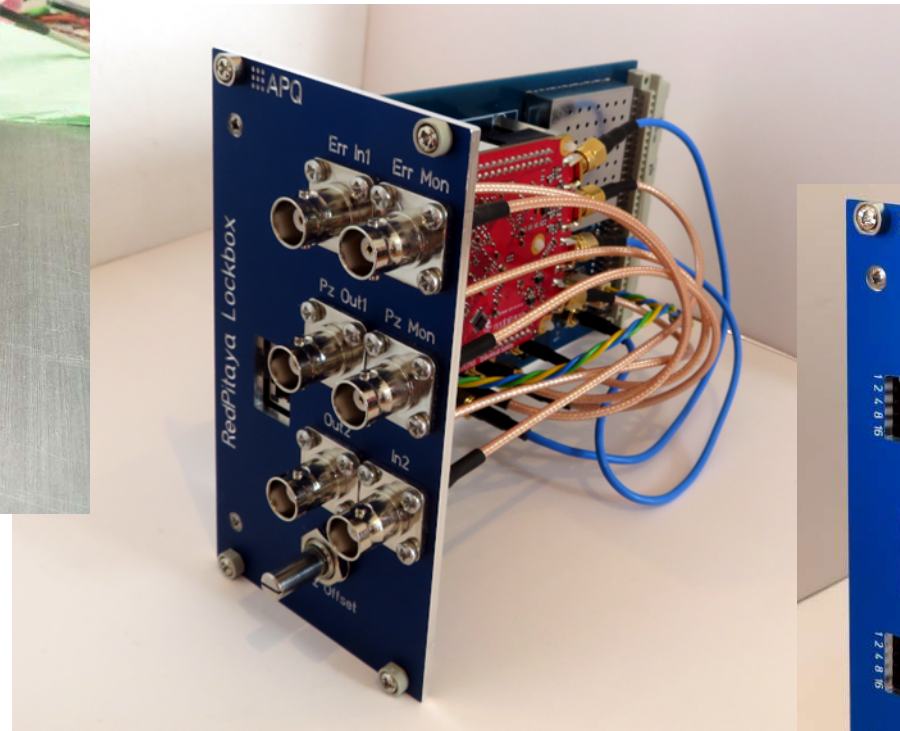


State-of-the-Art Lasers, Electronics, & Software



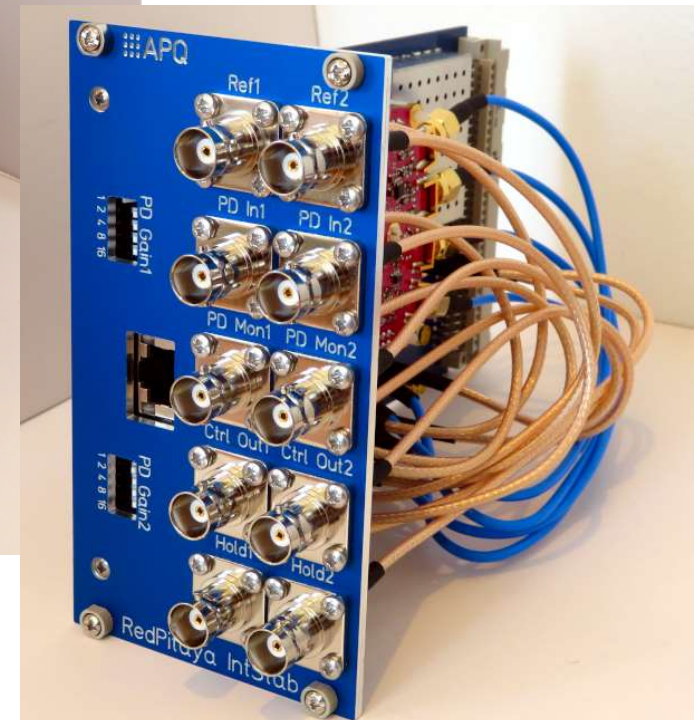
Ultra-stable Digital Laser Current Driver

