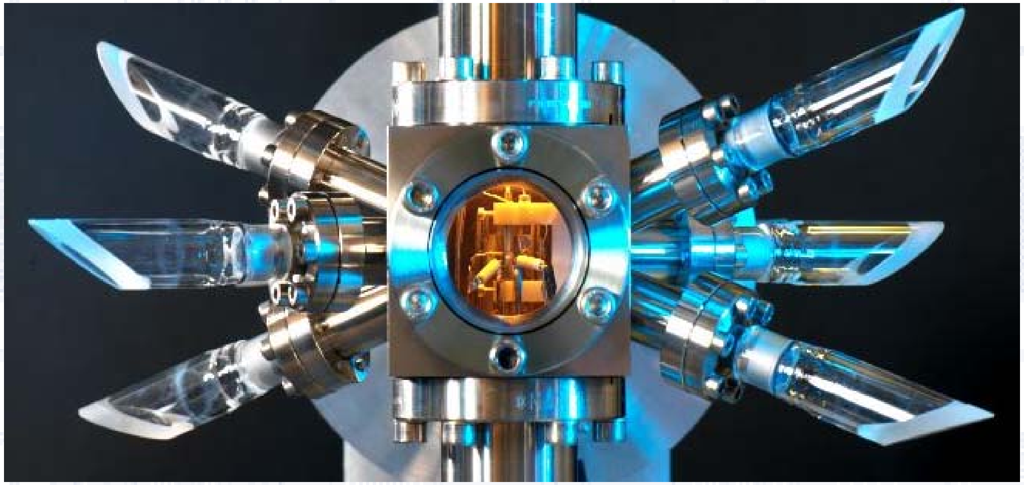
National Physical Laboratory

High Accuracy Strontium Ion Optical Clock



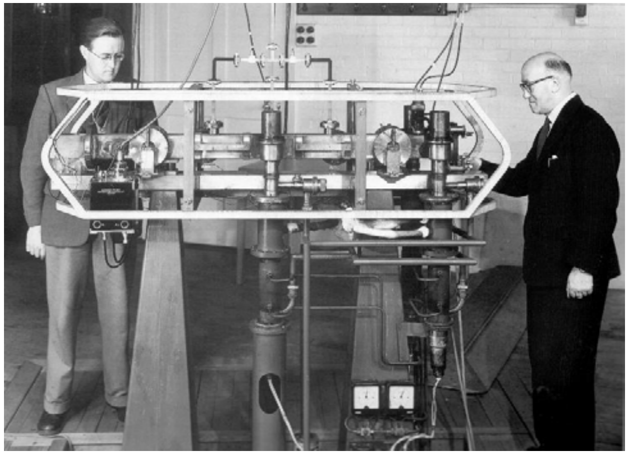
Helen Margolis, Geoff Barwood, Hugh Klein, Guilong Huang, Stephen Lea, Krzysztof Szymaniec and Patrick Gill

T&F Club 15th April 2005

Outline

- Optical frequency standards and optical clocks based on trapped ions
- Strontium ion trap standard at NPL
- Results of recent measurements and future prospects

A bit of history



50 years ago the definition of the second was based upon the movement of the earth.

1955: First caesium atomic clock produced at NPL, accurate to 1 part in 10^{10}.

1967: Caesium clock adopted as the basis for the international definition of time.

The second is currently defined as

> "the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom".

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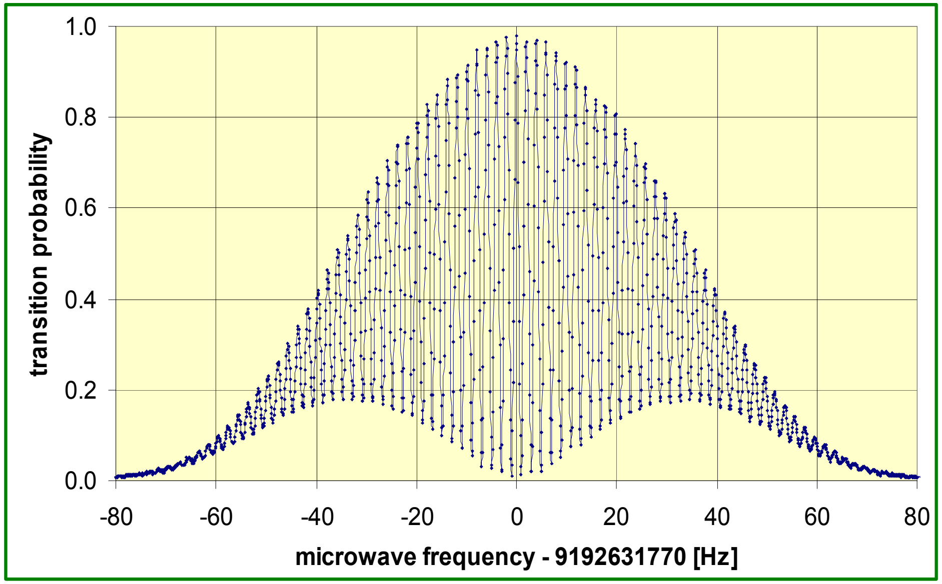
The NPL caesium fountain

Accuracy 1×10^{-15} (1σ)

(with several days averaging time)



Szymaniec et al. Metrologia **42** 49 (2005)

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Optical clocks

instability $\sigma \propto \frac{\Delta f}{f} \frac{1}{(S/N)}$

- Based on forbidden optical transitions in atoms or ions
- Frequencies ~10^5 times higher than microwave frequencies
- Q-factor ~10^{15} (or even higher)

Reference
(Single trapped ion)

+

Oscillator
(Ultra-stable laser)

+

Counter
(Femtosecond comb)

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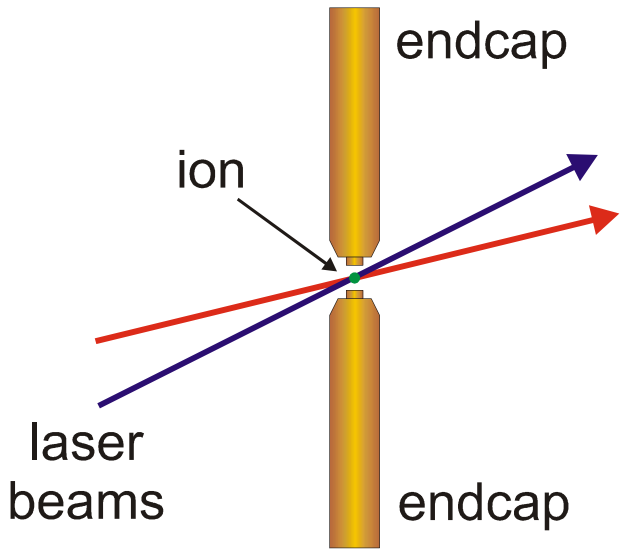
Trapped ion optical frequency standards or optical clocks

- **Laser-cooled single trapped ion**
- **High-Q optical clock transitions (10^{15} or higher)**
- **Low perturbation environment**



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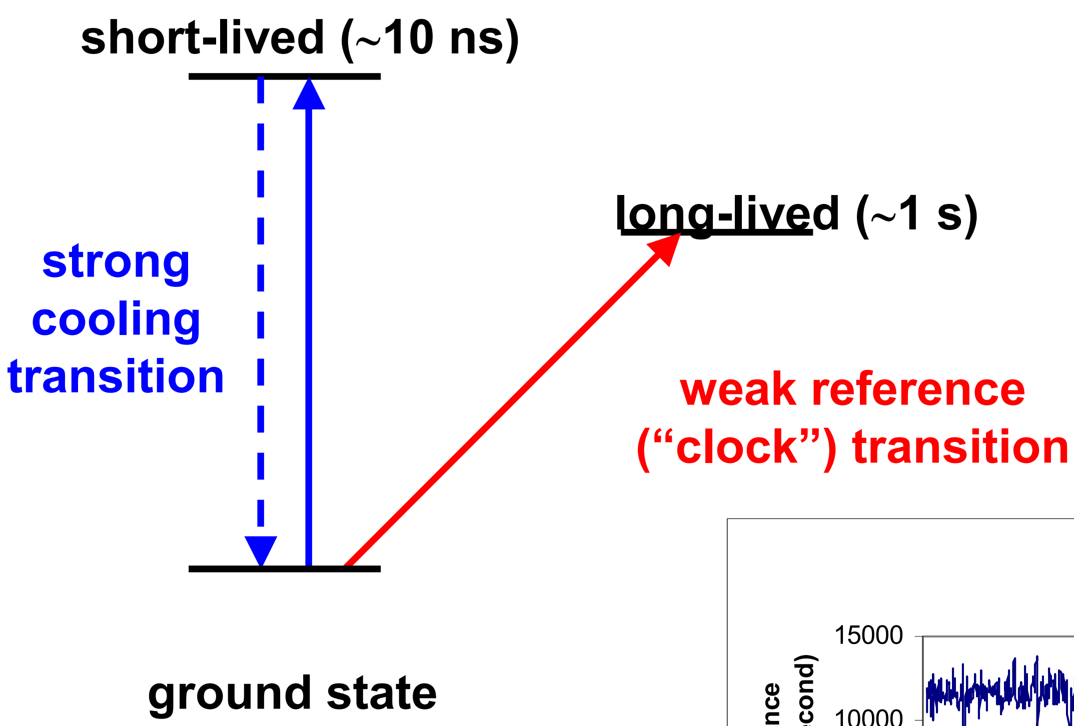
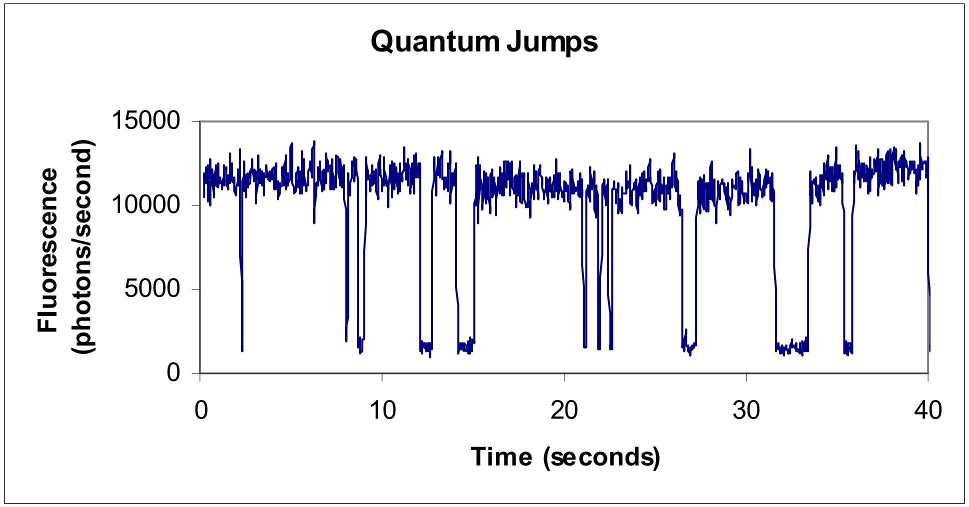
Quantum jumps





