Program of the COST-IOTA Workshop
IonTech: Techniques for Trapped Ions
Siegen, Germany

May 7-9, 2012

Organizing Committe:
Laurent Hilico, *Laboratoire Kastler Brossel, Paris, Evry University, France*
Roee Ozeri, *Weizmann Institute of Science, Rehovot, Israel*
Frédéric Rosu, *Laboratoire de Spectrométrie de Masse, Université de Liége, Belgium*
Christof Wunderlich, *Universität Siegen, Deutschland*
`http://www.ion-tech.org`

Credits:
Cover design: Michael Johanning

Welcome

Trapping of charged or neutral atoms and molecules is essential for very diverse research fields including astrophysics, chemistry, precision measurements in physics, and quantum information science. In addition, mass spectrometers widely used in research and industry often rely on similar technologies. This workshop will address technical challenges in trapping and manipulating particles that arise in many such experimental applications independent of their particular research background. Emphasis will be on modern laser light and microwave/ radio-frequency sources and their use in sophisticated trapping experiments, as well as cutting-edge micro- structured traps. This workshop will offer tutorials particularly suited for students and postdocs who wish to gain an overview of and insight into these experimental techniques and technology.

Supported by the COST network “Ion Traps for Tomorrows Applications“

Information for Participants

Accommodation

BEST WESTERN Park Hotel Siegen:

Koblenzer Straße 135
57072 Siegen
Tel: +49 (0) 271-33810

RAMADA Hotel Siegen:

Kampenstraße 83
57072 Siegen
Tel.: +49 (0)271 / 5011-0

Shuttle busses between the hotels and conference location will be provided for your convenience.

Conference Dinner

The Conference Dinner will be on tuesday 19 pm at the Berghotel Johanneshöhe.

Berghotel Johanneshöhe
Wallhausenstraße 1
57072 Siegen
Tel. +49 (0)271 / 387879-0

There will be an organized bus transfer from the workshop site and the physics campus to the dinner. A bus transfer back to the hotels will be provided, too.

Conference Site

Central activities like registration, talks and poster presentations will take place at the Artur-Woll-Haus.

Artur-Woll-Haus
Am Eichenhang 50
57076 Siegen

Internet Access

There are two possible ways to connect to the universities WLAN network:

- The eduroam network is available on all campus sites and can be accessed with already existing accounts.
- The second possibility is to use the workshop wireless network:

  SSID: tagung
  Password: *see printed version*

  This network is limited to the Artur-Woll-Haus.

Lab Tours

There will be three possible dates to visit the laboratories of the local quantum optics group. Interested participants are asked to enlist for one date at the registration office.

The lab tours will take place at the Emmy-Noether-Campus.

Emmy-Noether-Campus
Walter-Flex-Straße 3
57072 Siegen

There will be an organized bus transfer from the workshop site to the campus.

Luggage

Luggage can be stored in a locked room at the workshop site on wednesday.

Oral Presentation

The conference room is equipped with a data projector with VGA input. Laptops must be provided by the speakers.

Poster Presentation

Authors are asked to mount their posters at monday morning. Material for mounting the posters will be provided. The presenting authors should be present for discussing at their poster at least during one afternoon poster session. Please mark this time on the prepared note at the poster board.

Snacks and Coffee Breaks

Coffee, tea and beverages are served during the conference at the foyer.

Transport

A shuttle bus between the hotels, conference location, conference dinner and physic laboratories will be provided for your convenience.

Timetable

Time	Monday, 7 May	Tuesday, 8 May	Wednesday, 9 May
$8^{\underline{45}}$ - $9^{\underline{00}}$	Welcome		
$9^{\underline{00}}$ - $9^{\underline{50}}$	*Winfried Hensinger:* **Micro-fabricated ion traps I** (Tutorial)	*Philipp Treutlein:* **Generation, control, guiding and imaging of microwaves** (Tutorial)	*Rainer Blatt:* **Quantum Gates** (Tutorial)
$9^{\underline{50}}$ - $10^{\underline{10}}$	Coffee Break & Posters	Coffee Break & Posters	Coffee Break & Posters
$10^{\underline{10}}$ - $11^{\underline{00}}$	*Jonathan Home:* **Cryogenic ion trapping** (Tutorial)	*Roee Ozeri:* **Diode lasers for coherent manipulation of ions** (Tutorial)	$10^{\underline{10}}$ - $10^{\underline{35}}$ *Stephen Webster:* **High-Finesse Optical Cavities for Laser Locking** (Special) $10^{\underline{35}}$ - $11^{\underline{00}}$ *Wolfgang Alt:* **Imaging of single atoms and ions** (Special)
$11^{\underline{00}}$ - $11^{\underline{30}}$	Coffee Break & Posters	Coffee Break & Posters	Coffee Break & Posters
$11^{\underline{30}}$ - $12^{\underline{15}}$	*Ferdinand Schmidt-Kaler:* **Shuttling ions** (Overview)	*Ulrich Warring:* **Microwave Near-Field Quantum Control of Trapped Ions** (Overview)	*Jürgen Eschner:* **Laser Locking** (Overview)
	Lunch	Lunch	Lunch
$14^{\underline{00}}$ - $14^{\underline{30}}$	*Laurent Hilico:* **Ion capture and sympathetic cooling** (Special)	*Stephan Schiller:* **Laser sources for trapped molecular ion experiments** (Special)	*Jürgen Stuhler:* **Diode Lasers** (Special)
$14^{\underline{30}}$ - $15^{\underline{00}}$	*Yves Colombe:* **Micro-fabricated ion traps II** (Special)	*Thilo Hannemann:* **Review of DDS frequency sources** (Special)	$14^{\underline{30}}$ - $16^{\underline{30}}$: Posters & Lab tour
$15^{\underline{00}}$ - $15^{\underline{30}}$	Coffee Break & Posters	Coffee Break & Posters	
$15^{\underline{30}}$ - $16^{\underline{15}}$	*Jason M. Amini:* **Surface electrode ion traps: From concept to operation** (Overview)	*Michael Johanning:* **RF and Microwave Manipulation of Cold Ions** (Overview)	
$16^{\underline{15}}$ - $17^{\underline{00}}$	*Roman Schmied:* **Planar Trap Design** (Overview)	*David Lee Hayes:* **Control of hyperfine qubits with mode-locked pulsed lasers** (Overview)	
$17^{\underline{00}}$ - $19^{\underline{00}}$	Posters & Lab tour	Posters & Lab tour	
$19^{\underline{00}}$		Conference Dinner	

WORKSHOP PROGRAM

Monday

Morning

1 *Winfried Hensinger*
Microfabricated Ion Traps

2 *Jonathan Home*
Cryogenic ion trapping

3 *Ferdinand Schmidt-Kaler*
Shuttling ions

Afternoon

4 *Laurent Hilico*
Ion capture and sympathetic cooling

5 *Yves Colombe*
Micro-fabricated ion traps

6 *Jason Amini*
Micro-fabricated ion traps

7 *Roman Schmied*
Planar Trap Design: Overview

Tuesday

Morning

8 *Philipp Treutlein*
Generation, control, guiding and imaging of microwaves

9 *Roee Ozeri*
Diode lasers for coherent manipulation of ions

10 *Ulrich Warring*
Microwave Near-Field Quantum Control of Trapped Ions

Afternoon

11 *Stephan Schiller*
Laser sources for trapped molecular ion experiments

12 *Thilo Hannemann*
Review of DDS frequency sources

13 *Michael Johanning*
RF and Microwave Manipulation of Cold Ions

14 *David Lee Hayes*
Control of hyperfine qubits with mode-locked pulsed lasers

Wednesday

Morning

15 *Rainer Blatt*
Quantum Gates

16 *Stephen Webster*
High-Finesse Optical Cavities for Laser Locking

17 *Wolfgang Alt*
Imaging of single atoms and ions

19 *Jürgen Eschner*
Laser Locking

Afternoon

20 *Jürgen Stuhler*
Diode Lasers

Posters

21 *Joseba Alonso*
Development of a cryogenic surface-electrode ion-trap setup

Microfabricated Ion Traps

Winfried Hensinger

Department of Physics and Astronomy, University of Sussex, Falmer, Brighton, East Sussex, BN1 9QH, United Kingdom

Ion traps offer the opportunity to study fundamental quantum systems with a high level of accuracy highly decoupled from the environment. Individual atomic ions can be controlled and manipulated with electric fields, cooled to the ground state of motion with laser cooling and coherently manipulated using optical and microwave radiation. Microfabricated ion traps hold the advantage of allowing for smaller trap dimensions and better scalability towards large ion trap arrays also making them a vital ingredient for next generation quantum technologies. With this tutorial I will provide an introduction into the principles and operation of microfabricated ion traps.