Red Pitaya (STEMlab) Digital Lock Box

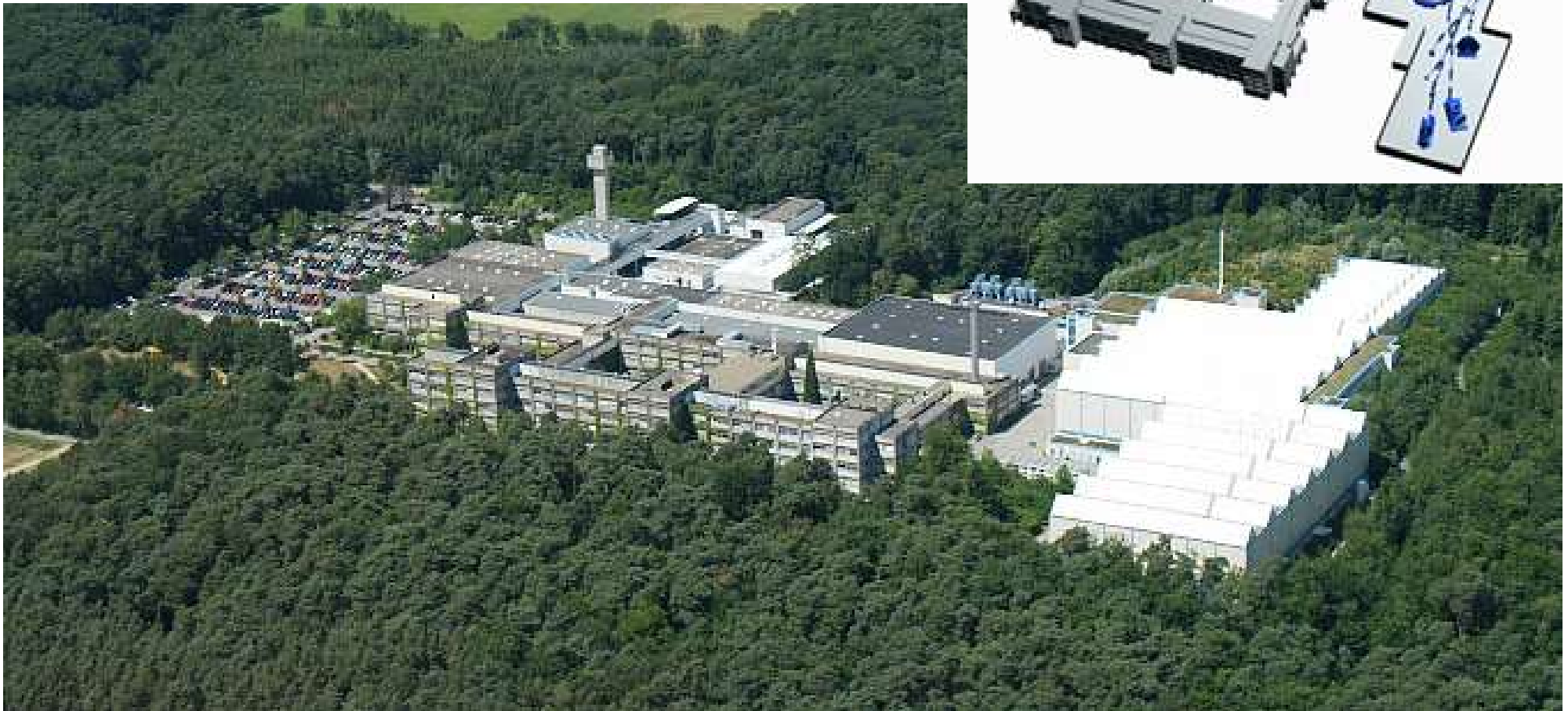


T. Preuschoff, M. Schlosser, G. Birkl
Rev. Sci. Instr. **91**, 083001 (2020)

