# NPL Cs fountain clocks – robust design and performance

- NPL Cs fountains – main features
- Robust design and performance
- Time scale steering
- ‘mini-fountain’

Krzysztof Szymaniec

*9th SFSM, Kingscliff, October 2023*

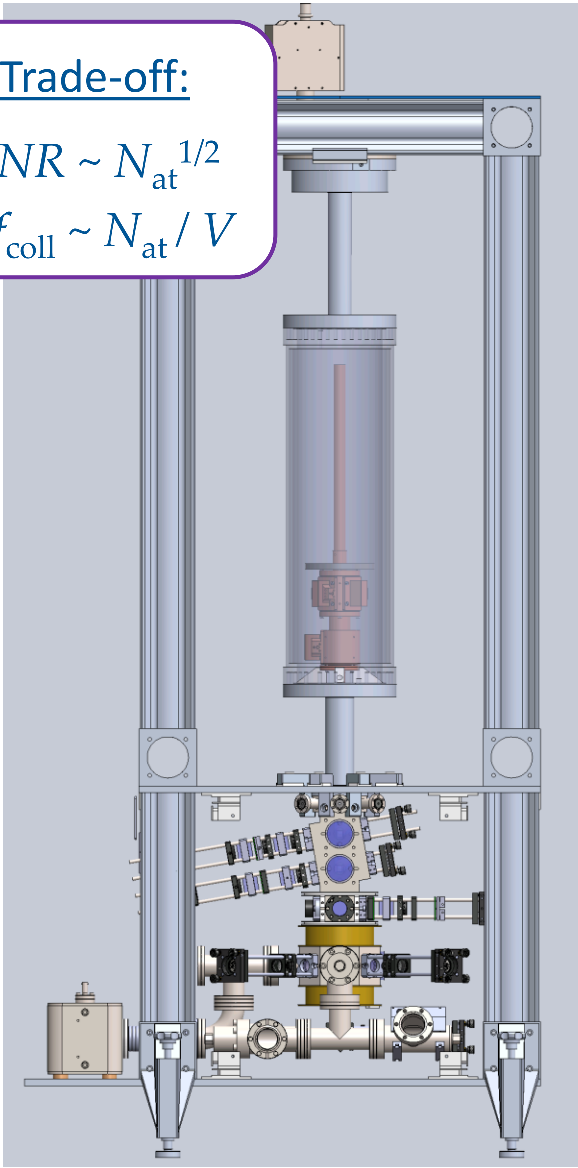
# Atomic fountains – primary frequency standards

NPL
National Physical Laboratory

**Trade-off:**

$SNR \sim N_{at}^{1/2}$

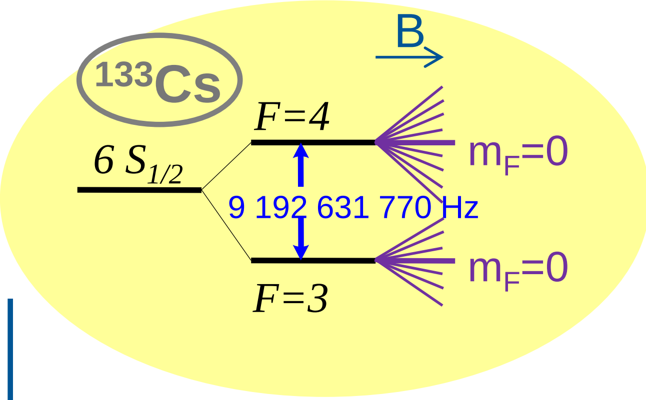
$f_{coll} \sim N_{at} / V$



② free flight
&
Ramsey interaction

state preparation

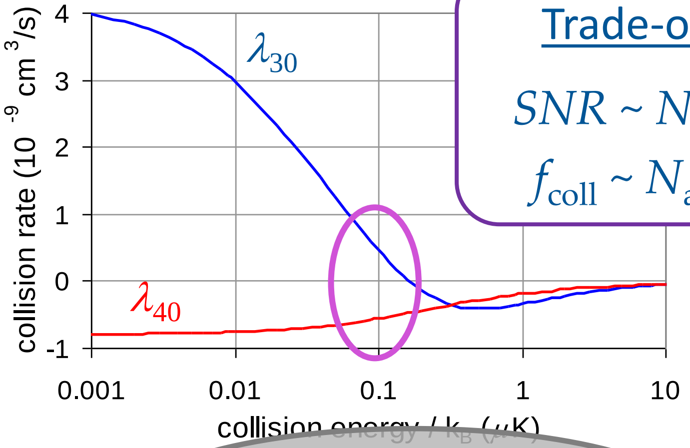
① launch
atom cooling



③ state readout

# Atomic fountains – NPL approach

## Collisional shift cancellation

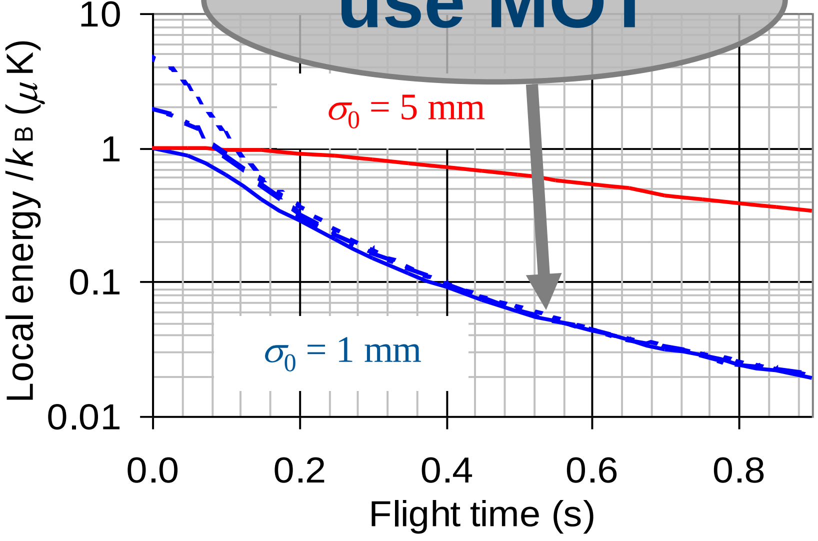


**Trade-off:**

$SNR \sim N_{at}^{1/2}$

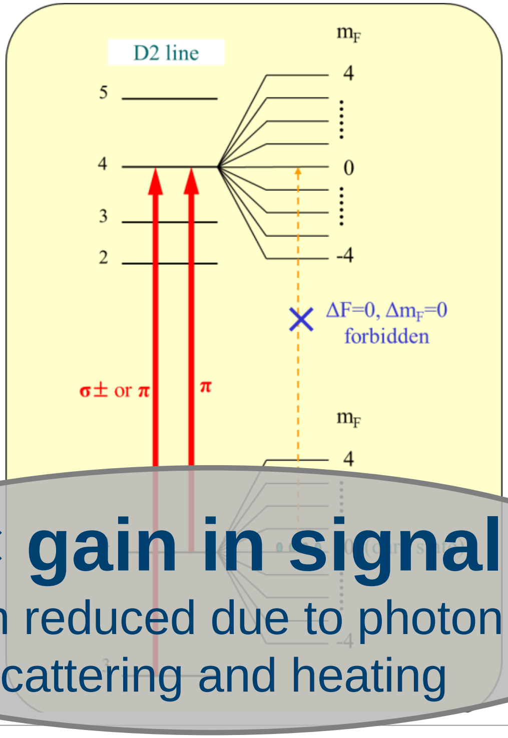
$f_{coll} \sim N_{at} / V$

**use MOT**



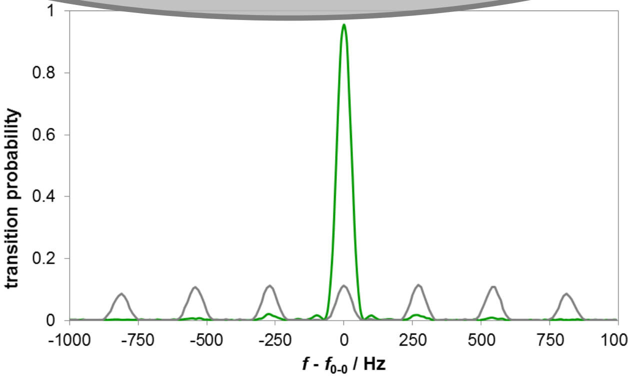
K.S. et al. Phys. Rev. Lett 2007, Metrologia 2010

## Optical pumping



**5× gain in signal**

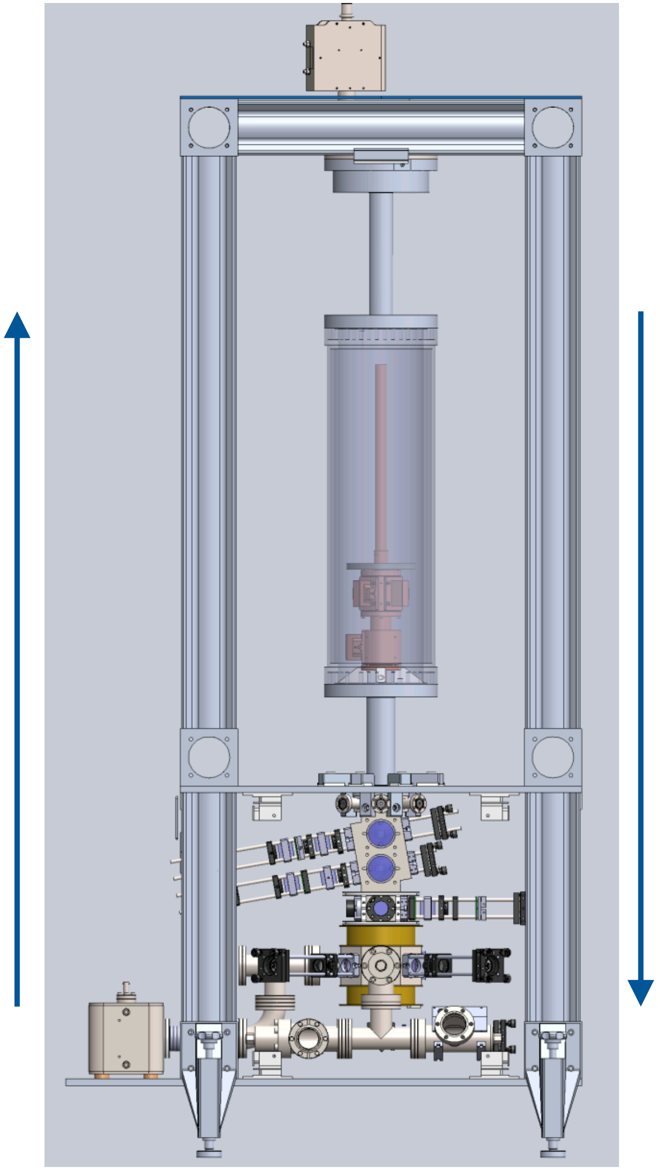
gain reduced due to photon scattering and heating