Advantages of ion trap based optical standards

- No 1st-order Doppler shift (Lamb Dicke regime)
- Minimum 2nd-order Doppler shift
- Field perturbations minimised at trap centre
- Background collision rate low
- Electron shelving technique - quantum jumps give high detection efficiency

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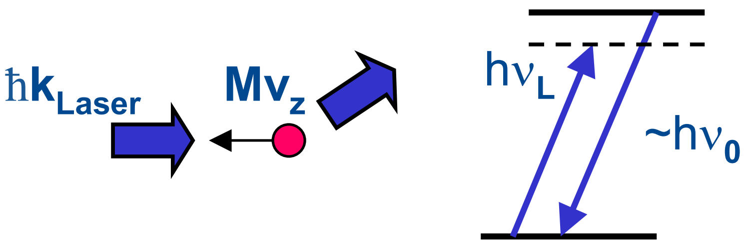
Laser Cooling



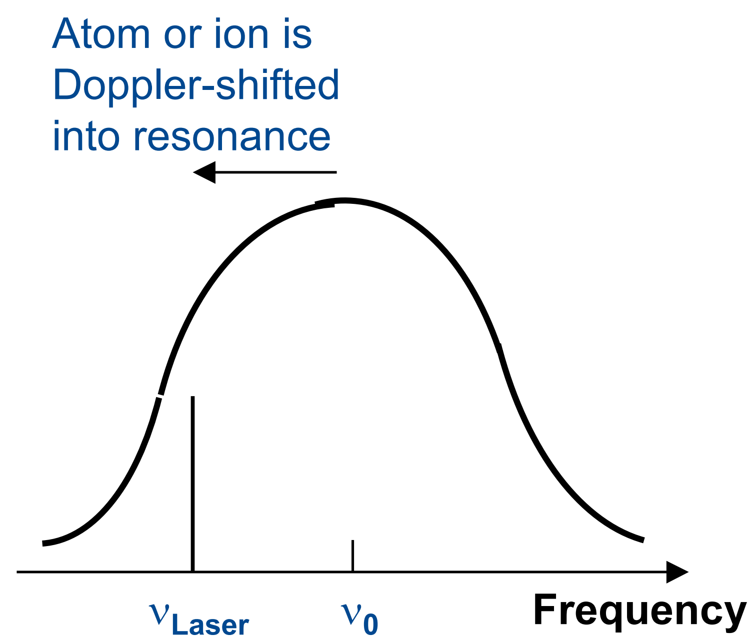
$k_{Laser} = \omega/c = 2\pi/\lambda_{laser}$

For each photon absorption and emission the ion velocity is reduced

$$dv = \hbar k / M$$

v(thermal) ~ few x 100 metres per sec
dv ~ few cm per sec

10^4 scattering events to reach mK level.



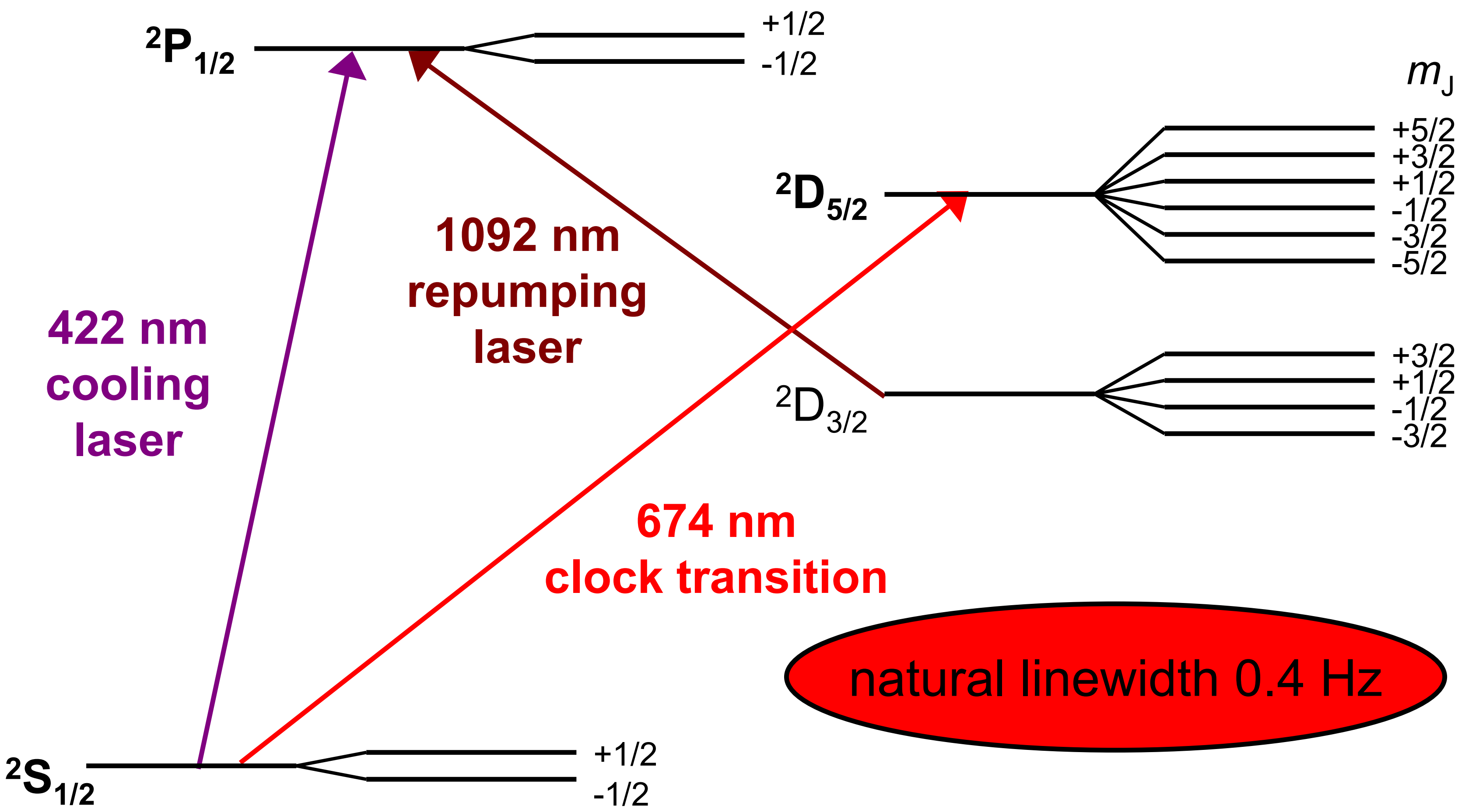
Spectral profile for a Doppler-broadened absorption

Trapped ion optical clock candidates

Ion	λ	Transition	Linewidth Theory	Linewidth Expt	Freq uncert.	Laboratory
$^{88}Sr^+$	674 nm	$^2S_{1/2}$ - $^2D_{5/2}$	0.4 Hz	70 Hz	1.5 Hz	NPL, NRC
$^{199}Hg^+$	282 nm	$^2S_{1/2}$ - $^2D_{5/2}$	1.7 Hz	7 Hz	1.5 Hz *	NIST
$^{171}Yb^+$	435 nm	$^2S_{1/2}$ - $^2D_{3/2}$	3 Hz	30 Hz	6 Hz	PTB
$^{115}In^+$	236 nm	$^1S_0$ - $^3P_0$	1 Hz	170 Hz	230 Hz	MPQ
$^{171}Yb^+$	467 nm	$^2S_{1/2}$ - $^2F_{5/2}$	0.5 nHz	180 Hz	600 Hz	NPL
$^{43}Ca^+$	729 nm	$^2S_{1/2}$ - $^2D_{5/2}$	0.14 Hz	1 kHz	-	Uibk, CRL
$^{27}Al^+$	266 nm	$^1S_0$ – $^3P_{0,2}$	0.5 mHz	-	-	NIST

*(unpublished)

$^{88}Sr^+$ term scheme



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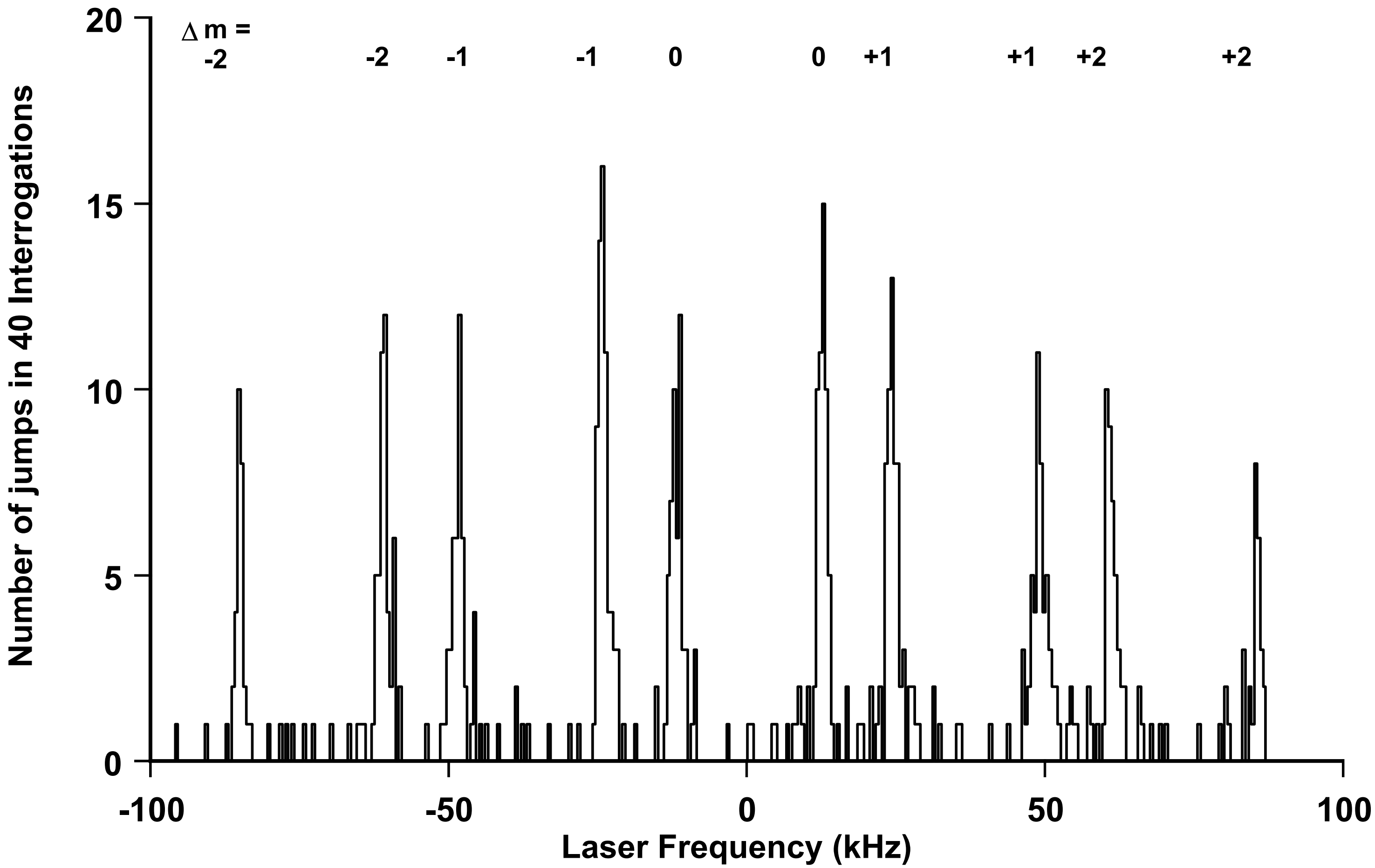
Zeeman structure of the $^{88}Sr^{+}$ clock transition



