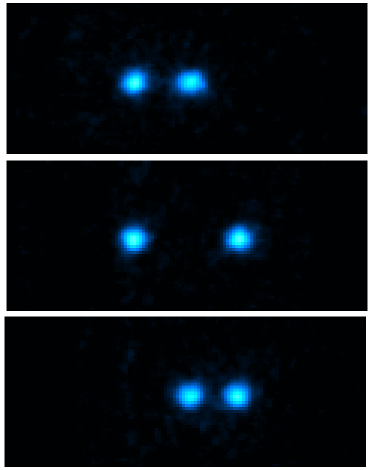

New Approaches To An Indium Ion Optical Frequency Standard

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Outline

1. Introduction

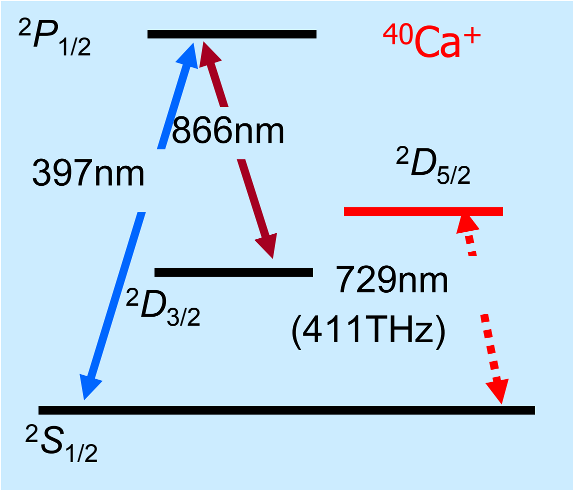
2. New approaches

3. Status of the project
   (0) In^+-Ca^+ chain synthesis
   (1) quantum logic spectroscopy
   (2) VUV excitation
   (3) $^1S_0$-$^3P_1$ excitation

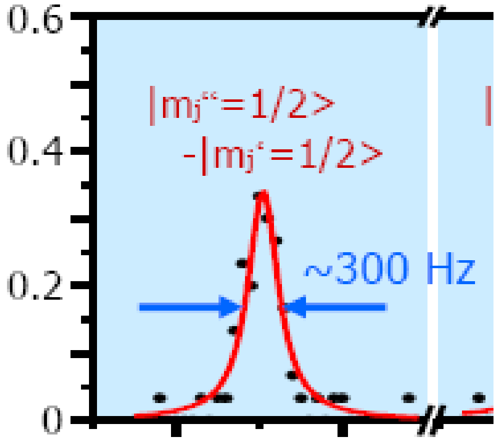
4. Summary

Motivation: smaller frequency uncertainty

$^{40}Ca^+$ optical clock at NICT



1st system: no magnetic shield

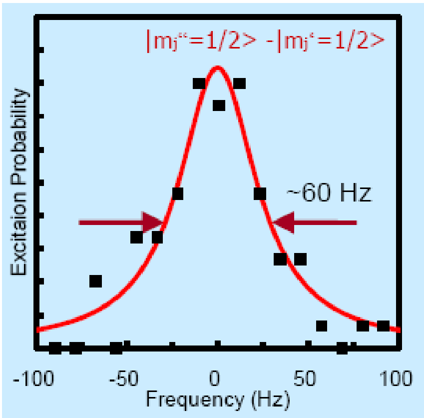


clock pulse duration 4ms

411 042 129 776 390 (7) Hz
(2×10^{-14})
Appl. Phys. Expr. **1**, 067011(2008)

411 042 129 776 393.2 (1.0) Hz
Innsbruck, PRL.**102**, 023002 (2009)

2nd system: with magnetic shield



clock pulse duration 20ms

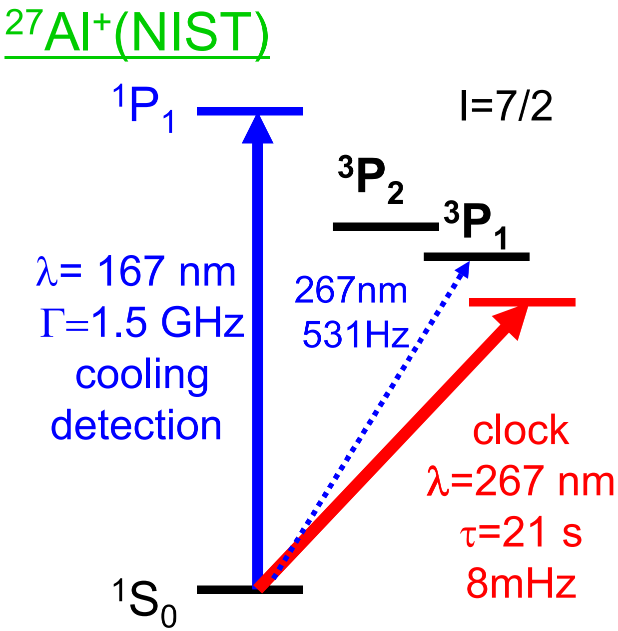
However,
fractional uncertainty is limited to in the order of 10^{-15}
due to quadrupole shift, black body radiation(BBR) shift

need of IIIA ions (B^+, Al^+, Ga^+, In^+, Th^+)
for smaller fractional uncertainty

Energy structure of IIIA ions

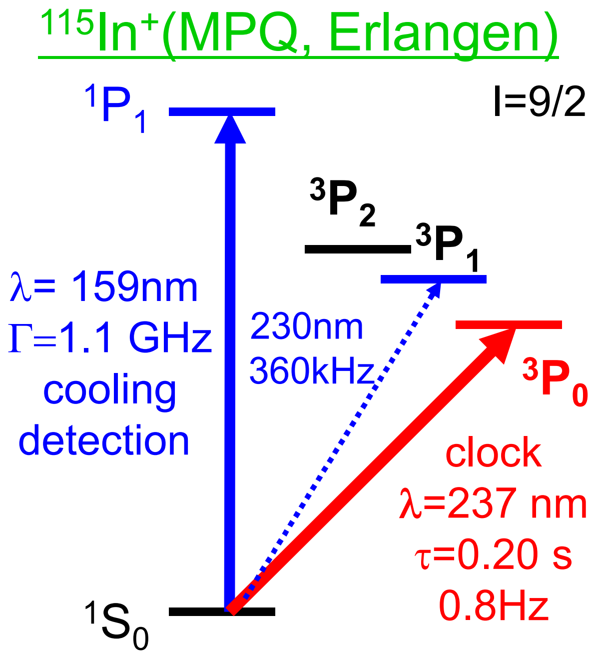
Common feature of III A ions

- good clock transition ($^1S_0$-$^3P_0$)
  - high Q value
  - no quadrupole shift
  - small BBR shift
- cooling/detection transition ($^1S_0$-$^1P_1$) in VUV hard to access



