Trapped ion optical clock for future space deployment

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PT-UK Quantum Sensing and Metrology Workshop

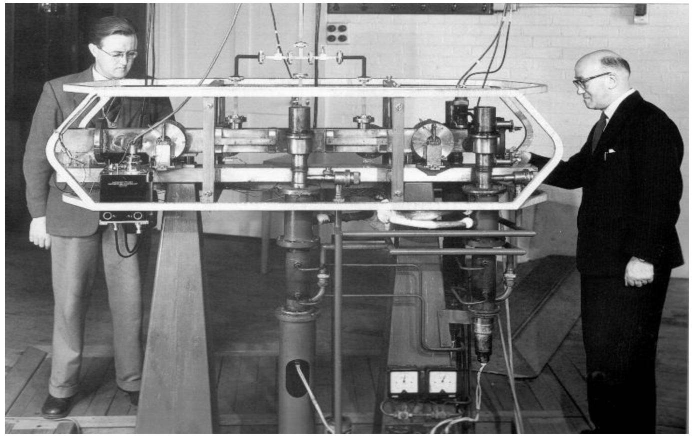
Introduction

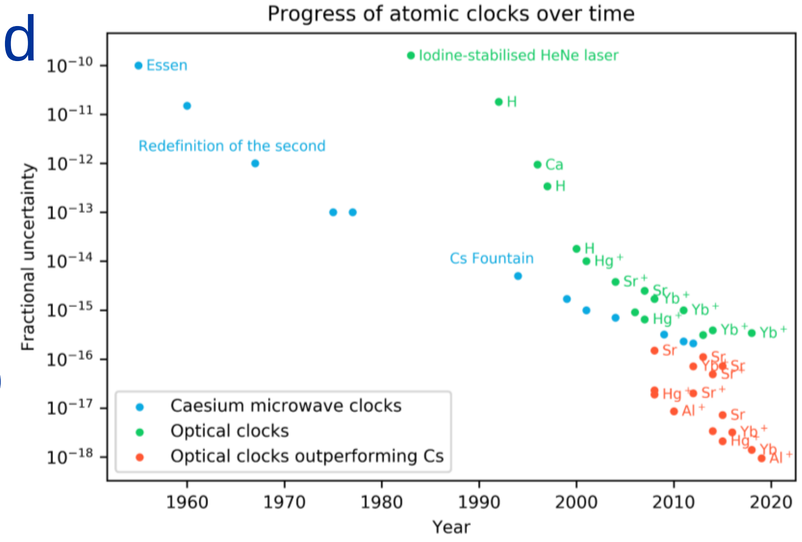
- Background motivation for optical clock development – e.g. the planned optical redefinition of the second
- Development of optical clocks and cavities for space
- Outline of the major sub-systems of an optical clock, namely the physics package, high finesse optical cavity and frequency comb
- Introduction to our $^{88}Sr^{+}$ trapped ion optical clock for future space deployment
- Compact optical cavities for space, particularly with application to clocks

Funding:

Background

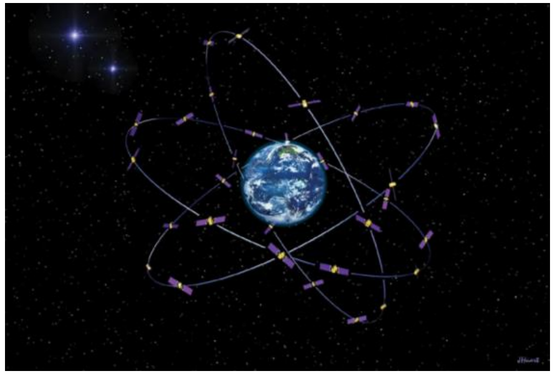
- First Cs atomic clock developed at NPL in 1955 (upper right)
- Caesium (~9.2 GHz) the definition of the second
- Optical frequency standards more reproducible and stable than Cs microwave (lower, right). Both neutral (lattice) and ion clocks being developed worldwide
- BIPM maintains a list of recommended optical secondary representations of the second using ions and atoms (one of these is a transition in $^{88}Sr^{+}$)
- Caesium expected to be replaced by an optical definition around 2030
- Talk will focus on NPL work on $^{88}Sr^{+}$ with application to future space deployment and our associated optical cavity development for short-term stability

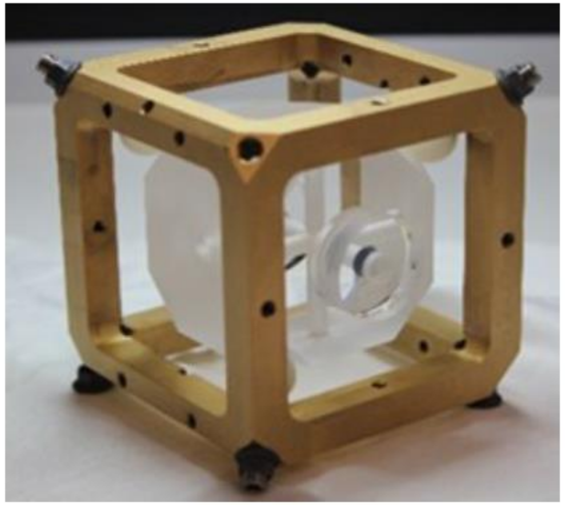




Why cavities & optical clocks in space?

- Navigation – a future GNSS using optical clocks and cubic cavity (will discuss later)
- LISA (gravity wave detection; e.g. see Greve *et al*, “Space based lasers for gravitational wave detection”, (Laser Applications Conference, Vienna, Sept. 2019); Stacey *et al*, “Laser frequency stabilisation for the LISA mission using a cubic cavity” (ICSO 2022)
- Fundamental physics (e.g. Lorentz invariance violations; see Sanjuan *et al*, Optics Express, 27, 36206 (2019))
- Next Generation Gravity Missions (e.g. see Dahl *et al*, “High Stability Laser for Interferometric Earth Gravity Measurements” SPIE Proc 10562, (ICSO 2016) 105620J (2017)

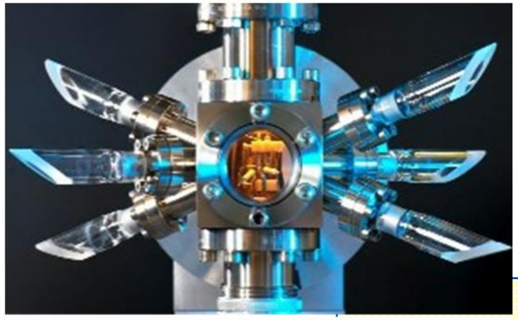


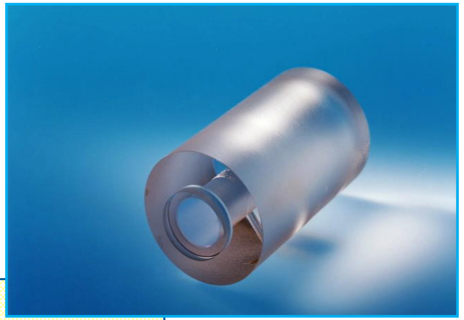


lisa

Major sub-systems of an optical clock

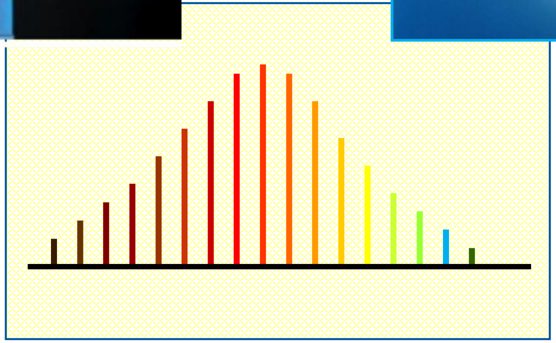
Single cold
trapped ion
(atomic reference)





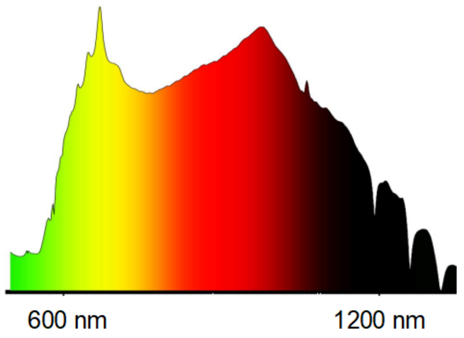
Ultra-stable cavity
("optical flywheel",
providing short-term
frequency stability)

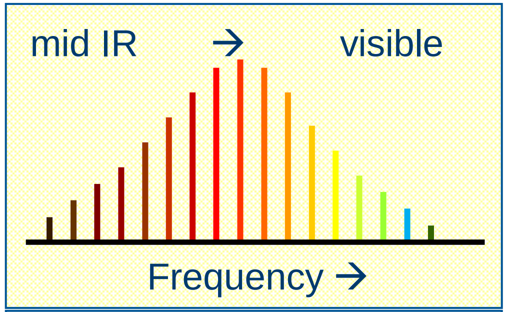
$^{191}Hg^{+}$, $^{88}Sr^{+}$, $^{171}Yb^{+}$, $^{40}Ca^{+}$, $^{115}In^{+}$, $^{27}Al^{+}$



