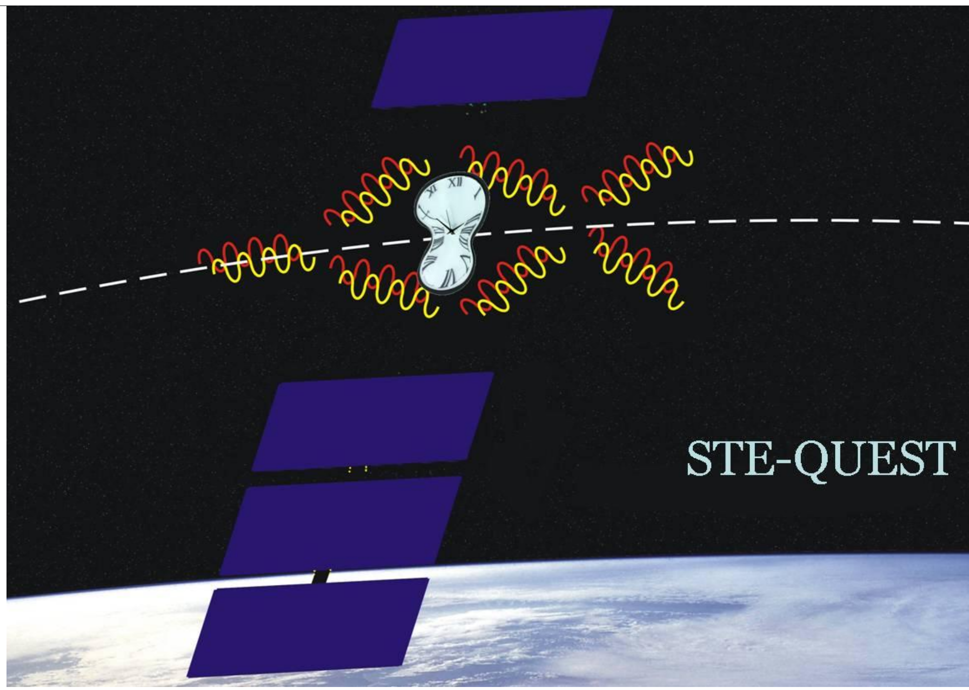
STE-QUEST Mission: Atom Interferometer Performance Assessment And Error Estimations



Leibniz Universität Hannover

Cosmic Vision Mission

STE-QUEST
Atom Interferometer

Christian Schubert
for the STE-QUEST ATI consortium

Motivation

STE-QUEST SciRD:

- Weak Equivalence Principle Tests: Test the universality of the free propagation of matter waves to an uncertainty in the **Eötvös parameter better than 1.5·10^{-15}**.

Eötvös ratio in space:

$$\eta(A,B) = \frac{|a_A - a_B|}{g} = \frac{\Delta a}{g}$$

acceleration a

local gravitational acceleration g

differential acceleration Δa

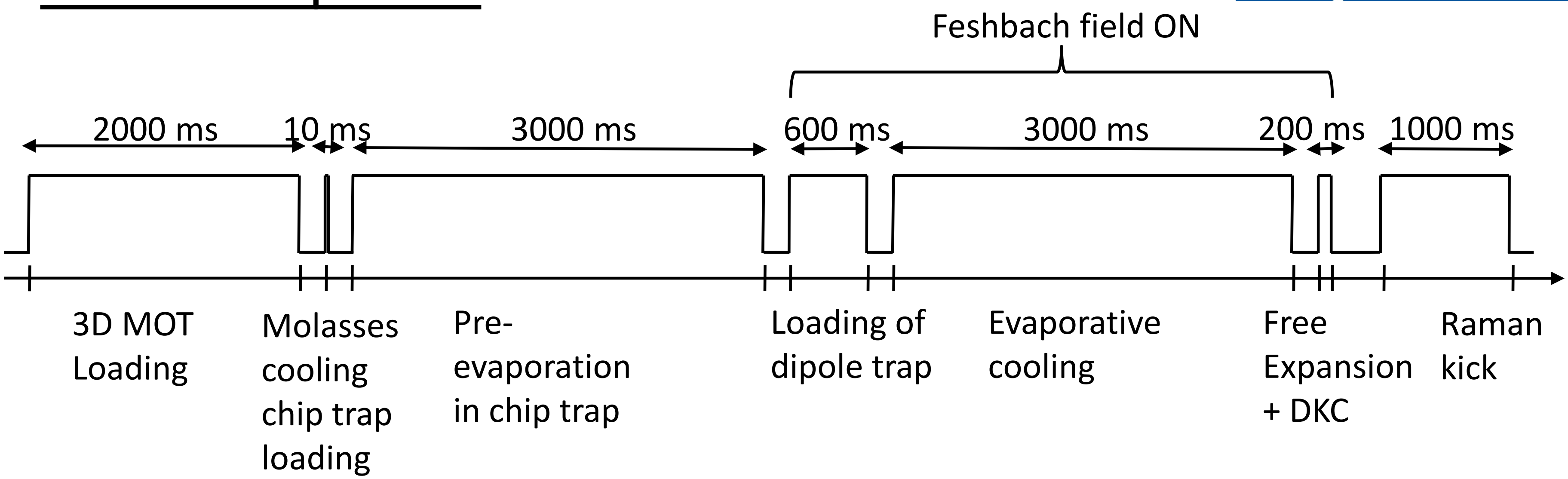
STE-QUEST will use a dual ^{87}Rb/^{85}Rb atom interferometer to measure $\eta(A,B)$ to 1.5·10^{-15} over a mission duration of 5 years.