Cryogenic ion trapping

Jonathan Home

Institute for Quantum Electronics, ETH Zurich, Schafmattstrasse 16 / HPF E8, Switzerland

I will give a tutorial on issues surrounding the operation of ion traps at cryogenic temperatures. Cryogenic ion traps have recently been shown to exhibit reduced anomalous heating compared to room temperature traps, and also offer long ion lifetime due to the low kinetic energy of background gas atoms.

Shuttling ions

Ferdinand Schmidt-Kaler

Institut für Physik, Universität Mainz, D-55128 Mainz, Germany

Ion capture and sympathetic cooling

Laurent Hilico

Laboratoire Kastler Brossel, UMR 8552, UEVE, CNRS,UPMC, ENS
Universit dEvry Val dEssonne, rue du pre Andr Jarlan, 91025 Evry
4 place Jussieu, 75252 Paris Cedex 05

A number of ion species of spectroscopic interest cannot be directly laser cooled. Thank to Coulomb interaction, they can be sympathetically cooled by laser cooled ions in a trap. This technique is now used in many experiments and under very different experimental conditions, from ion pair cooling down to the quantum regime [1] for quantum logic spectroscopy and ion clocks, to ion chains for quantum information processing [2], and to large ion clouds for atomic or molecular ion high resolution spectroscopy. Several projects involving sympathetic cooling by a cloud of laser cooled ions are currently developed or have been proposed. (i) H_2^+ two-photon vibrational spectroscopy and HD^+ single or two-photon ro-vibrational spectroscopy projects at the 0.1 ppb level are currently developed for m_p/m_e optical determination and fundamental constant variation analysis [3,4,5]. (ii) Visible fine structure transitions in highly charged ions (HCI) have been proposed as very interesting clock transitions with low systematic effects [6]. (iii) The GBAR project [7, 8] aims at producing antihydrogen at rest by photodetachment of the excess positron of sympathetically cooled positive antihydrogen ions $\overline{H}^+$. In the two later cases, the ions are produced by external sources (e.g. ECRIS sources or ELENA at CERN) at relatively high energies (keV) and high kinetic energy dispersion (tens of eV).

Ion capture efficiency, sympathetic cooling dynamics and steady state velocity distribution of the sympathetically cooled ions are important issues that are worth be numerically simulated [9].

I will first discuss the simulation model including Coulomb interaction and laser cooling process and the computer requirements. I will then discuss sympathetically cooled ion velocity distribution and the consequence on single photon and two-photon Doppler effect. Finally, I will discuss high energy ion capture and sympathetic cooling efficiency.

[1] T. Rosenband et al, Science 319, 1808 (2008)
[2] T. Monz et al., Phys. Rev. Lett. 106, 130506 (2011)
[3] J.-Ph. Karr et al., Phys. Rev. A 77, 063410 (2008)
[4] J. C. J. Koelemeij et al., Phys. Rev. Lett. 98, 173002 (2007)
[5] J.C.J.Koelemeij et al., Appl. Phys. B (2012) DOI: 10.1007/s00340-011-4802-y
[6] S. Schiller, Phys. Rev. Lett. 98, 180801 (2007)
[7] J. Walz, T. Hnsch, General Relativity and Gravitation 36, 561 (2004)
[8] SPSC-P-342 CERN proposal
[9] M. Bussman et al., IJMS 251, 179 (2006)

Micro-fabricated ion traps

Yves Colombe

National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

Surface electrode ion traps: From concept to operation

Jason M. Amini

Georgia Tech Research Institute, Atlanta, GA 30332, USA

I will cover a number of issues and concepts regarding the fabrication, operation, and characterization of surface-electrode ion traps. This includes results from the growing trap catalog developed by the Quantum Information Systems (QIS) Group at GTRI, demonstrating such features as integrated micromirrors, junctions, and microwave lines. The QIS groups trapping laboratory provides the detailed trap characterization needed to ensure that delivered traps perform as specified and to provide information for improving trap design, modeling, and fabrication.

Planar Trap Design: Overview

Roman Schmied

Department of Physics, University of Basel, Switzerland

Many current quantum technologies rely on trapping atoms or ions in free space in order to achieve long coherence times as well as easy experimental access. Scaling such experiments to relevant sizes and complexities requires scaling of the underlying trapping technology. Chip-based planar atom and ion traps offer unrivaled scalability of individually addressable quantum-mechanical systems. Despite being very different physically, both planar atom and ion traps can be described mathematically with very similar techniques, which I will present here.

I will start by reviewing efficient methods for calculating the three-dimensional electromagnetic fields generated by planar structures, including planar electrodes [2], wires, and permanently magnetized regions of an experimental chip [4]. Some specific limitations of these field calculation methods are discussed and quantified.

Following the critical discussion of the calculation methods, I will consider the theory and applications of design methods for determining the optimal surface layout of such planar structures (see fig. 1) for generating three-dimensional atom/ion trapping potentials with desired characteristics [1,3].

In conclusion, I will introduce briefly a freely available software package [5] which can be used to design and analyze planar atom and ion trapping structures.

[1] RS, J.H. Wesenberg, D. Leibfried, PRL **102**,233002 (2009)
[2] RS, NJP **12**,023038 (2010)
[3] RS, D. Leibfried, R.J.C. Spreeuw, S. Whitlock, NJP **12**,103029 (2010)
[4] RS, J.H. Wesenberg, D. Leibfried, NJP **13**,115011 (2011)
[5] http://atom.physik.unibas.ch/people/romanschmied/code/SurfacePattern.php

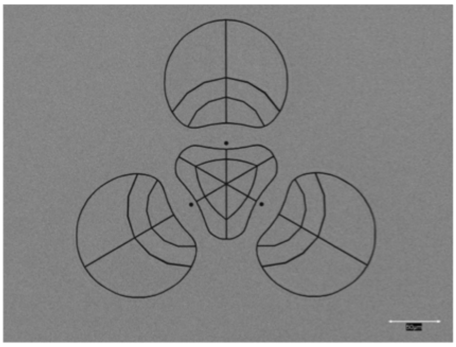


Figure 1: SEM image of the segmented electrodes of an optimally designed three-ion surface Paul trap (Sandia National Labs 2011).

Generation, control, guiding and imaging of microwaves

P. Böhi, M. F. Riedel, C. Ockeloen, R. Schmied, and P. Treutlein

University of Basel, Department of Physics, Klingelbergstrasse 82, 4056 Basel, Switzerland

Microwaves are a versatile tool for coherent manipulation of ultracold neutral atoms and ions. In experiments with atom and ion chip traps, it is desirable to directly integrate microwave fields on the chip using carefully designed waveguides [1]. In this talk, we will discuss the design, fabrication, and operation of such on-chip microwave guiding structures as well as the generation and control of the microwave signals that are launched onto the chip. Moreover, we will present a novel technique for high-resolution imaging of the on-chip microwave fields [2,3]. Our technique is based on spatially resolved detection of hyperfine Rabi oscillations in a cloud of atoms, see Fig. 1. We have experimentally implemented this technique both with ultracold [2] and room-temperature [3] atomic ensembles.

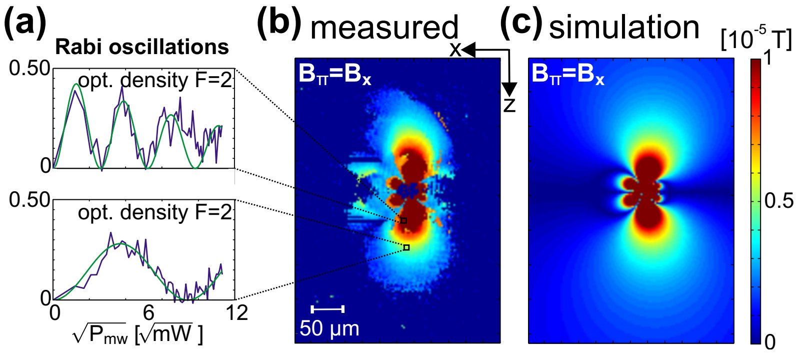


Figure 1: Microwave field imaging with ultracold atoms [2]. (a) Hyperfine Rabi oscillations in a cloud of ultracold ^{87}Rb atoms at two exemplary points near a coplanar waveguide. (b) Image of the microwave magnetic field component B_x in a cross section of the coplanar waveguide reconstructed from the measured Rabi frequencies. (c) Corresponding simulation.