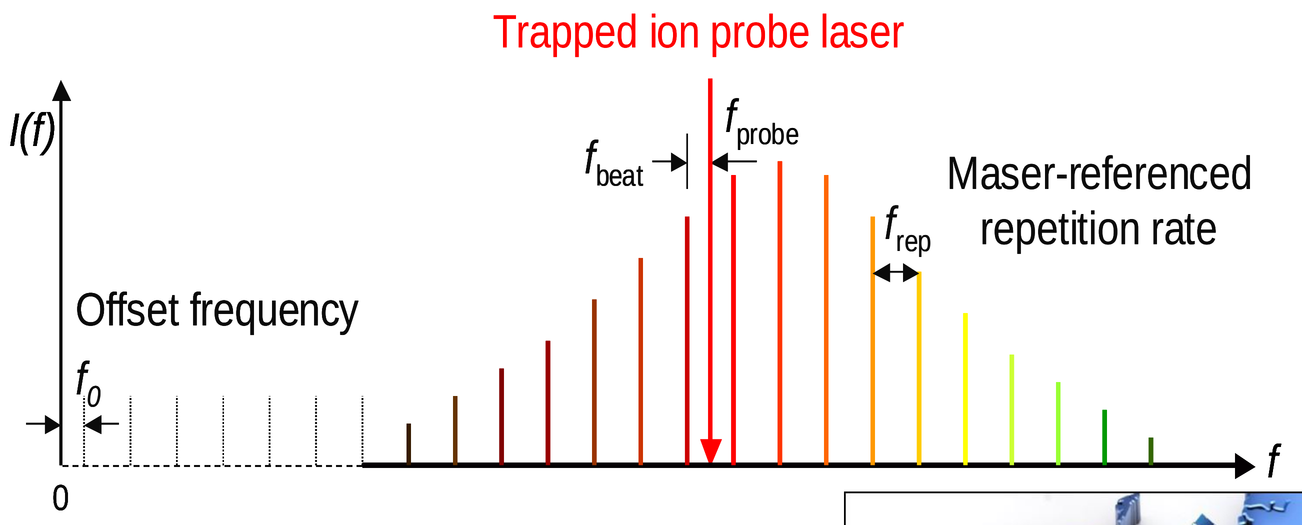
Femtosecond comb (counter;
compares optical frequencies or
outputs an RF/ microwave signal)

Frequency combs and intercomparisons

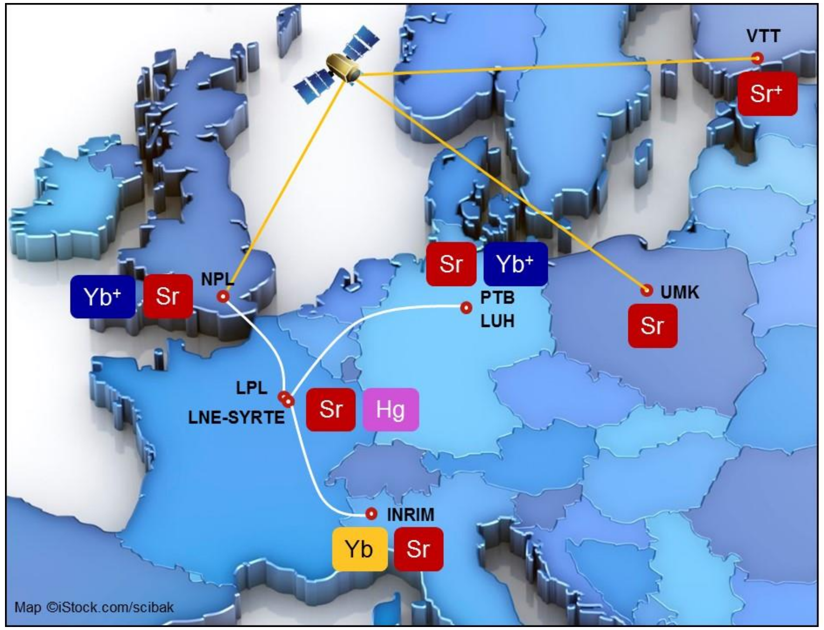




→ millions of modes across visible/IR with known frequency

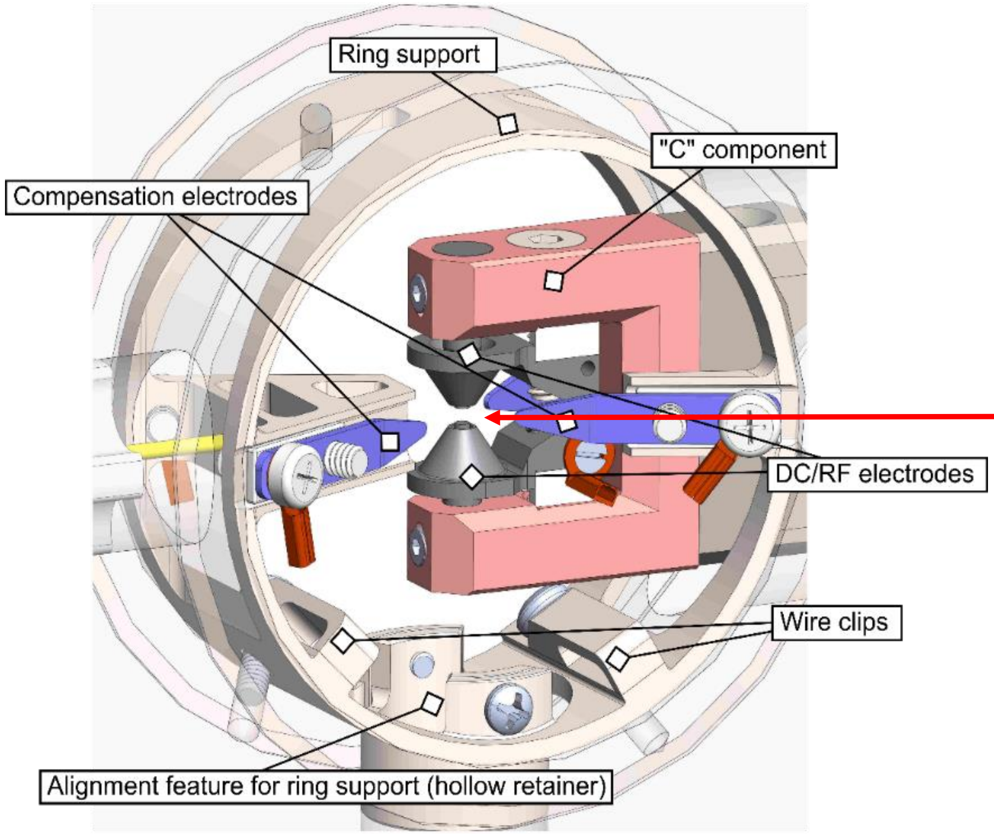


$$f_{\text{probe}} = m\, f_{\text{rep}} \pm f_0 \pm f_{\text{beat}}$$



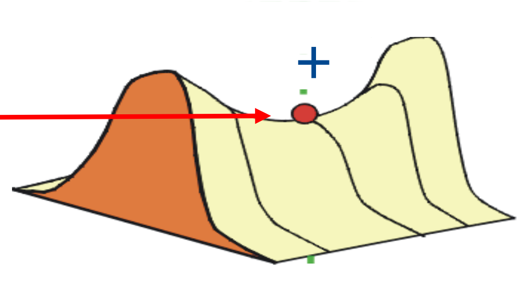
International intercomparisons via satellite or fibre links (right)

Ion traps – an introduction



Nisbet-Jones et al, “A single-ion trap with minimized ion–environment interactions”, Appl. Phys. B 122, 57 (2016)

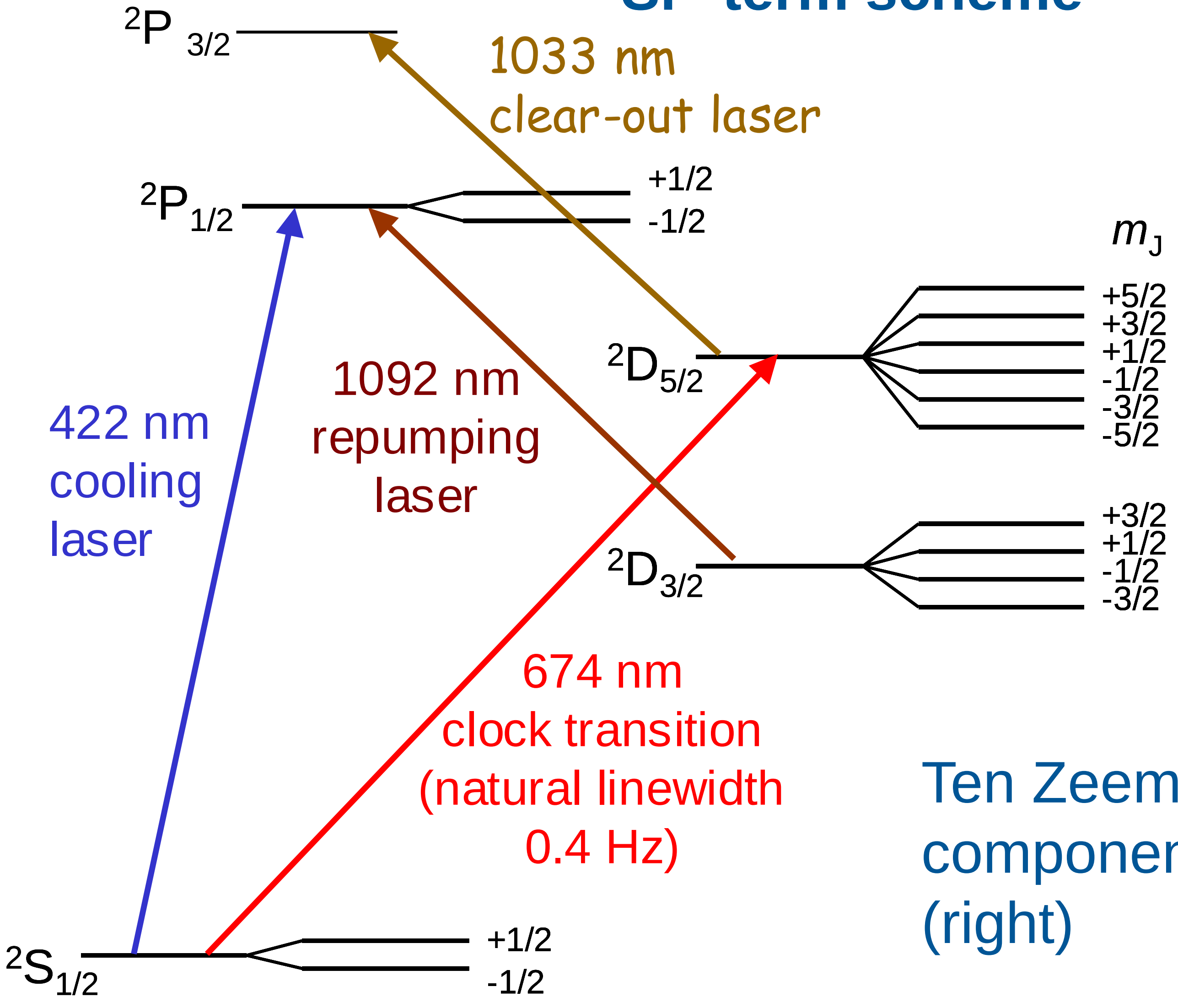
Positively charged ion



A static potential cannot trap ions in all three directions. A mechanical analogue is the rotating saddle trap.