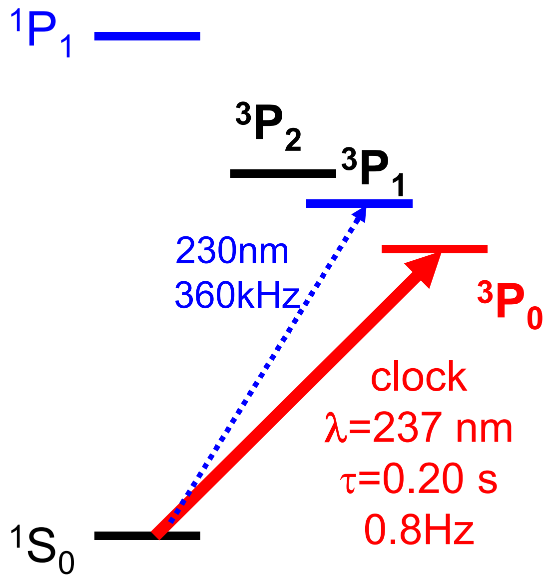
Quantum logic spectroscopy (QLS) recorded the smallest uncertainty of 8.6×10^{-18}

Phys. Rev. Lett. **104**, 070802 (2010)



$^1S_0$-$^3P_1$ transition can supply cooling and detection

Traditional In^+ optical clock (MPQ, Erlangen)



Single In^+ in a Paul-Straubel trap
- bicromatic sideband cooling at 230nm

clock transition ($^1S_0$-$^3P_0$)
- linewidth 0.8Hz
- no quadrupole shift
- small BBR shift estimated at 300K
  - $< 7 \times 10^{-17}$ Becker *et.al*. PRA 63,051802(2001)
  - 4.7×10^{-17} Peik (2002)
  - 3.8×10^{-17} Wang *et. al.* (2006)
  - 2.0×10^{-17} Kajita (2010)

Fractional uncertainty in the order of 10^{-18} is expected

However, reported numbers remain in the order of 10^{-13}

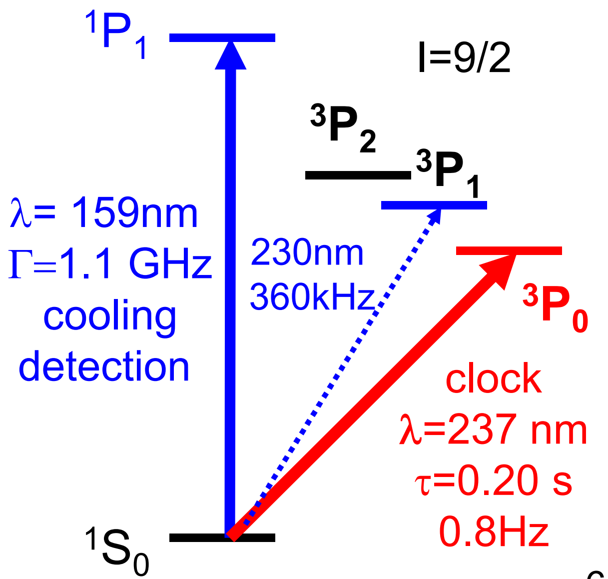
1 267 402 452 899.92 (0.23) kHz (1.8×10^{-13})
von Zanthier *et. al.* Opt. Lett. **25**, 526(2000)

1 267 402 452 901.265 (0.256) kHz (2.35×10^{-13})
Y.H Wang, *et. al.* Opt. Commun. **273**, 526(2007)

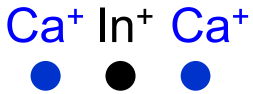
New approaches

- Basic configuration: In^+ in a linear trap with other ions
  - Cooling is provided by sympathetic cooling (currently by $^{40}Ca^+$, in future by $^{115}Cd^+$)
  - Detection is provided by three methods

1. Quantum logic spectroscopy (QLS)
2. Vacuum ultraviolet (VUV) excitation at 159nm
   multimode pulses generated by high harmonic generation(HHG) of Ti:S laser (795nm) might be used.
3. $^1S_0$-$^3P_1$ excitation at 230nm
   slow detection is compensated by clock laser locked to Sr optical lattice clock.



Procedure of building Ca^+- In^+ chains

Target example: 

1. prepare a Ca^+ chain

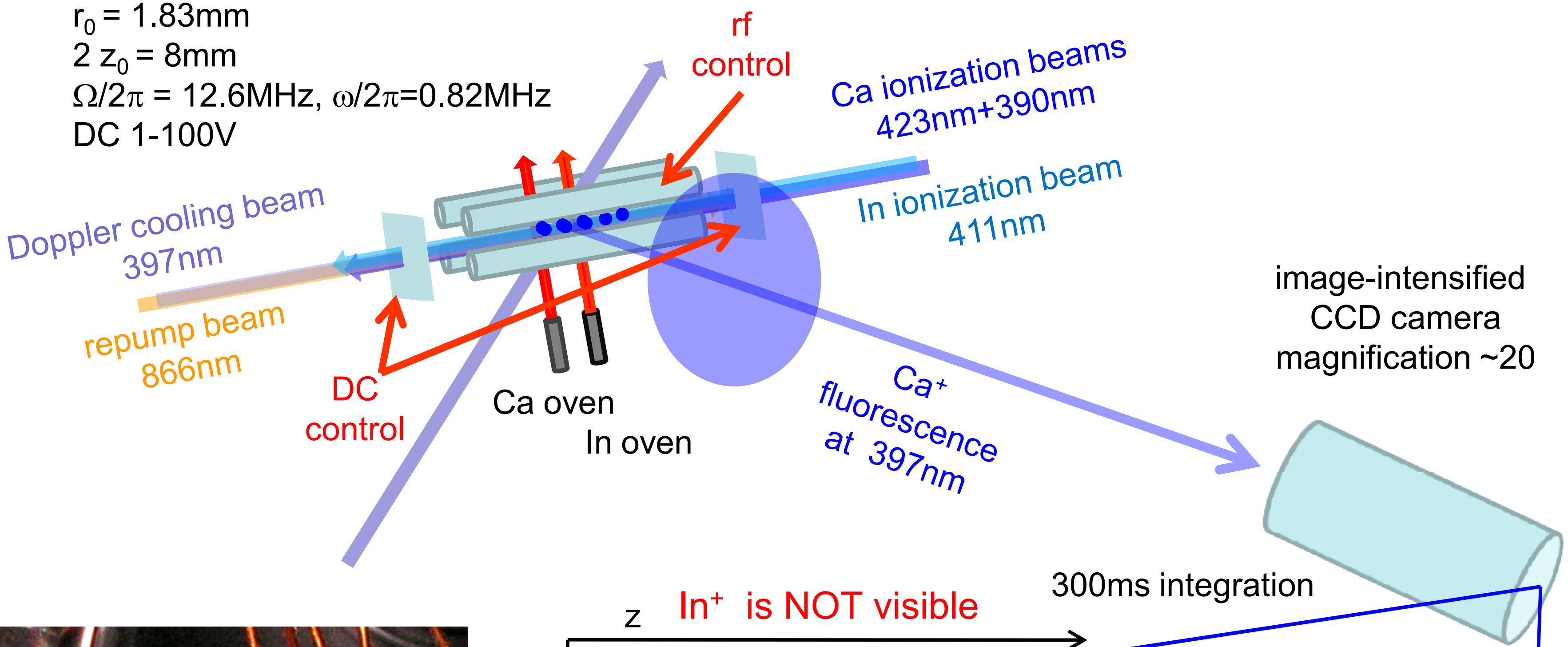
2. load In^+ by resonant photo-ionization