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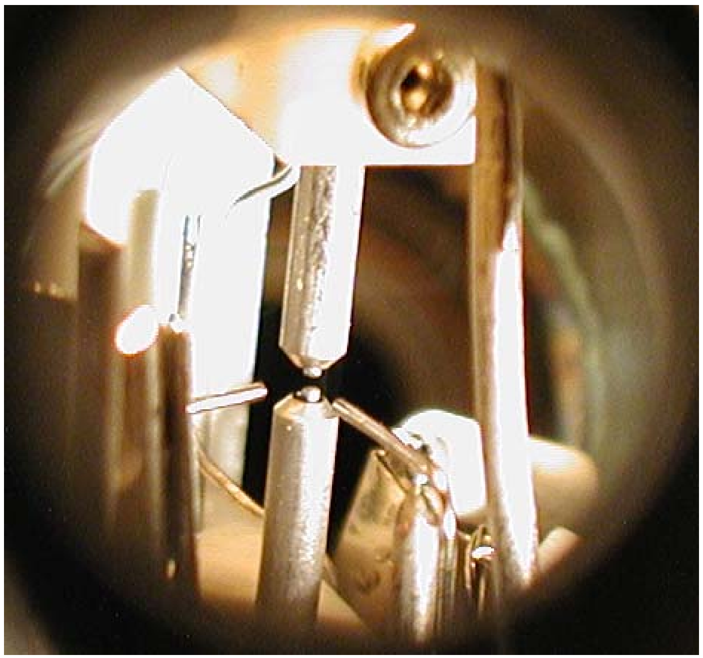
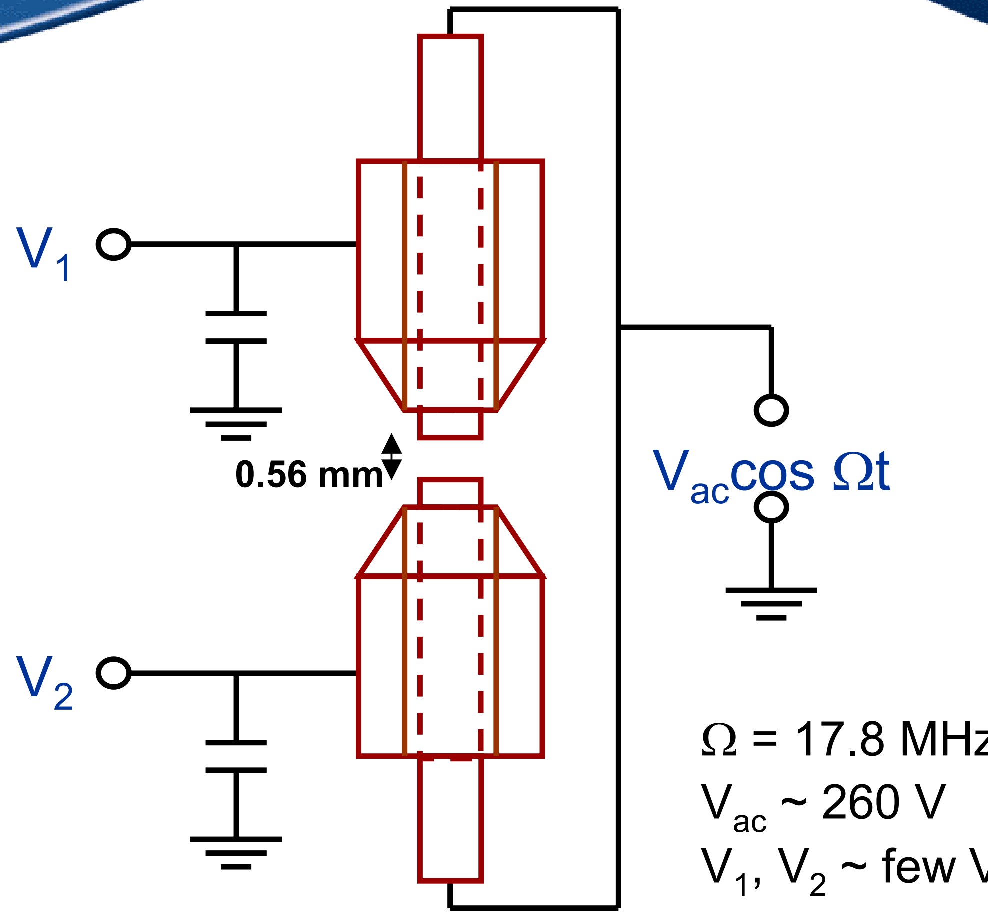
Strontium endcap trap