$^{88}Sr^+$ – overview

$^{88}Sr^+$ term scheme



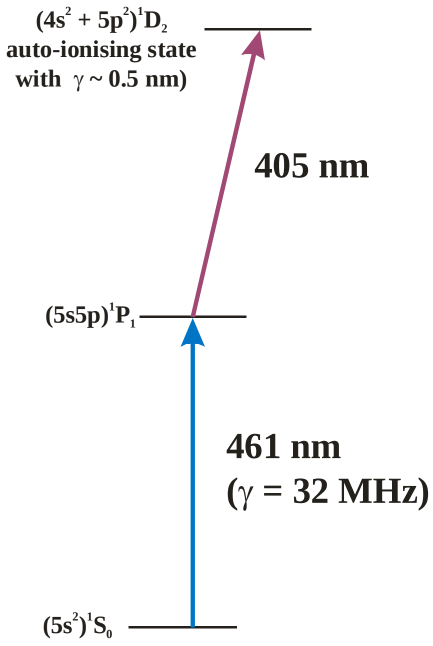
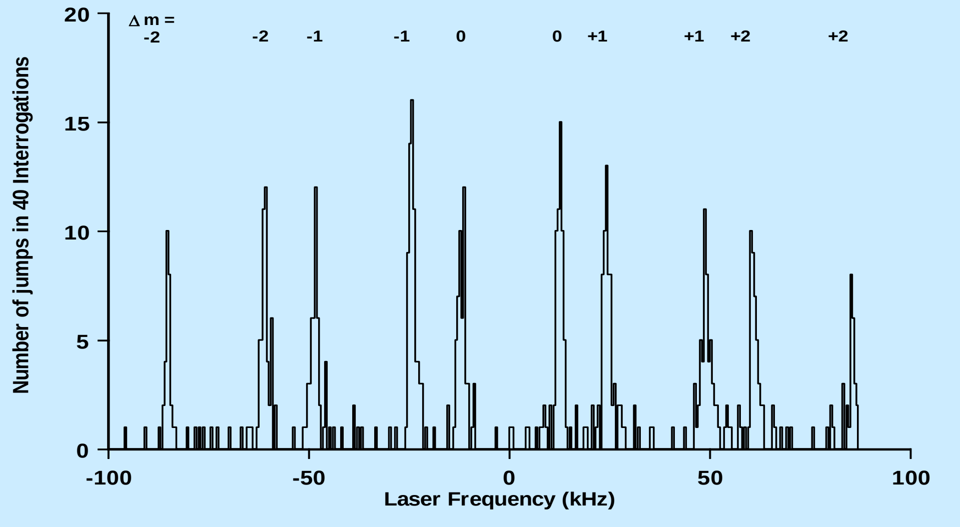
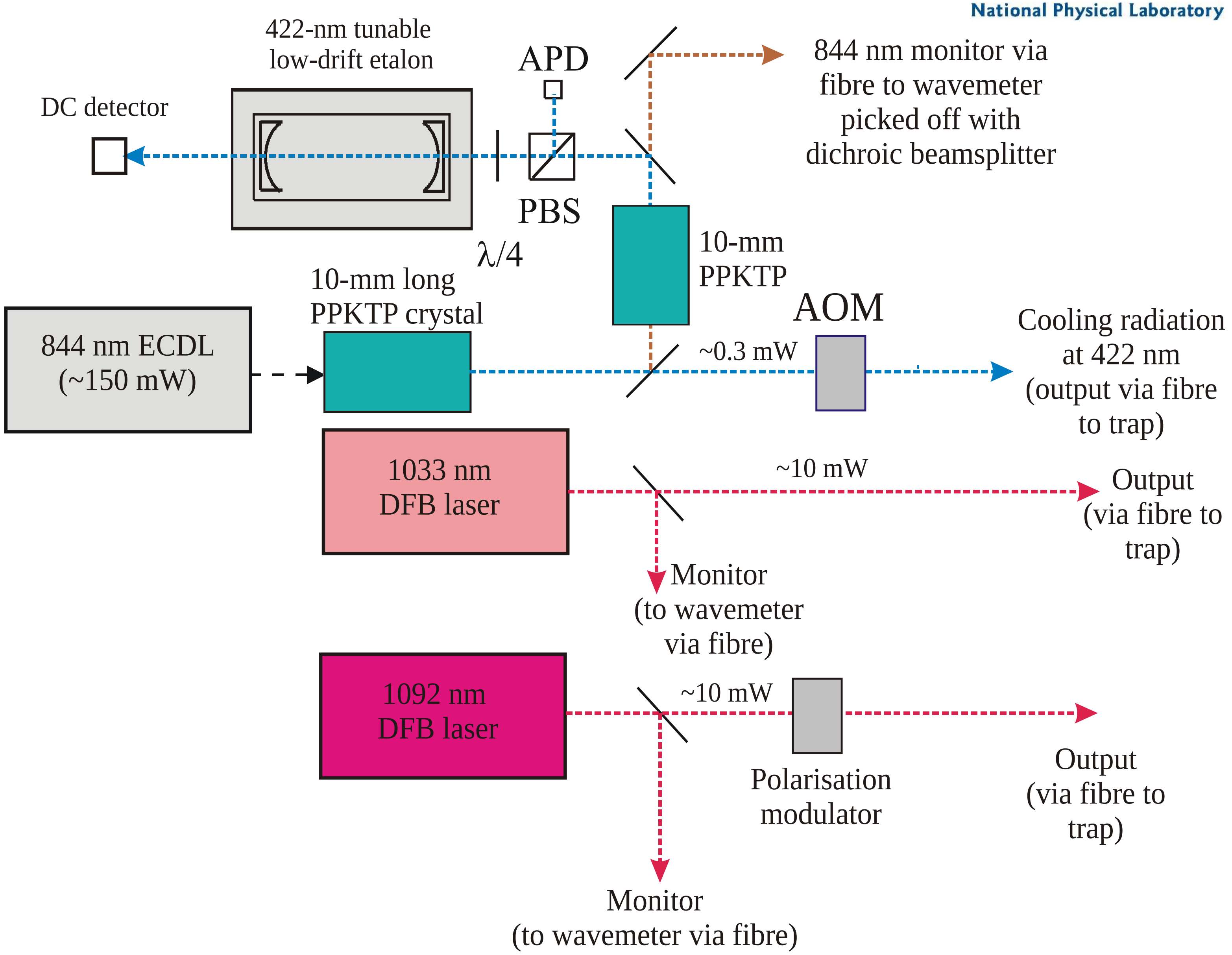