G. Avila et al. Phys. Rev. A 36 (1987)

K.S. et al. Appl. Phys. B 111 (2013)

# NPL design – fountain cycle



Free flight in constant magnetic field

Ramsey interaction I

State preparation

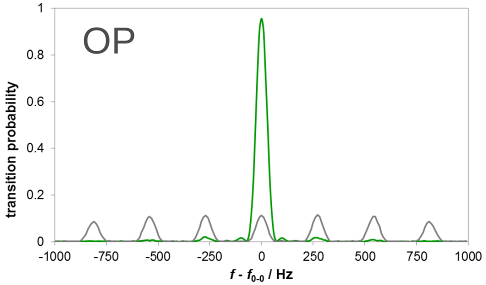
Optical pumping

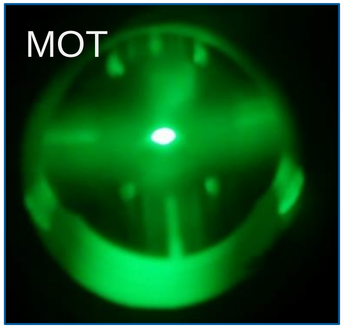
Atom cooling and launch

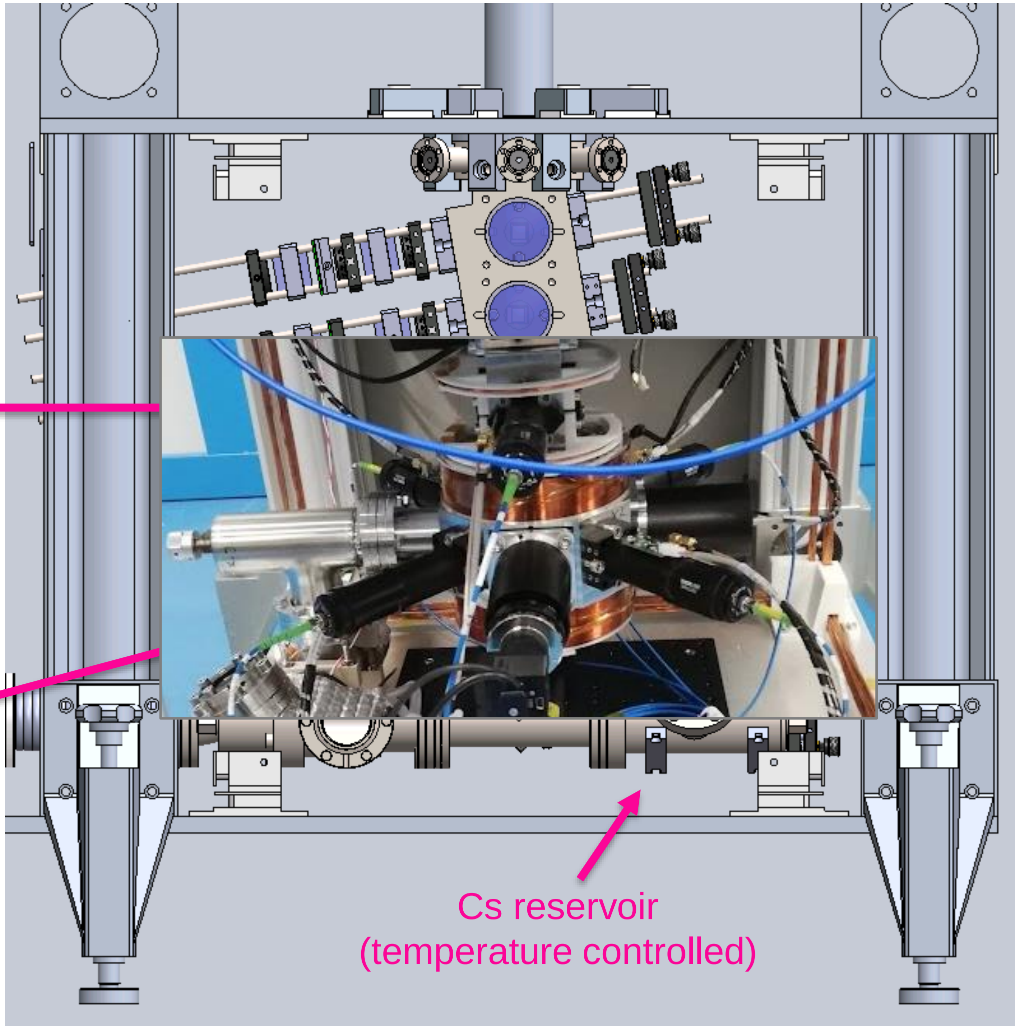
Ramsey interaction II

State readout
(transition probability)

# NPL design – cold atom preparation and launch





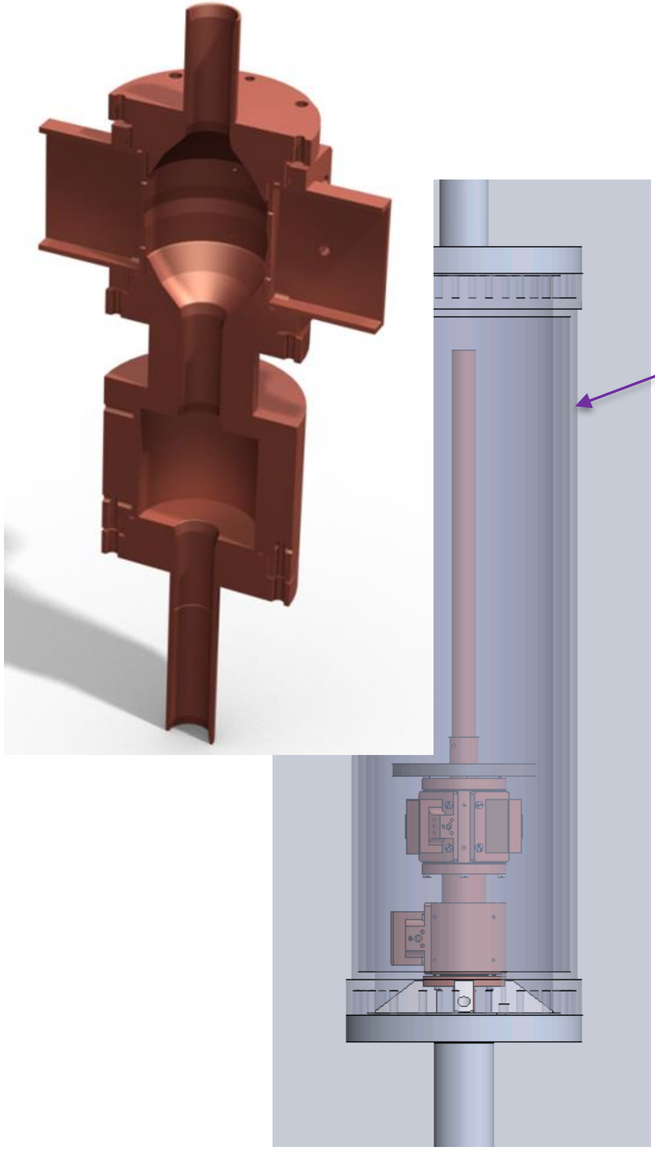

Cs reservoir
(temperature controlled)

# NPL design – microwave interaction

K. Gibble et al.
CPEM (2012)

Magnetic field:
magnitude ≈ 125 nT
homogeneity ≈ 300 pT
stability < 50 pT

Temperature stability
≈ 100mK



*water jacket for temperature control*

flight-tube
(w/g below cut-off)

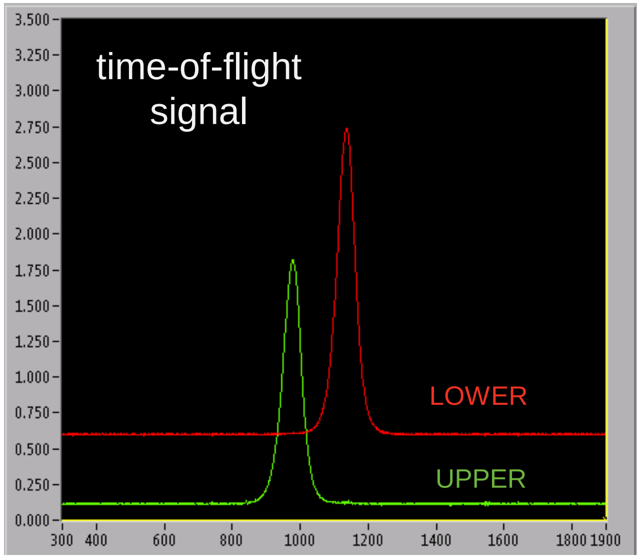
Ramsey cavity

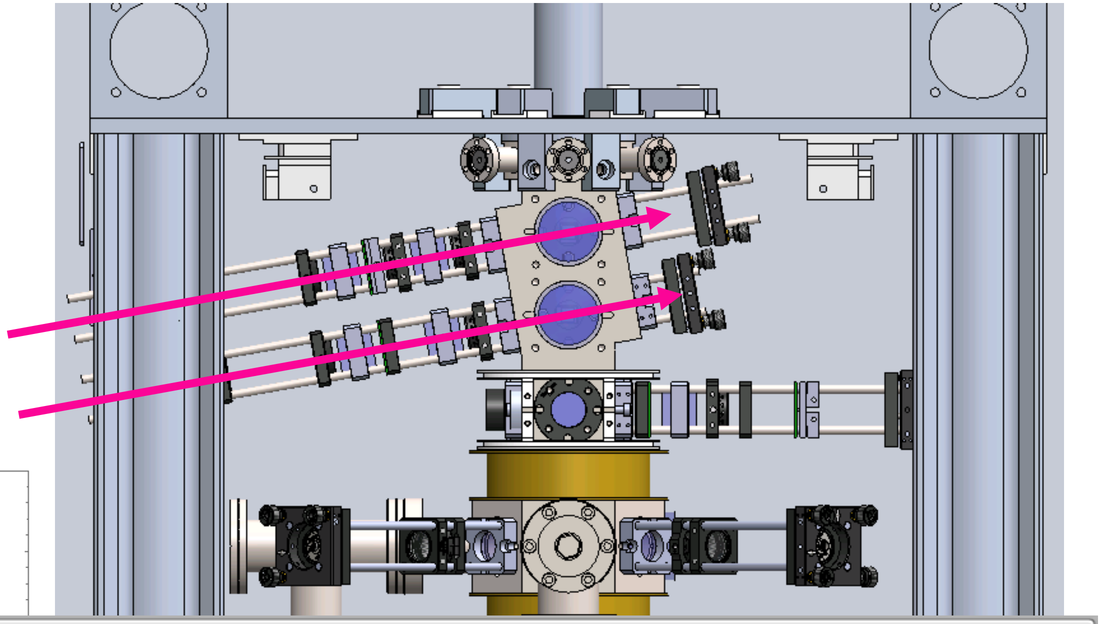
State selection
(state clean-up
& density control)