[1] P. Böhi, M. F. Riedel, J. Hoffrogge, J. Reichel, T. W. Hänsch, and P. Treutlein, Nature Phys. 5, 592 (2009).
[2] P. Böhi, M. F. Riedel, T. W. Hänsch, and P. Treutlein, Appl. Phys. Lett. 97, 051101 (2010). U.S. patent application 12/729,812
[3] P. Böhi and P. Treutlein, to be published (2012), European patent application EP12161027

Diode lasers for coherent manipulation of ions

Roee Ozeri

Dep. Of Physics of Complex Systems, Weizmann Institute of Science, 234 Herzl Street,
Rehovot, Israel

Lasers are heavily used in trapped-ions experiments. Cooling, state selective fluorescence, the operation of optical-clocks and the generation of high-fidelity entanglement gates, are all done using frequency-stabilized lasers. In the past few years and especially since the development of GaN ultra-violate diode lasers, many of these required laser systems are available using diode lasers. The use of diode laser systems greatly reduces the cost of trapped-ion experiments and will enable to significantly reduce the system size, power consumption and weight. In this tutorial I will review the advantages and disadvantages of using diode-laser systems for the purpose of coherently manipulating trapped-ions. In particular I will focus on Raman lasers that manipulate ground-state; e.g. hyperfine or Zeeman; superpositions and on narrow line-width diode laser systems that drive optical quadrupole transitions.

Microwave Near-Field Quantum Control of Trapped Ions*

Ulrich Warring

NIST Ion Storage Group, Boulder, CO

Surface-electrode traps may provide a route toward scalable trap architectures for future quantum processors. In this geometry, micro fabrication techniques enable the generation of complex trap structures, which can incorporate zones for loading, storage, transport, detection, and manipulation. So far, quantum control in ion trap experiments is accomplished primarily with laser based techniques, in many cases implemented via Raman transitions addressing hyperfine qubits. Here, we discuss results for fully microwave driven quantum control, demonstrating individual single-qubit and entangling two-qubit gatesthe basis for a universal gate set in quantum information processing. Our microwave approach requires small distance scales between ions and electrodes, which can be achieved in surface-electrode traps. This method considerably reduces the laser overhead for implementing full quantum control, which can be important for future ion-based quantum processor architectures.

* Work supported by IARPA, ONR, DARPA, NSA, and the NIST Quantum Information Program

Laser sources for trapped molecular ion experiments

Stephan Schiller

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany

In this talk I will present a few examples of lasers and nonlinear-optical conversion systems used in our trapped molecular ion experiments. The emission wavelengths range from the mid-IR (5 μm) to the UV (313 nm).

Review of DDS frequency sources

Thilo Hannemann[1]

[1] *Erlangen, Germany*

A direct digital synthesizer (DDS) generates its output signal by computing the desired waveform digitally and using a digital-to-analog converter (DAC) to produce the analog signal. Advantages of the direct digital synthesizer over phase-locked-loop (PLL) based synthesizers are its high frequency resolution, high frequency agility and fast phase modulation capabilities as well as its generic capability to achieve phase continuous frequency switching. Its disadvantage is that its performance is ultimately limited by the performance of the DAC, in particular its sampling frequency and bit-width.

As ever faster and wider DACs become available, the DDS has become increasingly attractive as the frequency source of choice in the frequency range of up to several 100 MHz when fast modulation is required. However, direct digital synthesis has properties that are fundamentally different to that of the common phase-locked-loop based synthesizer. They are due to the sampled and quantized nature of the frequency generation process. Already in the digital domain the limited width of the sine lookup table gives rise to phase truncation spurs. Their frequencies and amplitudes depend strongly on the frequency tuning word that corresponds to the desired signal frequency. The limited resolution of the DAC results in wideband noise, while the DAC's non-linearities produce unwanted harmonics.

As with every sampled process, the output of a DDS is subject to frequency aliasing, which requires the use of an analog anti-aliasing filter behind the output of the DAC. This filter determines the frequency response together with the $sin(x)/x$ roll-off due to the sample-and-hold characteristics of the DAC. Those effects may be compensated digitally at the expense of signal-to-noise ratio at lower frequencies.

The long term frequency stability of a DDS is determined solely by the stability of its reference frequency source, while the narrowband noise is determined by the reference frequency source and the clock management of that particular DDS circuit.

In practice, when purchasing a frequency source, the device manufacturer has already taken the design decisions and the performance of the device is fixed. It is important then for the physicist to be able to read the data sheet and understand the impact of the device's performance on his experiment. This review shall give the fundamentals necessary for a critical examination und understanding of the performance figures listed for DDS devices as well as provide a starting point for an experimental characterization of a DDS device.

RF and Microwave Manipulation of Cold Ions

Michael Johanning

Lehrstuhl für Quantenoptik, Universität Siegen, 57068 Siegen, Germany

The manipulation of long lived Zeeman levels in hyperfine ground state manifold by rf and microwave radiation can be regarded as a cure to laser based limitations when using cold ions for quantum information, also loosening the requirements on ground state cooling and heating rates.

Addressability, as well as the coupling of internal and motional states can be achieved by applying an inhomogeneous magnetic field, which leads to a state dependent potential and force. As a result, the ions experience an effective tunable spin-spin coupling, which can be used to create highly entangled states, for example, for measurement based quantum computing, as well as for quantum simulations.

We discuss the pros and cons of this approach and discuss technical details of its experimental implementation. The two main aspects of this implementation will be the creation of steep magnetic gradients and the generation of the rf and microwave signals. Magnetic gradients can be created by different means, and we will give examples for macroscopic and 3d traps, as well as for planar traps.

On the other side, we will give an overview of the rf and microwave signal chain including frequency normals, signal generators, mixers, amplifiers and antenna concepts.

Control of hyperfine qubits with mode-locked pulsed lasers

Hayes David Lee

Joint Quantum Institute, University of Maryland Department of Physics, College Park, Maryland 20742, USA

In this talk, I will review our recent work in quantum control of trapped ion systems using the spectral features of mode-locked pulsed lasers in two distinct regimes. In the first regime, the laser power is low enough so that the effect of a single pulse on the state of the system is negligible but coherent accumulation of the effects of many pulses leads to the emergence of the resolved sideband limit allowing for ground state cooling, single qubit control and multi-qubit entangling operations. In the second regime, the laser power is high enough to change the state of the system with a single pulse and the speed of operations can be many orders of magnitude faster than the trapping frequency. Operating in the high power limit has allowed us to demonstrate ultra-fast control of a single spin and its entanglement with the motional state. I will also review the unique technical requirements and advantages gained by using pulsed laser systems.

Quantum Gates

Rainer Blatt[1,2]

[1] *Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25/4, 6020 Innsbruck, Austria*
[2] *Institut für Quantenoptik und Quanteninformation der Österreichischen Akademie der Wissenschaften, Otto Hittmair-Platz 1, 6020 Innsbruck, Austria*

High-Finesse Optical Cavities for Laser Locking

Stephen Webster

National Physical Laboratory, UK

Optical cavities find wide application in atomic, optical and laser physics [1], telecommunications, astronomy, gravitational wave detection [2], test of fundamental physics [3], quantum information science [4] and metrology [5] where they are used as laser resonators, for power build-up, filtering and spectroscopy. In laser stabilization, the frequency of the laser is locked to a mode of a passive optical cavity consisting of two highly reflective mirrors contacted to a glass spacer. The laser frequency is then defined by the optical length of the cavity, thus, for spectral purity, perturbations to this length must be minimized. To this end, the cavity is both highly isolated from its surroundings [6] and designed to be insensitive to environmental fluctuations [7]. Having suppressed the effects of technical noise a fundamental limit is reached, that due to thermal noise [8], and the lowest fractional frequency instabilities to have been reported are in the 10^{-16} region on a timescale of 0.1-100 s [9, 10]. Several applications of optical clocks, including earth-observation [11], tests of fundamental physics in space [12] and generation of ultra-stable microwaves for radar [13], demand that the supreme performance of an ultra-stable laser be available for use in a non-laboratory environment with stabilities targeted at the 10^{-15} level. For these purposes, cavities have now been developed which are insensitive to both vibrations and orientation [14, 15].