Photo-ionisation: 461 nm ~32 MHz linewidth & 405 nm multi-mode

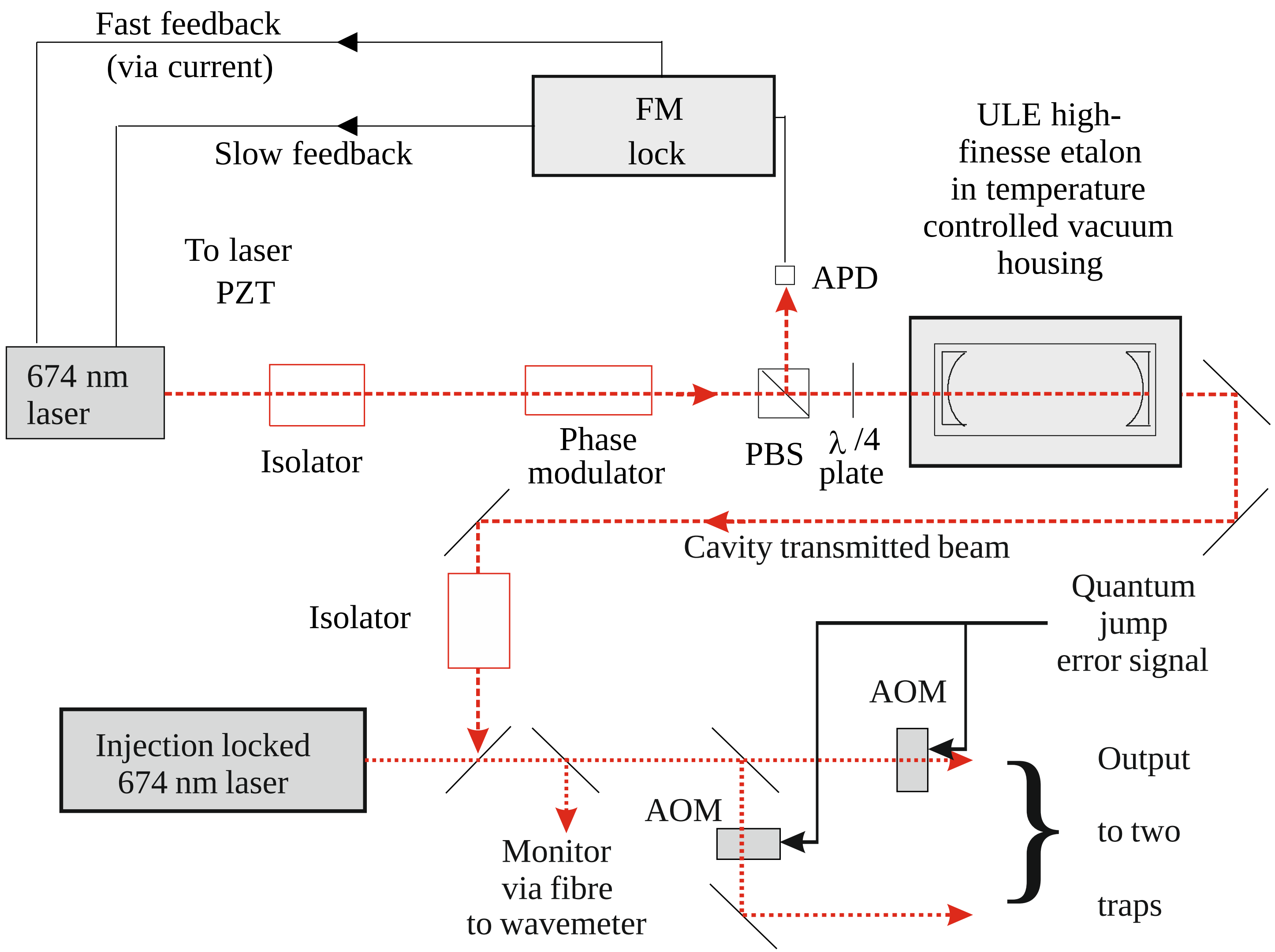
Ten Zeeman components (right)



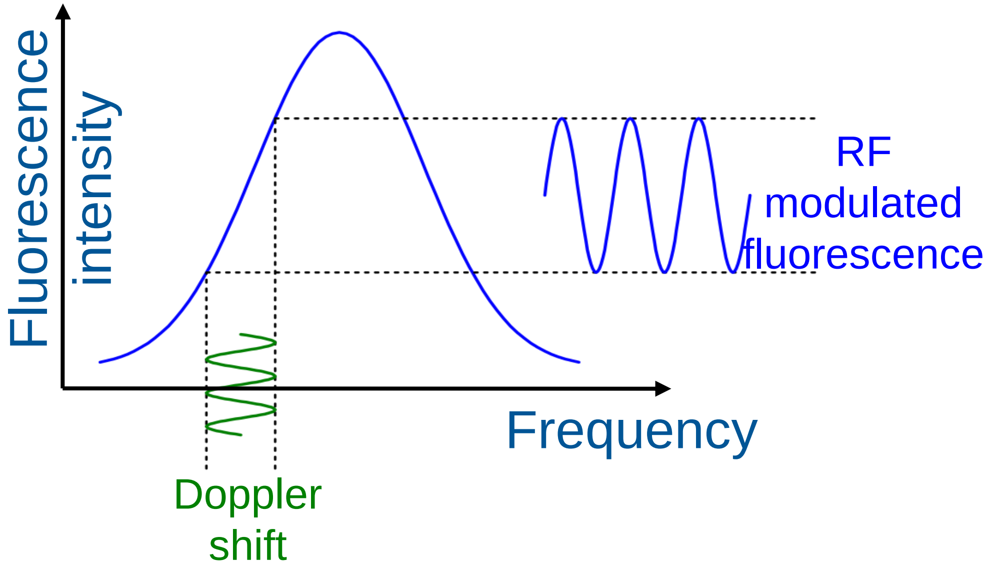
Cooling and clear-out lasers for $^{88}Sr^{+}$



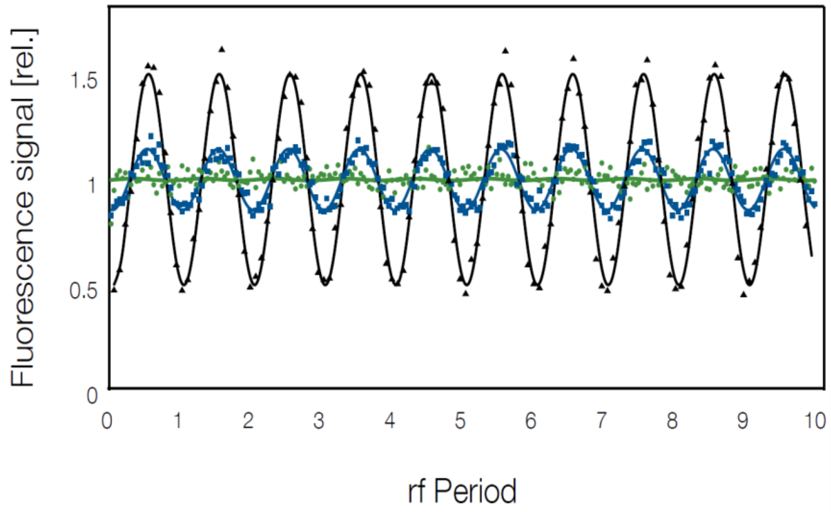
Probe laser system



Micromotion observation and minimisation

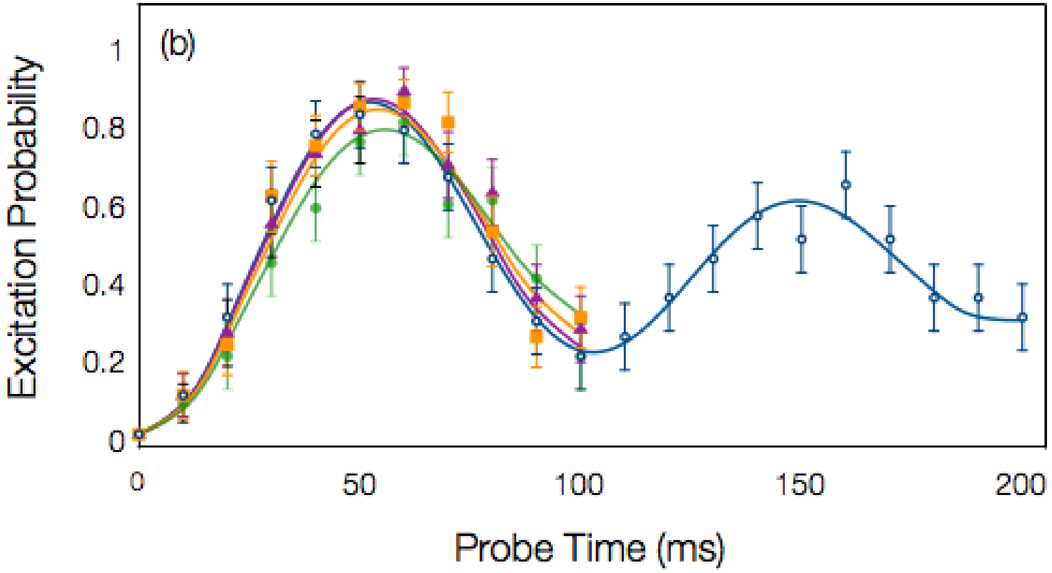


For Sr^+, a 14.4 MHz drive frequency is used to cancel Stark & Doppler shifts due to the micromotion.



- Micromotion is motion at the trap RF drive frequency
- Micromotion detection (above) and minimisation (right)

Monitoring of the ion heating rate



From Nisbet-Jones et al, “A single-ion trap with minimized ion–environment interactions”, Appl. Phys. B 122, 57 (2016)

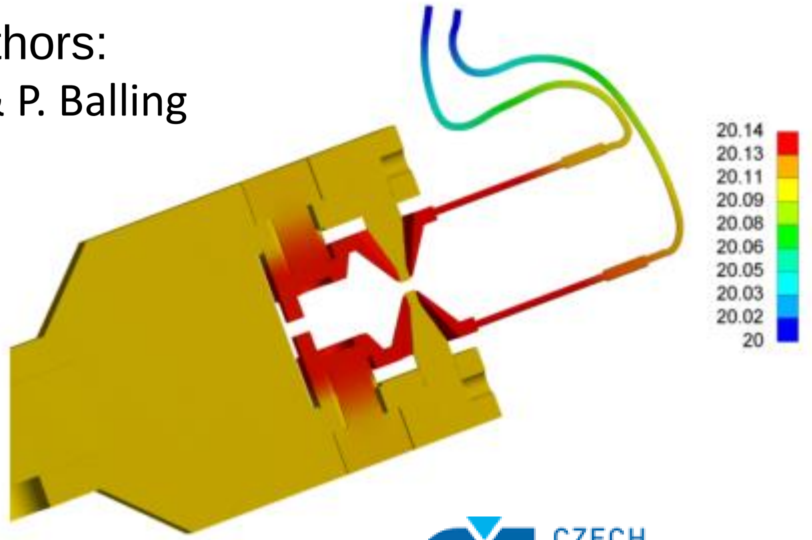
Rabi oscillation decay on the E3 transition for different post-cooling delay times

$$\frac{d\langle n\rangle}{dt} = 24^{+30}_{-24}s^{-1}$$

Electrode temperature and blackbody shift evaluation

$$\Delta\nu_{BBR}(T) = -\frac{1}{2h}\Delta\alpha_s^{dc}\left(794\frac{\mathrm{V}}{\mathrm{m}}\right)^2\left(\frac{\mathrm{T}}{300\mathrm{K}}\right)^4$$