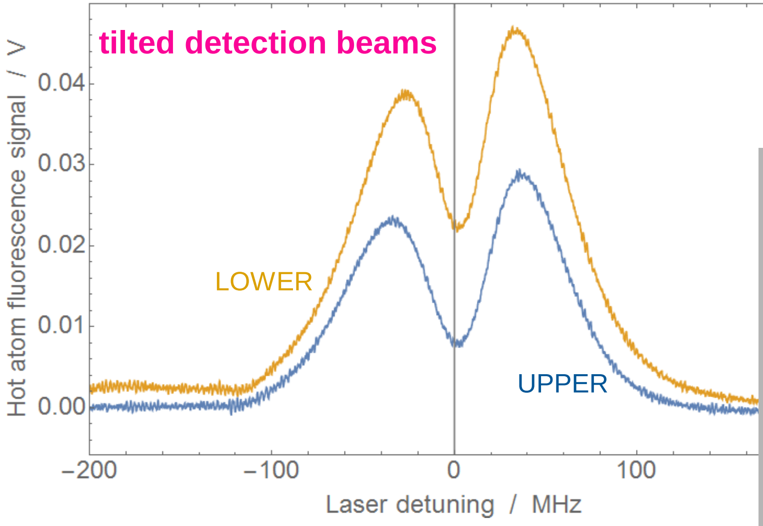
Metrologia 47, 534 (2010)

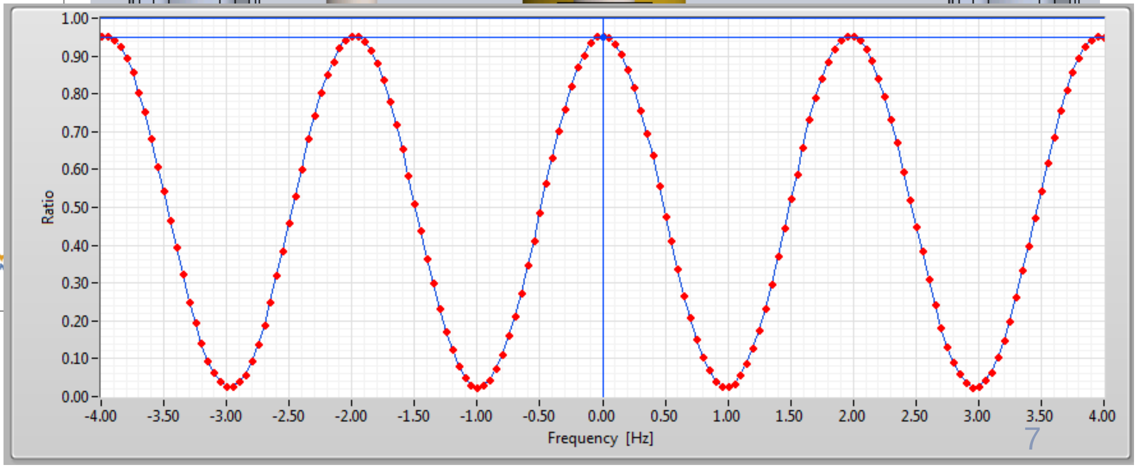
# NPL design – state detection

NPL
National Physical Laboratory







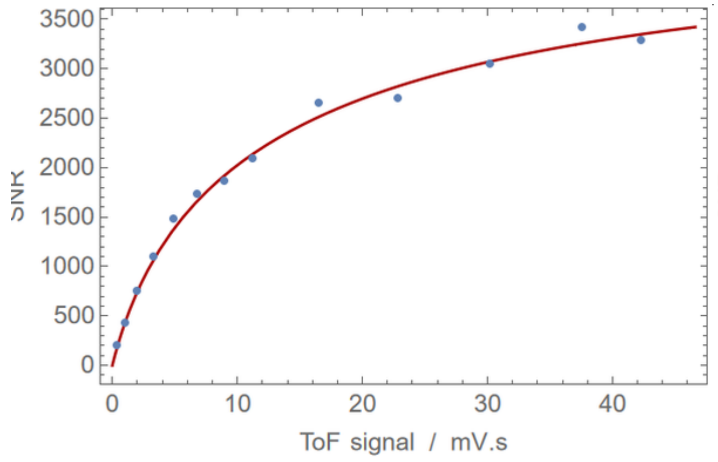


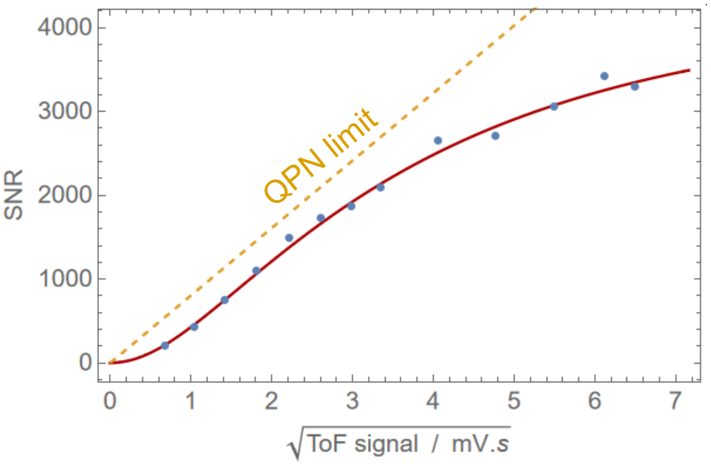
Ph. Laurent et al, Appl. Phys. B 84 (2006)

# NPL design – state detection

National Physical Laboratory

*SNR* ≈ 3300



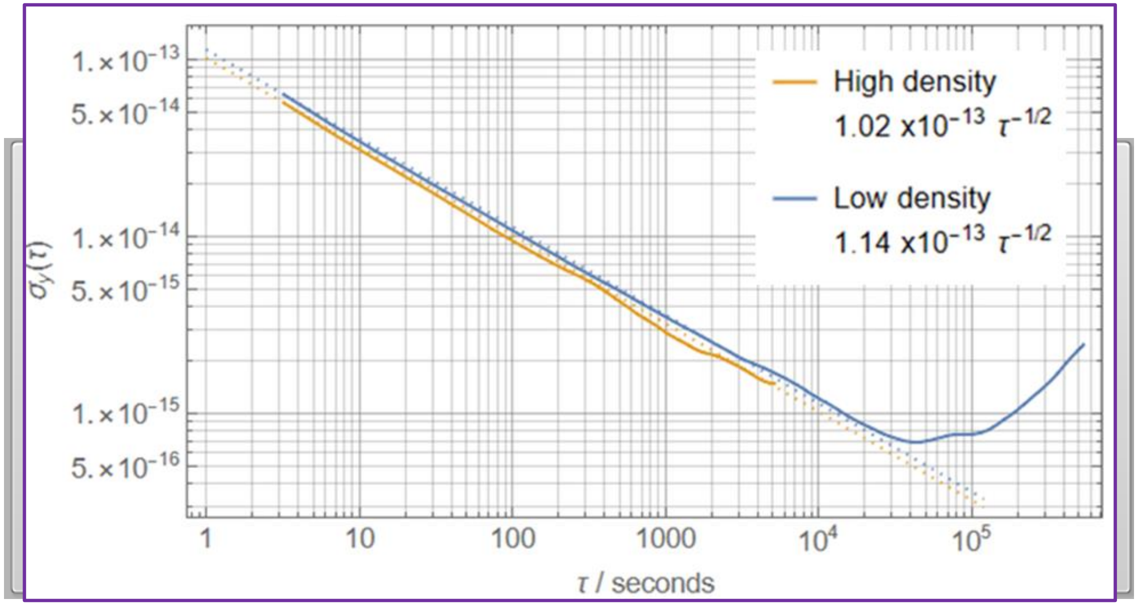


## Short-term stability:

$\sigma_y(1s) \approx 0.3 \times 10^{-13}$ OLO/CSO

$\sigma_y(1s) \approx 1.0 \times 10^{-13}$ quartz

$\sigma_{ext}(1s) \approx 1\text{-}2 \times 10^{-13}$ extrapolated to zero density



# NPL design – ‘commercial’ realisations

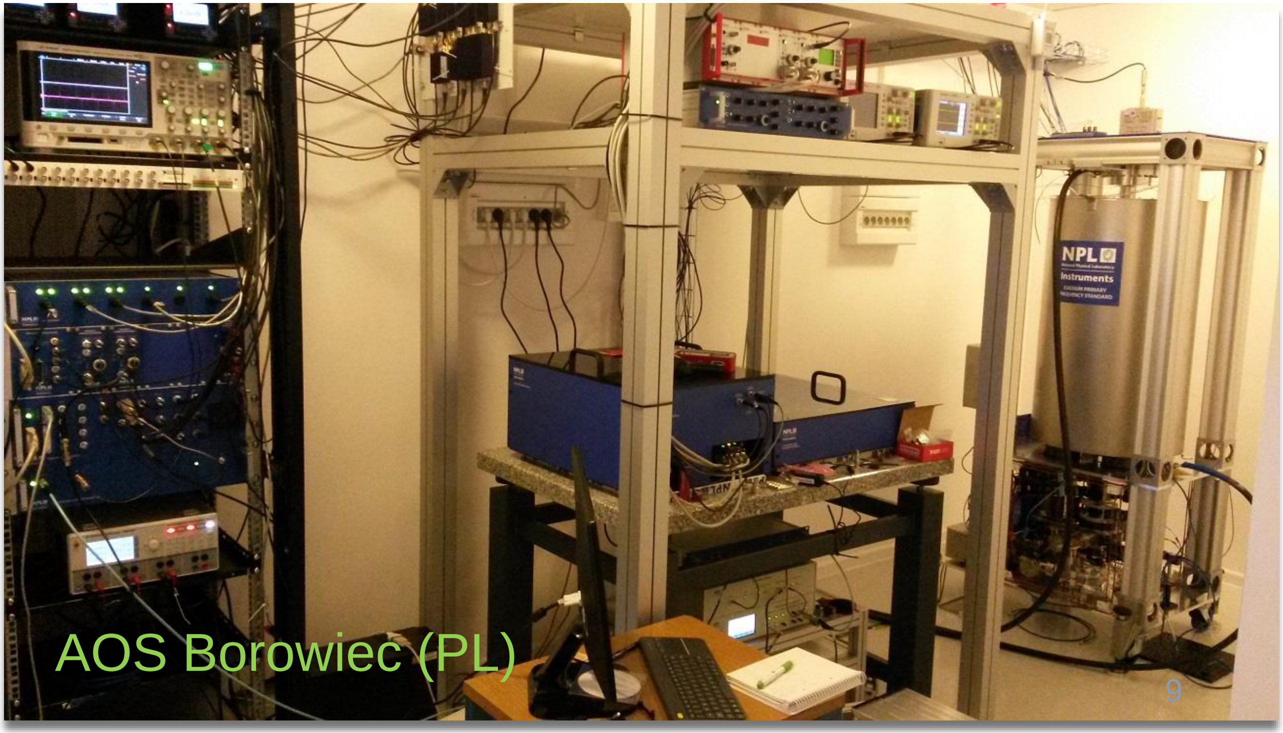

**IOP** Publishing

Metrologia **57** (2020) 035010 (15pp)