This tutorial will give an overview of all the essential aspects of stabilizing a laser to high-finesse cavities. It will cover the transmission spectrum, absorption, mode-matching, Pound-Drever-Hall locking, servo design, temperature and vibration sensitivities and stability measurements.

[1] G. Brooker, Modern Classical Optics, Oxford University Press, 2003.
[2] B. Willke et al., Class. Quantum Grav. 25, 114040 (2008).
[3] C. Eisele, A. Y. Nevsky, and S. Schiller, Phys. Rev. Lett., 103, 090401 (2009).
[4] H. Rohde, PhD thesis, (2001).
[5] P. Gill, Metrologia 42, S125 (2005).
[6] S. A. Webster, M. Oxborrow, and P. Gill, Opt. Lett. 29, 1497 (2004).
[7] S. A. Webster, M. Oxborrow, S. Pugla, J. Millo, and P. Gill, Phys. Rev. A, 77 033847 (2008).
[8] K. Numata, A. Kemery, and J. Camp, Phys. Rev. Lett. 93, 250602 (2004).
[9] B. C. Young, F. C. Cruz, W. M. Itano, and J. C. Bergquist, Phys. Rev. Lett. 82, 3799 (1999).
[10] Y. Y. Jiang et al., Nat. Phot. 5, 158 (2011).
[11] C. W. Chou, D. B. Hume, T. Rosenband, and D. J. Wineland, Science 329, 1630 (2010).
[12] The Einstein Gravity Explorer mission, Exp. Astron. 23, 573 (2009).
[13] T. M. Fortier et al., Nature Photon. 5, 425 (2009).
[14] D. R. Leibrandt et al. Opt. Expr. 19, 3471 (2011).
[15] S. A. Webster and P. Gill, Opt. Lett. 36 3572 (2011).

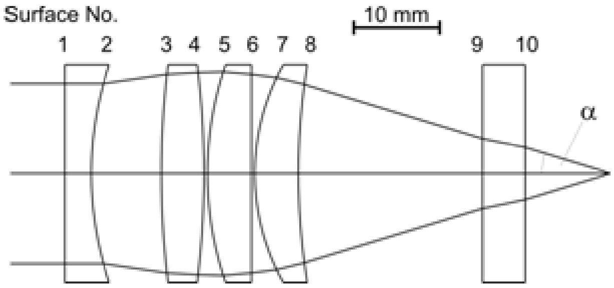
Imaging of single atoms and ions

Wolfgang Alt

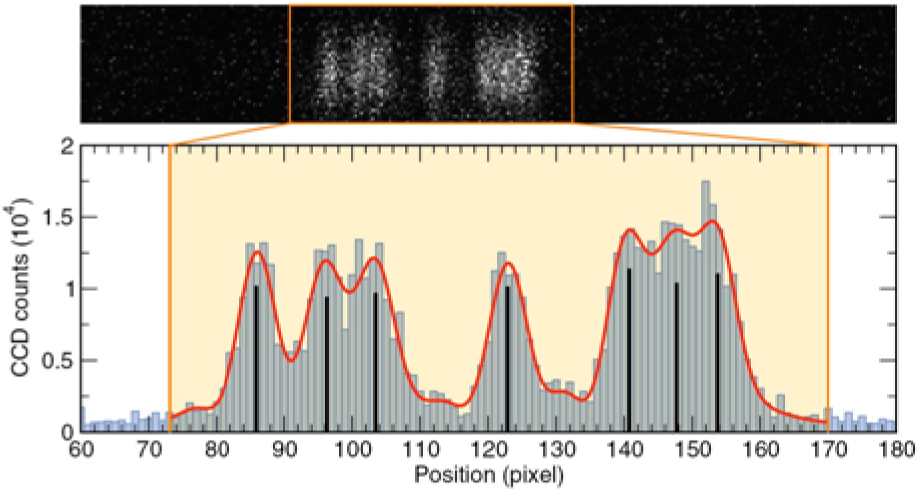
Universität Bonn, Institut für Angewandte Physik, Wegelerstr. 8, 53115 Bonn, Germany

Working with single trapped atoms and ions has enabled many ground-breaking experiments in the fields of quantum optics, quantum information processing and precision measurements which would remain inaccessible with large ensembles. A major requirement is the reliable detection of the individual atoms, which is typically achieved by fluorescence imaging.

I will give an overview of our experience on high-resolution single atom imaging by presenting the design, test and implementation of a cheap, diffraction-limited, long working distance and vacuum-window-corrected objective lens system [1].



Further topics include alternative imaging solutions and numerical post-processing of images for sub-diffraction-limited resolution [2,3,4].



[1] W. Alt: An objective lens for efficient fluoresence detection of single atoms, Optik 113, 142 (2002).

[2] I. Dotsenko, W. Alt, M. Khudaverdyan, S. Kuhr, D. Meschede, Y. Miroshnychenko, D. Schrader and A. Rauschenbeutel: Submicrometer position control of single trapped neutral atoms, Phys. Rev. Lett. 95, 033002 (2005).
[3] M. Karski, L. Frster, J. Choi, W. Alt, A. Widera and D. Meschede: Nearest-Neighbor Detection of Atoms in a 1D Optical Lattice by Fluorescence Imaging, Phys. Rev. Lett. 102, 053001 (2009).
[4] M. Karski, R. Reimann, L. Frster, A. Alberti, W. Alt, A. Widera, and D. Meschede: Analyzing fluorescence images of trapped atoms for single-site detection in a 1D optical lattice, in preparation

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Laser Locking

Jürgen Eschner

Experimentalphysik, Universität des Saarlandes, D-66123 Saarbrücken, Germany

Diode Lasers

Jürgen Stuhler

TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing, Germany

Development of a cryogenic surface-electrode ion-trap setup

Joseba Alonso[1], Florian Leupold[1], Ludwig de Clercq[1], Jonathan Home[1]

[1] *Institute for Quantum Electronics, ETH Zürich, Schafmattstrasse 16, 8093 Zürich, Switzerland*

We are developing a cryogenic ion-trap setup for investigating quantum control of trapped ions in micro-scale surface-electrode trap arrays, which can be fabricated using standard cleanroom techniques. The experiments we will perform involve quantum control of both beryllium and calcium ions, such that a coolant ion can be used to sympathetically cool a qubit ion while it is shuttled within the trap array. The combination of miniaturization and using two ion species will help tackle a major issue regarding quantum computation: scalability. In this poster, the challenges of developing such an experimental setup will be presented, along with the innovative solutions being implemented, and the current status of the project.

Ion trapping in a deep parabolic mirror

Marianne Bader [1,2], Robert Maiwald [1,2], Andrea Golla [1,2], Martin Fischer [1,2], Simon Heugel [1,2], Benoît Chalopin [1,3], Markus Sondermann [1,2], Gerd Leuchs [1,2]

[1] *Max Planck Institute for the Science of Light, 91058 Erlangen, Germany*
[2] *Institute of Optics, Information and Photonics, University Erlangen-Nuremberg, 91058 Erlangen, Germany*
[3] *Laboratoire Collisions Agrégats Réactivité, Université Paul Sabatier, 31062 Toulouse Cedex 09, France*

An efficient light-matter interaction is essential for various applications, e.g. quantum memories or gate operations. Aiming at a coupling efficiency close to unity of the electromagnetic field and a single trapped Ytterbium ion, we pursue a free space approach. Therefore we place the ion in the focal point of a deep parabolic mirror which can convert a suitably shaped plane wave into a dipole mode matching the dipole properties of the atomic transition [1]. The employed ion trap resembles the stylus trap described in ref. [2] which hardly reduces the accessible solid angle. Figure 1 shows the intensity profile of the trapped ion's fluorescence light leaving the parabolic mirror.

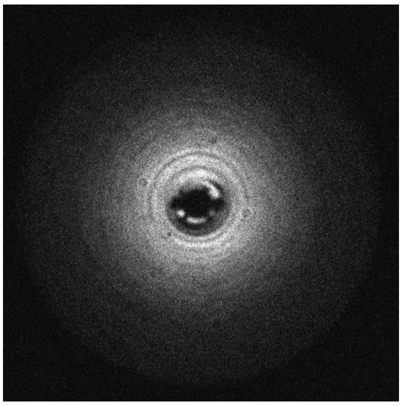

Figure 1: Fluorescence light of a single ion in the focus of a deep parabolic mirror.