Red Pitaya (STEMlab) Intensity Stabilization

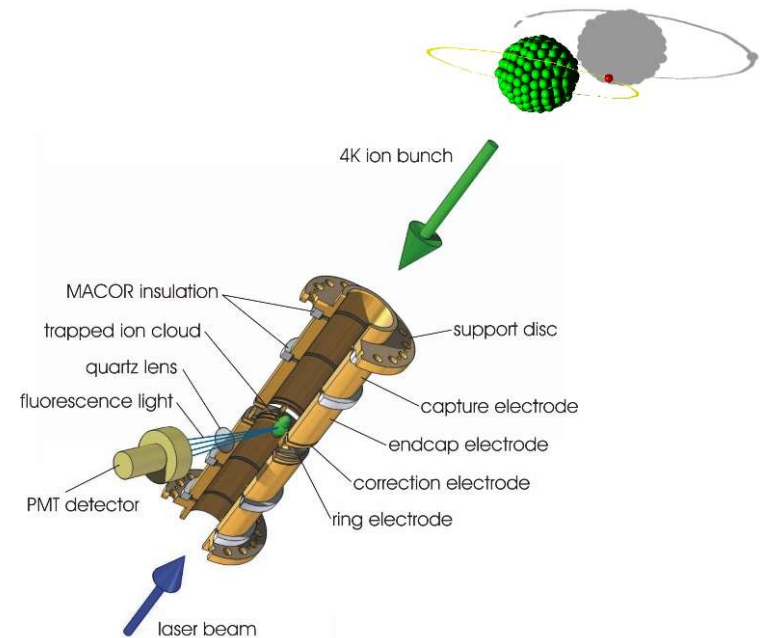
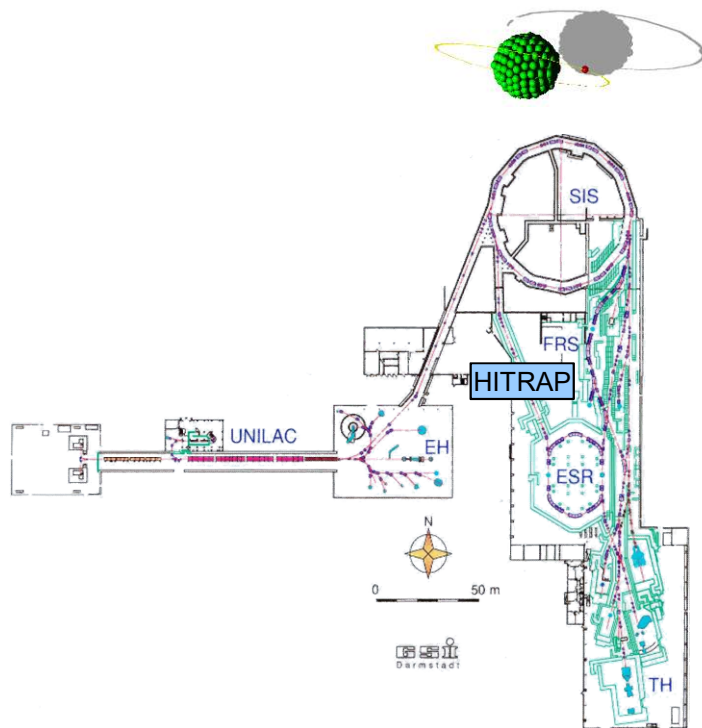
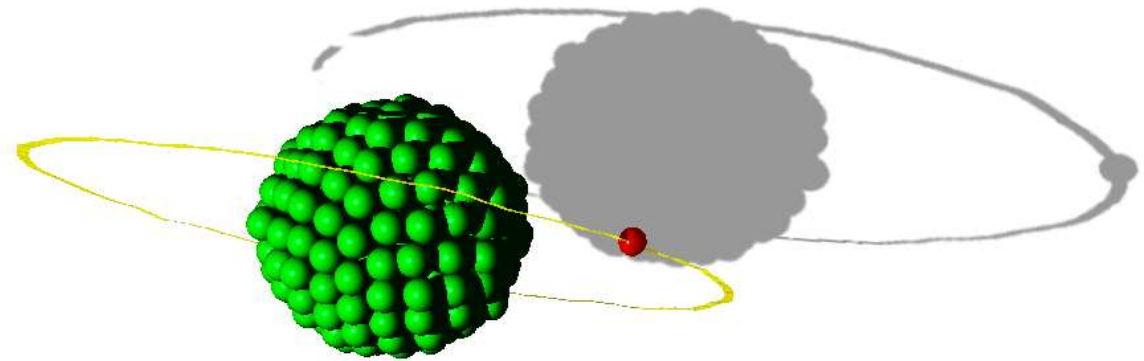