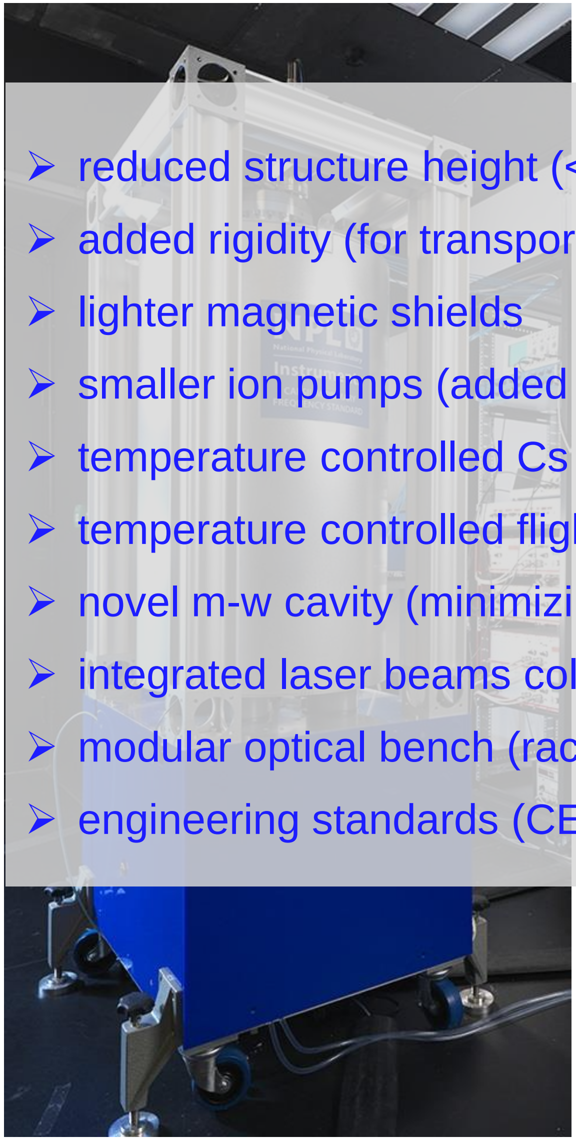
**First accuracy evaluatio**
**NRC-FCs2 primary frequ**

**Scott Beattie[1], Bin Jian[1], John Alcock[1], Marina G**
**Krzysztof Szymaniec[2] and Kurt Gibble[3]**

[1] National Research Council Canada, Ottawa, ON, K1A 0R6, Canada
[2] National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, Ur
[3] Department of Physics, The Pennsylvania State University, University Park
United States of America


AOS Borowiec (PL)

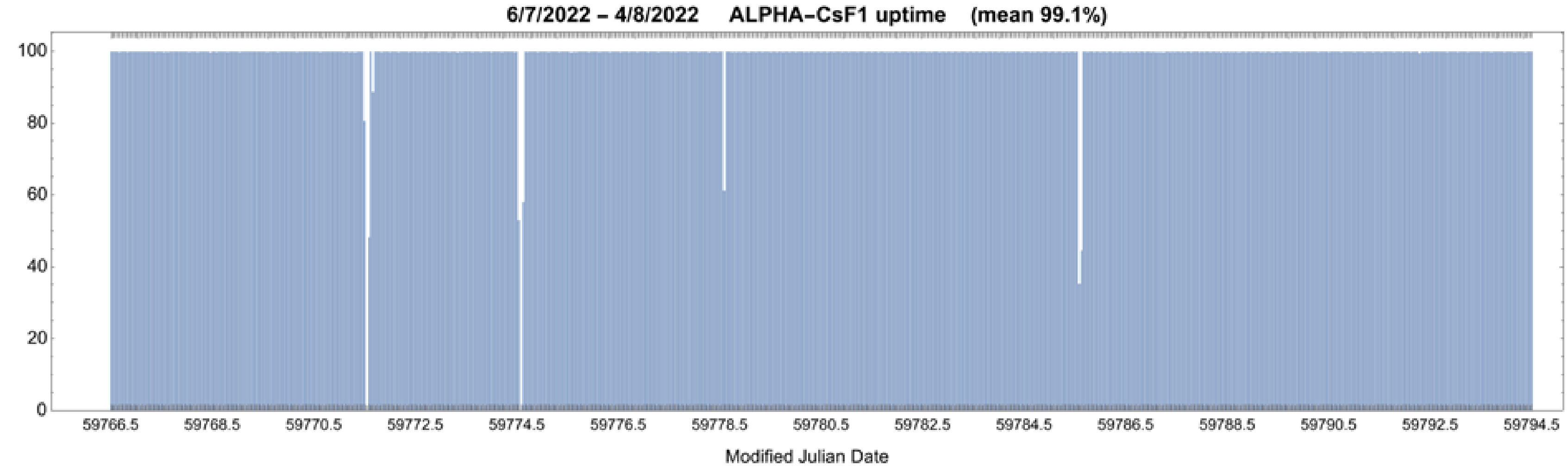
# NPL design - ‘commercial’



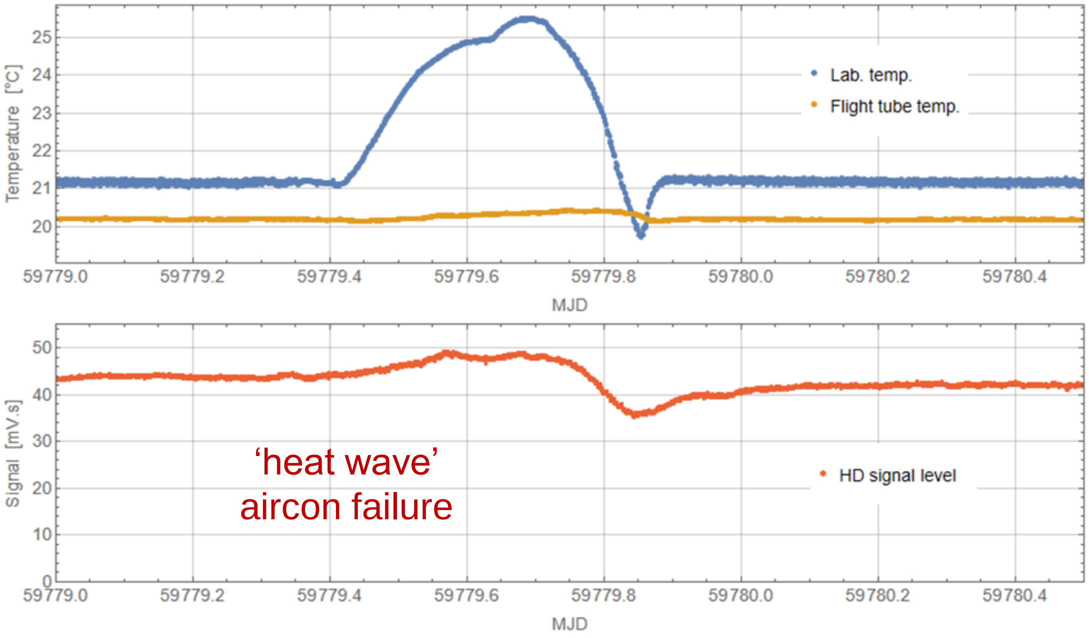
- ➢ reduced structure height (<2 m max)
- ➢ added rigidity (for transport)
- ➢ lighter magnetic shields
- ➢ smaller ion pumps (added getter pumps)
- ➢ temperature controlled Cs reservoir
- ➢ temperature controlled flight tube
- ➢ novel m-w cavity (minimizing phase grad.)
- ➢ integrated laser beams collimators
- ➢ modular optical bench (rack mounted)
- ➢ engineering standards (CE mark)

CERN
ALPHA
collaboration

# NPL build – performance (reliability)



6/7/2022 – 4/8/2022 ALPHA-CsF1 uptime (mean 99.1%)



‘heat wave’
aircon failure

Failure cases:

- automation software
- temperature control (pump)
- mechanical shutters
- DBR laser diode lifetime

# NPL build – performance (expected accuracy)

| Effect | Expected uncertainty / $10^{-16}$ |
|---|---|
| Black-body radiation | 0.7 |
| 2nd-order Zeeman | 0.4 |
| Microwave leakage | 0.5 |
| Distributed cavity phase | 1.1 ← |
| Gravity | 0.1 |
| Cold collisions | 0.3 |
| Background gas collisions | 0.3 |
| Microwave lensing | 0.3 |
| **Total** | **< 2** |

# DCP (distributed cavity phase effect)

National Physical Laboratory

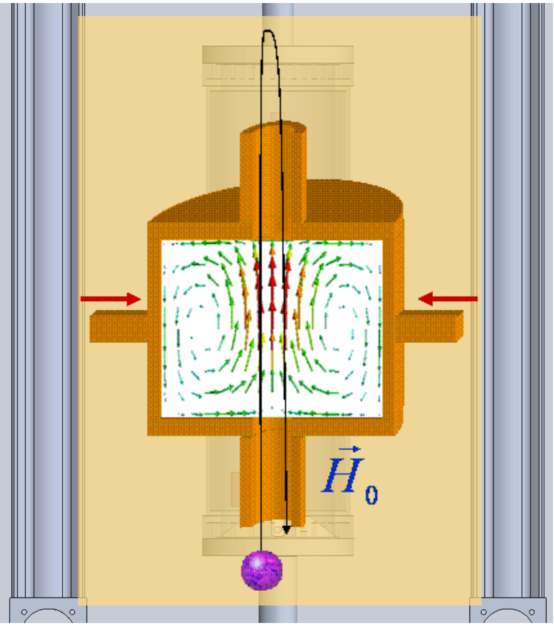
R. Li & K. Gibble,
Metrologia 41 (2004)