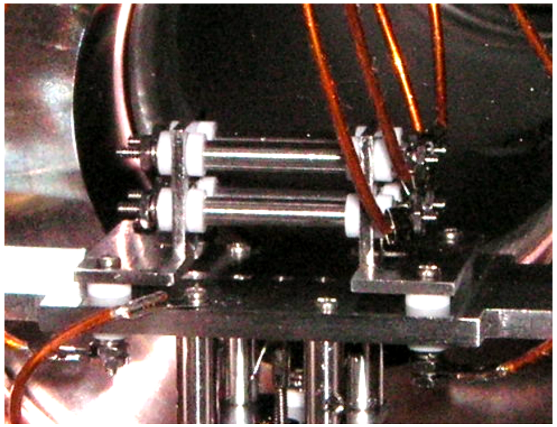
3. reduce number of In^+ by rf-kick

4. adjust position of In^+ by axial potential adjustment

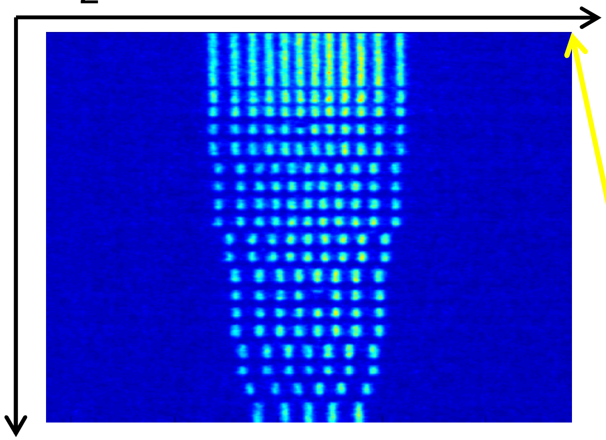
Experimental setup

linear trap
r_0 = 1.83mm
2 z_0 = 8mm
$\Omega/2\pi$ = 12.6MHz, $\omega/2\pi$=0.82MHz
DC 1-100V

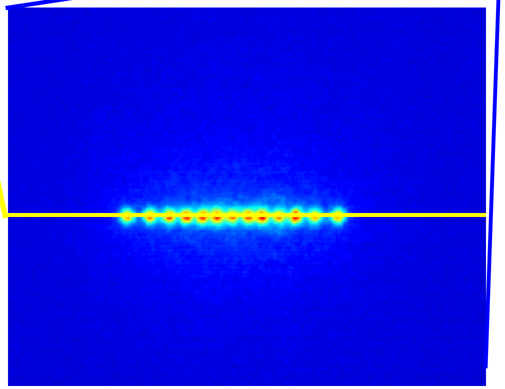




In^+ is NOT visible

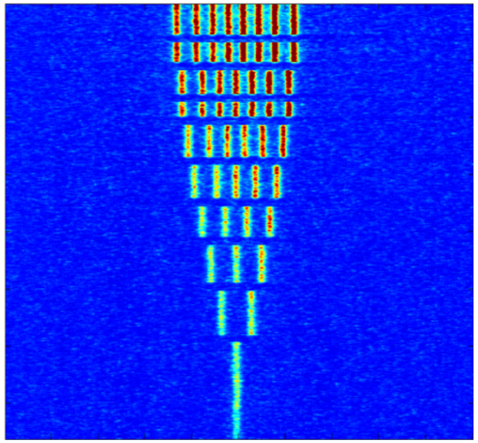


300ms integration



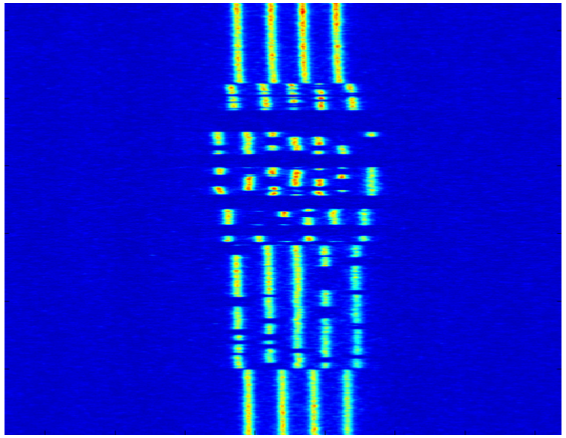
Snapshot of Ca^+-In^+ chain synthesis

Ca^+ number adjustment by rf control



rf voltage
430V->60V
1s

In^+ number adjustment by rf control

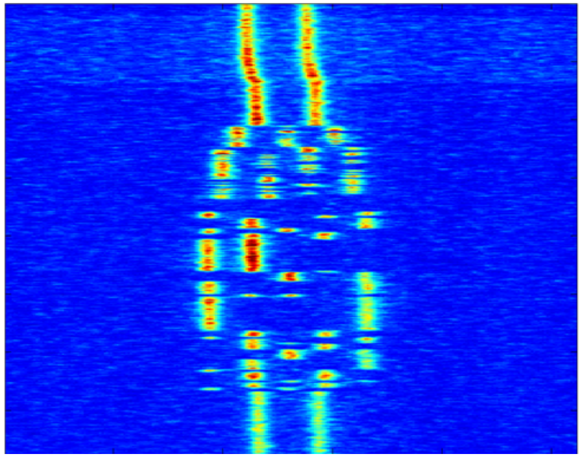


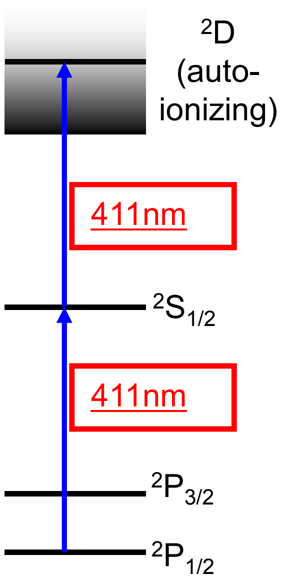
$$\omega_r = \frac{eV_0}{\sqrt{2}mr_0^2\Omega_0} \propto \frac{1}{m}$$

$$\frac{\omega_r(^{115}In^+)}{\omega_r(^{40}Ca^+)} = 0.35$$

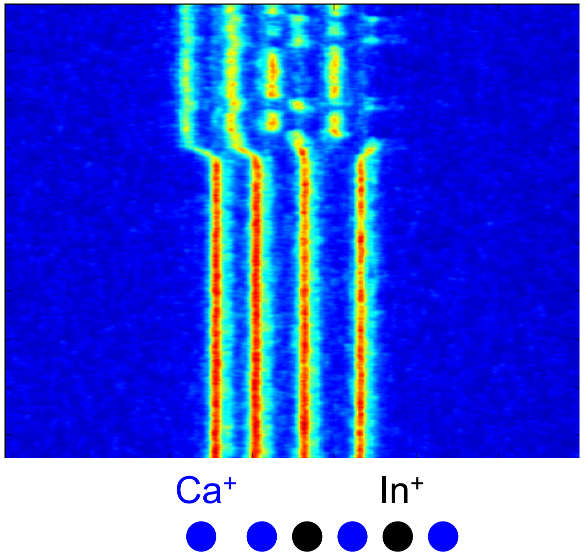
V_0=98V 1sec
$\omega_r(Ca^+)/2\pi$=177kHz
$\omega_r(In^+)/2\pi$=62kHz