Laser Spectroscopy of Highly Charged Ions at GSI and FAIR

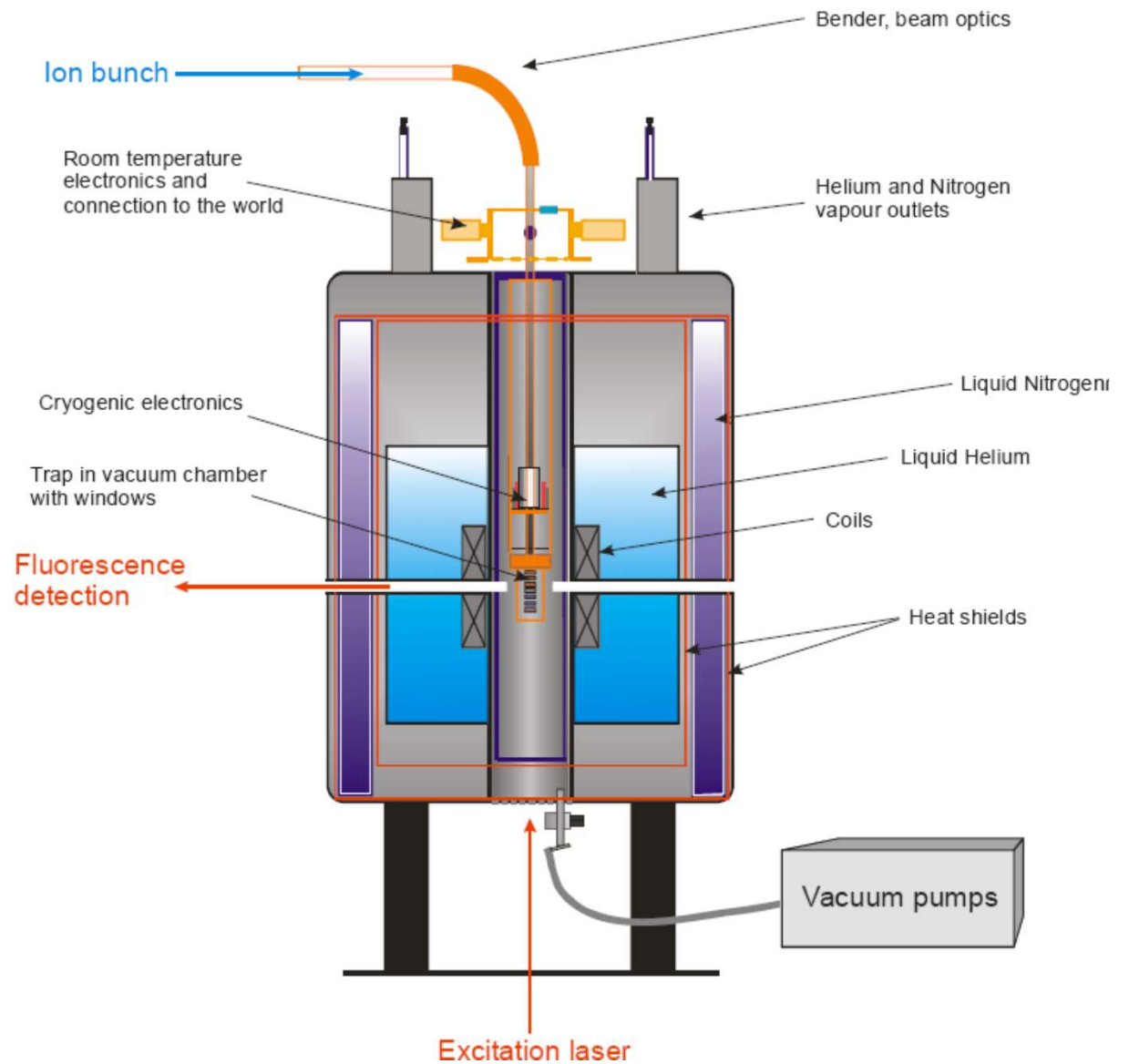
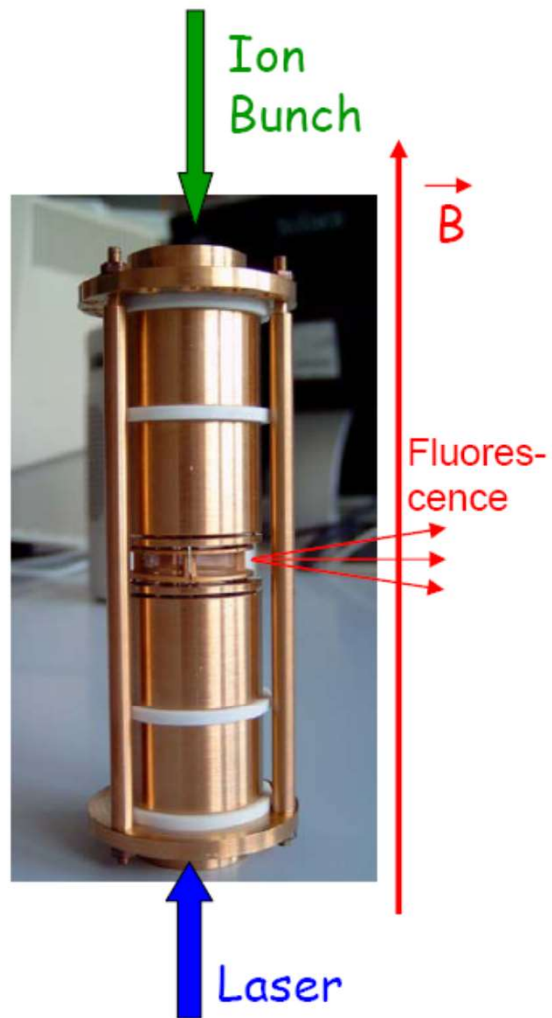