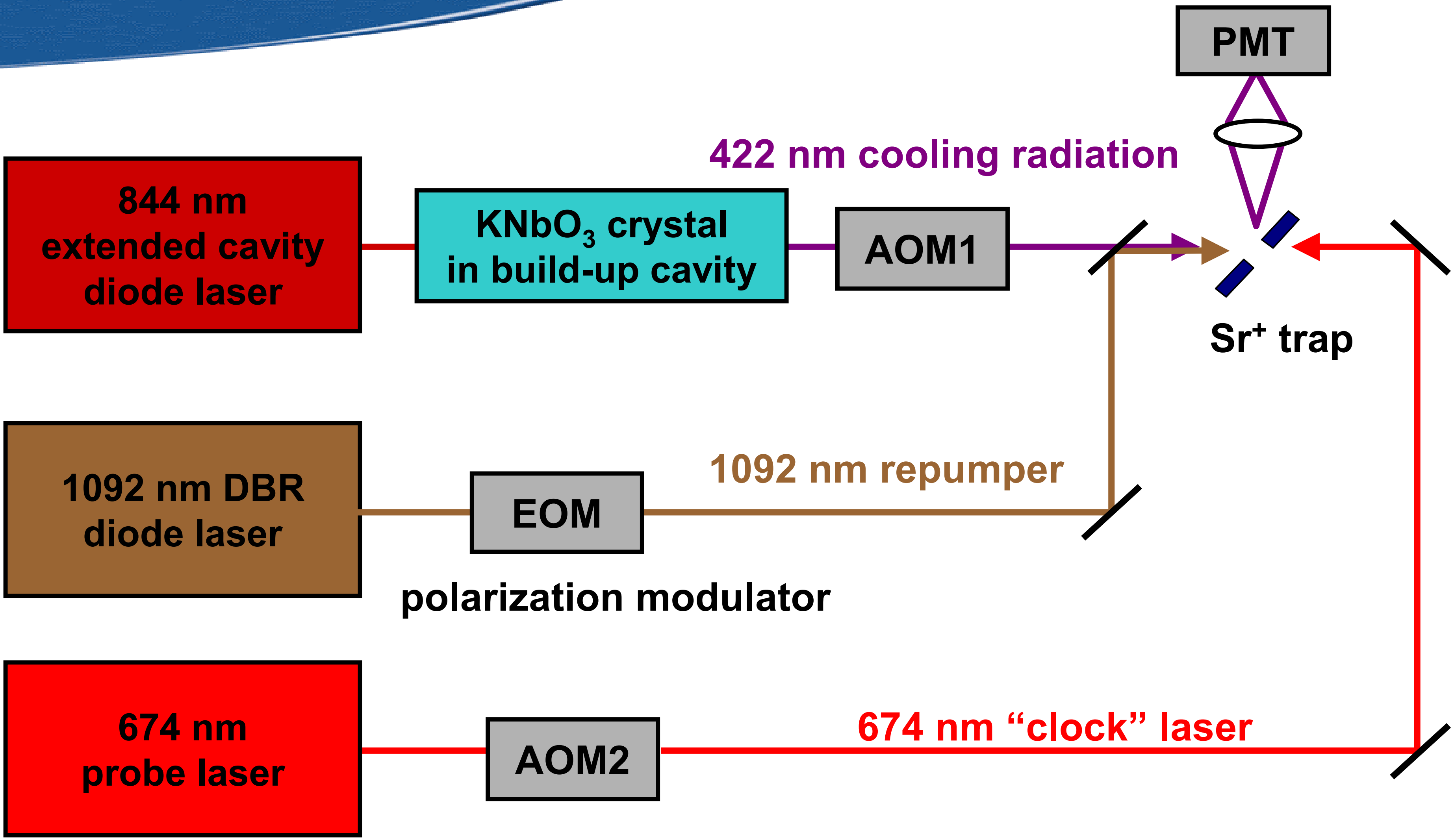




Allows monitoring of ion motion along all three axes via rf-photon correlation

→ 3D micromotion control

Experimental arrangement



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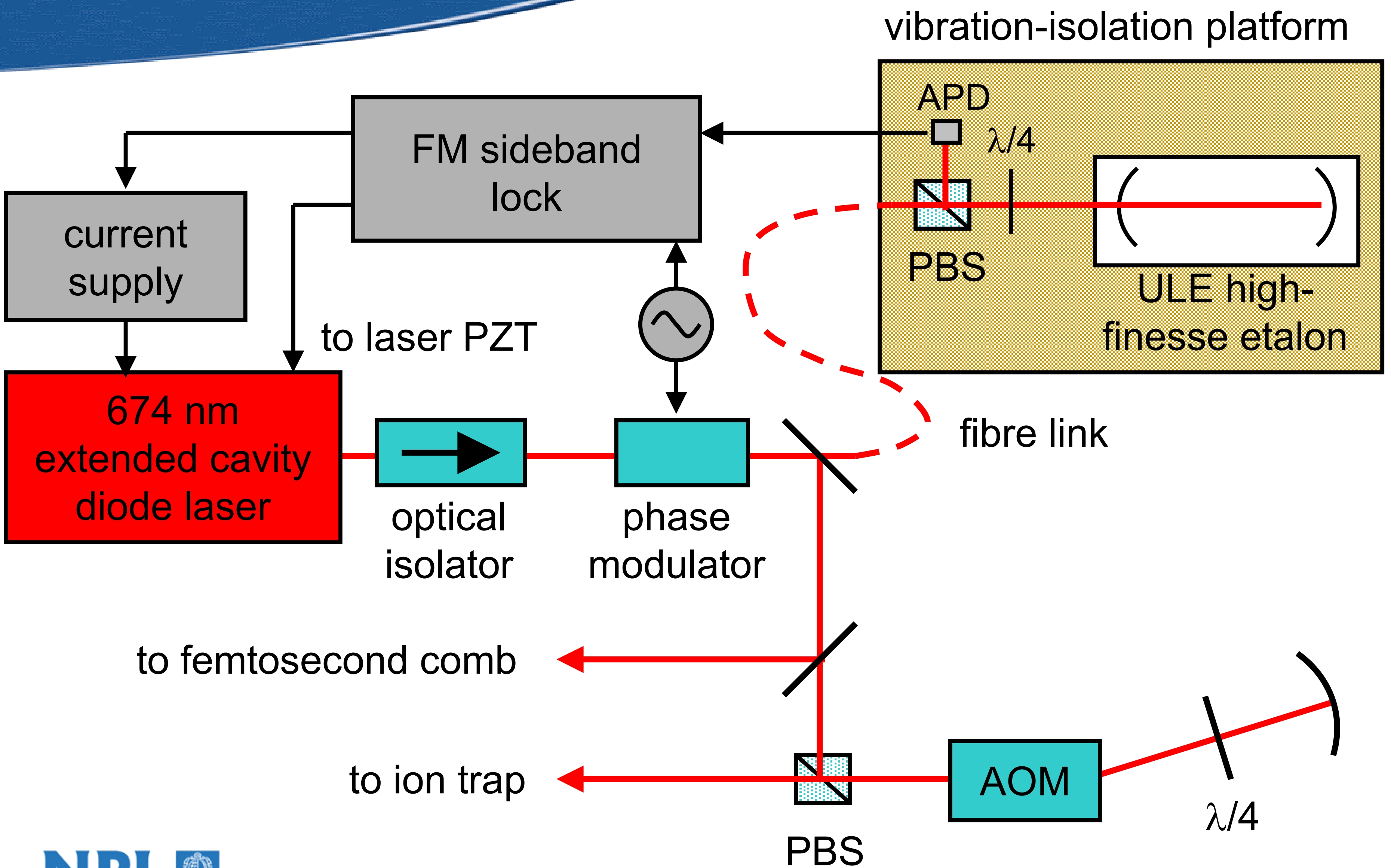
674 nm probe laser system



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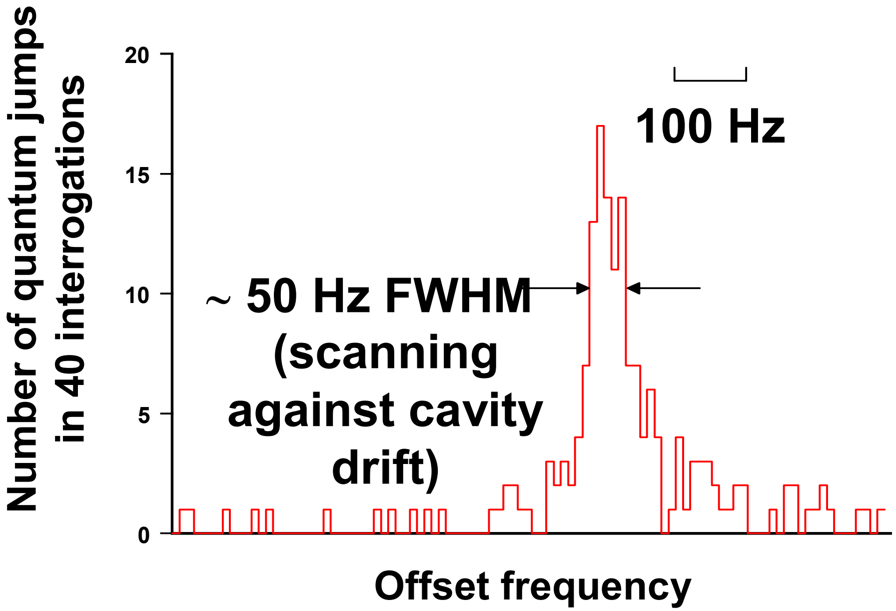
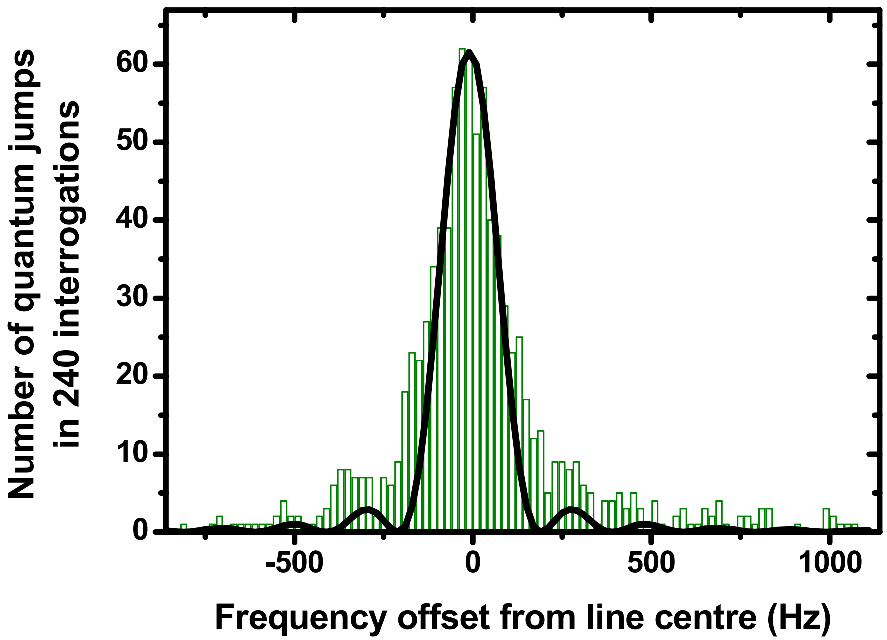
Probe laser linewidth



Scan across one component of clock transition in $^{88}Sr^{+}$:

linewidth ~70 Hz



Broadened to ~ 200 Hz for absolute frequency measurements (probe pulse length 5 ms)

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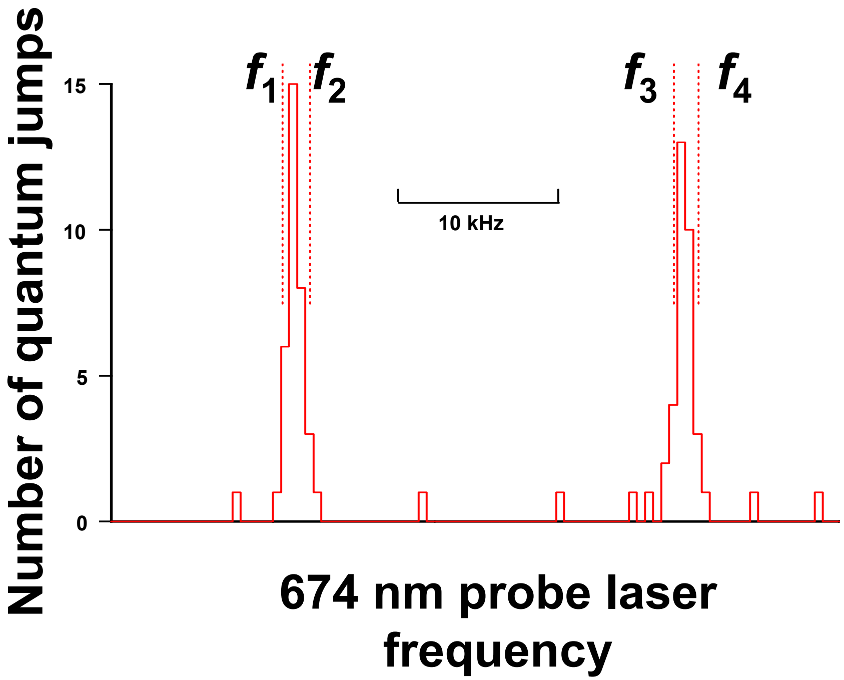
Locking the probe laser to the clock transition



- Servo scheme uses two Zeeman components symmetrically placed about line centre
- Number of quantum jumps is sampled at four frequencies f_1 to f_4
- Error signals N_2-N_1 and N_4-N_3 are generated

- Applied correction combines proportional control $\Delta f = \frac{G\,(N_2-N_1)}{(N_1+N_2)}$

