Centre for Quantum Engineering and Space-Time Research

Quantum Sensors with Cold Ions

Jonas Keller, Karsten Pyka, Norbert Herschbach, Tanja E. Mehlstäubler

QUEST-Institut an der Physikalisch-Technischen Bundesanstalt, Bundesallee 100, 38116 Braunschweig

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

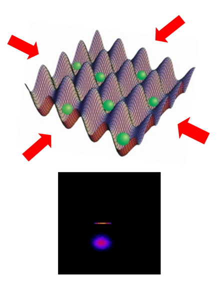
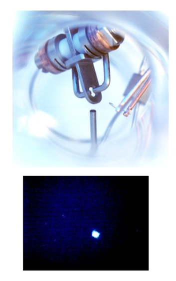
One atomic sensor allowing for the most accurate measurements in physics yet is an optical clock. For trapped ion clocks, a relative frequency inaccuracy as low as 1 part in 10^{18} is within reach.
The precise measurement of frequency can open up new fields such as:

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

Therefore, we need robust, reliable, accurate and stable clocks with high short term stabilities to reach targeted accuracy within hours and not days.
⟶ systematic errors at this level can only be evaluated with reasonably short integration times

[1] Murphy et al., Mon. Not. R. Astron. Soc. **345**, 609 (2003)
[2] Reinhold et al., PRL **96**, 151101 (2006)

Today's State of the Art

Neutral Atom Clocks	Single Ion Clocks
	
N ~ 10^4 atoms trapped and localized in optical lattice	N ~ 1 atom trapped and localized in RF trap

Short term instability of a frequency standard scales like: $\frac{1}{S/N}\frac{1}{Q}\sqrt{T_c}$

with quality factor: Q $\frac{}{0}$

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

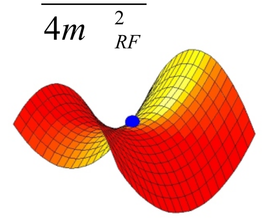
inaccuracy = 8.6×10^{-18}
stability ~ 2.8×10^{-15} in 1s

Higher Q: clock laser performance and long interrogation time place severe limits

[3] Chou et al.,arXiv:0911.4527v2 (2010)

Ion Traps

- ion trapped in ponderomotive pseudo-potential $\frac{e^2E^2}{4m\ \ ^2_{RF}}$
- compact, robust systems
- long storage times in trap: 1d to months
- demolition free detection of ions, large trap depth $T_{Trap} = 10^4$ K (comp. T_{Trap} = 50 µK in lattice)
- high control of ion dynamics in RF trap



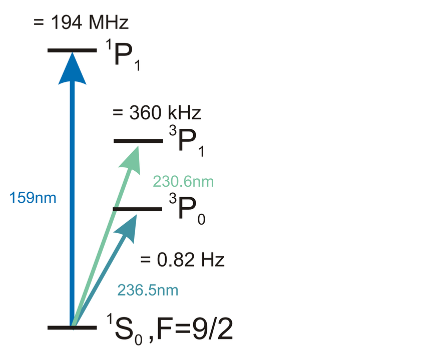
But for single ion: S/N ~ 1
stability limited by quantum projection noise

$$\frac{S}{N} \quad \frac{p_{ex}p_{max}}{\sqrt{p_{ex}p_{max}(1 \quad p_{ex}p_{max})}}$$

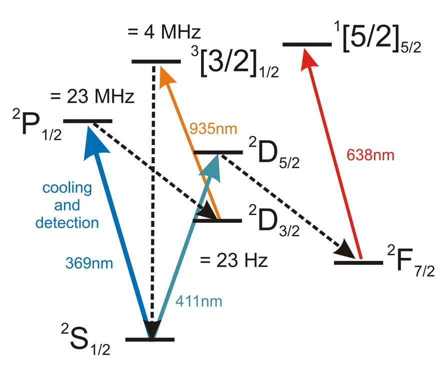
Ansatz:
new trap geometries to trap and store *many* ions, fast locking of clock laser onto atomic transition

suitable for ions with = 0 (In^+, Al^+, Si^{++}, etc...)
quadrupole shift: $h \quad \langle JFm | E \quad | JFm \rangle$
(Coulomb interaction produces E gradient)