Quantum Electrodynamics (QED) in Highly-Charged Ions

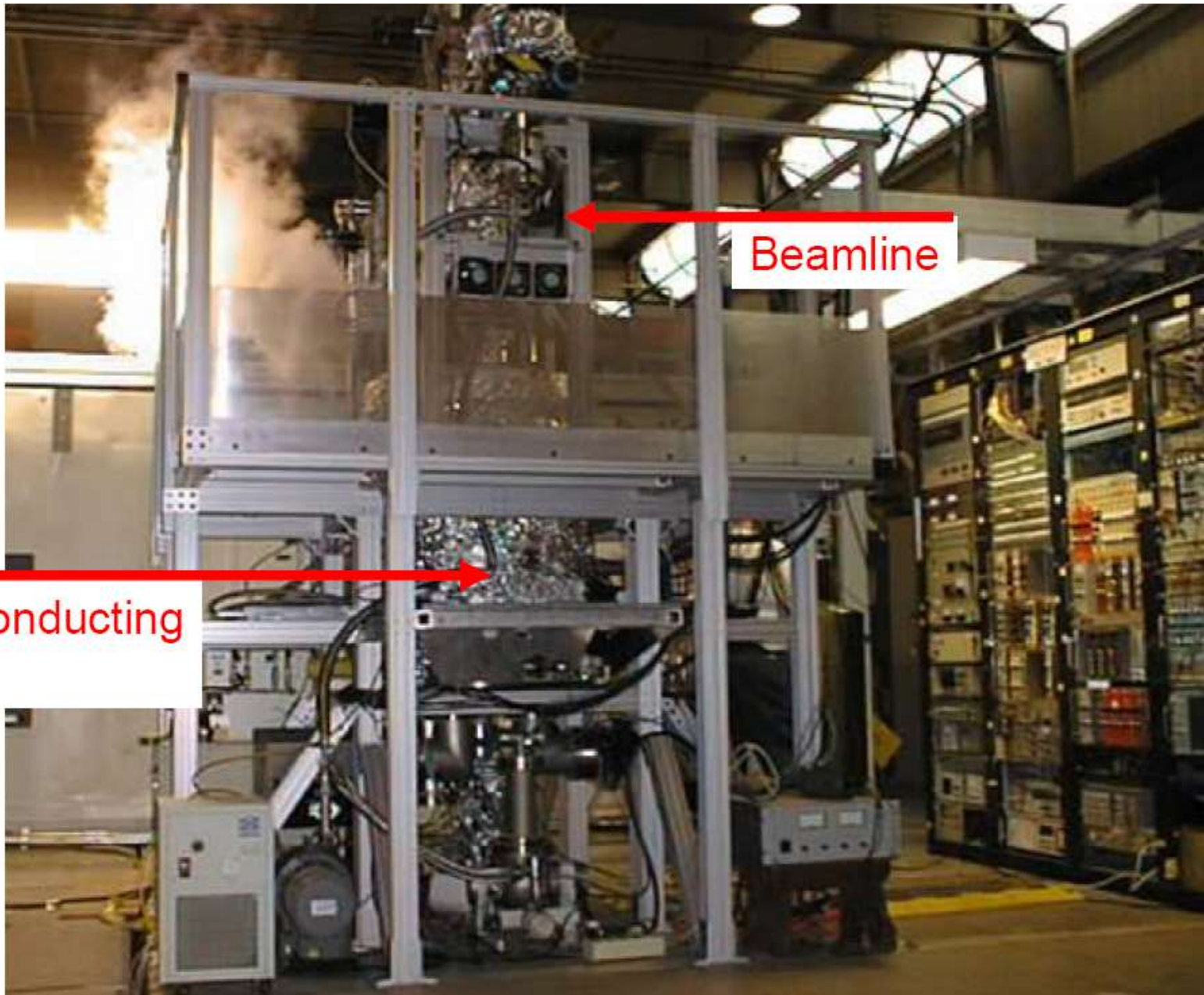
Tests of QED in strong electric fields generated by highly ionized heavy ions