Loading of In^+ by resonant photo-ionizaiton



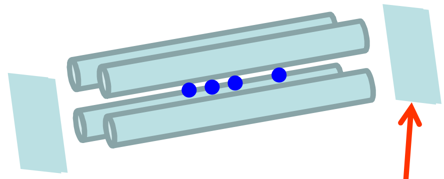


Configuration control by DC control



DC electrode
voltage
10->22V

Identification of In^+

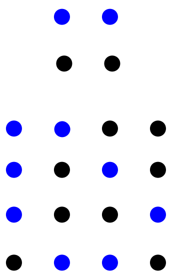


vibrational frequencies depend on mass
⇒identification of the mass possible

configuration

$$\omega_z(mixed)/\omega_z(Ca^+)$$

(of the lowest mode)

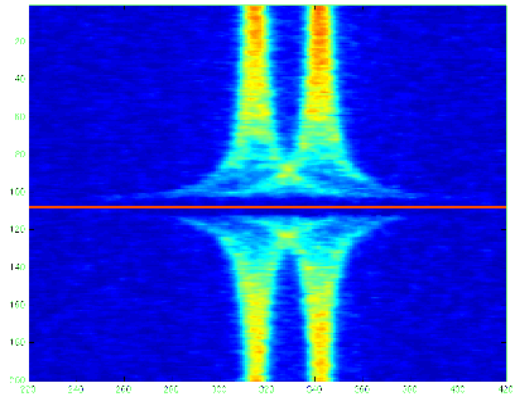


configuration	$\omega_z(mixed)/\omega_z(Ca^+)$
$^{40}Ca^+$	1.00
$^{115}In^+$	0.59
	0.689
	0.703
	0.702
	0.702

G. Morigi, et al, Euro. Phys. J. D 13, 261(2001)

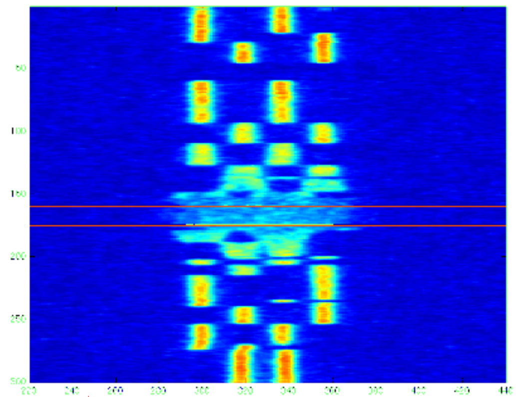
2 $^{40}Ca^+$

frequency on DC electrode



110.1kHz

2 $^{40}Ca^+$ + 2 X^+

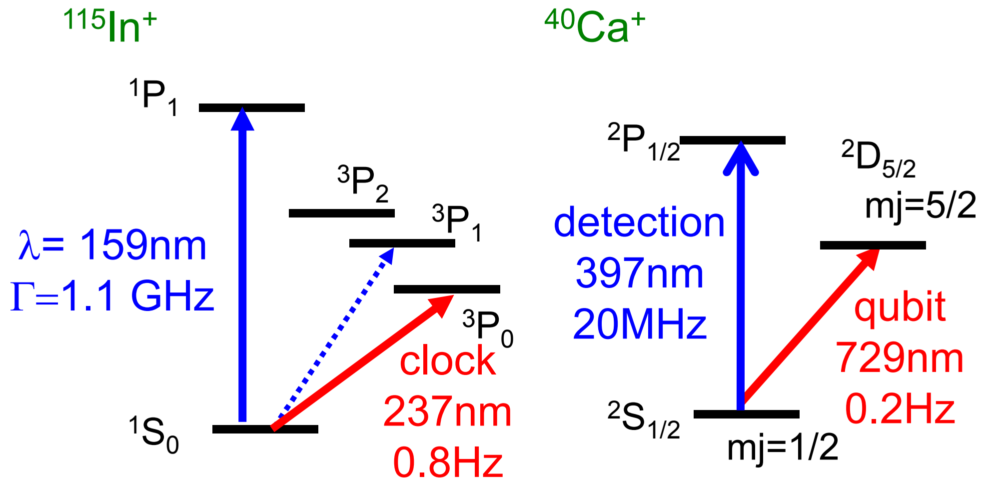


75.9kHz
77.8kHz

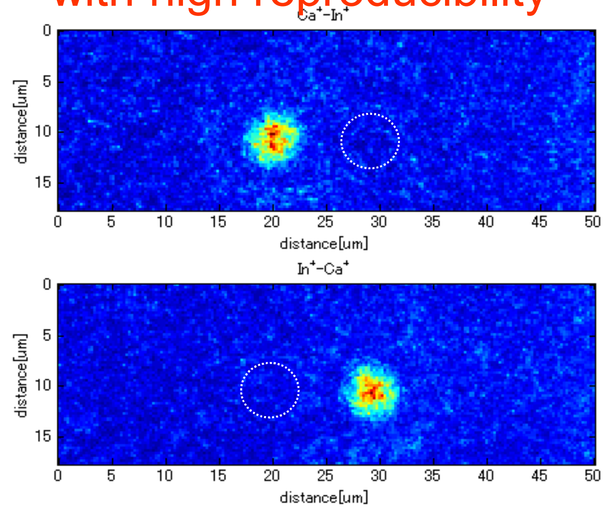
X^+ = $^{115}In^+$ is identified

Quantum logic spectroscopy

Collaboration with Prof. Urabe group at Osaka univ.



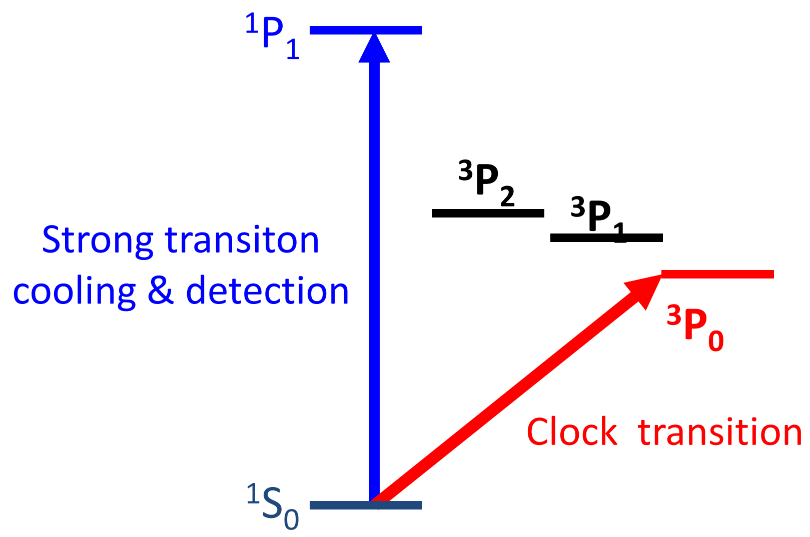
In$^+$ + Ca$^+$ chain is generated with high reproducibility