CMI co-authors:
M.Doležal & P. Balling



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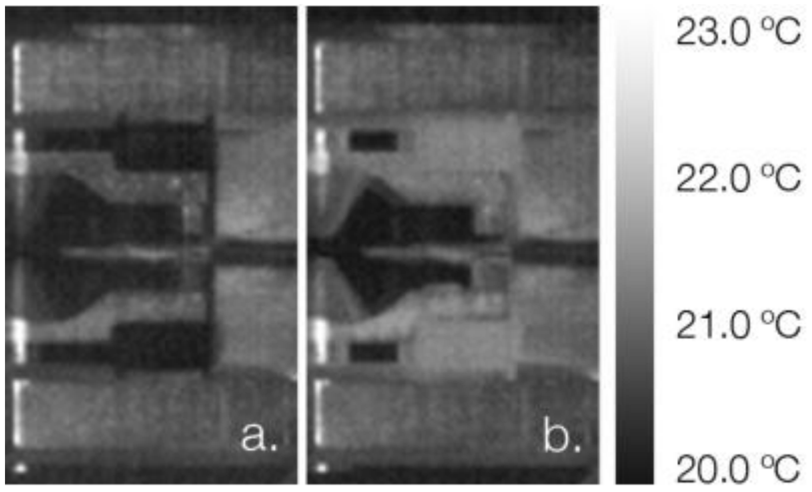
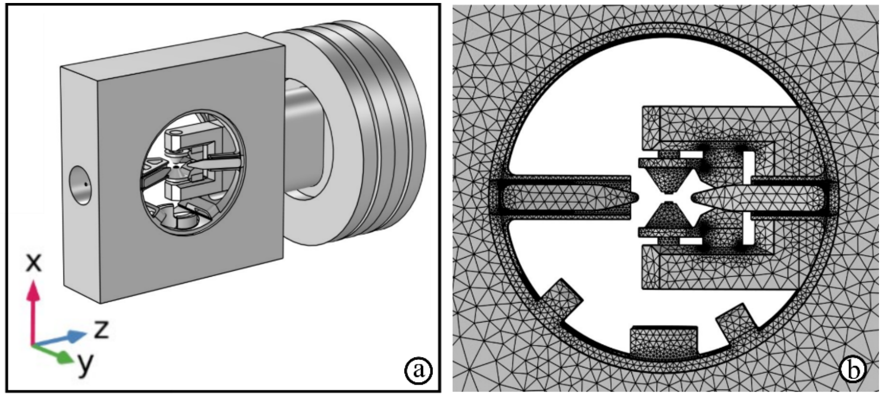
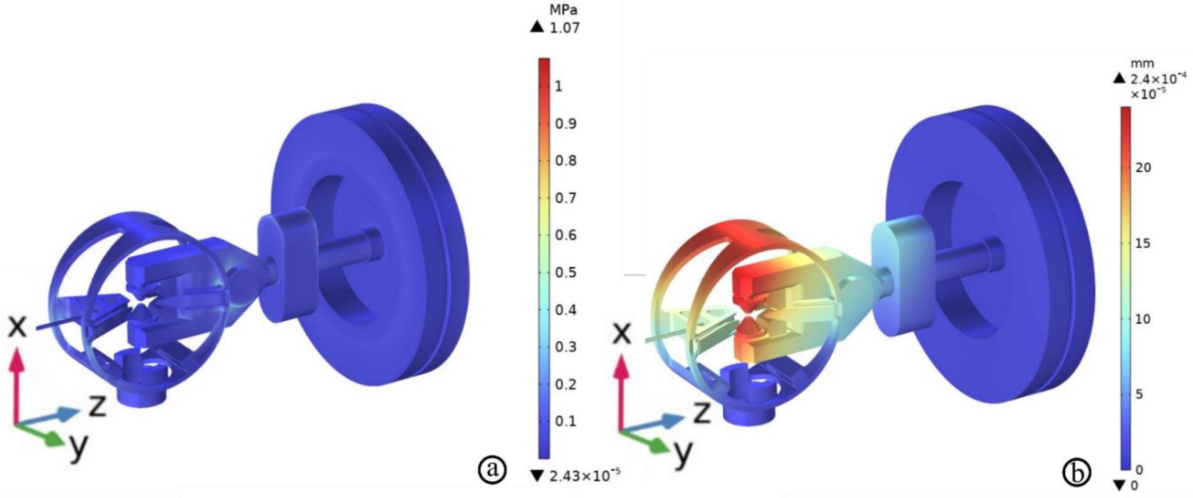


Nisbet-Jones Appl.Phys.B **122** 57 (2016)

Effective temperature rise at the ion’s position of T(ion) = 0.14 ± 0.14 K
For $^{88}Sr^{+}$, this reduces the BB relative frequency shift to 1 x 10^{-18}

Virtual shake and shock modelling

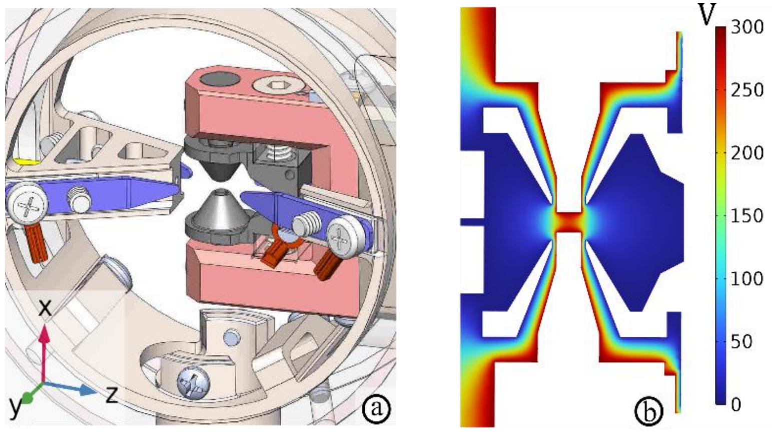


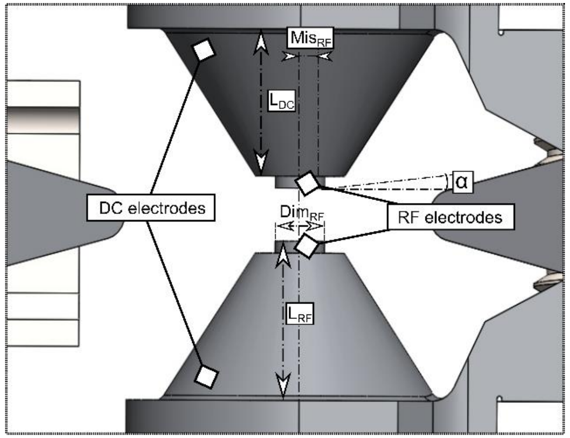


- Defeaturing (a) upper left and meshing (b) of the trap electrode structure prior to modelling of the response to virtual shake and shock tests
- Maximum equivalent stress (a) and maximum deflection (b) for the ion trap key components (upper right)

A. Spampinato et al, “Progress towards development of a trapped strontium-ion space optical clock”, Proc SPIE, 12335, 1233502 (2023)

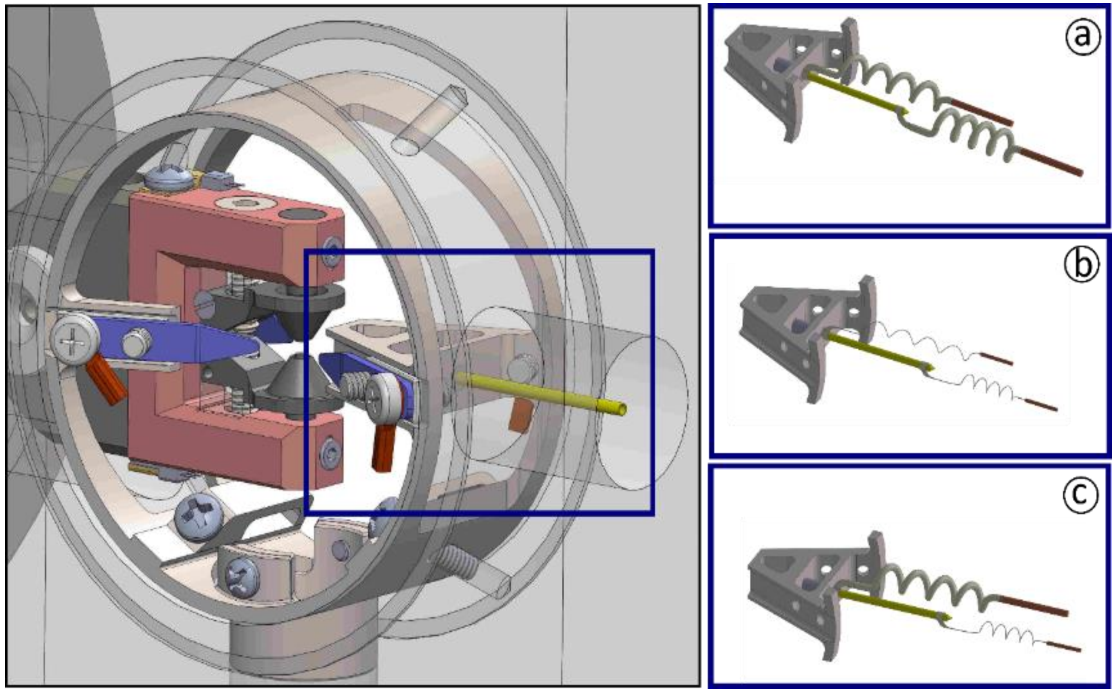
Electromagnetic modelling of the trapping potential