Traps for Highly-Charged Ions

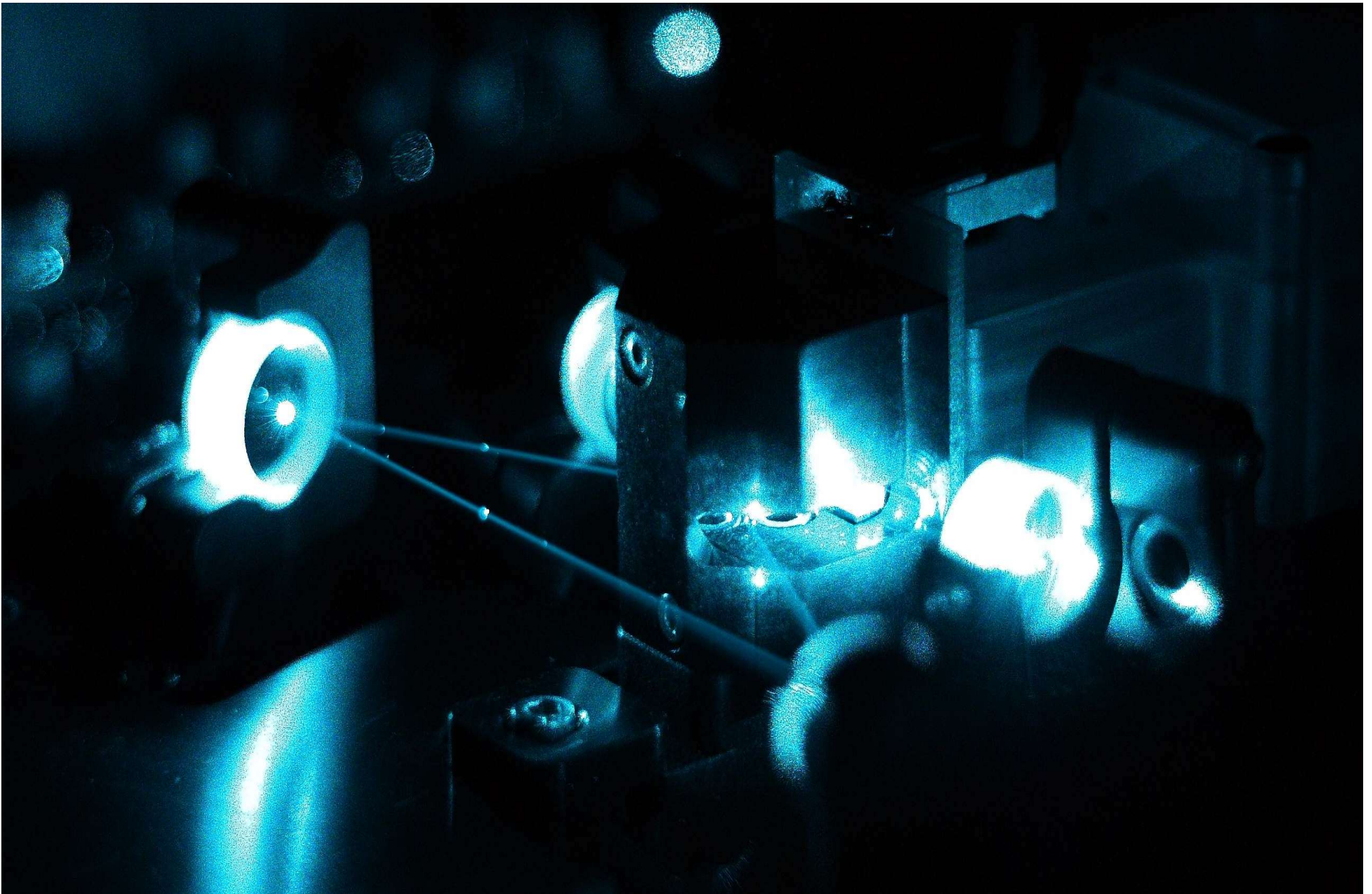


SPECTRAP – Experiment at GSI



Beamline

Superconducting
Magnet



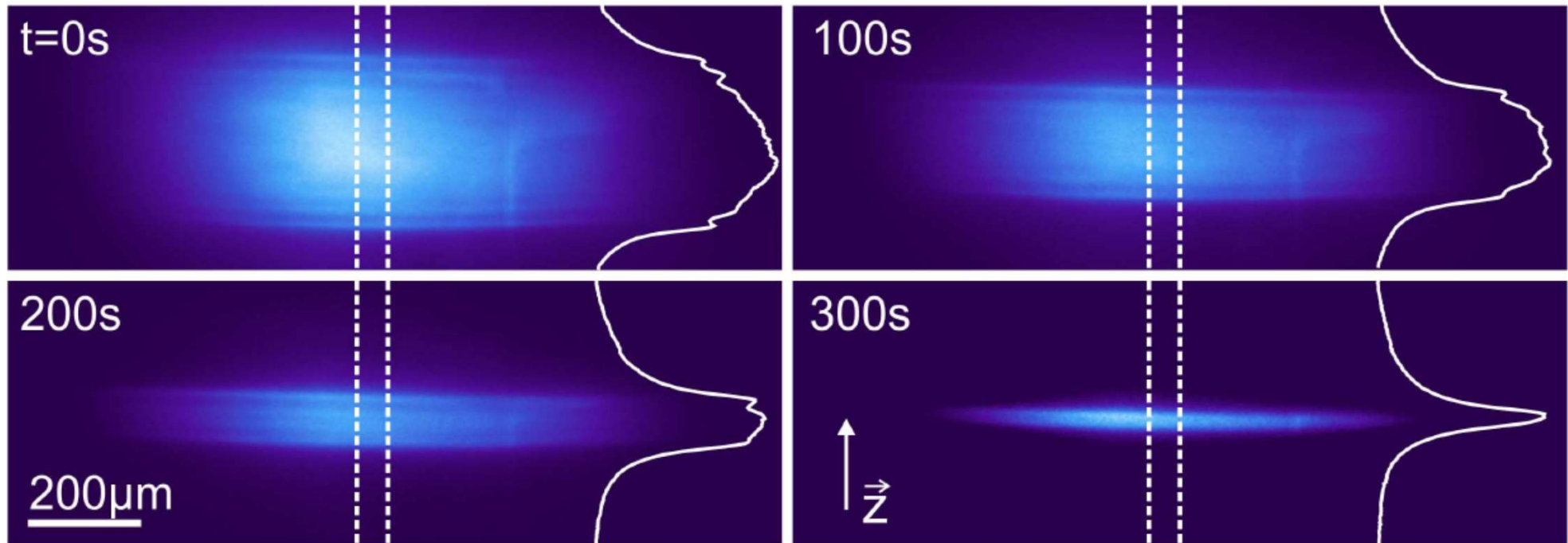
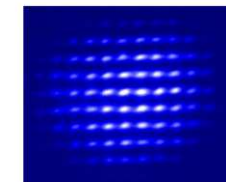


Figure 4.9: Four images of a Mg^+ ion crystal at different times. The trap's axis of symmetry is in vertical direction and the shell structure is visible in the images as well as in the cross sections through the central region (area within the dashed lines). With time, the number of ions and thus the number of shells decreases due to ion loss. At $t=0$, the