sideband cooling
(729nm)
to the ground state
is in progress

Coherent VUV source for optical clocks

Common level structure of atomic clocks

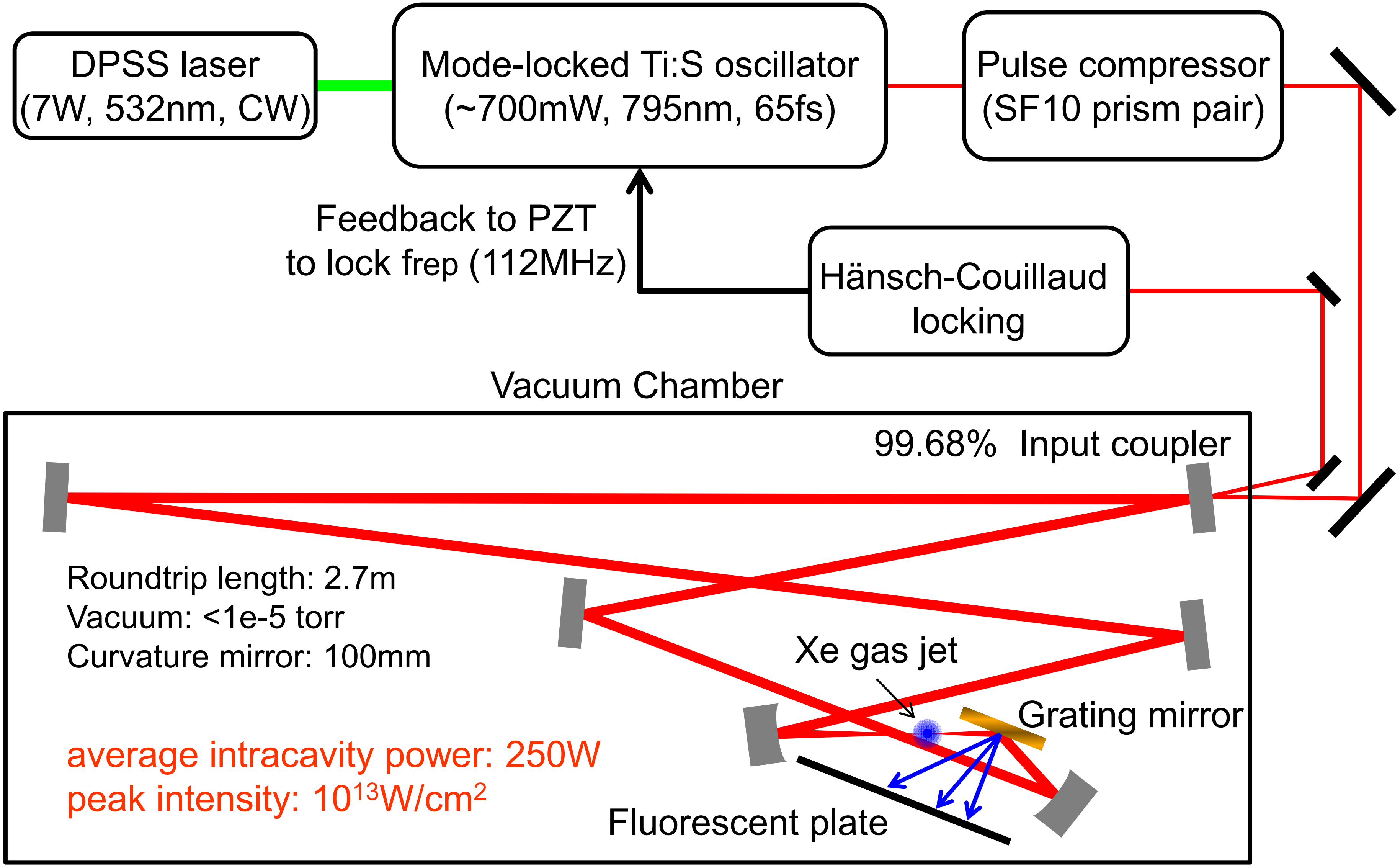


	Sr	Al^+	In^+	Th
Clock scheme	Lattice clock	Quantum logic spectroscopy	Single ion	??
Clock transition	$^1S_0$-$^3P_0$	$^1S_0$-$^3P_0$	$^1S_0$-$^3P_0$	Nuclear transition
λ of clock transition (nm)	698	267	237	164±11
λ of $^1S_0$-$^1P_1$ transition (nm)	461	167	159	

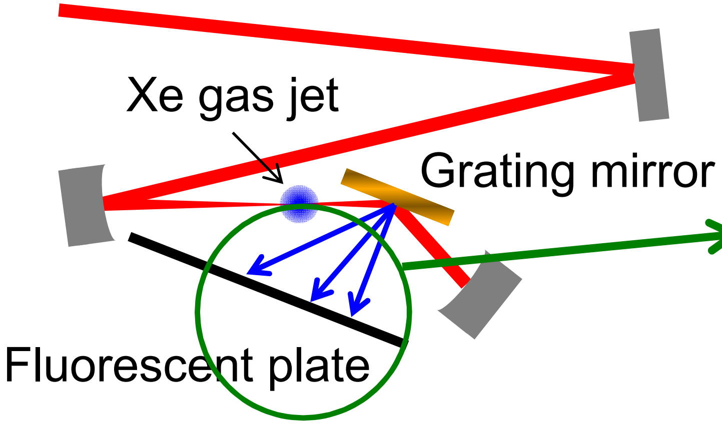
All within 5th harmonic of Ti:S!