The parabolic mirror not only acts as a mode converter, but also allows for a high collection efficiency of the fluorescence photons. With a collection efficiency of around 50% we go beyond the limit of fluorescence collection with a single lens.

We present the trapping of a single Ytterbium ion in the deep parabolic mirror as well as the scheme for fluorescence collection.

[1] Markus Sondermann, Robert Maiwald, Hildegard Konermann, Norbert Lindlein, Ulf Peschel, Gerd Leuchs, Appl. Phys. B 89, 489 (2007).
[2] Robert Maiwald, Dietrich Leibfried, Joe Britton, James C. Bergquist, Gerd Leuchs, David J. Wineland, Nature Physics 5, 551 (2009).

Quantum logic operations in $^{40}\mathrm{Ca}^{+}$ and $^{43}\mathrm{Ca}^{+}$ using microwaves and lasers

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Ion traps are currently the most mature technology for building a quantum information processor. All the operations needed to implement a processor have been demonstrated at good fidelity. However to build a scalable processor these operations have to be performed with small enough infidelity that error correction is possible ($\epsilon \lesssim 10^{-3} - 10^{-4}$). We present two experimental projects being pursued within the Oxford ion trap group aimed at increasing the fidelity of two-qubit gates.

Firstly, we have successfully implemented a magnetic field insensitive qubit in the intermediate field (146G) in the ground state manifold of $^{43}\mathrm{Ca}^{+}$. For this purpose, we have designed and built in-house a microfabricated surface ion trap based on a structured single gold layer on a sapphire substrate with integrated microwave waveguides and resonators. We are working on motional gates using the large gradient present in the evanescent field above the microwave resonators as recently demonstrated [1]. We used a full Bloch equation simulation of the 64 states in the $(S_{\frac{1}{2}}, P_{\frac{1}{2}}, D_{\frac{3}{2}})$ manifold to find a simple Doppler-cooling scheme for $^{43}\mathrm{Ca}^{+}$ at intermediate field. Preliminary results indicate that the trap has a heating rate amongst the lowest measured in a surface trap at room temperature, and that the qubit has a coherence time of order 10 seconds.

Secondly, we are aiming to implement a two-qubit gate using two different isotopes of Ca ($^{40}\mathrm{Ca}^{+}$ and $^{43}\mathrm{Ca}^{+}$) in a macroscopic linear Paul trap. The isotope shift on the order of 1 GHz is small enough to be spanned by optical modulators, which simplifies the laser systems, while allowing us to individually address the two ions. Transitions are driven by a pair of injection-locked frequency-doubled Raman lasers which can manipulate both isotopes. The high optical power in the Raman beams should allow us to drive transitions with low scattering error while maintaining a high Rabi frequency [2]. We have achieved Raman sideband cooling to the ground state ($\overline{n} < 0.1$) and are now implementing simultaneous readout on both isotopes as the final ingredient towards a high-fidelity entangling gate.

[1] C. Ospelkaus et al. Nature, 476(7359) 181-184 (2011).
[2] R. Ozeri et al. Phys. Rev. A, 75(4) 1-14 (2007).

An optically excited single ion oscillator

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We report on optically excited mechanical oscillations of a single, trapped ion. In our experiments we study axial motion of a $^{24}\mathrm{Mg}^{+}$ ion in a linear RF trap. We illuminate the ion with two laser beams near-resonant to the D_2 cycling transition; a cooling laser, which is red-detuned and damps the motion, and a gain laser, which is blue-detuned and increases the motional energy. The ion is not simply heated once the gain exceeds the cooling power, instead we observe optically excited oscillations in the trap potential.

At small gain laser power the ion's motional state is thermal, i.e. the time-averaged ion position follows a Gaussian distribution, which can be optically resolved in a shallow trap potential and enables thermometry with sub-millikelvin resolution [1]. As we increase the intensity of the blue-detuned laser we observe the thermal distribution evolving to oscillations with a stable amplitude over many cycles. Thus, the mechanical ion oscillator exhibits macroscopic features known from optical laser oscillators, such as gain saturation, and a transition from thermal to oscillatory operation. A quantized treatment shows that the amplification process arises from stimulated generation of phonons and the system can be considered as a phonon laser [2]. Here, the term phonon is associated with the quantized vibrational excitation in the axial trap potential. The origin of oscillatory operation is most intuitively understood from a power balance of a laser-driven sinusoidal oscillation. The detunings are modulated during each oscillation cycle due to the Doppler effect, so the cycle-averaged light pressure of both laser beams depends on the oscillation amplitude. In particular the gain saturates towards large oscillation amplitudes and stable operation points are found at defined oscillation amplitudes.

To deepen the analogy to optical lasers we demonstrated injection locking of the system. The presence of a gain mechanism, in this case established by the blue-detuned laser, enables the amplification of weak external signals close to the free-running oscillation frequency. We inject an RF signal which gets amplified, while the free-running oscillation is suppressed due to gain competition. The injection locking dynamics are studied by analyzing the oscillator spectrum with a spatially selective Fourier transform technique and the oscillator phase with stroboscopic imaging [3]. In both cases we find agreement with theory inside and outside the locking range. We attain phase synchronization with forces as low as $5(1)\times10^{-24}$ N, so this system might be promising for the detection of ultraweak oscillating forces.

[1] S. Knünz, M. Herrmann, V. Batteiger, G. Saathoff, T. W. Hänsch, and Th. Udem, Phys. Rev. A. **85**, 023427 (2012).
[2] K. Vahala, M. Herrmann, S. Knünz, V. Batteiger, G. Saathoff, T. W. Hänsch and Th. Udem, Nat. Phys. **5**, 682 (2009).
[3] S. Knünz, M. Herrmann, V. Batteiger, G. Saathoff, T. W. Hänsch, K. Vahala, and Th. Udem, Phys. Rev. Lett. **105**, 013004 (2011).

Molecular hydrogen ions, the proton-electron mass ratio and the proton size

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The molecular hydrogen ions (H_2^+, HD^+, *etc.*) consist of three elementary particles, which interact according to the laws of QED. Recently, theorists in the field have advanced the QED description of the molecular hydrogen ions to an accuracy level at which fundamental particle properties, such as the proton-electron mass ratio and the proton size, contribute substantially to the inaccuracy of calculated level energies [1-3]. Comparisons of theoretical level calculations with accurate spectroscopic data can therefore lead to new and improved values of fundamental particle properties, as well as stringent tests of QED. As molecular hydrogen ions possess long-lived rovibrational states, they are amenable to the most accurate spectroscopic technique to date, namely optical spectroscopy of laser-cooled ions stored in a trap. Here we report progress towards a new determination of the proton-electron mass ratio, based on high-resolution rovibrational laser spectroscopy of laser-cooled HD^+ [4], and towards a precision measurement of HD^+ hyperfine intervals through rf spin flips, which may be used to determine the proton Zemach radius. Furthermore, we show that ultrahigh-resolution vibrational spectroscopy of HD^+ will be affected by ac-Stark shifts due to blackbody radiation only at the 10^{-16} level [5].

[1] V.Korobov, Phys. Rev. A 77, 022509 (2008)
[2] V.Korobov, L.Hilico, J.-Ph.Karr, Phys. Rev. A 79, 012501 (2009)
[3] D.Bakalov, V.Korobov, S.Schiller,Phys. Rev. Lett. 97, 243001 (2006)
[4] J.C.J.Koelemeij et al., Appl. Phys. B (2012) DOI: 10.1007/s00340-011-4802-y
[5] J.C.J.Koelemeij, Phys. Chem. Chem. Phys. 13, 18844 (2011)

HD$^+$ frequency metrology

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Integrated quantum simulation and spectroscopy with trapped ions

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Laser-induced coupling between motional states and internal states of trapped ions enables both scalable quantum information processing and precision spectroscopy with trapped ions. It has recently been shown experimentally [1] how such operations can be realized using near-field microwave sources rather than laser beams, with important implications for scalability and potential high-fidelity operation. We discuss applications of these techniques to precision spectroscopy and quantum simulation.

In particular, we discuss the perspective of inducing spin-spin interactions in a quantum emulator through near-field techniques. The realization of this goal will require quantitative modelling and optimization of near-field microwave geometries. As a first step, we report on efficient numerical simulations of the trap structure used in [1]. We obtain excellent agreement with experimental "tomographic" data using the ion as a field probe.