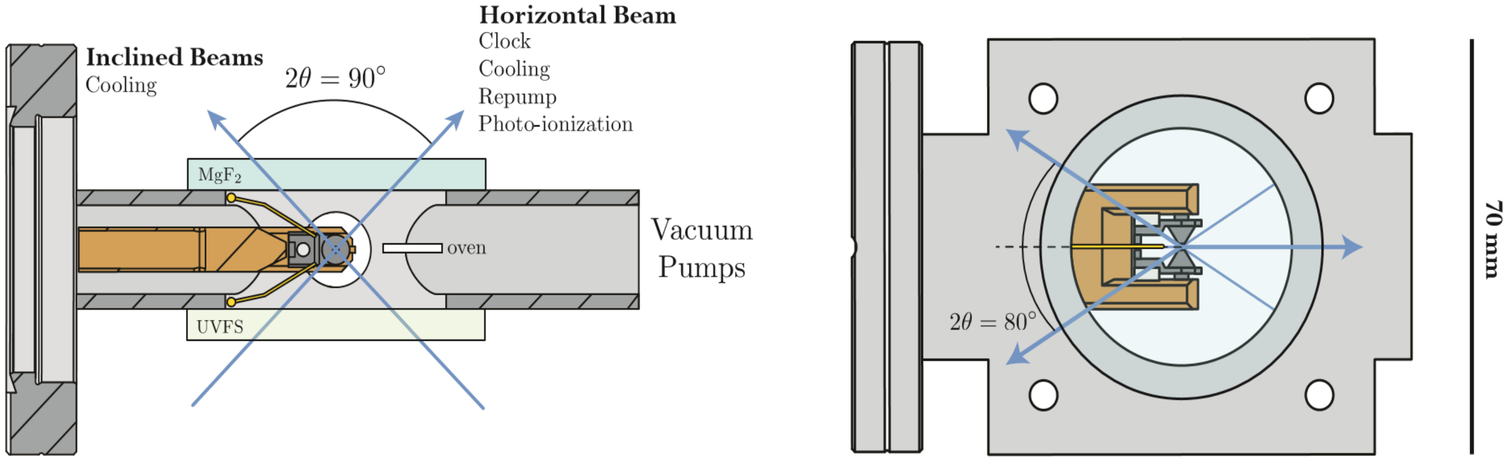
- Reference system for the ion trap (upper left) during the electrostatic study (a) and electric potential distribution (b)
- The key parameters for the trap geometry are shown upper right
- An RF voltage on the inner electrodes creates a harmonic pseudo-potential

Modelling of thermal response of different oven designs



- Oven configurations modelled for electro-thermal FE analysis: a) thick wires (1 mm in diameter), b) thin wires (0.1 mm in diameter), c) both thick and thin wires

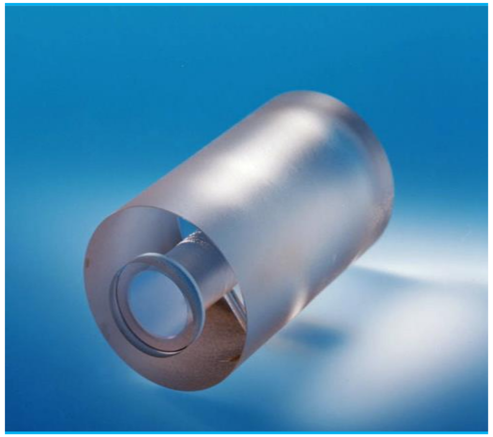
Fluorescence detection and input beam optics



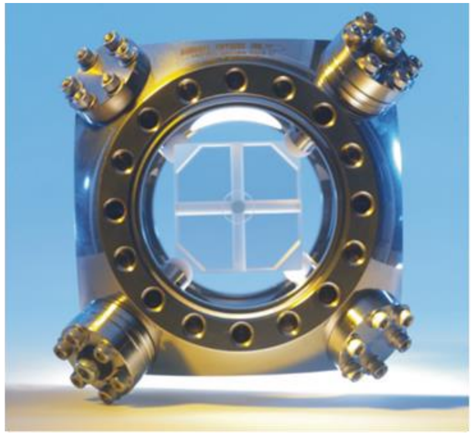
One window is MgF_2 – transparent to 8 μm; for thermal imaging & Stark shift measurements in the IR.

For Sr^+, photonic crystal fibre will deliver 422 nm, 1092 nm, 1033 nm and 674 nm. A PM fibre will deliver 422 nm & 461 nm, 405 nm (photo-ionisation)

Compact optical cavities for space



Cylindrical cavities (far left) have a high sensitivity to acceleration. The lowest acceleration sensitivity comes from a symmetric cubic geometry with tetrahedral supports (right). This mounting can be adapted to withstand forces at launch



OPTICS LETTERS / Vol. 36, No. 18 / September 15, 2011

Force-insensitive optical cavity

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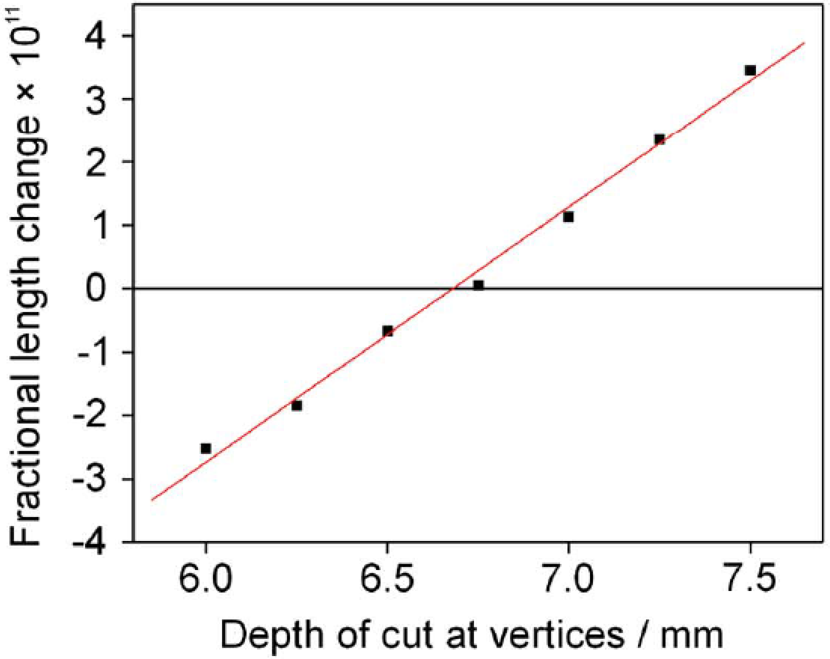
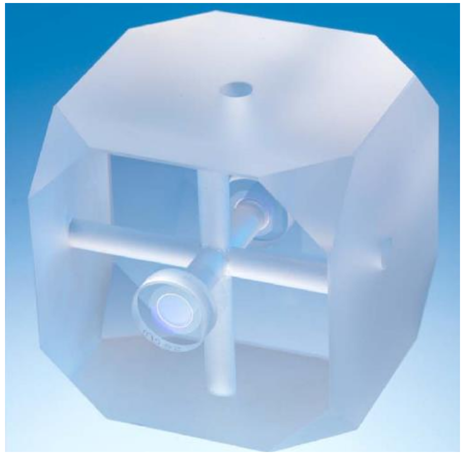
National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK
**Corresponding author: stephen.webster@npl.co.uk*

Received June 20, 2011; revised August 11, 2011; accepted August 11, 2011;
posted August 12, 2011 (Doc. ID 149376); published September 9, 2011

- Cubic cavity work is a development from the paper (left) published in Optics Letters in 2011