  with "feed-forward" drift compensation to reduce servo errors

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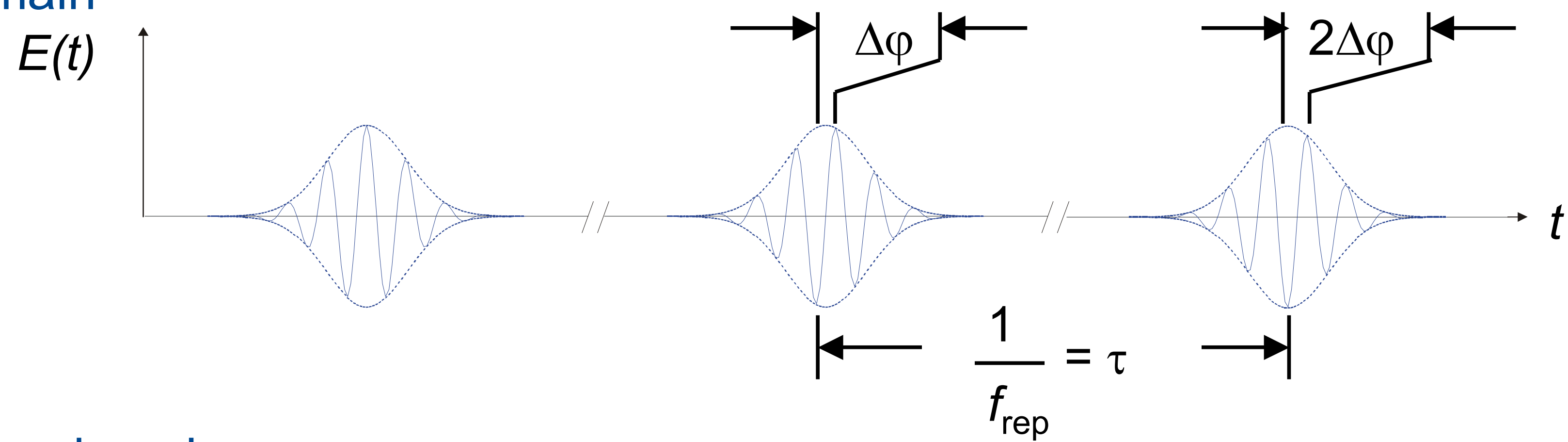
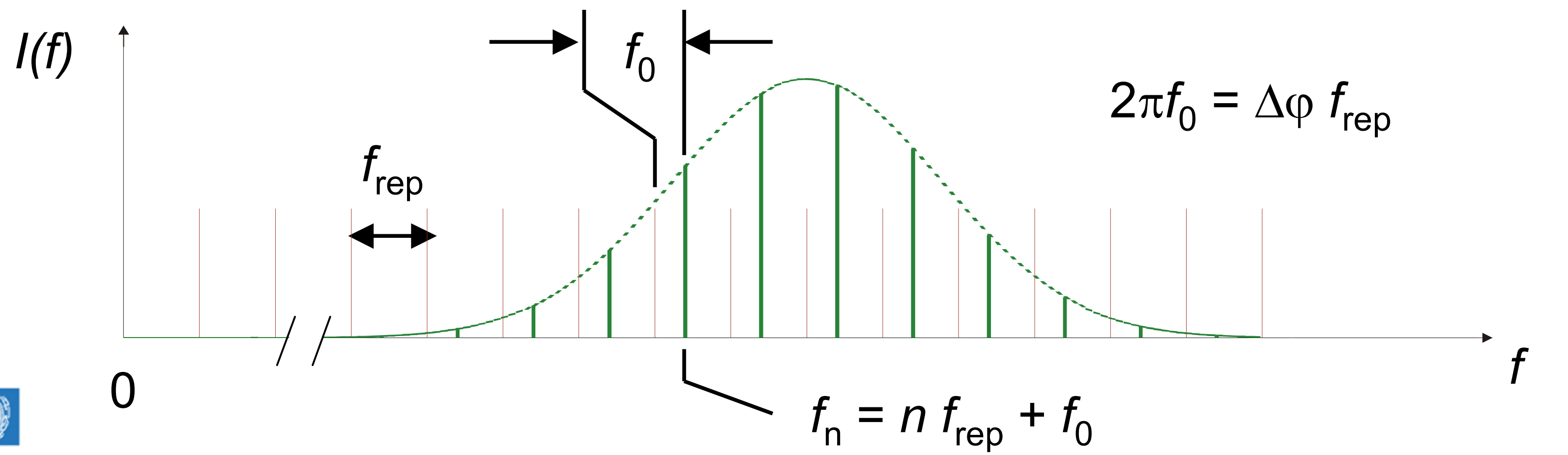
Femtosecond optical frequency comb

Time domain

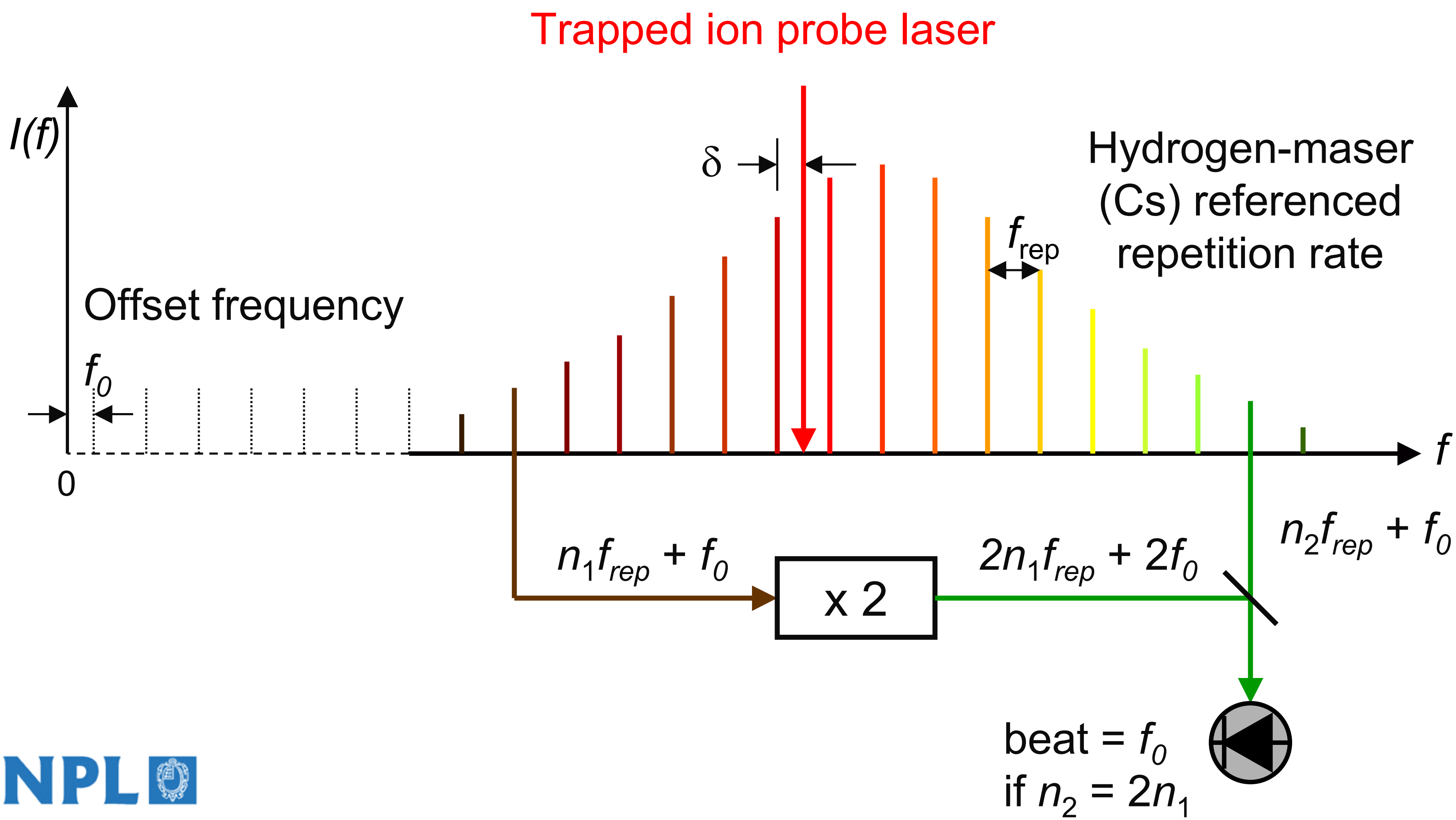


Frequency domain



Self-referenced optical frequency comb

$$f_{\text{probe}} = m\, f_{rep} \pm f_0 \pm \delta$$



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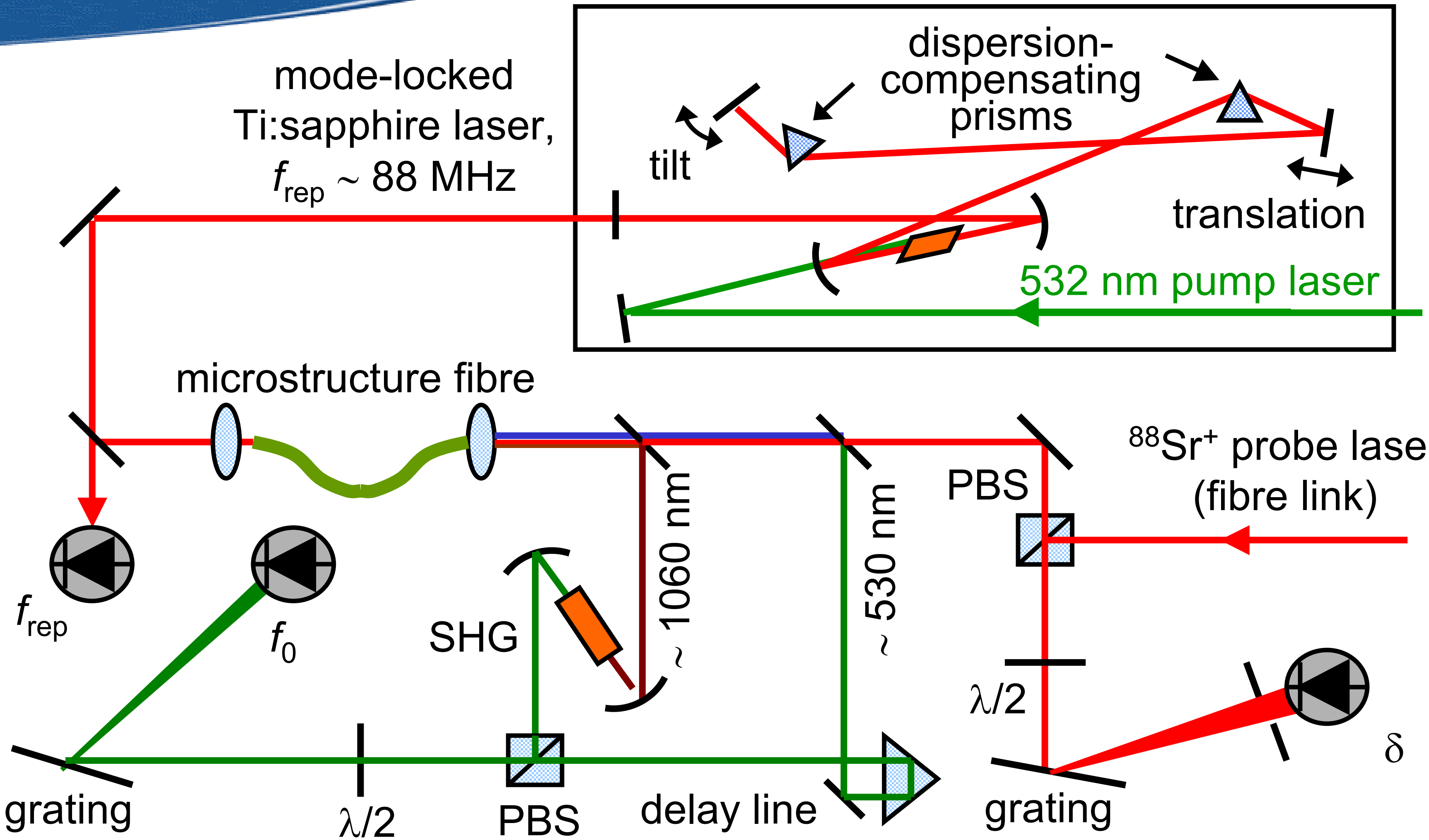
Femtosecond optical frequency comb