Furthermore, we present the design of a low-vibration closed-cycle cryogenic ion trap setup. The setup features an integrated 1 Tesla vector magnet which will be used to access field-independent qubits as well as for a proposed experiment on precision quantum logic spectroscopy of the (anti-)proton [2,3]. The setup features excellent optical acces, a bakeable internal vacuum system as well as rapid turnaround for trap testing.

[1] C. Ospelkaus *et al.*, Nature **476**, 181 (2011).
[2] D. J. Heinzen and D. J. Wineland, Phys. Rev. A **42**, 2977 (1990).
[3] D. J. Wineland *et al.*, J. Res. NIST **103**, 259 (1998).

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Control and manipulation of cold molecular ions

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Due to their rich level structure, long trapping time and good isolation from the environment, molecular ions confined in the rf-Paul trap are attractive for precision measurements, spectroscopy and studies of the quantum mechanical aspects of chemical reactions [1]. However, the preparation and detection of quantum states of molecular ions remains a difficult task. Here, we introduce a scheme to cool both the motional and internal states of the molecular ions [2]. The molecular ion is sympathetically cooled to the ground state of motion via co-trapped atomic ions, while the molecular rovibrational states (internal states) are initialized with the help of optical pumping by broadband light [3] and manipulated via stimulated Raman transition with a frequency comb [4]. We also describe the associated quantum logic scheme to detect the state of the molecular ion [5]. The progress towards its experimental implementation is presented as well.

[1] L. D. Carr, D. Demille, R. V. Krems, J. Ye, New J. Phys. 11, 055049 (2009).
[2] S. Ding, D. N. Matsukevich, New J. Phys. 14, 023028 (2012).
[3] M. Viteau, et. al., Science 321, 232 (2008).
[4] D. Hayes, et. al., Phys. Rev. Lett. 104, 140501 (2010).
[5] P. O. Schmidt, et. al., Science 309, 749 (2005).

A linear trap for sympathetic cooling by Be^+ ions.

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The Kastler Brossel laboratory is involved in three high precision experiments with trapped ions that need to be sympathetically cooled :

- H_2^+ for an improved determination of the proton-to-electron mass ratio m_p/m_e [1],
- Highly charged ions HCI for fine/hyperfine structure spectroscopy [2],
- $\overline{H}^+$ ions for the GBAR international collaboration aiming at a measurement of gravitational properties of antimatter [3].

All these ions, having low mass-to-charge ratios (from 1 for $\overline{H}^+$ to ∼3 for HCI) can be sympathetically cooled by laser cooled Be^+ ions.

To cool the Beryllium ions we are currently developing an all-solid-state laser source at 313nm [4]. A new ion trap to confine Be^+ and H_2^+ ions is being fabricated. (figure1)

Be^+ ion fluorescence will be monitored with a CCD camera located on the trap side. State selected H_2^+ ions will be created by a REMPI process at 303 nm from H_2 molecules. H_2^+ spectroscopy will be performed by REMPD with a QCL IR source at 9.2 μm injected in an enhancement Fabry-Perot cavity implemented around the ion trap [5], and a UV dissociation laser at 248 nm [6].

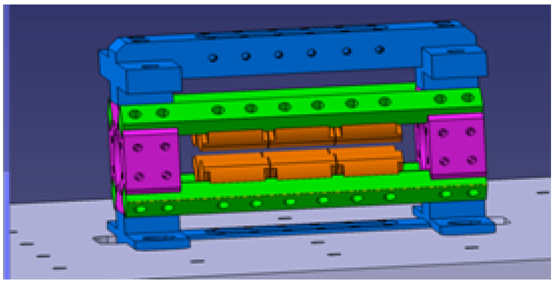

Figure 1: Linear trap design (side view). The different lasers will be shined either along the trap or with a small angle.

[1] J. Ph. Karr, A.Douillet, L. Hilico, to appear in Appl. Phys. B (2012).DOI : 10.1007/S00340-011-4757-Z
[2] S. Schiller, Phys. Rev. Lett 98, 180801 (2007)
[3] http://gbar.in2p3.fr/
[4] A. C. Wilson et al., Appl. Phys. B 105, 741 (2011)
[5] F. Bielsa et al., Optics letters 32, 1641-1643 (2007)
[6] J.-Ph. Karr et al., Appl. Phys. B, DOI : 10.1007/s00340-011-4757-z (2011)

A free space hybrid entanglement scheme

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For quantum communication networks to work over long distances, repeater stations similar to those used in classical optical communication are required. These quantum repeaters can be realized by generating entangled pairs of qubits distributed between the two communicating parties. The scheme we are presenting here follows the proposal of a hybrid quantum repeater [1], where trapped ions act as memories and a bright coherent pulse as a bus to generate the entanglement.

The crucial aspect of this kind of entanglement generation is to be able to discriminate between the phase of a pulse that has dispersively interacted with an ion and the phase of one that has not. Thus the fidelity of the generated entanglement greatly depends on the magnitude of the phase shift that can be induced. Up until now only small amounts of phase shifts compared to the theoretical possible in a free space geometry have been observed [2]. For larger phase shifts the light field incident onto an ion has to be tailored such, that the overlap between the incoming wave and the dipole mode of the atomic transition is as high as possible. With the setup proposed in Ref. [3] due to it's high solid angle coverage phase shifts of π could possibly be achieved while the excitation probability of the ion can be kept close to zero (see Fig. 1).

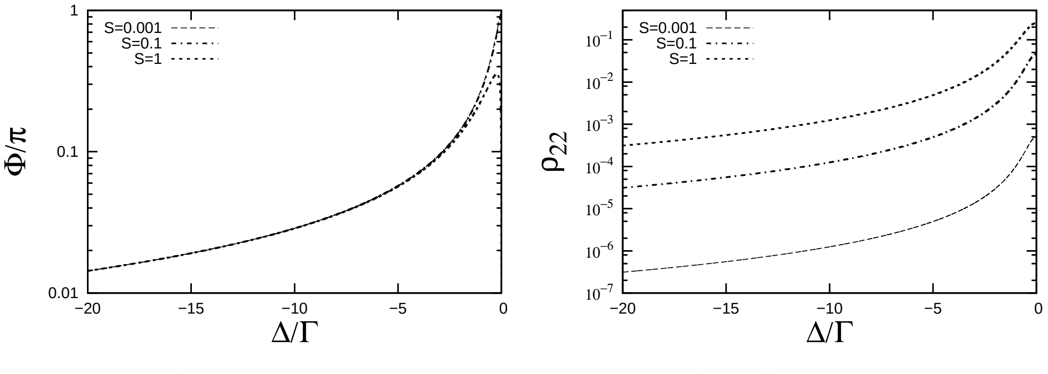

Figure 1: Phase shift over detuning and excitation probabilities for different saturation parameters S. For the figures a solid angle coverage of $\Omega_{rel} = 93.6\%$ and an overlap of the incident field with the emitted one of $\eta = 98.2\%$ were assumed, which are a realistic estimates for our system.

We present measurements of a light mode optimized for our setup as well as steps towards inducing a conditional phase shift on a bright coherent state depending on the superposition state of a single ion, acting as the dispersive medium.

[1] P. van Loock, T. D. Ladd, K. Sanaka, F. Yamaguchi, K. Nemoto, W. J. Munro and Y. Yamamoto, Phys. Rev. Lett. **96**, 240501 (2006).
[2] S. A. Aljunid, M. K. Tey, B. Chng, T. Liew, G. Maslennikov, V. Scarani, and C. Kurtsiefer, Phys. Rev. Lett. **103**, 153601 (2009).
[3] N. Lindlein, R. Maiwald, H. Konermann, M. Sondermann, U. Peschel G. Leuchs, Laser Phys. **17**, 927-934 (2007)

A cavity QED ion-photon interface

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Trapped ions have proven to be well-suited as stationary qubits at the nodes of a quantum network, allowing efficient initialisation, coherent manipulation, and readout of the quantum state. For coherent information transfer between different nodes, the polarisation state of a single photon is an ideal implementation of a flying qubit.

We implement a coherent interface between stationary and flying qubits by coupling a single trapped $^{40}\mathrm{Ca}^+$ ion to two orthogonal polarisation modes of a high-finesse optical resonator. By driving a vacuum-stimulated Raman transition, we generate single photons in the cavity on the $4\mathrm{P}_{3/2} \leftrightarrow 3\mathrm{D}_{5/2}$ transition. A laser on the narrow qubit transition $4\mathrm{S}_{1/2} \leftrightarrow 3\mathrm{D}_{5/2}$ enables the initialisation of the ion and the readout of its final state.