Vibration insensitivity

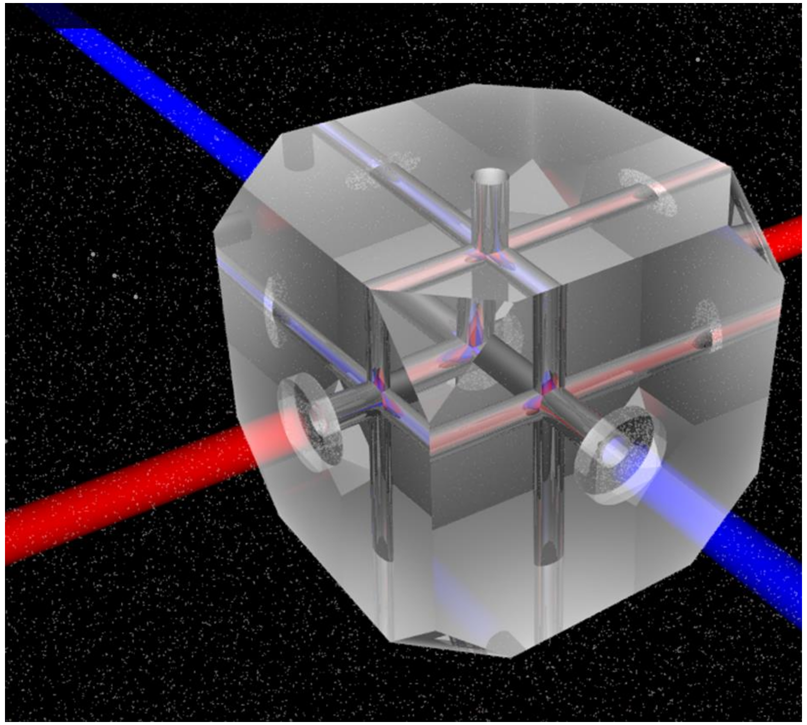


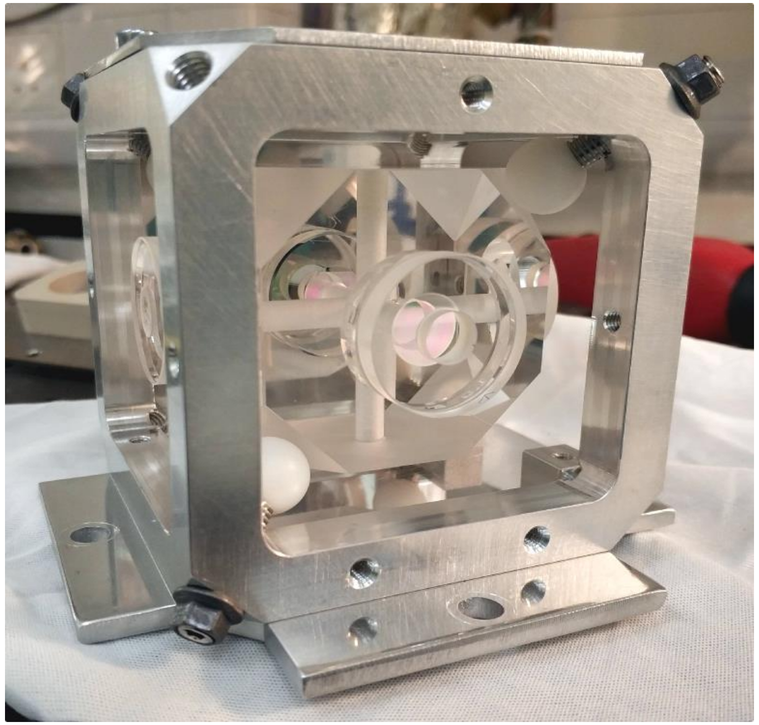


- Webster & Gill “Force-insensitive optical cavity”, Opt Lett, 36, 3572 (2011)
- Vibration insensitivity comes from the symmetry of the cubic spacer and the symmetric (tetrahedral) supporting structure. The mirrors result in asymmetry but the resulting sensitivity to vibration can be minimised by choosing the correct cut-out depth
- A dual-axis axis cavity has been developed for clock applications, see Hill et al, “Dual-axis cubic cavity for drift-compensated multi-wavelength laser stabilisation”, Opt Express, 29, 36758 (2021); next slides

Clock control unit

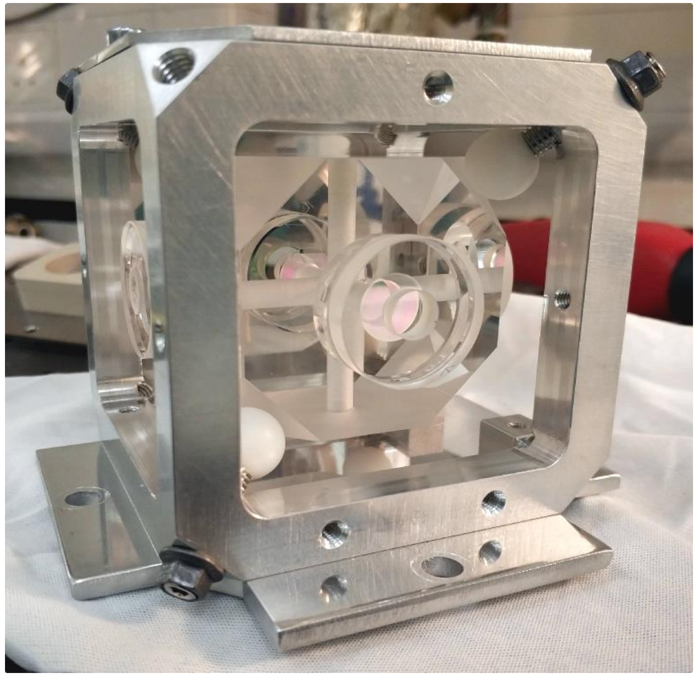
- I. R Hill, R. J. Hendricks, S. Donnellan, P. Gaynor, B. Allen, G. P. Barwood, and P. Gill, “Dual-axis cubic cavity for drift-compensated multi-wavelength laser stabilisation”, Opt Express, 29, 36758 (2021)
- One bore to pre-stabilise the clock laser frequency and the other to stabilise the cooling, clear-out and photo-ionisation lasers

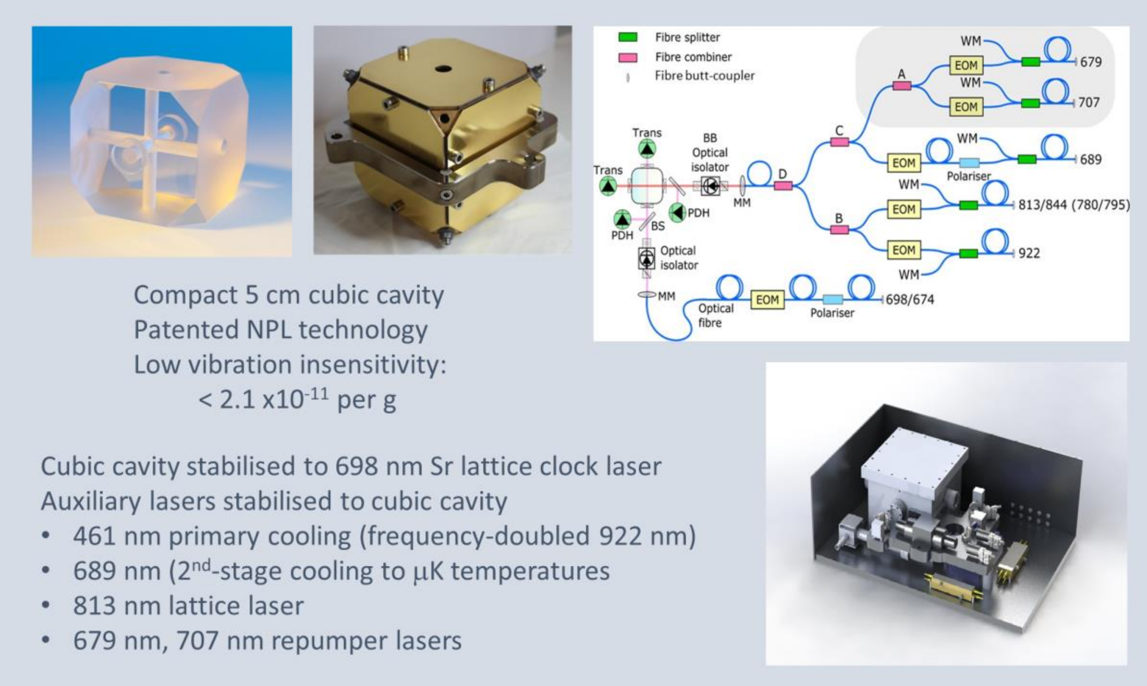




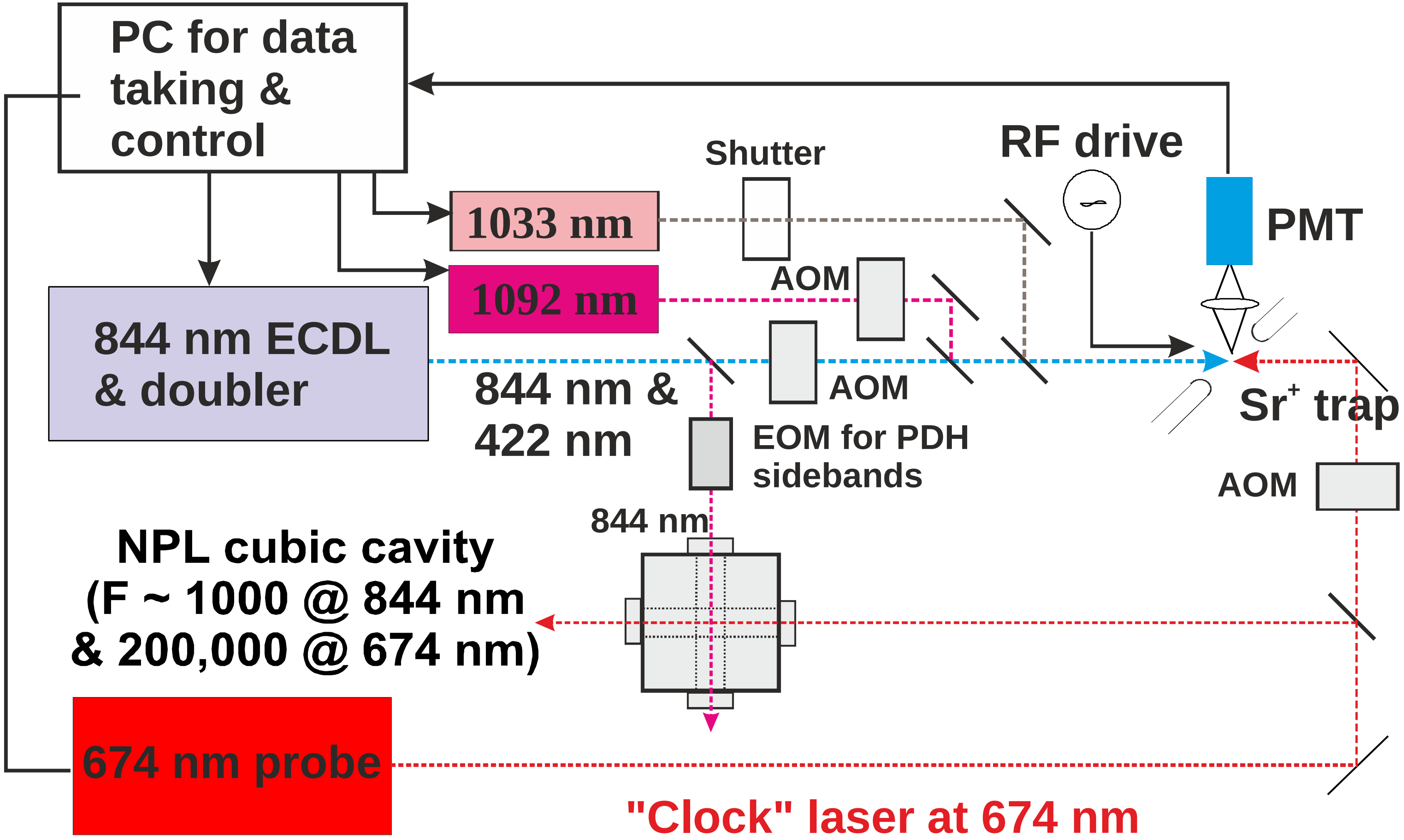
Clock control unit

- For space, the cavity mounting needs to be sufficiently robust for space deployment
- TRL6 demonstrated (R. Sütterlin *et al*: "Towards space deployable laser stabilisation systems based on 5-cm vibration insensitive cubic cavities," in Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium, 2021.)