K. Gibble et al.,
CPEM (2012)

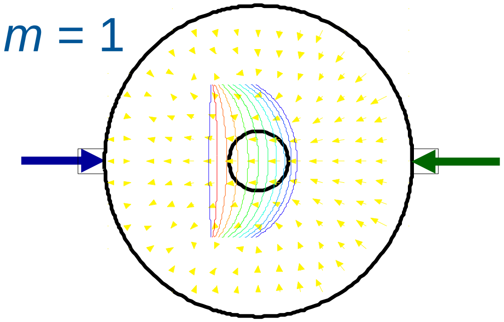
M-w field has travelling wave components (Doppler effect); can be expressed as azimuthal series

$$\mathbf{H}(\mathbf{r}) = \mathbf{H}_0(\mathbf{r}) + (2\Delta\omega/\Gamma + i) \times \{\Sigma \mathbf{g}_m(\rho,z)\cos(m\phi)\}$$

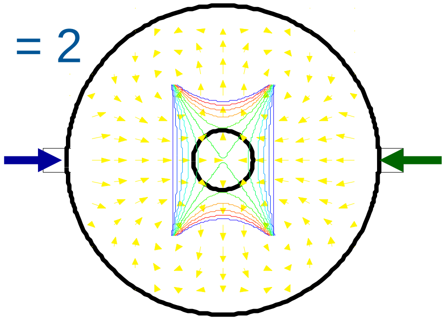
only the lowest orders contribute: $m = 0, 1, 2$

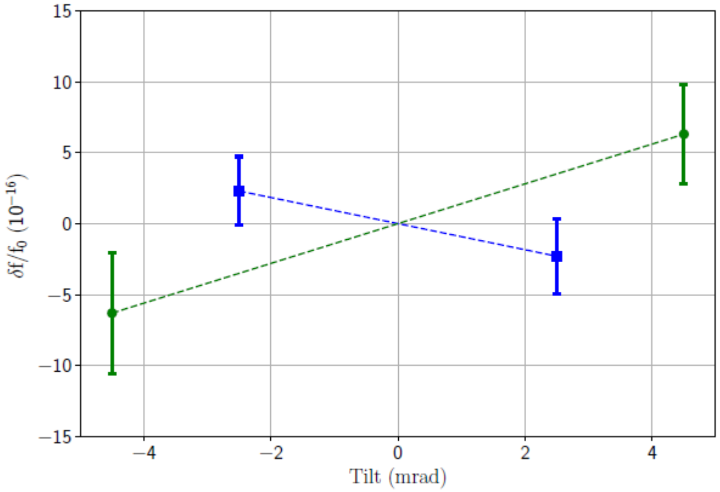


$m = 1$



$m = 2$





S. Beattie et al. Metrologia 57 (2020)

**need to know and control cavity crossing positions**

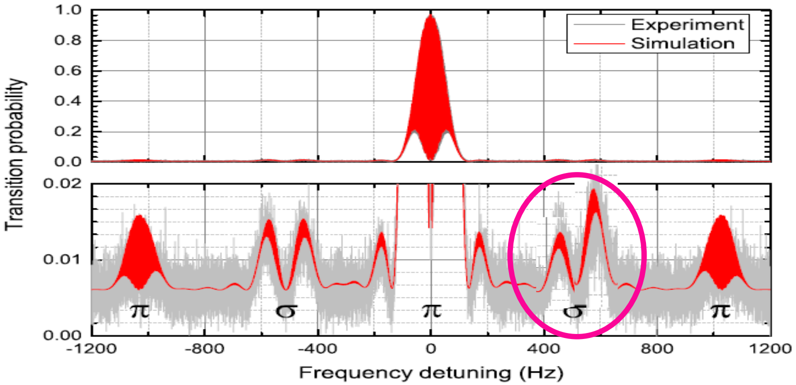
# DCP – cavity crossing positions

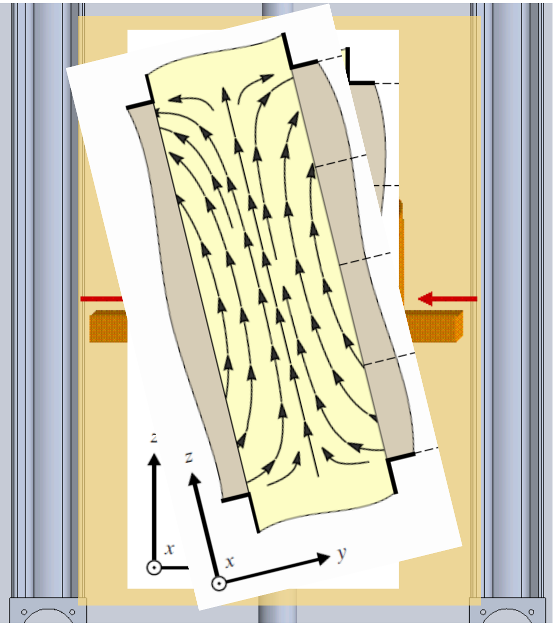
N. Nemitz et al.
Metrologia 49 (2012)

Atoms passing off-axis see transverse component

180° phase change = cw + ccw rotation

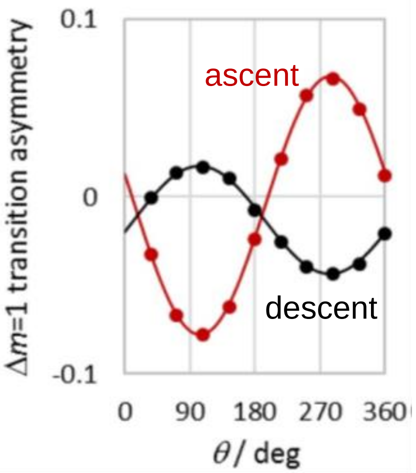
→ split resonance of the σ transition





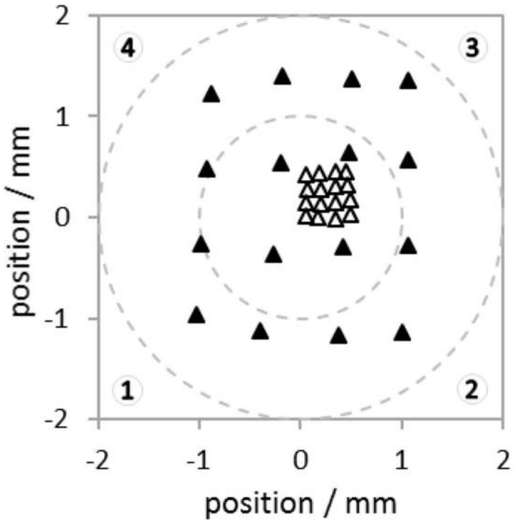
If cavity tilted with respect to C-field
& atoms displaced along tilt
→ the split resonance becomes asymmetric

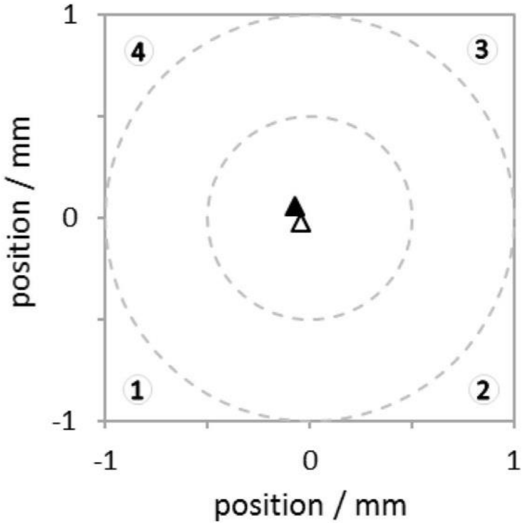
By adding and rotating a horizontal component to C-field, measuring the asymmetry
→ get radial <u>distance</u> and <u>orientation</u> of the **centre of mass** of the detected atoms



K. Burrows et al. Metrologia 57 (2020)

# DCP – cavity crossing positions



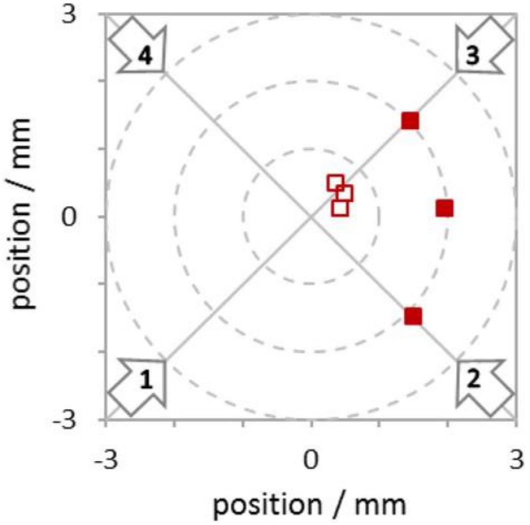


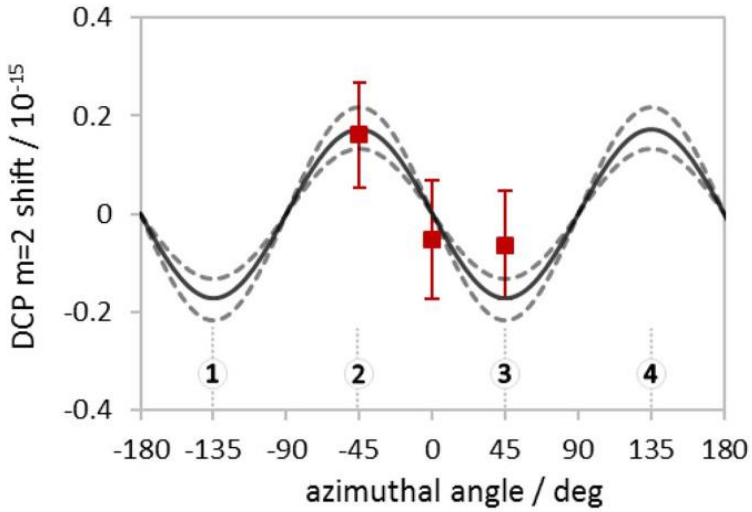
- tilt of entire fountain
- shim coils to move the MOT

→ **full control of crossing pos.**

Results:

- ascent & descent aligned to 50 μm
- DCP (m=1) < 1 × $10^{-17}$





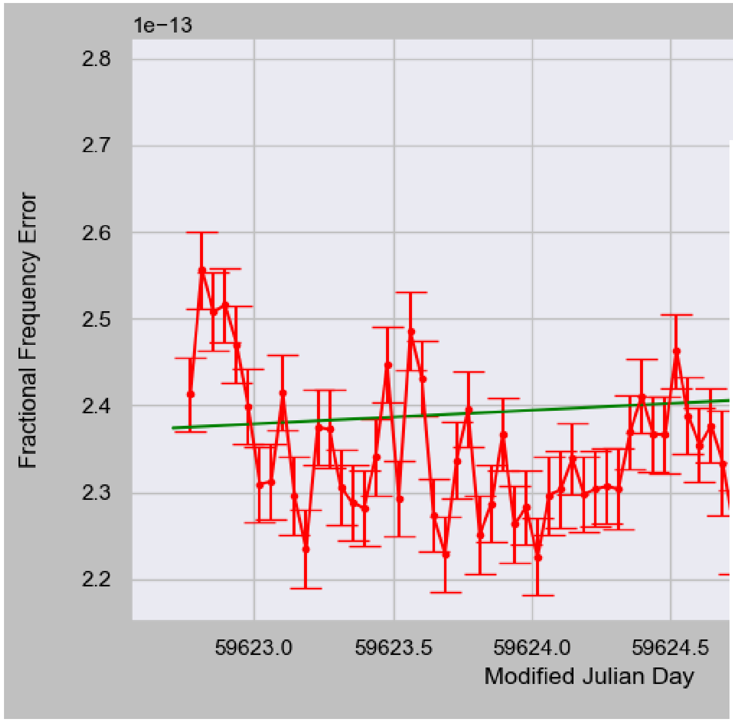
- confirmation of the theoretical model for DCP (m=2)
- (m=2) shift <1 × $10^{-17}$ if crossing centred to 0.4 mm