$$f_{Sr} = m\,f_{rep} \pm f_0 \pm \delta$$

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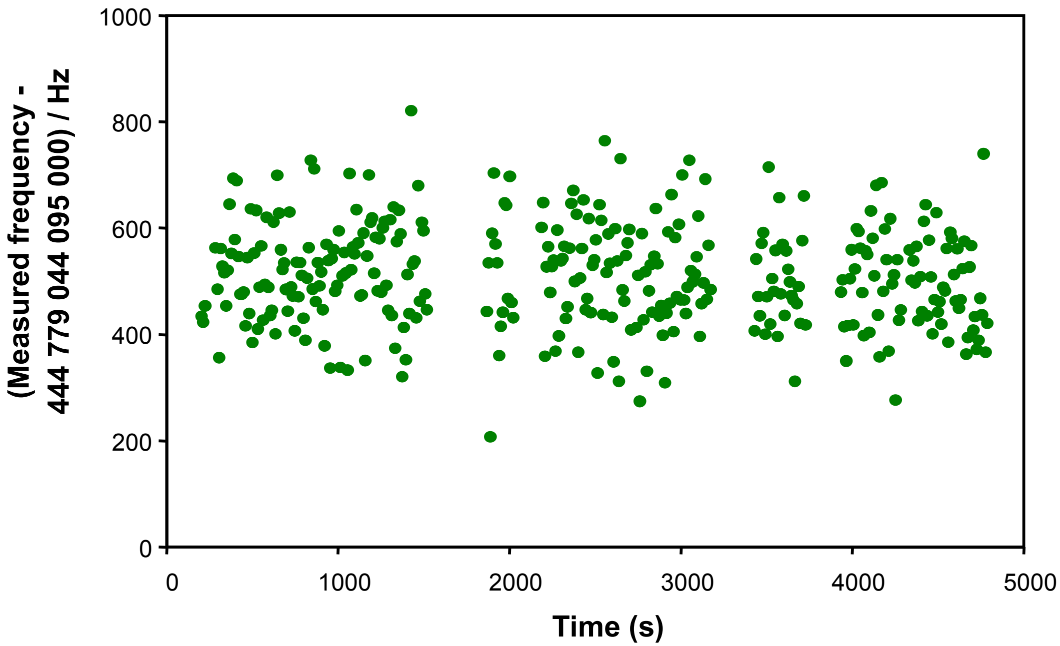
Stability of frequency measurements

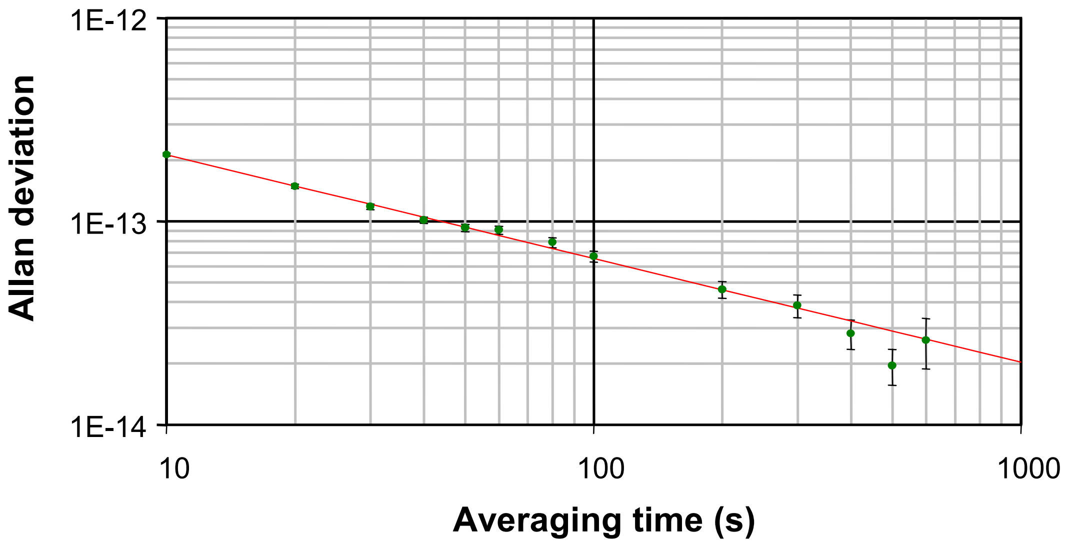
10s counter gate time

(Frequency values not corrected for maser offset from 10 MHz)



Allan deviation

2×10^{-13} at 10 s



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Electric quadrupole shift

Due to the interaction between the electric quadrupole moment of the 4d $^2D_{5/2}$ state with any residual electric field gradient at the position of the ion.

Frequency shift of the 4d $^2D_{5/2}$ state with magnetic quantum number m_j is:

$$\Delta\nu = A\left(\frac{35}{12} - m_j^2\right)\left(3\cos^2\beta - 1\right)$$

where $A = 3\, Q_{dc}\, \Theta(D,5/2) / 10\, h$

β = angle between quadrupole field axis and magnetic field

Q_{dc} = quadrupole field gradient

$\Theta(D,5/2)$ = quadrupole moment of 4d $^2D_{5/2}$ state

h = Planck's constant

Q_{dc} is determined from measurements of the trap secular frequencies and minimized by adjusting the voltages on the outer endcap electrodes.

The 4d $^2D_{5/2}$ state quadrupole moment was measured see:

G. P. Barwood et al., Phys. Rev. Lett. ***93****, 133001 (2004)*

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Nulling the quadrupole shift

$$\Delta\nu = A\left(\frac{35}{12} - m_j^2\right)\left(3\cos^2\beta - 1\right)$$

Method A:

- Select a particular pair of Zeeman components
- Carry out frequency measurements for three mutually orthogonal magnetic field directions
- Average quadrupole shift is zero

Method B:

- Carry out frequency measurements for three different pairs of Zeeman components, corresponding to $|m_j| = 1/2$, $3/2$, and $5/2$
- Average quadrupole shift is zero independent of magnetic field direction

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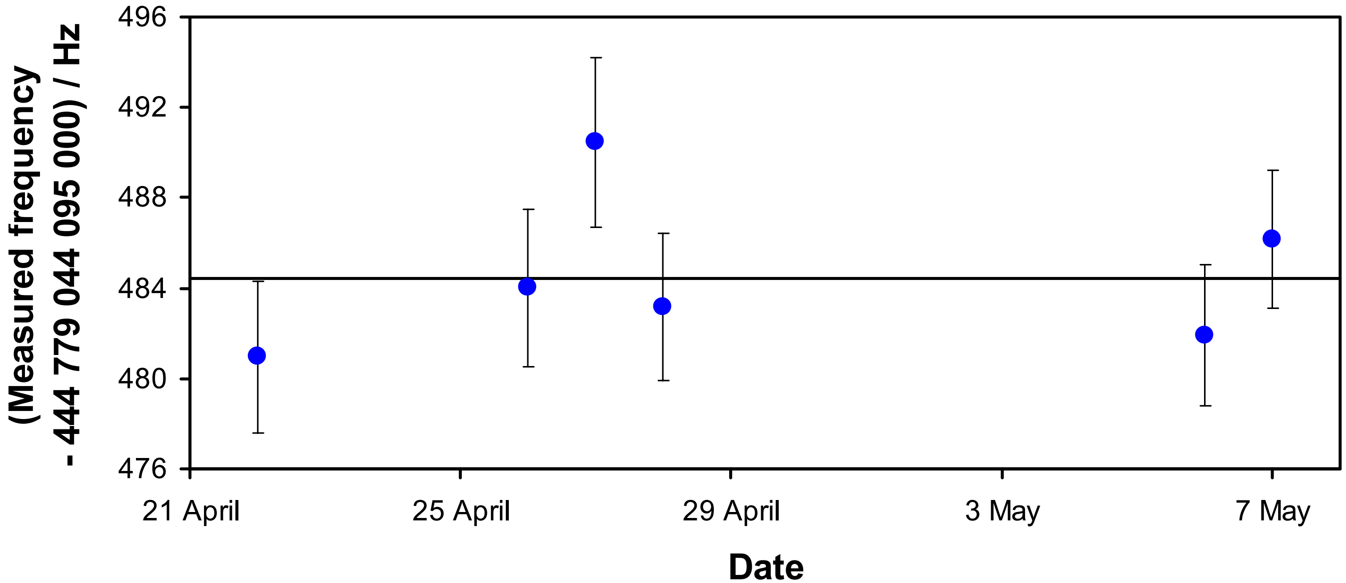
$^{88}Sr^{+}$ frequency measurements: method A



- Measurements carried out relative to the NPL caesium fountain
- Quadrupole shift nulled by measuring in 3 orthogonal B-field directions
- 6 days of data, statistical uncertainty 1.3 Hz

f_{Sr} = 444 779 044 095 484.3 (1.9) Hz

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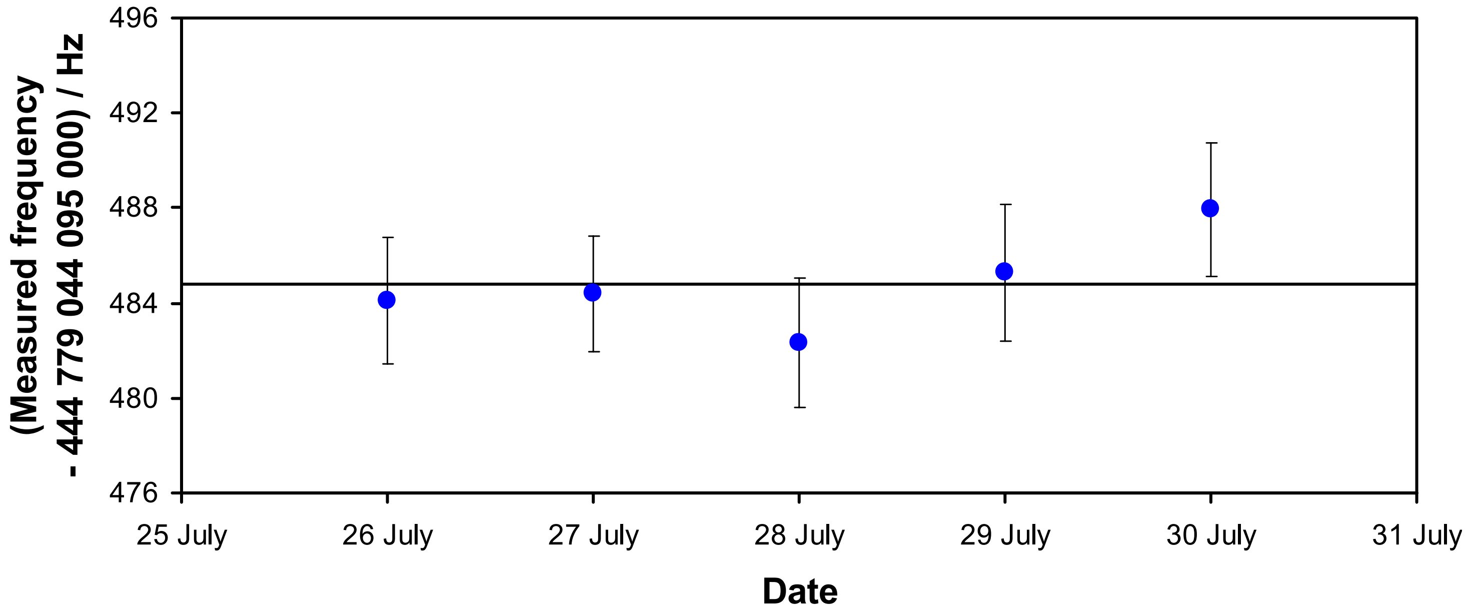
$^{88}Sr^+$ frequency measurements: method B