images shows $3 \cdot 10^4$ ions that are irradiated by the laser beam. From the total (invisible) cloud volume, one can estimate the total ion number to be $N \approx 3 \cdot 10^5$.

Forschungsarbeit ist Teamarbeit. Wir brauchen engagierte Mitarbeiter und Mitarbeiterinnen für erfolgreiche Forschung. z.B. Sie!



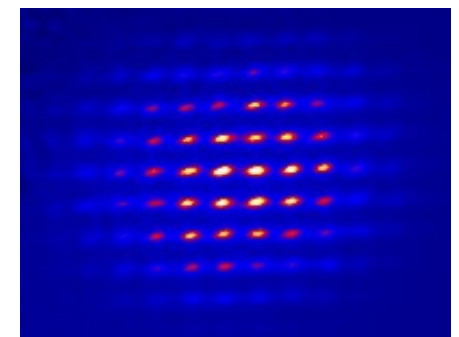
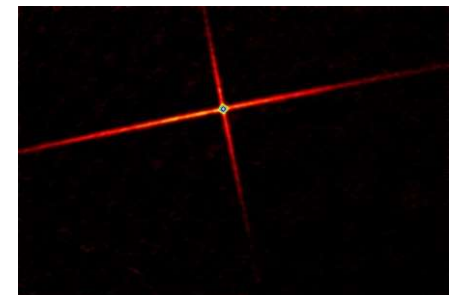
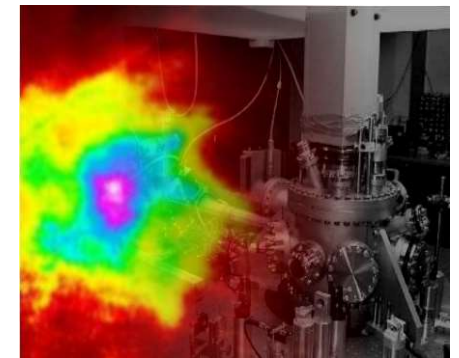
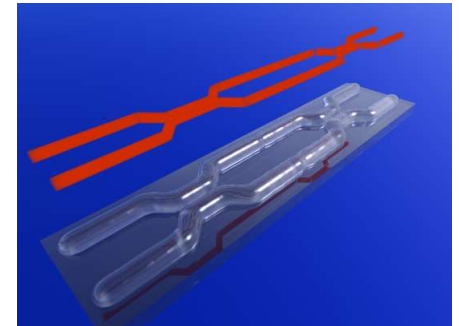
Fachbereich Physik
Institut für Angewandte Physik
ATOME - PHOTONEN - QUANTEN
Prof. Dr. Gerhard Birkl