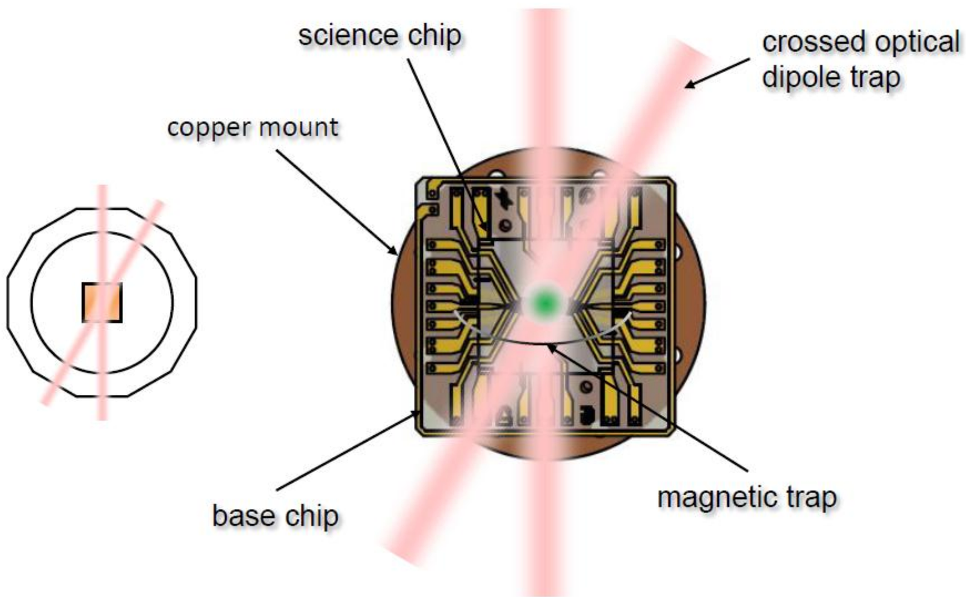
Scientific challenges

- Interferometry:
  - Choice of ^{87}Rb / ^{85}Rb – high common mode rejection ratio
  - Differential single shot sensitivity of $3\cdot10^{-12}$ m/s^2 @ 20 s cycle time (shot noise limited)
  - Free evolution time 2T = 10 s
  - Bias terms < $4.5\cdot10^{-15}$ m/s^2

- Source:
  - Simultaneous preparation of each 10^6 ^{87}Rb / ^{85}Rb atoms in 10 s
  - ^{85}Rb scattering length tuning via Feshbach resonance
  - Miscibility
  - Very low effective atomic temperatures ~ 70 pK