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

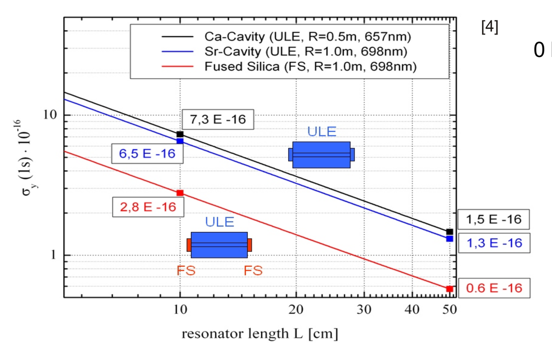


Sympathetic Cooling and first Tests with $^{172}Yb^+$



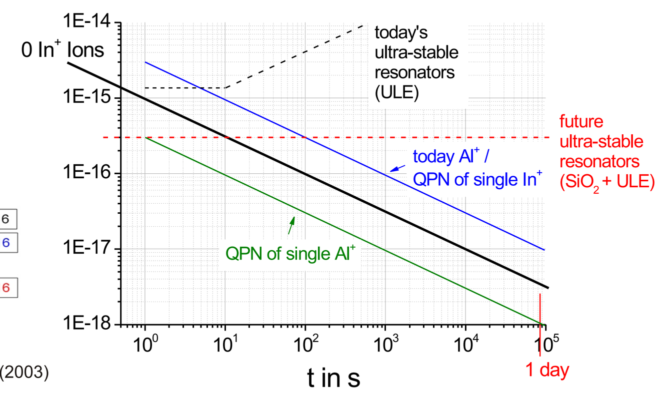
-efficient cooling and detection
-storage times of weeks
-all diode laser systems
-no hyperfine structure

Thermal Noise Limit of Clock Laser:



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

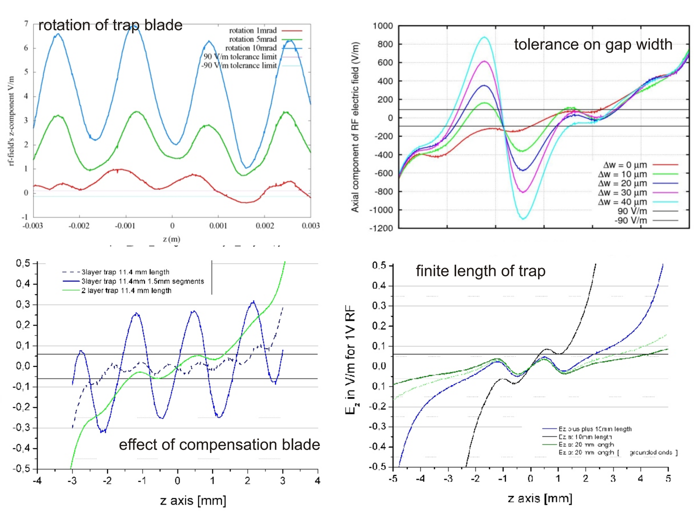
Targeted Clock Performance :



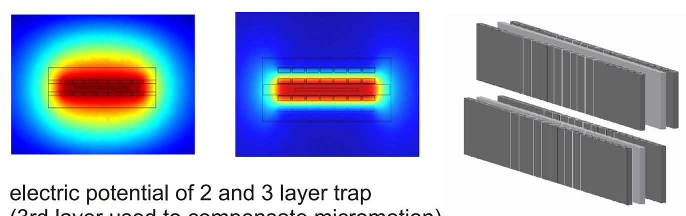
Scalable Trap Structures for Clocks with 10^{-18}?