Mögliche Themen für

Bachelor- und Masterarbeiten und Miniforschung

- Quanten-Simulation und Quanten-Computing
- Ultrakalte Quantengase
- Bose-Einstein-Kondensation (BEC)
- ATOMTRONICS = ‘Schaltkreise’ für Quantenmaterie
- Anwendungen der Mikrooptik in der Atomphysik
- Laserspektroskopie an hochgeladenen Ionen an der GSI
- Entwicklung und Aufbau von Lasersystemen (Optik)
- Entwicklung und Aufbau von Lasersystemen (Elektronik)

www.iap.tu-darmstadt.de/apq



Abgeschlossene Bachelor-Arbeiten (Auswahl)

- Bau eines Instruments zur Bestimmung des Radius von Laserstrahlen
- Aufbau und Test eines rauscharmen Stromtreibers für Diodenlaser
- Polarisationsstester für optische Fasern
- Durchstimmverhalten von gitterstabilen Diodenlasern
- Aufbau eines Laserdiodensystems im roten Wellenlängenbereich
- Entwicklung einer auf Radiofrequenzmodulation basierenden Stabilisierung für Diodenlaser
- Frequenzstabilisierung eines Diodenlasers durch Modulation eines Offsetmagnetfeldes
- Strahlformung und Aufbau eines Regelkreises zur Stabilisierung eines Diodenlasers
- Aufbau und Charakterisierung eines semi-konfokalen Resonators für Laserlicht bei 780 nm
- Realisierung und Optimierung einer Zwei-Frequenz-Steuerung eines Akusto-Opt. Modulators
- Aufbau und Test einer spektroskopischen Referenz für Rubidium
- Realisierung einer Sättigungsspektroskopie zur Stabilisierung von Diodenlasern
- Entwicklung einer elektronischen Ansteuerung für optomechanische Komponenten
- Untersuchungen zur Durchstimmbarkeit von Diodenlasern
- Computergestützte Steuerung und Auswertung v. Experimenten mit lasergekühlten Atomen
- Characterizing Microlenses for Optical Dipole Trap Arrays
- Aufbau und Charakterisierung eines Diodenlasers zur Chipkühlung von Rubidium
- Aufbau eines Diodenlasersystems bei 640nm
- Aufbau und vergleichende Charakterisierung von interferenzstabilisierten Diodenlasern
- Realisierung einer kompakten und fasergebundenen Diamanteinzelphotonenquelle

Abgeschlossene Master-Arbeiten (Auswahl)

- Kontrollierte Adressierbarkeit eines optischen Dipolfallenregisters
- Bose-Einstein Kondensate und optische Wellenstrukturen
- Bose-Einstein Kondensate und ringförmige mikrooptische Dipolpotentiale
- Planung und Aufbau eines Experiments zur Manipulation einzelner neutraler Atome
- Aufbau eines UV-Lasersystems für die Laserspektroskopie an gespeich. hochgeladenen Ionen
- Kohärente Präzisionsspektroskopie in einem Register optischer Dipolfallen
- Charakterisierung einer UV-Laserlichtquelle zur Spektroskopie von wasserstoff-ähnlichem Bi
- Detektion von Einzelatomen in Dipolfallenregistern
- Kohärente Manipulation von lasergekühlten metastabilen Neon-Atomen mittels Stimulated Raman Adiabatic Passage
- Bose-Einstein Kondensate in eindimensionalen Gittern
- Charakterisierung von Dipolfallenregistern für die Quanteninformationsverarbeitung mit neutralen Atomen
- Optimierte Detektion neutraler Atome in Dipolfallenregistern
- Experimente mit Isotopenmischungen von kalten metastabilen Neonatomen
- Präparation von Superpositionszuständen in metastabilem Neon
- Kohärenter Transport atomarer Quantenzustände in Registern optischer Dipolfallen
- Weiterführende Arbeiten am UV-Lasersystem u. Aufbau u. Charakterisierung von EIT-Spektr.
- Kohärenzeigenschaften von Bose-Einstein-Kondensaten in ringförmigen Dipolpotentialen
- Zustandabhängige Stoßwechselwirkungen lasergekühlter, metastabiler Neonatome
- Vorarbeiten zur Implementierung von Quantengattern in Dipolfallenregistern