- Measurements carried out relative to the NPL caesium fountain
- Quadrupole shift nulled by measuring for 3 different values of m_j
- 5 days of data, statistical uncertainty 1.2 Hz

f_{Sr} = 444 779 044 095 484.8 (1.6) Hz

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Uncertainty estimate

Source	Method A		Method B	
	Shift (Hz)	Uncertainty (Hz)	Shift (Hz)	Uncertainty (Hz)
Statistics	**-**	**1.3**	**-**	**1.2**
Quadrupole shift	0	0.5	0	<0.01
2nd order Doppler shift (micromotion)	<0.01	0.01	<0.01	0.01
2nd order Doppler shift (secular motion)	<0.01	0.01	<0.01	0.01
Stark shift (micromotion)	+0.01	0.01	+0.01	0.01
Stark shift (secular motion)	<0.01	0.01	<0.01	0.01
Blackbody Stark shift	+0.30	0.08	+0.30	0.08
1092 nm ac Stark shift	0	0.02	0	0.02
422 nm ac Stark shift	**+1.4**	**0.8**	**+1.4**	**0.8**
Servo errors	**-1.0**	**0.6**	**-0.4**	**0.3**
Maser reference frequency	**0**	**0.7**	**0**	**0.7**
Gravitational shift	0	0.1	0	0.1
Total	+0.7	1.9	+1.3	1.6

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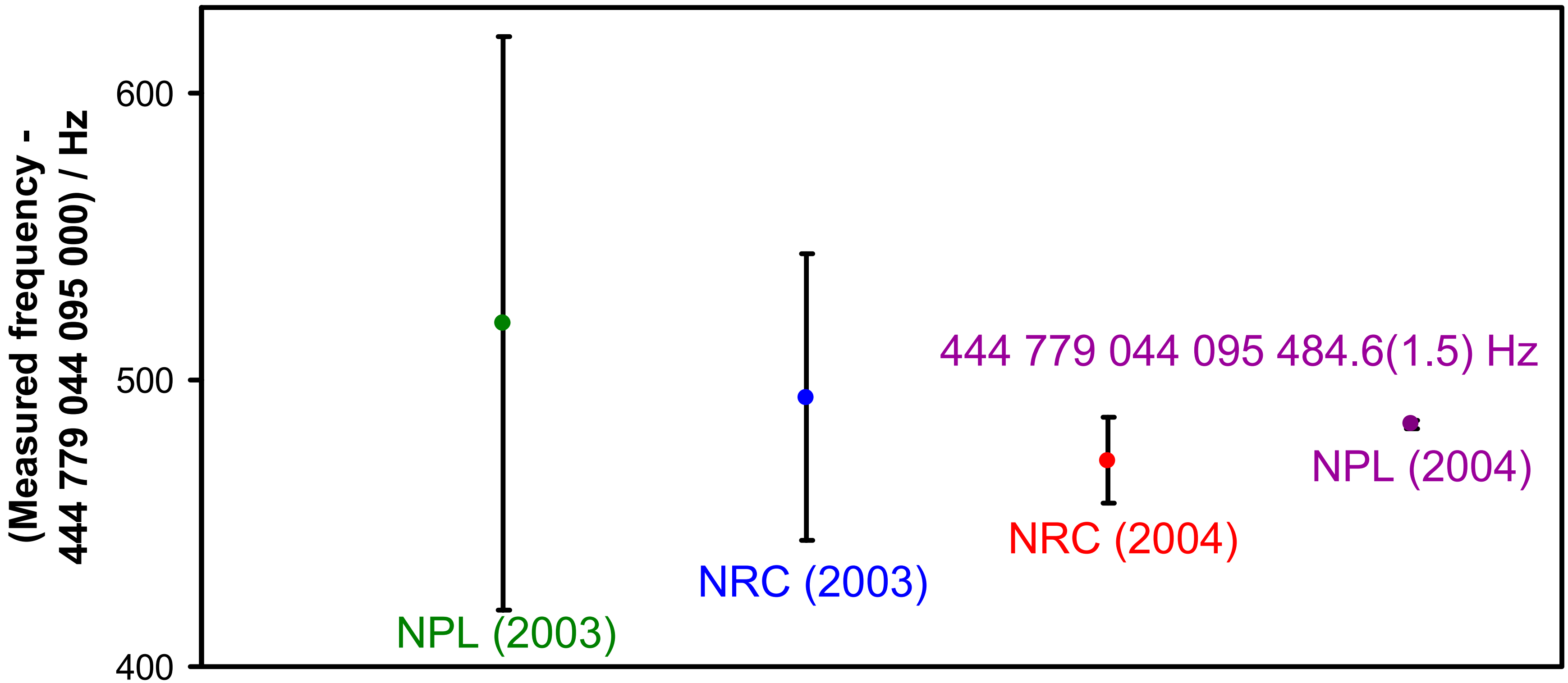
Comparison with previous results



NPL (2003): Margolis *et al*., Phys. Rev. A 67, 032501 (2003)
NRC (2003): Madej *et al*., Phys. Rev. A 70, 012507 (2004)
NRC (2004): Dubé *et al*., CPEM 2004 book of abstracts
NPL (2004): Margolis *et al*., Science 306, 1355 (2004)

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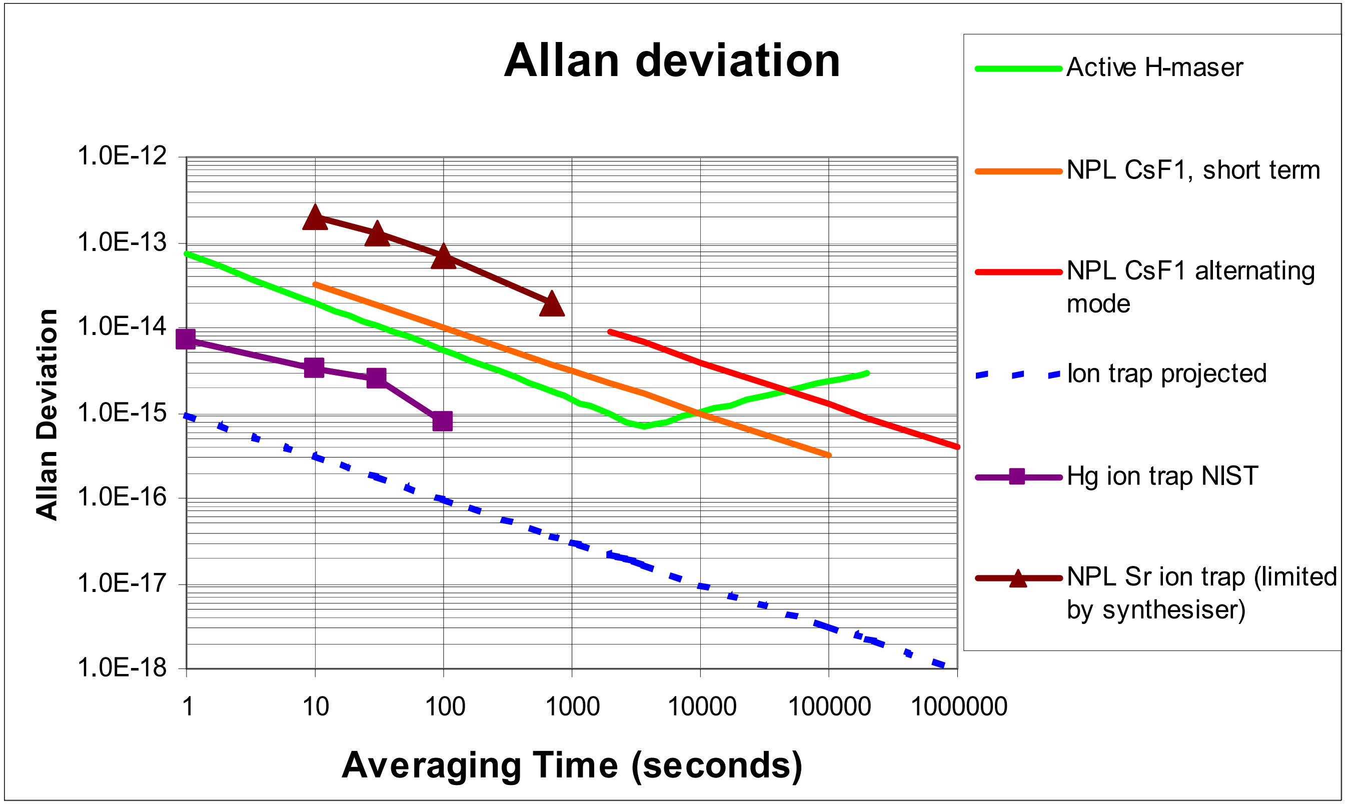
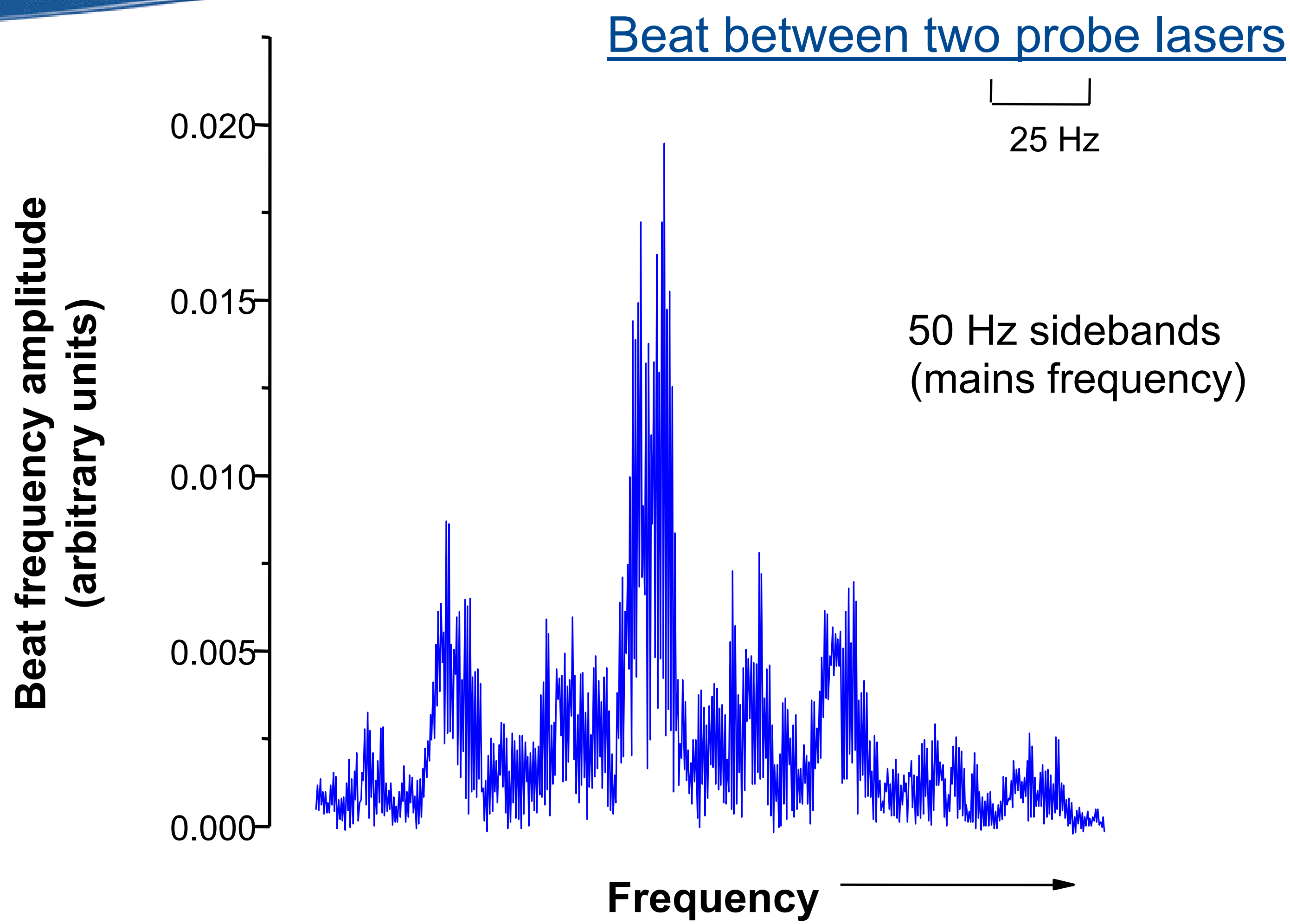
Stability