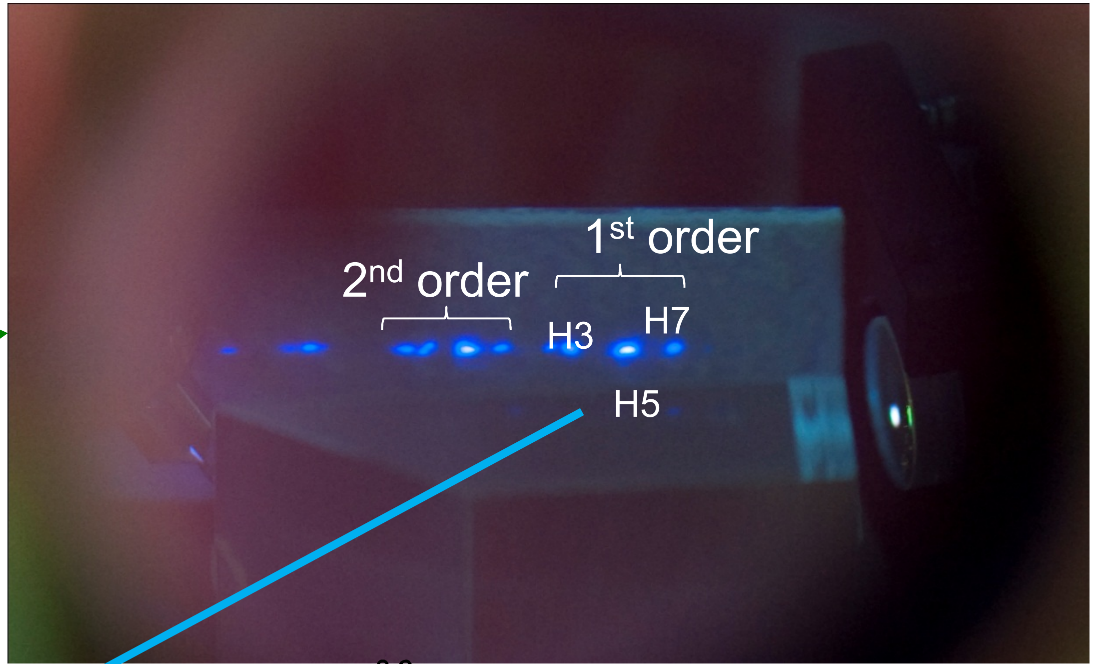
Our target

VUV generation Setup



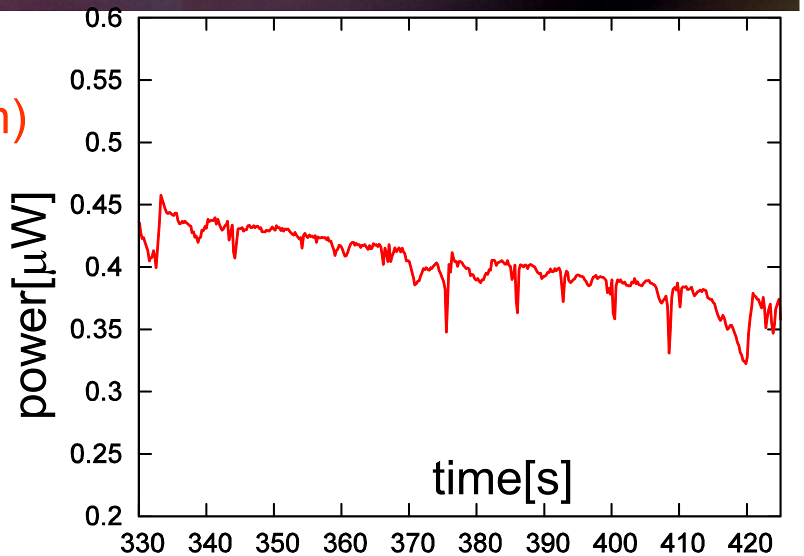
Observation of the VUV output



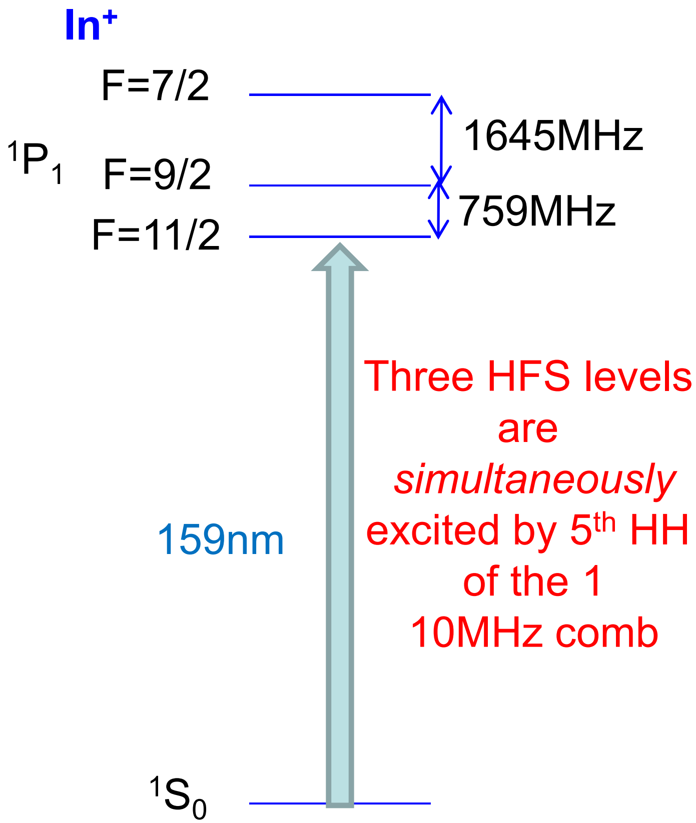


first measurement of 5th high harmonic (159nm)
with a phototube:
1.5μW
(4.2×10^5 modes total)

stable output is maintained over 1 minute
even with manual adjustment of f_{ceo}



Estimation of photon counting rate



HFS splitting calculated from
P. Jonsson, Martin Andersson
J. Phys. B:**40** 2417 (2007)

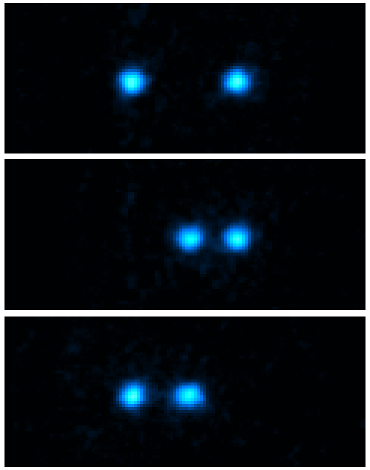
items	**value**
high harmonic average power	100μW*
Repetition rate	110MHz
Number of comb teeth	4.2×10^5
$^1S_0$-$^1P_1$ linewidth	177MHz
Focus diameter	1μm
Detection solid angle	2×10^{-3}
Detector efficiency	40%

single In^+ photon counting rate: 12,000 cps

*Fiber laser based system at JILA: 50uW at 153nm (7^{th})!!

Stabilization of In^+-Ca^+ configuration

a
b
c



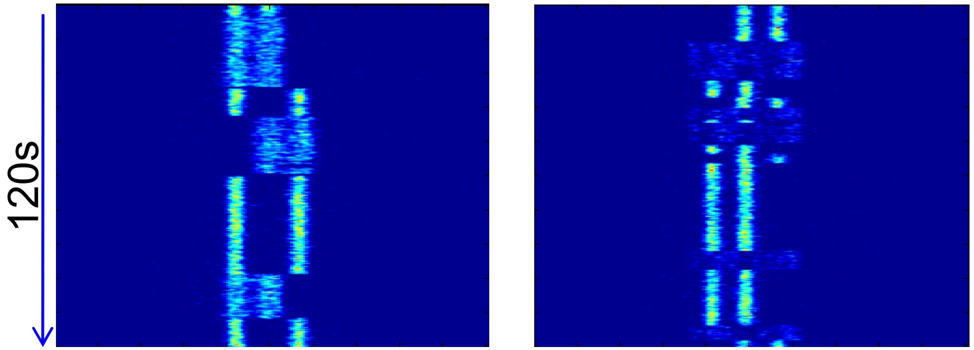
(Ca^+,In^+,Ca^+)
ν_0=100.5kHz

(In^+,Ca^+,Ca^+)
ν_0=98.5kHz

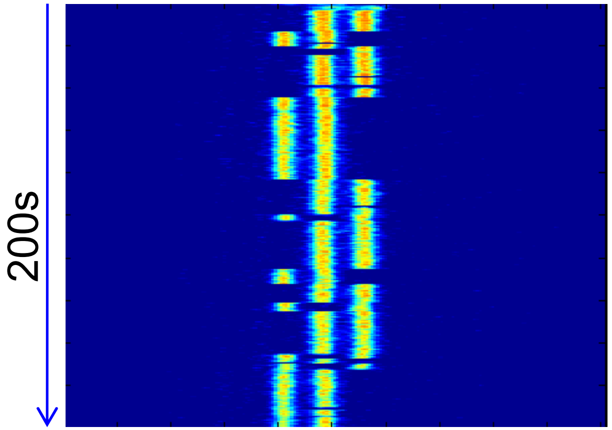
(Ca^+,Ca^+,In^+)
ν_0=98.5kHz

AM applied to Ca^+ laser (397nm)