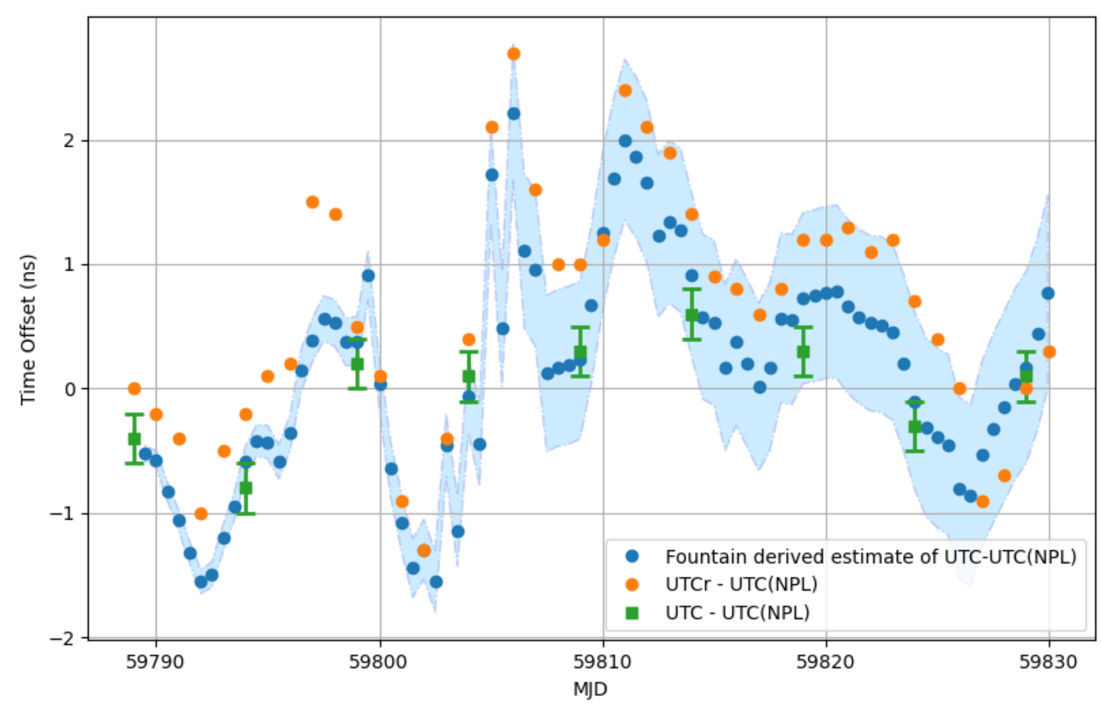
# Time scale steering – time offset prediction

- ❖ **High uptime → fountain as a clock → best representation of UTC**

| Instant. frequency correction | Maser drift correction | Accumulated time offset |
|---|---|---|
| Extrapolated maser frequency at time of steer | Expected frequency drift before next steer (feed-forward) | Includes value reported BIPM (τ ~ 5 days)<br>*Small gaps in fount. data!* |

- 3 components of frequency steer
- steers applied daily or 3/week



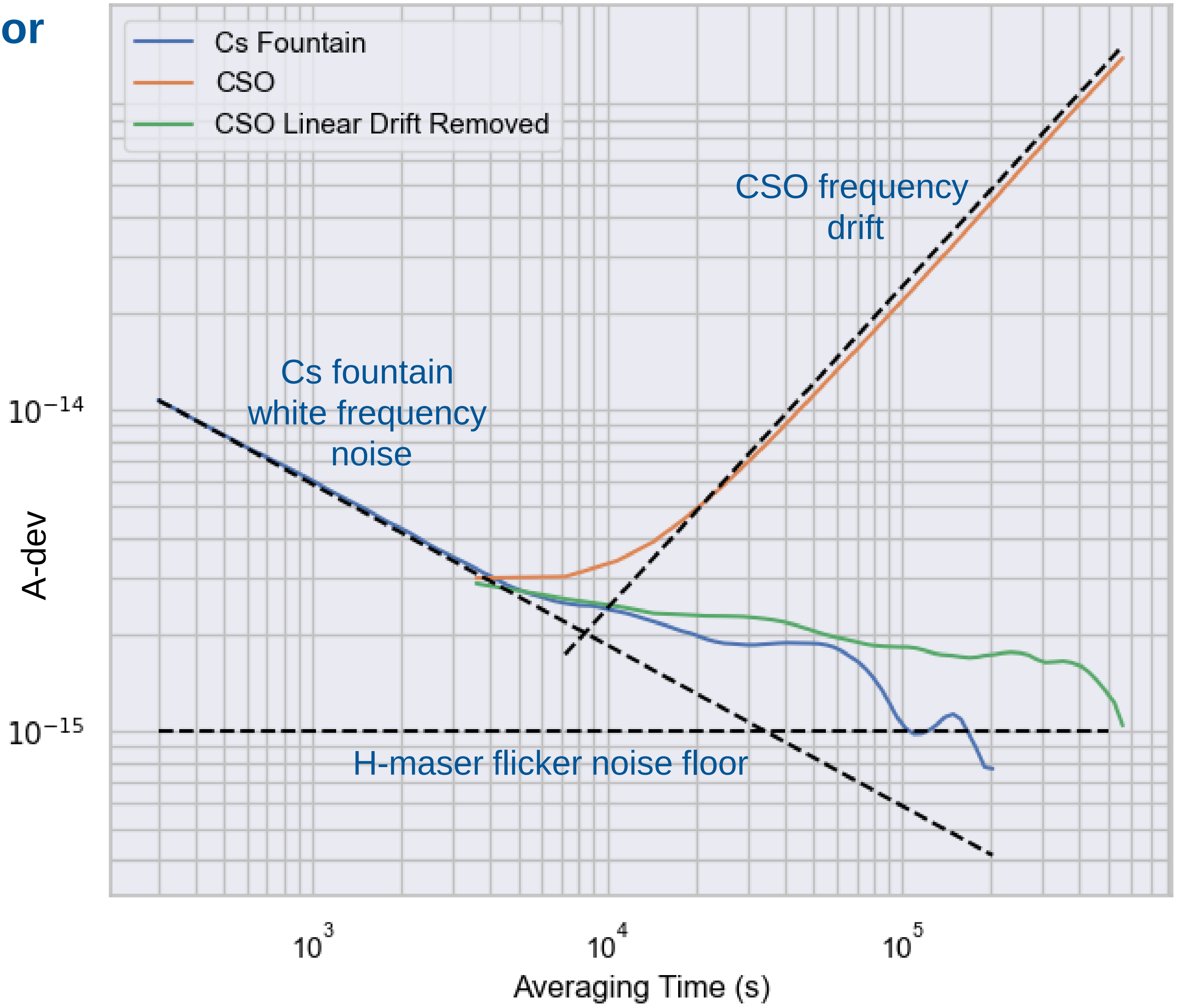


G.D. Rovera et al. Metrologia 53 (2016)
L. Galleani et al. Metrologia 57 (2020)

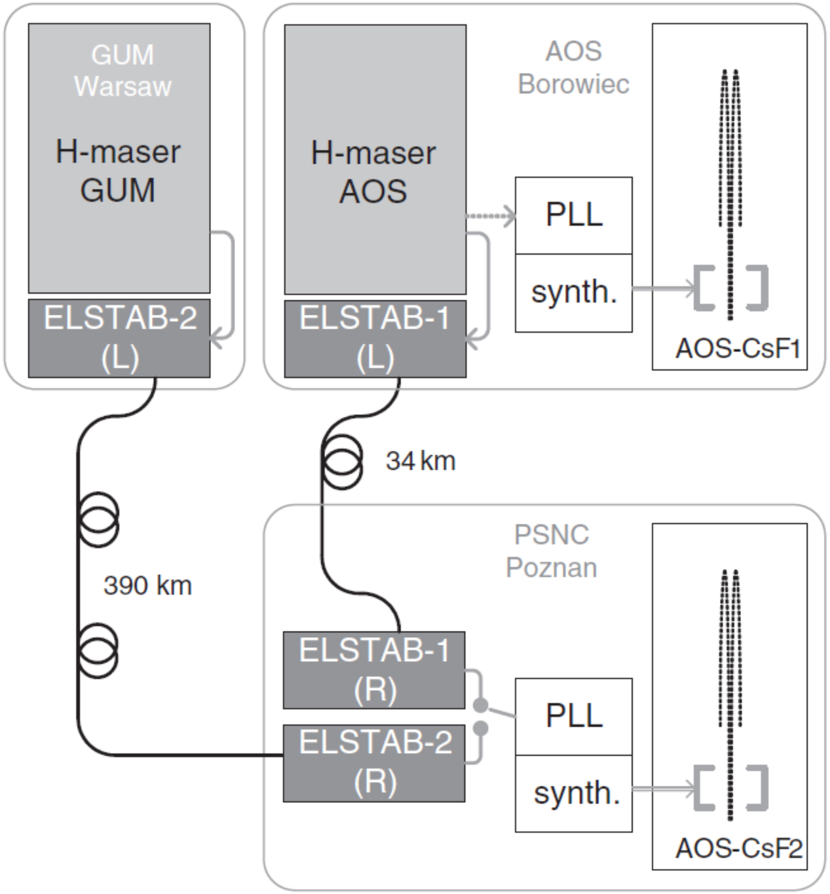
# Time scale steering – flywheel oscillator

