Centre for Quantum Engineering and Space-Time Research

Leibniz Universität Hannover

Micro-Structured Ion Traps for Optical Clocks

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The center for "**Q**uantum **E**ngineering and **S**pace **T**ime Research" devotes its work to fundamental questions in physics related to gravity and cosmological models and the development of new quantum sensors for experimental tests.

The most accurate measurements today are made in time and frequency metrology. An optical clock with a fractional frequency accuracy and stability of 10^{-18} allows for

- tests of the predictions of general relativity (local position invariance, gravitational redshift)
- search for a temporal variation of fundamental constants: α, m_e/m_p [1,2] (modern string theories predict variation, some astrophysical observations indicated variation)
- gravity sensing for geodesy
- future generations of navigation / space navigation

Short term instability of a frequency standard scales like:

$$\sigma = \frac{1}{\pi\, S/N}\,\frac{1}{Q}\sqrt{\frac{T_c}{\tau}}$$

with quality factor:

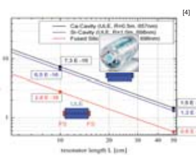
$$Q = \frac{\upsilon_0}{\Delta\upsilon}$$

Best result today: comparison of 2 ion clocks (Al^+/Al^+)[3]:

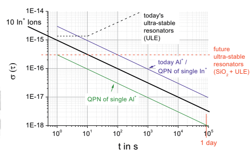
inaccuracy = 7.0×10^{-18}
stability σ ~ 2.0×10^{-15} in 1s

Clock laser performance and long interrogation time place severe limits for single ion standards:

Thermal Noise Limit of Clock Laser:

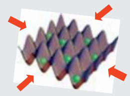


Targeted Clock Performance :



[4] calc.: Th. Legero based on Numata et al, PRL, 91, 260602 (2003)

High short term stability versus high accuracy:

Neutral Atom Clocks	Single Ion Clocks
	
N ~ 10^4 atoms	N ~ 1 atom

Our approach: combine advantages of both for better short term instability and shorter interrogation time.

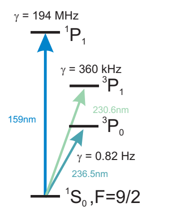
Arrays of ions with $\Theta = 0$

Quadrupole Shift:

$$h\Delta\nu = \langle \gamma J F m | \nabla E \bullet \Theta | \gamma J F m \rangle$$

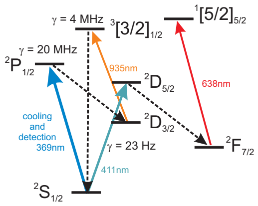
An optical frequency standard based on $^{115}In^+$ & $^{172}Yb^+$

Frequency Reference System: $^{115}In^+$



- direct detectable transition to $^3P_1$
- 2nd order Doppler shift in RF-field $\beta = \Delta\nu/\nu = -v^2/2c^2 \sim m^{-2} \rightarrow \beta_{Al+}/\beta_{In+}=18$
- low blackbody shift $\Delta\nu/\nu = 1.45\ 10^{-17}$ @ T=300K private comm. M. Safronova (to be published)
- no quadrupole shift, $\Theta = 0$
- 2nd order Zeeman: $^{27}Al^+$: 72 Hz/mT², $^{171}Yb^+$: 52 kHz/mT², $^{115}In^+$: 4.1 Hz/mT²

Sympathetic Cooling and first Tests with $^{172}Yb^+$



- efficient cooling & detection
- storage times of weeks
- YbH^+ is dissociated by cooling laser
- all diode laser system
- no hyperfine structure

Trap Technology Development

Trap assembly:

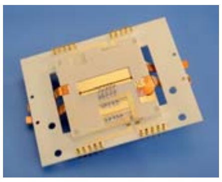
Electrode blades: (Al_2O_3, AlN, sapphire,...)
- precise machining: laser cutting, < 10µm tolerance
- low RF losses
- UHV compatible

SEM image of first laser cut Al_2O_3 waver

Metal coating - Au, Mo, Nb

Compact electronic devices:
- UHV compatible, non-magnetic capacitors and resistors for onboard filtering (low pass with 110Hz cutoff frequency, C=4.7nF, R=300kΩ)

Prototype:



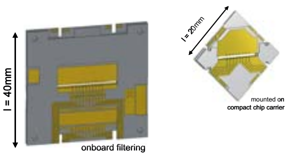
Top: closeup of trapping region
- SMD components for onboard filtering of DC voltages
- segmentation for axial confinement and transport
- compensation through extra layer on top and bottom of the trap

Left: Assembled trap
- soldering with Kester Sn96.5Ag3
- glued with Optocast 3410 Gen2
- ball bonding with 30µm gold wires
- RF connection: OFHC Cu foil

High end trap:

two designs:

- prototype design (onboard filtering)
- chip carrier based (separate filtering)



Scalable Trap Structures for Clocks at 10^{-18} level

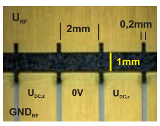
First trap design:

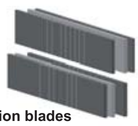
Material: Rogers 4350B, thickfilm gold electrodes

Parameters: U_{RF} = 1500V, $\Omega_{RF} = 2\pi$*25MHz, $U_{DC,z}$ = 10V

Loss factor: L = 1,27

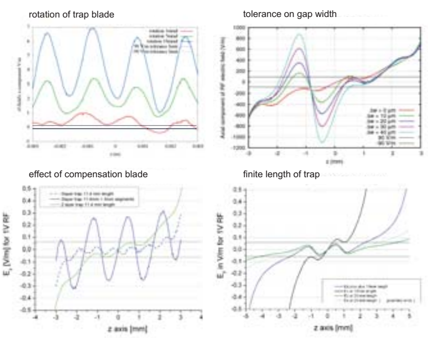
	$\omega_{sec,r}/2\pi$ [MHz]	$\omega_{sec,z}/2\pi$ [MHz]	q_r
$^{172}Yb^+$	0,951	0,175	0,11
$^{115}In^+$	1,422	0,215	0,16





3-layer trap with compensation blades

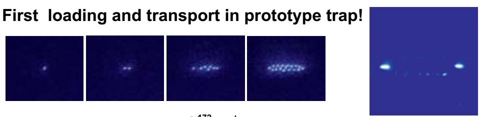
High resolution FEM simulations of RF fields:



(solid black lines indicate region with 2nd order Doppler shift < 10^{-19})

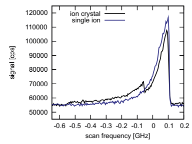
Experimental Set-Up

First loading and transport in prototype trap!



Deterministic loading of $^{172}Yb^+$

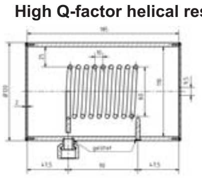
Trapping and cooling of ion chains and crystals before micromotion compensation



Flexible setup for testing

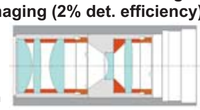
different trap geometries and spectroscopy methods
large solid angle for detection, 3D control of micromotion

High Q-factor helical resonator ($Q_{unloaded}$ = 1055)

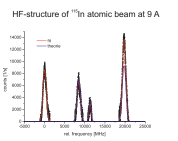


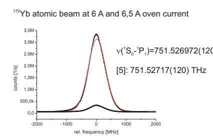
Self-built retrofocus lens for single-ion imaging (2% det. efficiency)

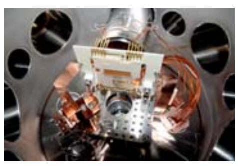
N/A = 0.27
wd = 31mm
EFL = 20.7mm



Atomic oven made of tantalum for In and Yb







Vacuum chamber inside: In & Yb oven, 41pin DC-feedthrough with kapton cables, OFHC Cu RF-connection

Vacuum chamber and board for optical setup

Cooperations:
PTB departments: "Time & Frequency", "Quantum Electronics", Clean Room Center
QUEST group "Experimental Quantum Metrology"
& ILP (Institute of Laser Physics) Novosibirsk

Challenges:
- Heating rates due to thermal fluctuations of patch potentials causing 2nd order Doppler shift (different materials?)
- Micromotion due to patch potentials, electrostatic stray fields, trap imperfections, RF phase shifts

[1] Murphy et al., Mon. Not. R. Astron. Soc. **345**, 609 (2003), [2] Reinhold et al., PRL **96**, 151101 (2006), [3] Chou et al., PRL 104, 070802 (2010), [4] calc.: Th. Legero based on Numata et al, PRL, 91, 260602 (2003), **[5]** A. H. Nizamani et al., arXiv:1006.3750v1 (2010)