Source sequence



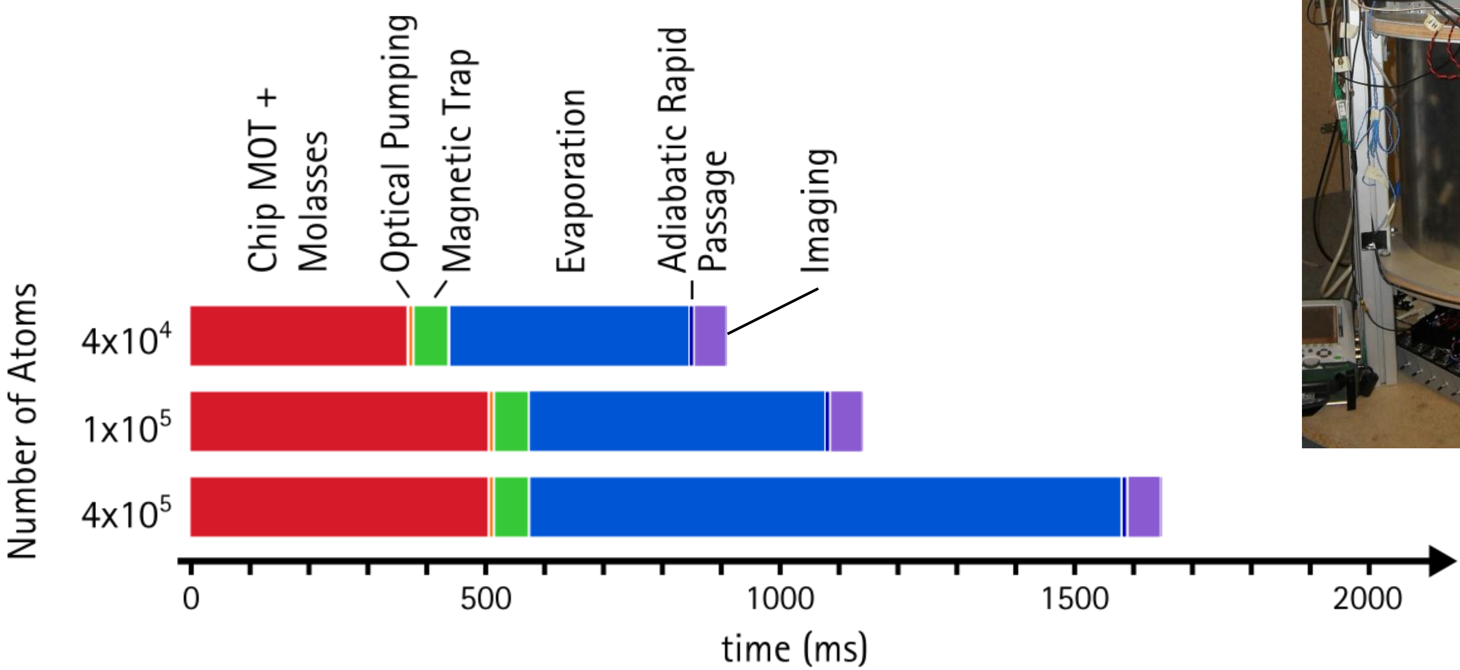


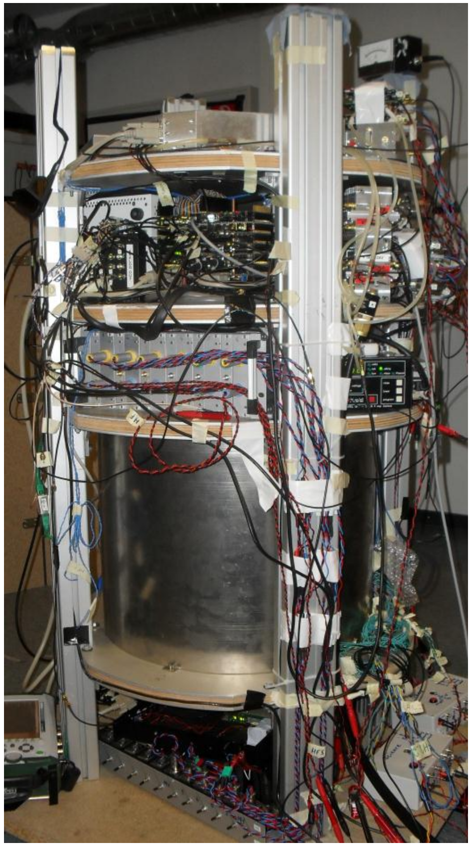
- total duration < 10 s
- ~ 1 nK after release from ODT
- ~ 0.07 nK after DKC
- 10^6 atoms of each isotope