The results of entanglement between the electronic state of the ion and the polarisation state of the photon are presented. The entanglement is generated by driving the Raman transition with a bichromatic beam. Both the amplitudes and the phase of the entangled state are fully controlled.

We also present results for the mapping of an arbitrary electronic superposition state of the trapped $^{40}\mathrm{Ca}^+$ ion to a polarisation superposition state of a single photon.

Control molecular ion by frequency comb

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A planar quadrupole guide for electrons

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Millikelvin System for Hybrid Quantum Devices

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Hybrid quantum systems based on ultracold atoms and superconductors have been proposed to be used in quantum information processing. In these systems the logical operations will be carried out by the solid state devices, while the cold atomic ensemble can be used as a long lived memory for quantum information.

We report on the construction of a Millikelvin system which meets the requirements of long coherence and strong coupling of superconducting devices and ultracold atomic samples. Fundamental effects as the influence of the Meissner Effect on the trap parameters and the enhanced spin coherence have been studied on a 4K system.

The atoms are loaded into the MOT via a Zeeman slower and transported close to the superconducting devices by means of a magnetic conveyor belt within the Millikelvin environment.

[1] D. Cano *et al.*, Phys. Rev. A 77, 063408 (2008)
[2] D. Cano *et al.*, Phys. Rev. Lett. 101, 183006 (2008)
[3] B. Kasch *et al.*, New J. Phys. 12, 065024 (2010)

Development of a segmented ion trap for quantum control of multi-species ion chains

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We are developing a new experimental setup for quantum information processing, simulation and state engineering with trapped atomic ions. The system is designed to simultaneously trap both beryllium and calcium ions using a segmented linear Paul trap. We have designed and optimized a trap with three zones for quantum control and two zones for separation of ion strings; each step of trap fabrication has now been run independently. Preparation, cooling and quantum control of both ion species will require a wide range of laser light sources, many of which are not commercially available. For beryllium we have developed a 7.2W source of 626nm light using sum-frequency generation of two commercial high-power fibre lasers – further frequency doubling of the light will use BBO crystals in resonant cavities. The laser sources required for the calcium ion are commercial systems, which we have stabilized to custom made optical cavities, including one with a finesse of 290 000. To detect fluorescence from both ion species simultaneously, we have designed a high numerical-aperture imaging system consisting of in-vacuum objective lenses plus dual-channel optics outside the vacuum. A custom high-speed control system based on FPGAs is under-development, that will be used to generate phase-coherent pulses. This work presents a number of experimental steps towards precision control of trapped ions.

Fabrication process of a surface ion trap with integrated magnetic field generating elements and segmented electrodes

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Small dimensions of ion traps are advantageous to build up complex trap-structures and trap-arrays. A promising approach for this is the development of 2-dimensional electrode structures. By designing suitable electrode structures, a magnetic field gradient of 1.2 T/m per Ampère can be reached at a distance of 100 μm above the surface. This gradient increases exponentially when reducing this distance. An important advantage of the surface trap is the possibility to use micro-system technology for its production. We present a possible fabrication procedure of such a trap-chip using clean room technology such as optical lithography, electro-plating and etching. For this purpose a gold-electroplating device was constructed and integrated into an inexpensive small, home-made clean room. 100 to 200 μm wide gold-electrode structures with a height of 8.5 μm and an inner electrode distance of 10 μm are produced onto a sapphire wafer. Also, the integration of the trap-chip into an ultra-high-vacuum-system via a home-made chip-carrier is shown. This carrier is produced using thick-film technology and includes electrical low-pass filters directly on the carrier.

Development of ion chips and coherent manipulation of ytterbium ion

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To achieve large scale quantum information processing with trapped ions, the development of scalable ion trap arrays capable of performing high fidelity shuttling, detection and gate operations is necessary. We present our work towards developing these ion trap arrays. We also discuss our work towards performing coherent qubit manipulation towards the realisation of high fidelity gates using microwave dressed states. We also present work towards increased breakdown voltages for ion traps. We will also show how to create optimal two dimensional ion trap arrays for quantum simulations.

Novel RF-Traps for Multi-Ion Clocks

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We present our new experimental setup to test scalable chip-based ion traps for the development of trap structures with reduced excess micromotion that allow precision spectroscopy on a large ensemble of ions. Based on finite-element calculations [1] a novel trap is built employing high-precision laser machining and surface coating processes at PTB.

To minimize alignment errors a pair of ceramic wafers with laser cut electrode arrays forms the quadrupole geometry when stacked on top of each other. The laser cutting is done by a nanosecond pulsed laser at 355 nm. As wafer material sapphire and aluminum nitride have been tested due to their low rf losses and high thermal conductivity. For the coating of the electrode surfaces gold and molybdenum are used in order to investigate heating rates in the trap due to the electrode surface properties. To reduce high-frequency noise non-magnetic UHV compatible low-pass filters are soldered on the wafers close to the electrodes. The electric layout is a two-layer design including in-house developed vias.

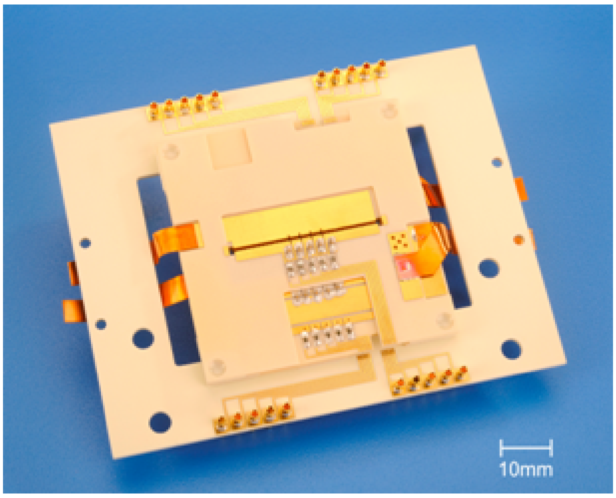

Figure 1: Prototype trap made of Rogers 4350B™ with non-magnetic UHV compatible low-pass filters.

In a prototype made of Rogers 4350B™ we have succesfully trapped linear chains and 3D-Coulomb crystals of $^{172}\mathrm{Yb}^{+}$ ions. We emphasize on the precision measurement of excess micromotion of a single $^{172}\mathrm{Yb}^{+}$ ion using photon-correlation spectroscopy. We are able to resolve a micromotion amplitude of 1.1 nm corresponding to a fractional frequency shift of the atomic transition of less than 10^{-19}.

With this resolution we were able to characterize our prototype trap to have an axial rf electric field gradient that allows the trapping of linear Coulomb crystals of twelve ions, that experience a fractional frequency shift due to time-dilation of less than 10^{-18}.

[1] Herschbach et al., Appl. Phys. B, (2011), DOI: 10.1007/s00340-011-4790-y

Building of a linear Paul trap for ultra-cold atom-ion collision experiment

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In the recent years the field of atom-ion interactions in the ultra-cold regime has gained a lot of experimental as well as theoretical attention. Atoms and ions interact through the polarization potential which scales as $-1/r^4$ at long distances. At short inter-nuclei separation molecular calculations yield approximate adiabatic energy curves of the atom-ion system. We are building a system which traps Rb atoms and Sr^+ ions and cools them to their quantum ground state. Atoms and ions will spatially overlap thus enabling the study of interactions in the ultra-cold regime (μK energy scale).

Our experiment is composed of two connected vacuum chambers. In one chamber atoms are collected and cooled to quantum degeneracy, whereas in the second chamber ultra-cold Sr^+ ions are trapped. A cloud of ultra-cold neutral atoms will be optically transported to overlap with the cold ions in the ion chamber.

Recent experiments [1,2] as well as semi-classical numerical Monte-Carlo simulations [3] have shown that the ion excess micromotion determines the energy of atom-ion collisions. We designed a linear segmented Paul trap in which excess micromotion amplitude is reduced to bellow the quantum limit of micromotion amplitude in the ground state.

[1] Zipkes C., Palzer S., Ratschbacher L., Sias C. and Köhl M., Phys. Rev. Lett. 105, 133202 (2010).
[2] Schmid S., Härter A. and Denschlag J. H., Phys. Rev. Lett. 105, 133202 (2010).
[3] Zipkes C., Ratschbacher L., Sias C. and Köhl M., New J. Phys. 13, 053020 (2011).