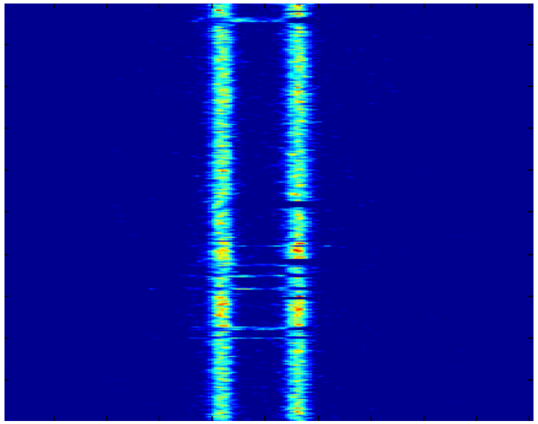
98.5kHz
100.5kHz



configuration-selective destabilization
is possible



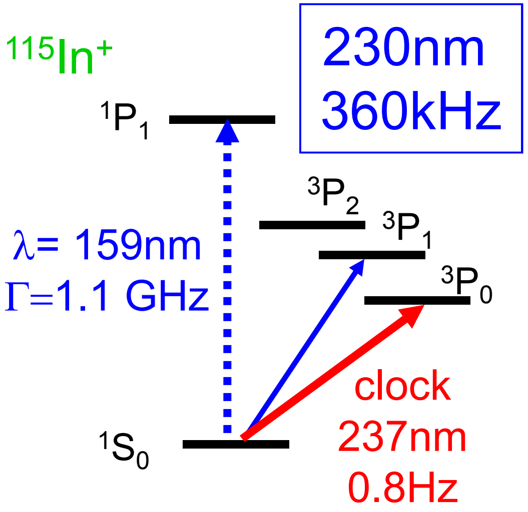
AM
(98.5kHz)
upon
finding
unwanted
config.

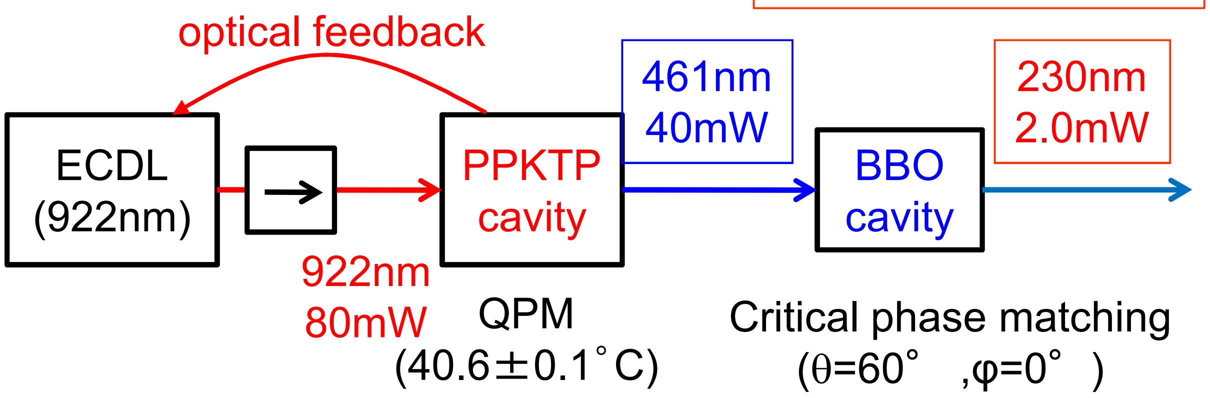


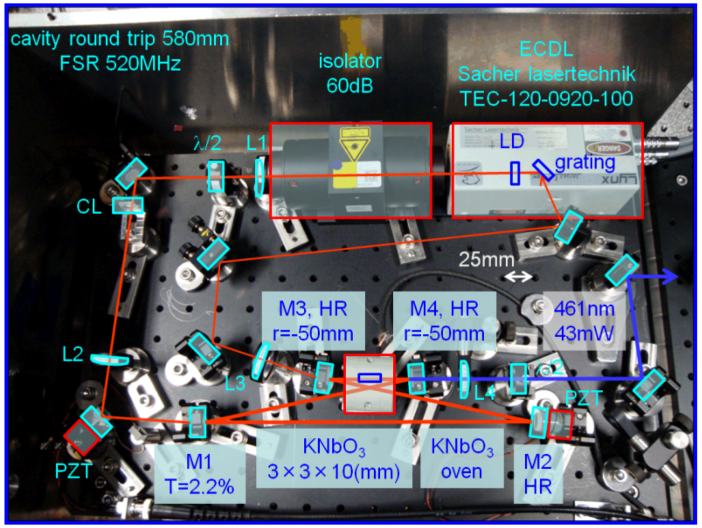
simple way
to keep
In^+-Ca^+
configuration