Allan deviation
1.0E-12
1.0E-13
1.0E-14
1.0E-15
1.0E-16
1.0E-17
1.0E-18
Allan Deviation
1
10
100
1000
10000
100000
1000000
Averaging Time (seconds)
Active H-maser
NPL CsF1, short term
NPL CsF1 alternating mode
Ion trap projected
Hg ion trap NIST
NPL Sr ion trap (limited by synthesiser)

674 nm probe laser linewidth improvements



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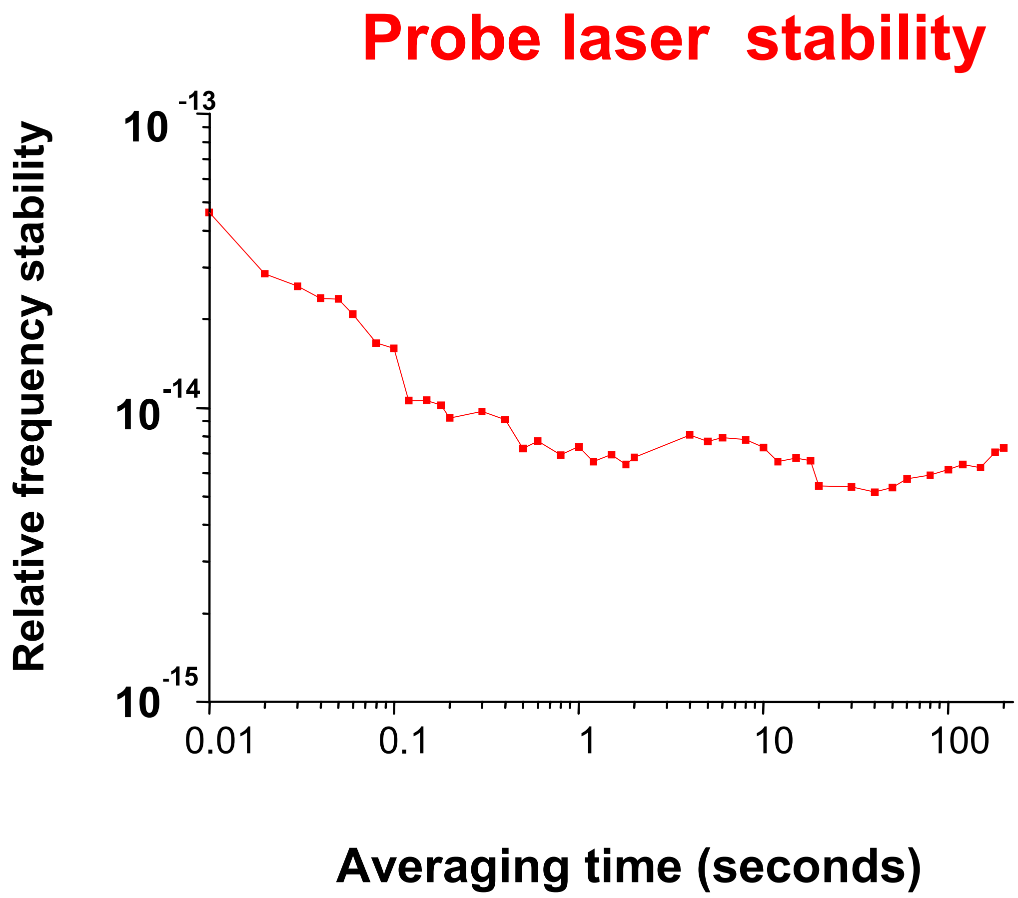
Allan deviation of beat between two probe lasers



Conclusion

- A measured absolute frequency of

  f_{Sr} = 444 779 044 095 484.6 (1.5) Hz
- Relative standard uncertainty $\sim 3.4 \times 10^{-15}$
  - Within a factor of three of the NPL caesium fountain standard
- Accurate enough to put forward as a secondary representation of the second

What next?

- Improvements in 422 nm extinction ratio (reduced ac Stark shift)
- Reductions in probe laser linewidth and drift (reduced servo errors)
- Additional AOM giving a drift-free source for frequency measurements
- Second endcap trap to enable trap comparisons
- Frequency measurements using a second (higher repetition rate) femtosecond comb

Our aim:

A $^{88}Sr^{+}$ optical frequency standard with stability and reproducibility exceeding that of the caesium fountain primary frequency standard

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With thanks to…

Witold Chalupczak and Dale Henderson
(Cs fountain)

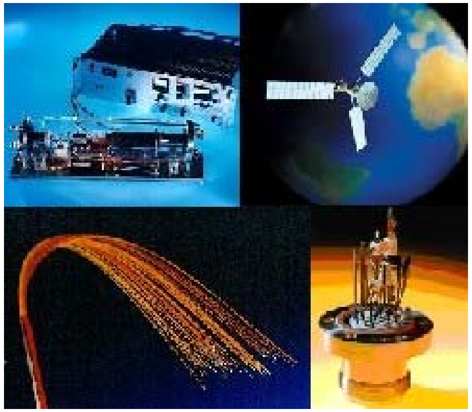
John Davis, Peter Stacey and Peter Whibberley
(masers and NPL timescale)

Neil Moore
(electronics support)

Fiona Auty
(media coverage)

and other members of the Time and Quantum Detection Team

Applications of atomic frequency standards



- Realisation of SI units
  - Time and length
- Fundamental physics
  - Tests of QED, general relativity
  - Measurements of fundamental constants
  - Laboratory searches for time-variation of fundamental constants
- Satellite navigation and ranging
  - GPS, Galileo and deep space
- Telecommunications
- Astronomy and survey
  - Gravity wave detection
  - Star and planetary survey using very deep baseline interferometry

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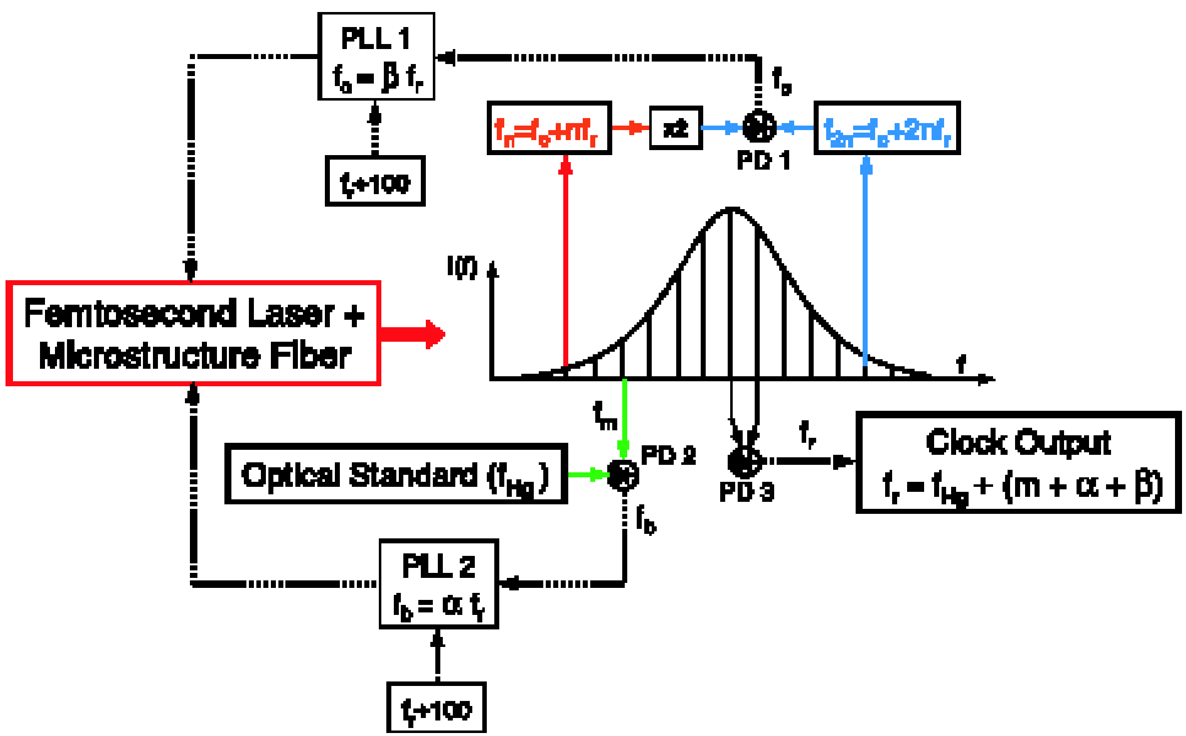
Optical clock

An Optical Clock Based on a Single Trapped $^{199}Hg^{+}$ Ion

S. A. Diddams,[1*] Th. Udem,[1†] J. C. Bergquist,[1] E. A. Curtis,[1,2]
R. E. Drullinger,[1] L. Hollberg,[1] W. M. Itano,[1] W. D. Lee,[1]
C. W. Oates,[1] K. R. Vogel,[1] D. J. Wineland[1]

Science **293** 825 (3 August 2001)



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