Design and development of a surface electrode ion trap for sympathetically cooled molecular ions

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Quantum state-controlled molecular ions cooled sympathetically by the interaction with laser-cooled atomic ions are of great interest for new applications in quantum information science, precision spectroscopy and collision studies [1-3]. Surface electrode radio frequency ion traps represent a new type of trapping architecture in which all electrodes lie in a plane and the ions are trapped above the surface [4]. These types of traps offer a high flexibility for manipulating, separating, and shuttling of cold ions, which is relevant for, e. g., large-scale quantum information processing [4] and quantum optics experiments with trapped molecules [3]. We have developed a six-wire surface electrode trap [5] for the sympathetic cooling and coherent manipulation of molecular ions [6]. We present a detailed discussion of the design, a theoretical characterization of the trap properties and first experimental results.

[1] S. Willitsch, Int. Rev. Phys. Chem., to be published.
[2] J. Mur-Petit, et al., Phys. Rev. A 85, 022308 (2012)
[3] D. I. Schuster, et al., Phys. Rev. A 83, 012311 (2011)
[4] J. Chiaverini, et al., Quantum Inf. Comput., 2005, 5, 419
[5] Allcock, D. T. C., et al., New Journal of Physics, 12 (5), 053026.
[6] I. M. Georgescu, S. Willitsch, Phys. Chem. Chem. Phys,13 (2011),18852.

Spin-Spin interactions of two ions

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Integrated quantum simulation

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An Ion Trap for Very Large Clouds

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The trapping of large ion clouds or crystals is gaining interest for various applications. Quantum information processing and microwave metrology are only two of possible topics. Our group is setting up an experiment destined to the investigation of the dynamics and thermodynamics of trapped ions. In particular the use of very large ion clouds is a challenge but may allow to reach interesting regimes for the study of phase transition and crystallization behaviour, or long-range interactions. Our trapping device is composed of zones of different geometry aligned along a common z-axis. A quadrupole and an octupole linear trap are mounted in line, the quadrupole part being separated in two zones by a center electrode. The geometry of trapping potentials has been optimized numerically [1]. The traps have been dimensioned to allow for the confinement of an ion cloud filling half the trap and reaching crystallization. Therefore the applied trapping voltages are of the order of several MHz with amplitudes of a couple of hundred volts (in order to trap Ca^+-ions).

Ions are created by photoionization from an atomic calcium beam crossing the first quadrupole zone. Clouds of more than 10^5 ions have been trapped and crystallized in the quadrupole part. These ion numbers correspond to cloud sizes which are still largely below 50 percent of the trap radius.

Shuttling of the ions between the different zones of the device is one of the challenges. In view of the large number of parameters (voltage amplitudes, durations, switching functions and times), protocols have to be optimized numerically. While different solutions for shuttling have been proposed for QIP, the present experiment has to take into account additional parameters, as for example the fact that the ion cloud is 3D, and or the ratio of transport distance to the number of DC electrodes which is several orders of magnitude larger than in microtraps. First experimental test are very promising and will be reported.

[1] J. Pedregosa, C. Champenois, M. Houssin, M. Knoop, IJMS 290, 100-105 (2010).

Progress towards studying cold ion-molecule reactions

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We present the design of a new experimental setup which combines buffer gas cooling and guiding of neutral polar molecules with a source of trapped laser-cooled ions. The molecular source uses a cryogenic cell filled with helium at 5 K to produce beams of translationally and internally cold polar molecules. The molecules are transported using an electrostatic quadrupole velocity selector to a vacuum chamber containing a linear Paul trap. Calcium ions stored in the ion trap are laser-cooled to produce so-called Coulomb crystals which provide a highly-localised ensemble of ions at mK temperatures. Chemical reactions of cold polar molecules with Ca+ or with sympathetically-cooled molecular ions will be studied. The apparatus will be used to measure reaction rate constants and branching ratios for a variety of cold ion-molecule reactions, and in particular those with H/D atom transfer channels.

Towards a portable optical Al^+ clock using quantum logic

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We present the status of our transportable optical clock based on quantum logic interrogation of a single Aluminium ion. The design goals for this frequency standard are an inaccuracy of 10^{-17} or better and relative stability of 10^{-15} in one second. $^{27}Al^+$ has been chosen as the clock ion since it has a narrow (8 mHz) clock transition at 267 nm which exhibits no electric quadruple shift and a low sensitivity to black-body radiation. The $^{27}Al^+$ clock ion will be trapped together with a $^{40}Ca^+$ ion which will act as a logic ion and is used for sympathetic cooling and internal state detection of the clock ion with techniques developed for quantum information processing. We set up a linear trap with sapphire insulators and titanium electrodes to improve thermal management and minimize magnetic field distortions. The short term stability of the clock is provided by a 39.5 cm long ultra-stable optical cavity. For clock comparisons beyond a fractional uncertainty of 10^{-16} we plan to build a portable system that allows us to travel to other places. We also present a design study of a new miniaturized monolithic ion trap for quantum logic clock applications. This gold coated trap will be machined from a AlN-rod by precision laser cutting. The monolithic trap design guarantees a highly symmetric geometry (i.e. parallelism, distances of the electrodes). Together with its small dimensions and mechanical robustness this should allow a better transportability and thereby make it interesting for space applications.

Large two dimensional Coulomb crystals in a radio frequency surface ion trap

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We designed and operated a surface ion trap, with an ion-substrate distance of 500 μm, realized with standard printed-circuit-board techniques. The trap has been loaded with up to a few thousand Sr$^+$ ions in the Coulomb-crystal regime. An analytical model of the pseudo-potential allowed us to determine the parameters that drive the trap into anisotropic regimes in which we obtain large ($N > 150$) purely two dimensional (2D) ion Coulomb crystals. These crystals may open a simple and reliable way to experiments on quantum simulations of large 2D systems.

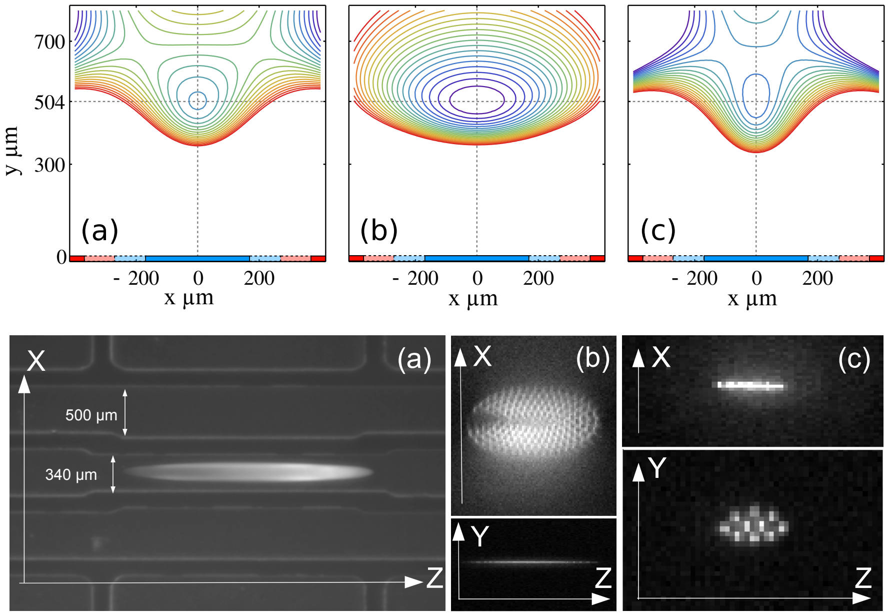

Figure 1: Pseudo-potential cross sections calculated and fluorescence images of the trapped ions for three configurations. (a) isotropic potential, top-view of a large 3D Coulomb crystal containing ~ 4500 ions. (b) anisotropic pseudo-potential, 2D Coulomb crystal containing ~ 150 ions arranged in a plane parallel to the trap surface (the inter-ion distance is 11 μm). The single-layer character is evidenced by the lateral view. (c) anisotropic pseudo-potential, Single-layer crystal arranged in the yz plane perpendicular to the printed circuit board (the inter-ion distance is 9 μm).

B. Szymanski et al. arXiv:1201.2584v1 (2012).

List of Speakers and Presenters