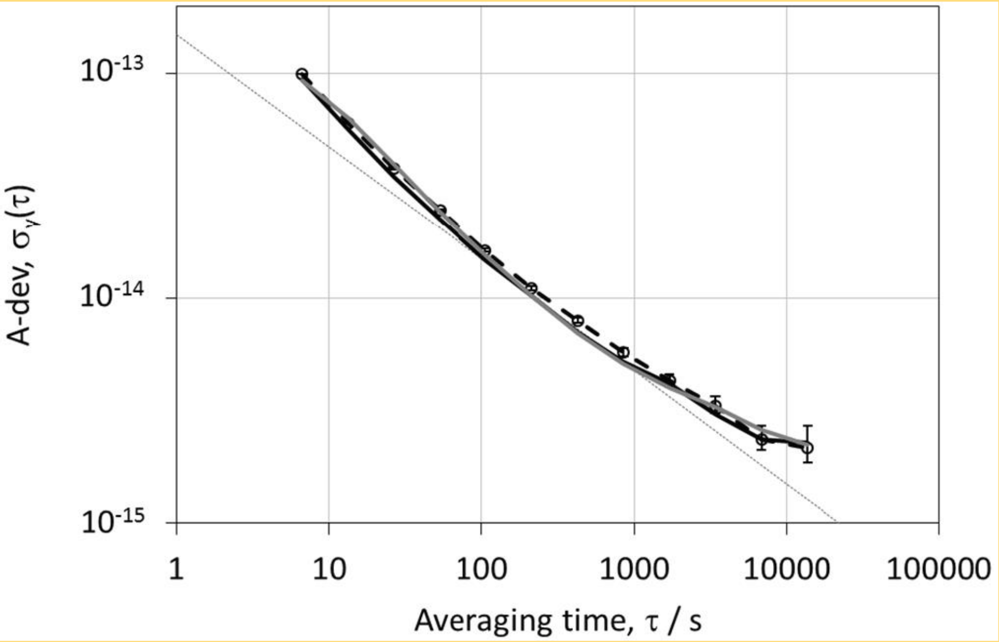
**Use CSO as local oscillator and fly-wheel?**

- LFD is large but stable (predictable)
- Need high up-time of the atomic reference ✓
- Gaps up to days tolerable
- *‘Maser-less’ time scale?*



# Time scale steering – remote maser reference





Results:

- No degradation of short-term stability for remote maser reference as compared to the co-located reference

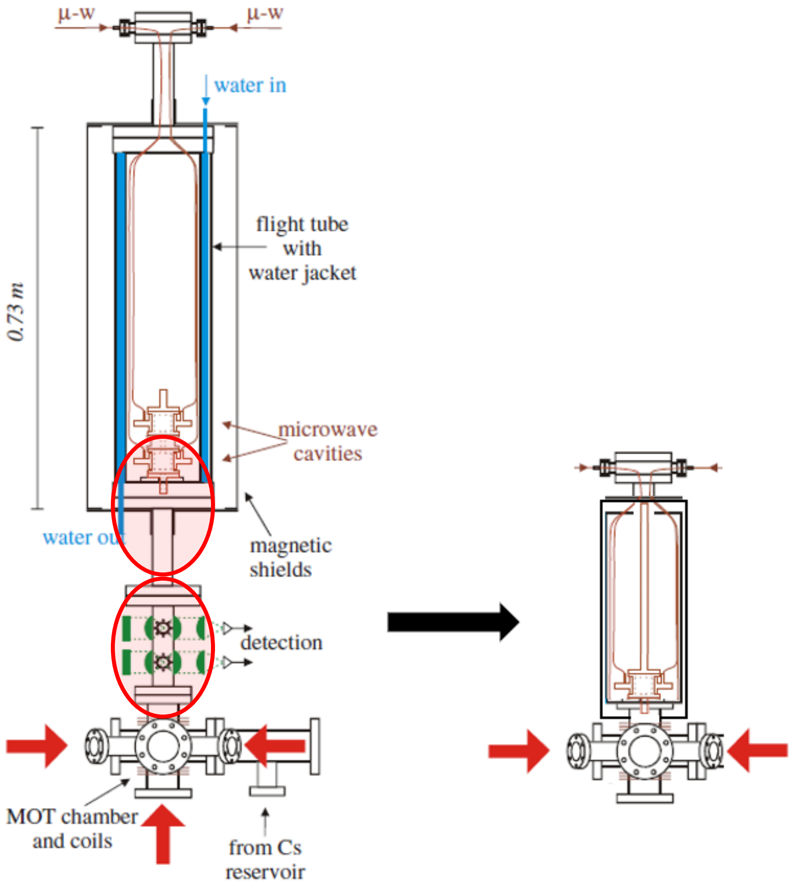
K. S. et al. Metrologia 55 (2018)

# mini-fountain

**Goals:**

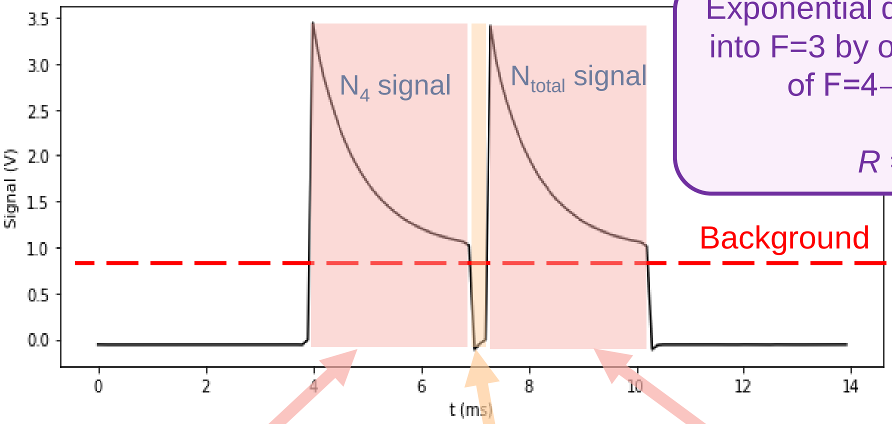
- **small form factor**
- **simple and more rigid build**
- **improved reliability (high uptime)**
- **long-term stability/accuracy $<10^{-15}$**
- **short-term instability $<3\times10^{-13}$ (1s)**

- No separate detection beams and chamber (perform detection with MOT beams)
- Quartz LO → required detection SNR ≥ 600
- No state-selection cavity
- Reduced and simplified magnetic shielding → Ramsey cavity close to MOT
- Fountain height preserved (above cavity)
- Simpler optical bench – all in-fibre optics
- $Rb^{87}$ – collisional shift easier to manage
  – simpler Zeeman structure



# mini-fountain – detection method

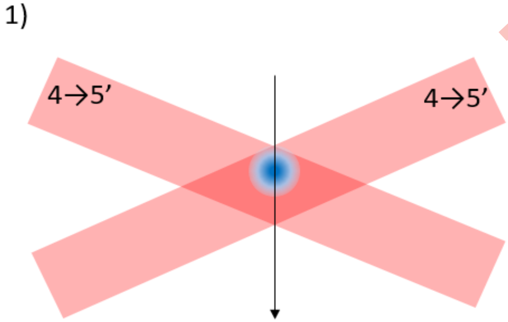
- Normalised dete
- Large beam size
- Two separate lig total; $R = N_4/N_{total}$



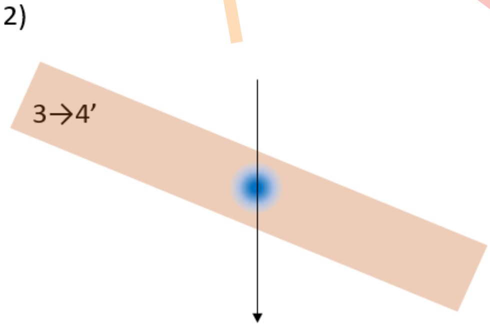
Exponential decay due to pumping into F=3 by off-resonant excitation of F=4→F’=4 transition

$R = N_4 / N_{total}$

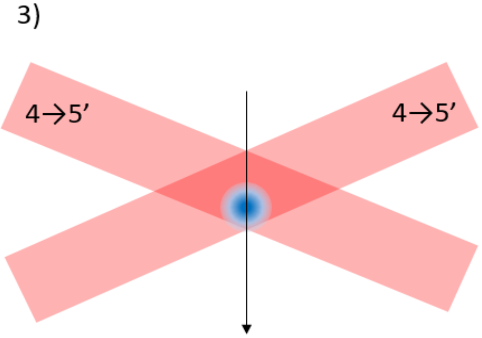
1)



2)



3)

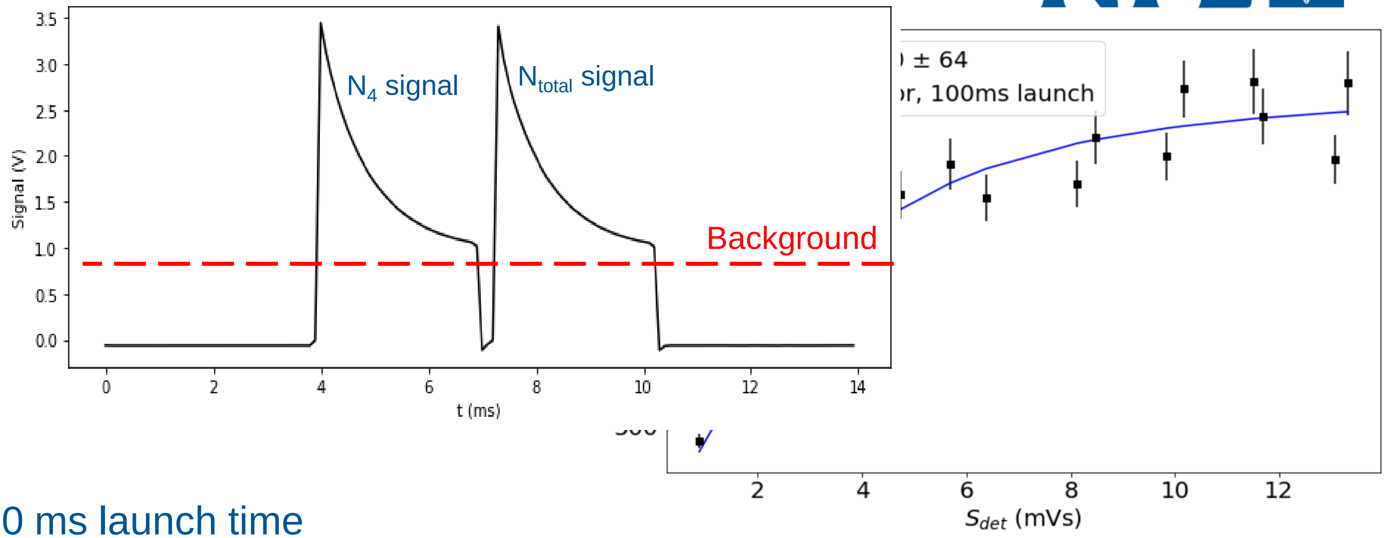


(1)
cooling beams ON
repump OFF
fluorescence signal $N_4$.