Challenges:
-Heating rates due to thermal fluctuations of patch potentials causing 2^{nd} order Doppler shift
-Micromotion due to patch potentials, electrostatic stray fields, trap imperfections, RF phase shifts

High resolution FEM simulations of RF fields



(solid black lines indicate region with 2nd order Doppler shift < 10^{-18})



electric potential of 2 and 3 layer trap
(3rd layer used to compensate micromotion)

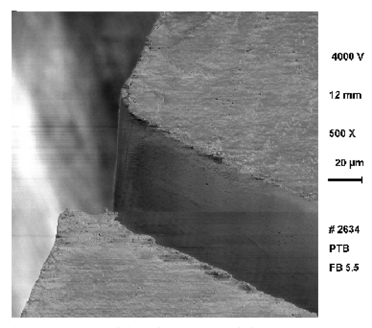
Testing chip based ion-traps

Trap assembly:

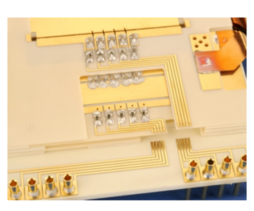
Electrode blades:
(Al_2O_3, AlN, sapphire,...)
precise machining:
laser cutting, < 10µm tolerance
low RF losses
UHV compatible

Metal coating - Au, Mb, Nb

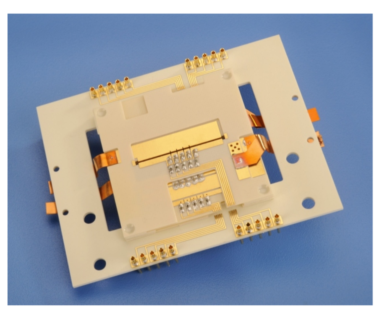
Compact electronic devices:
UHV compatible, non-magnetic capacitors and resistors for onboard filtering (low pass with 110Hz cutoff frequency)



SEM image of first laser cut Al_2O_3 waver

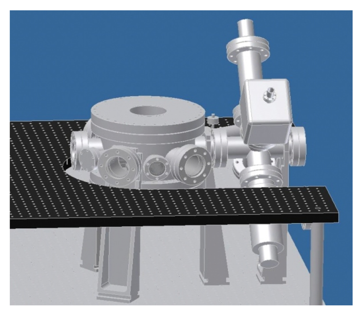


Top: closeup of trapping region
- SMD components for onboard filtering of DC voltages
- segmentation for axial confinement and transport
- compensation through extra layer on top and bottom of the trap

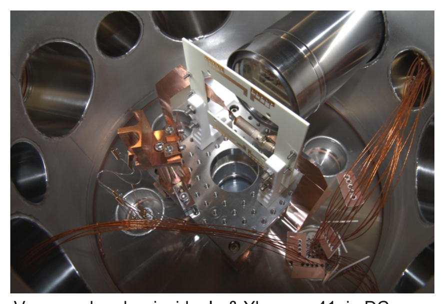


Left: assembled trap
- glued with Optocast 3410 Gen2
- soldering with Kester Sn96.5Ag3
- ball bonding with 30µm gold wires
- RF connection: OFHC Cu foil

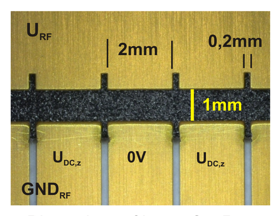
Flexible setup for testing different trap geometries and spectroscopy methods,
large solid angle for detection,
3D control of micromotion



Vacuum chamber and board for optical setup



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



Trap Dimensions of Laser Cut Rogers

First trap design:

Material: Rogers 4350B, thickfilm gold electrodes
Parameters: U_{RF} = 1500V, $_{RF}$ = 2 *25MHz, $U_{DC,z}$ = 10V
Loss factor: L = 1,27
Trap parameters:

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

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

www.quest-at-ptb.de www.quest.uni-hannover.de