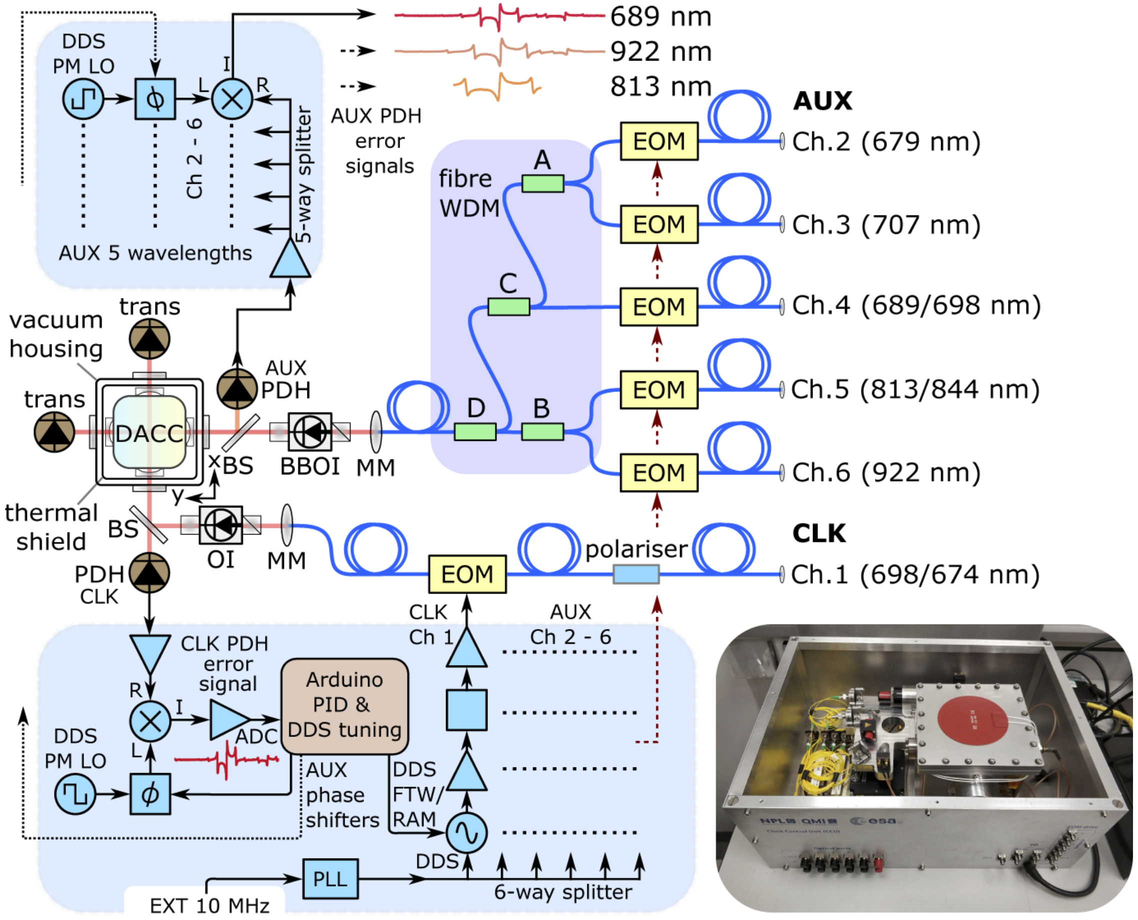


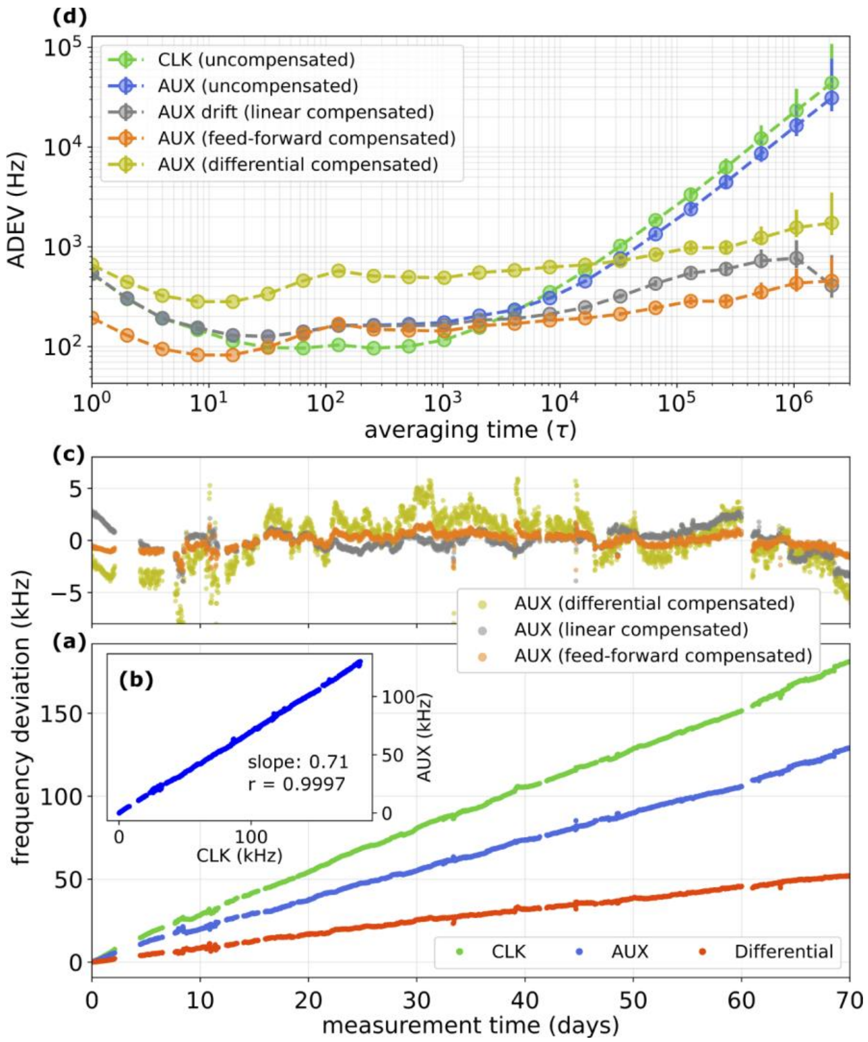


Planned cooling and clock lasers including dual-axis cubic cavity



Clock control unit – multiplexing light into the cavity and performance

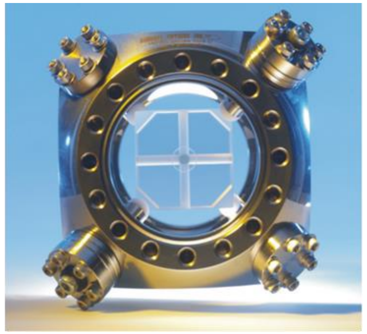




Thanks to…

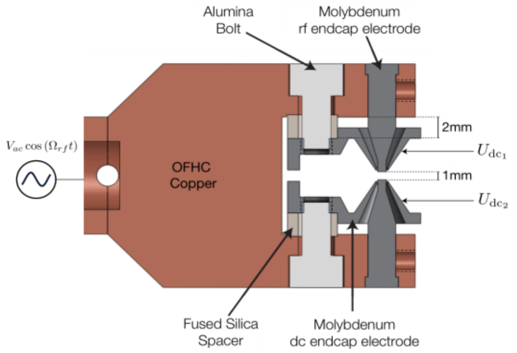
NPL National Physical Laboratory | QMI Quantum Metrology Institute

Cubic cavity projects



- Jonathan Stacey
- Alessio Spampinato
- Ian Hill
- Rich Hendricks
- Peter Tsoulos
- Gary Hockley

Strontium ion clock



- Sean Mulholland
- Alessio Spampinato
- Jonathan Stacey
- Billy Robertson
- Hugh Klein
- Guilong Huang

Patrick Gill
Geoff Barwood
(together with previous NPL staff members)

Funding: ESA & UK Space Agency (multiple projects spanning several years)

UK SPACE AGENCY esa

Conclusions and summary

- Requirement for optical clocks and cavities in space; future optical redefinition of the second
- Major sub-systems of an optical clock are the physics package (in this case the ion trap), high finesse optical cavity and frequency comb
- Introduction to our $^{88}Sr^{+}$ trapped ion optical clock for future space deployment
- Compact optical cavities for space, particularly with application to clock development
- Major frequency test and evaluation facilities currently being set up in our new advanced quantum metrology building (right)