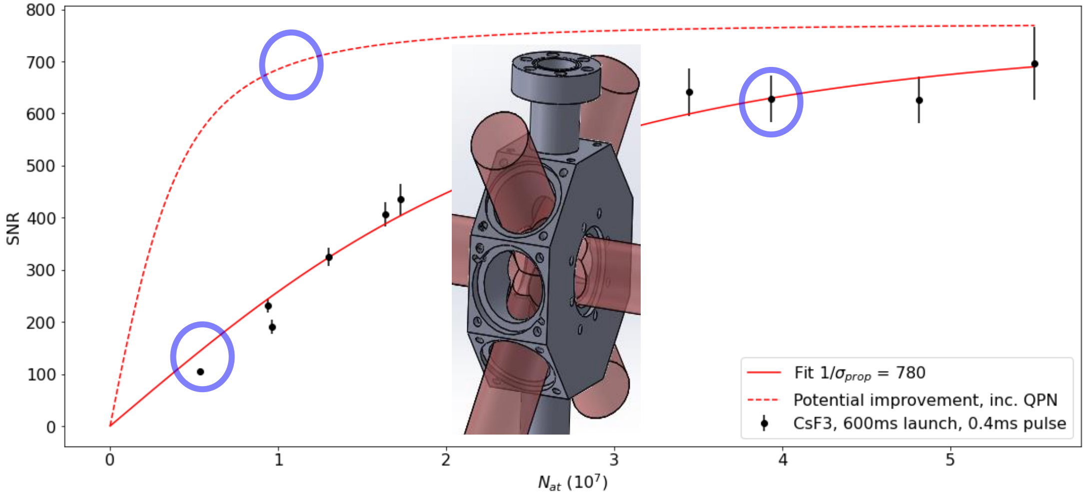
(2)
cooling beams OFF
repump ON (short pulse)
all atoms back into F=4.

(3)
cooling beams ON
repump OFF (or ON
fluorescence signal $N_{total}$

# mini-fountain – detection method



- Demo with short 100 ms launch time (0.5 m/s initial speed, 12 mm height)
- Test in CsF3 ('full size' fountain, 600 ms)
- Background from light scattered from chamber and thermal vapour
- Background measured with the third pulse and subtracted



→ expect **SNR > 700**

(limited by technical + background noise)

# mini-fountain – physics package

**Focus on long-term stability (accuracy evaluation optional)**

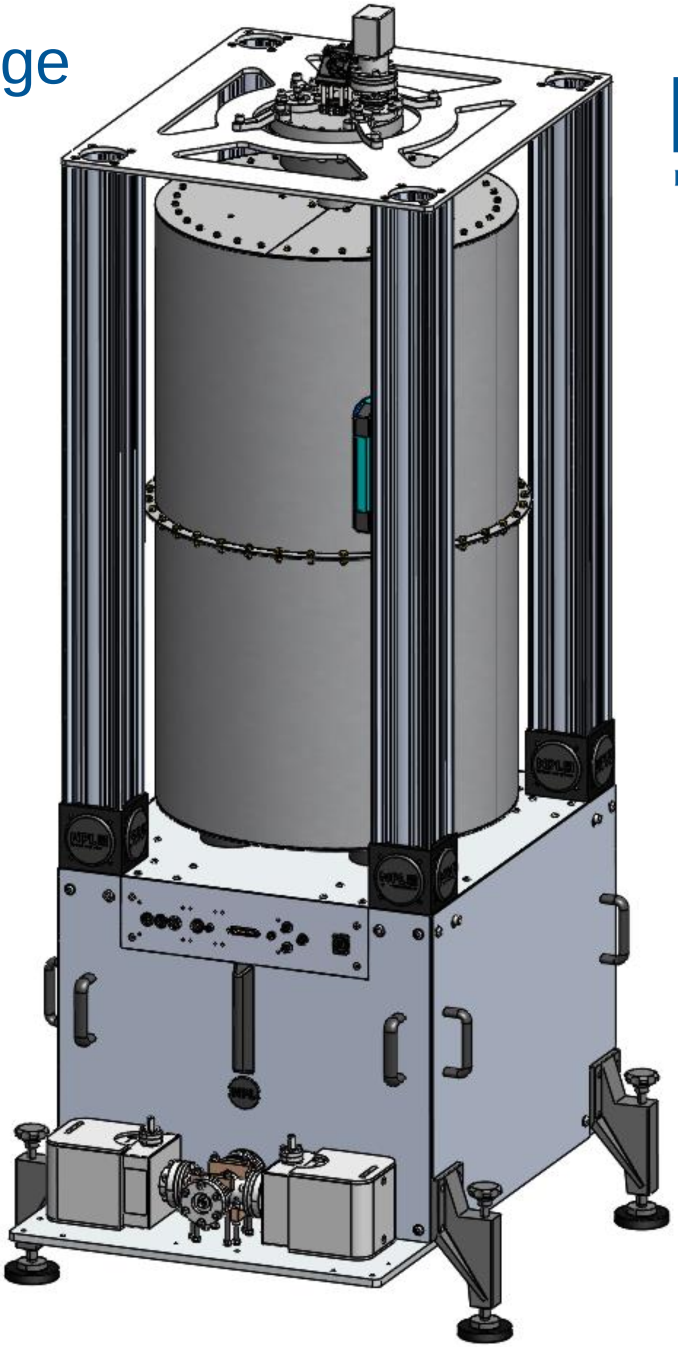
- 2nd order Zeeman:
  *two layers of magnetic shielding*
- BBR:
  *temperature stability to 1-2 K*
  *radiation from hot Rb dispensers*
- Cavity pulling:
  *aim for cavity Q ≈ 5000*
- DCP:
  *no independent feeds for bal./imbal.*
  *shift contained to low $10^{-16}$*

✓ Tests of new detection SNR

✓ Prototype physics package designed

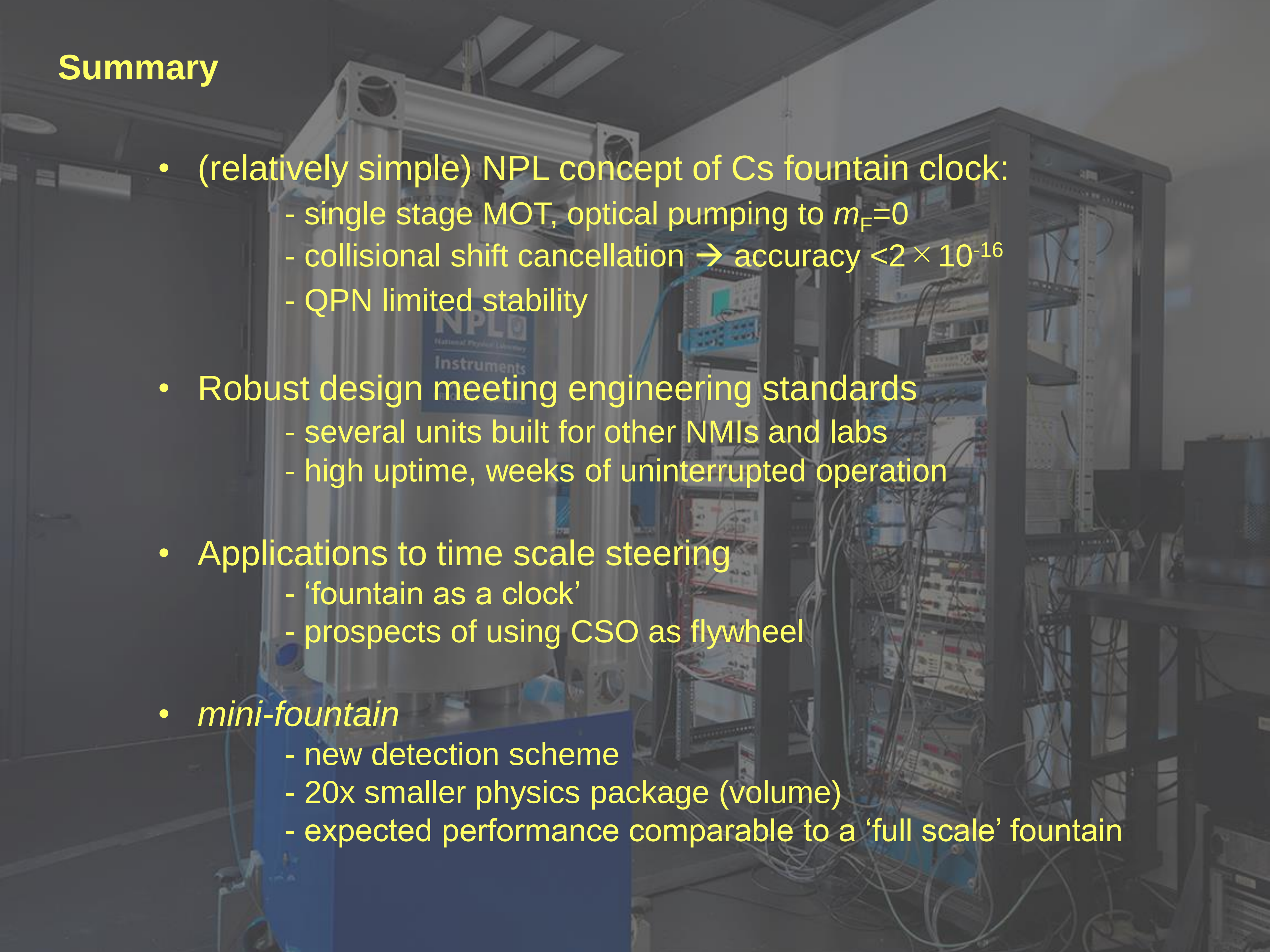
✓ Assembly underway

✓ Fibre coupled optics (COTS) procured and tested



- 20 × smaller in volume
- Entire system in half size 19'' rack

# Summary



- (relatively simple) NPL concept of Cs fountain clock:
  - single stage MOT, optical pumping to $m_F=0$
  - collisional shift cancellation → accuracy $<2 \times 10^{-16}$
  - QPN limited stability
- Robust design meeting engineering standards
  - several units built for other NMIs and labs
  - high uptime, weeks of uninterrupted operation
- Applications to time scale steering
  - ‘fountain as a clock’
  - prospects of using CSO as flywheel
- *mini-fountain*
  - new detection scheme
  - 20x smaller physics package (volume)
  - expected performance comparable to a ‘full scale’ fountain

# Acknowledgements

| | |
|---|---|
| Rich Hendricks, Josh Whale, Andrew Wilson, Sam Walby, Kathryn Burrows | (NPL) |
| Kurt Gibble | (Penn State) |
| Chris Foot | (Oxford) |
| Piotr Dunst, Bartlomiej Nagorny, Jerzy Nawrocki | (AOS, Borowiec) |
| Scott Beattie, Bin Jian | (NRC, Ottawa) |
| Stefan Eriksson, Janko Nauta, Edward Thorpe-Woods | (Alpha/CERN) |