QUANTUS II – ^{87}Rb BEC on an atom chip

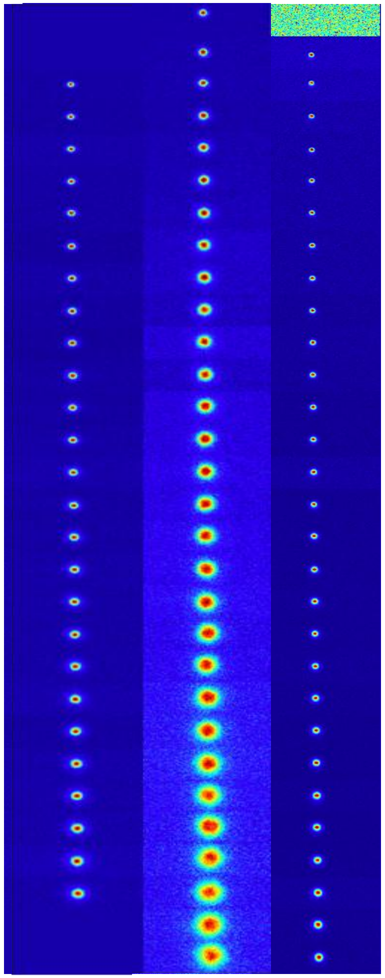
Particle number in dependence of preparation time:

- Largest BEC: 5×10^5 atoms in 3.5s
- Highest flux: 4×10^5 atoms in 2s
- Fastest BEC: 4×10^4 atoms in 1s

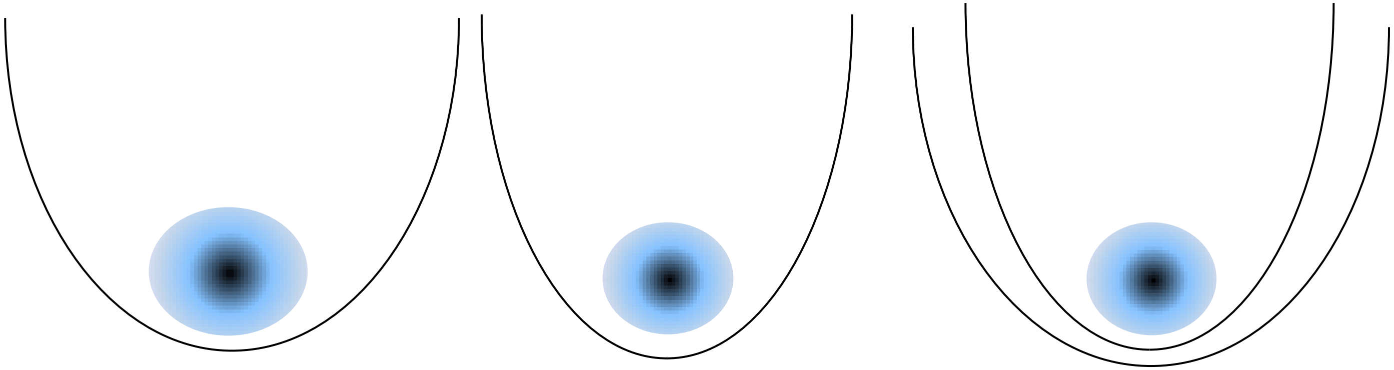




Delta-Kick Cooling principle (DKC)



- **Left**: expansion after a decompression of 402 ms
- **Middle**: expansion out of a steeper holding trap after a decompression of 152 ms
- **Right**: expansion out of the steeper holding trap with DKC after a decompression of 152 ms



[Müntinga et al., PRL 110, 093602 (2013); Dickerson et al., arXiv:1305.1700v1; Chu et al., Opt. Lett. 11, 73 (1986)]