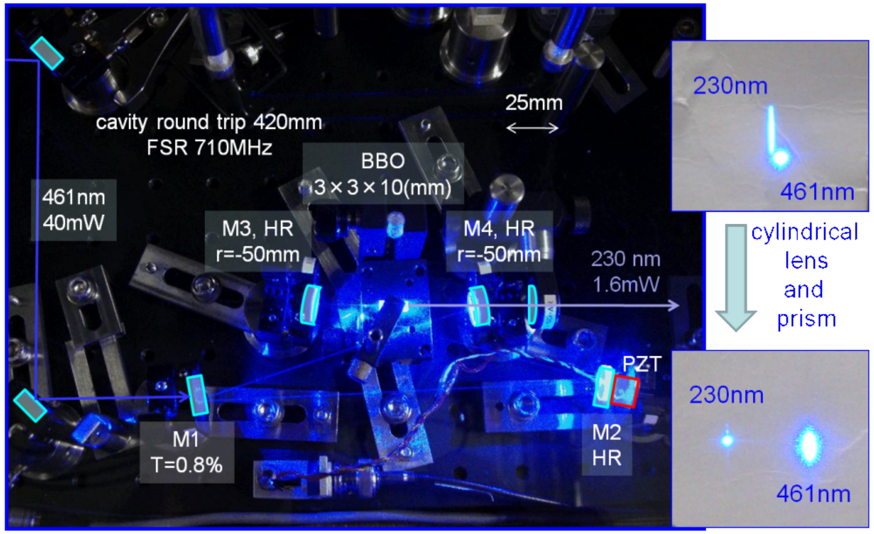
diode-laser based 230nm source

15mW is expected
for 300mW input
from MOPA at 922nm

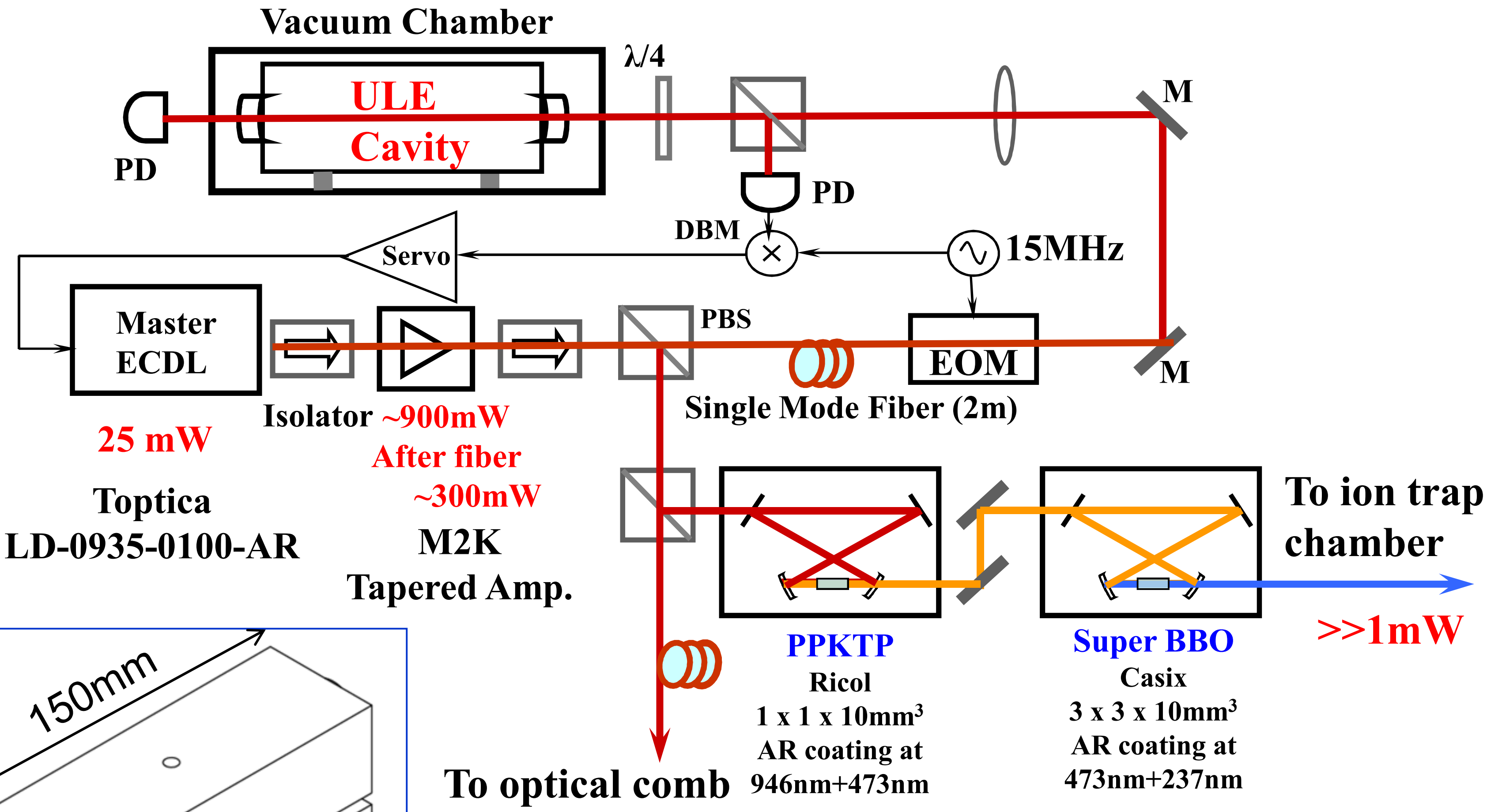


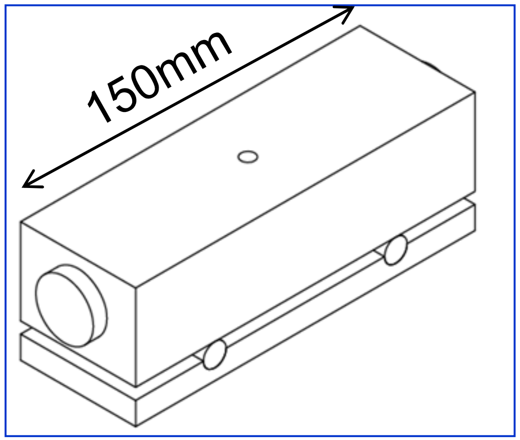






Clock laser under construction

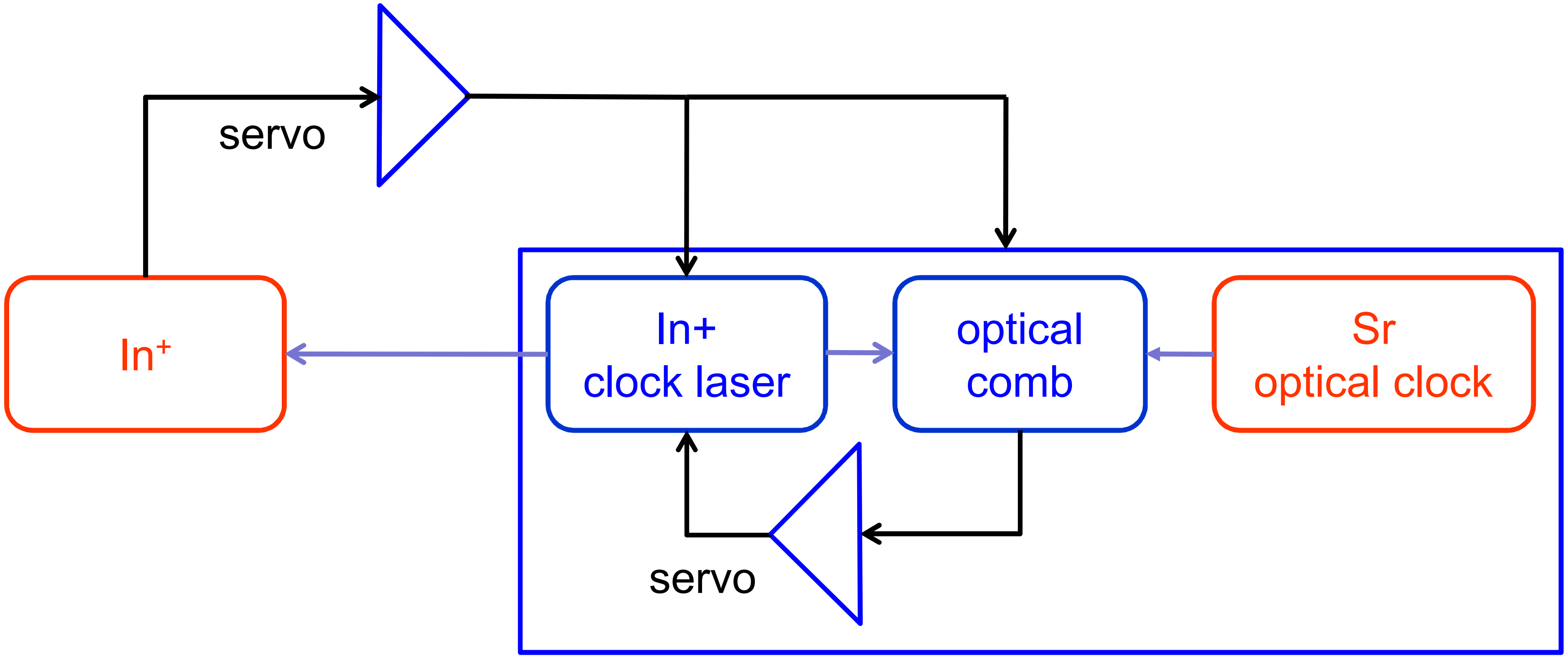




Vibration-insensitive
Cubic ULE cavity
designed finesse 250,000

Relative stability of 10^{-15} at 1s
is expected

Hybrid optical clock



A clock with

stability of optical lattice clock

and

accuracy of single ion clock

Summary

- New approaches to In^+ an optical frequency standard
  - Sympathetically cooled In^+ in a linear trap
  - Detection by three methods
    - Quantum logic spectroscopy
      - Initialization of In^+-Ca^+ is in progress
    - VUV excitation
      - 1.5μW at 159 nm was generated
      - 12,000cps expected when 100μW is available
    - $^1S_0$-$^3P_1$ excitation assisted by Sr optical clock
      - all components are almost ready
- Clock operation will be reported in the 2nd ECTI conference