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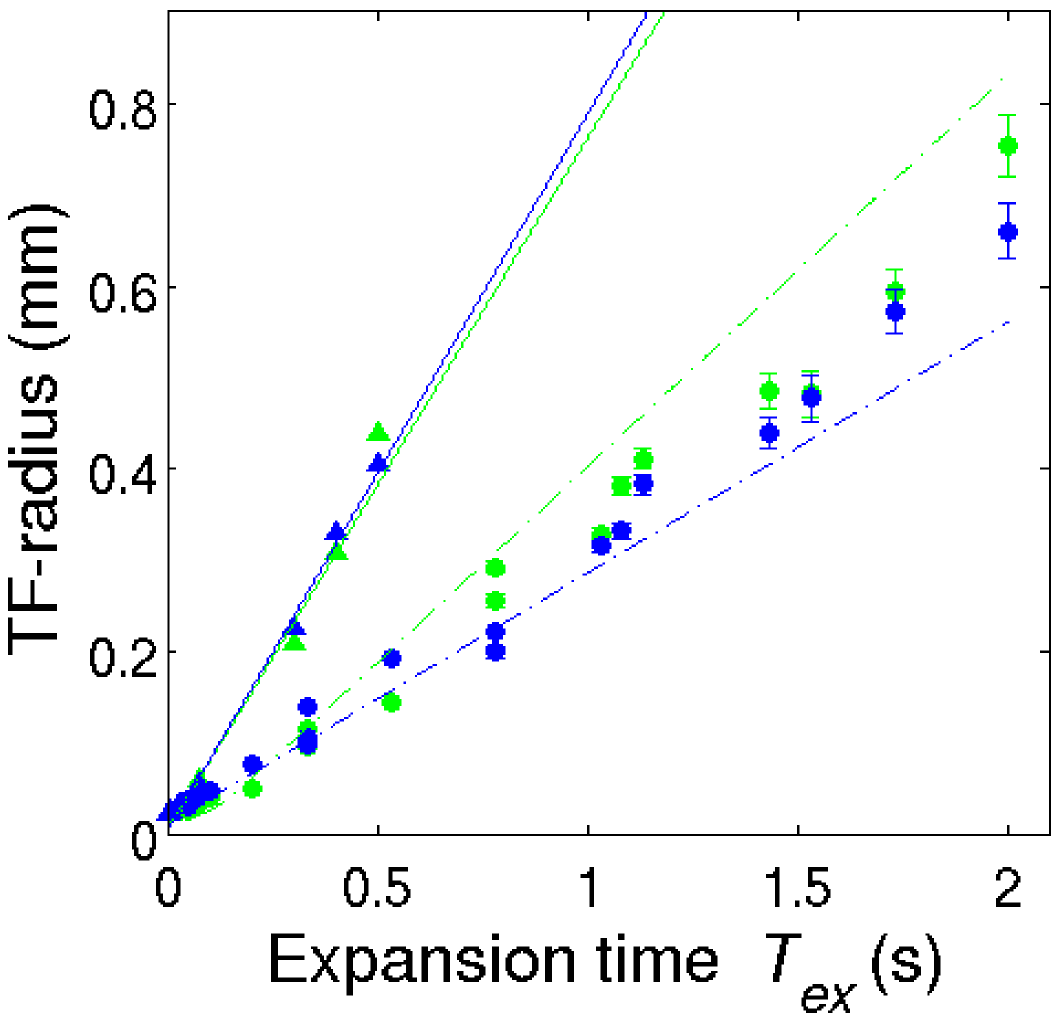

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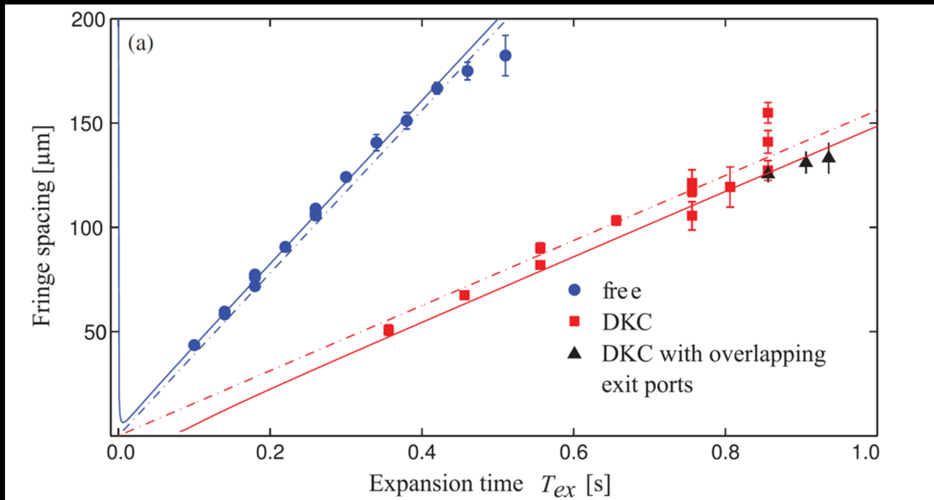
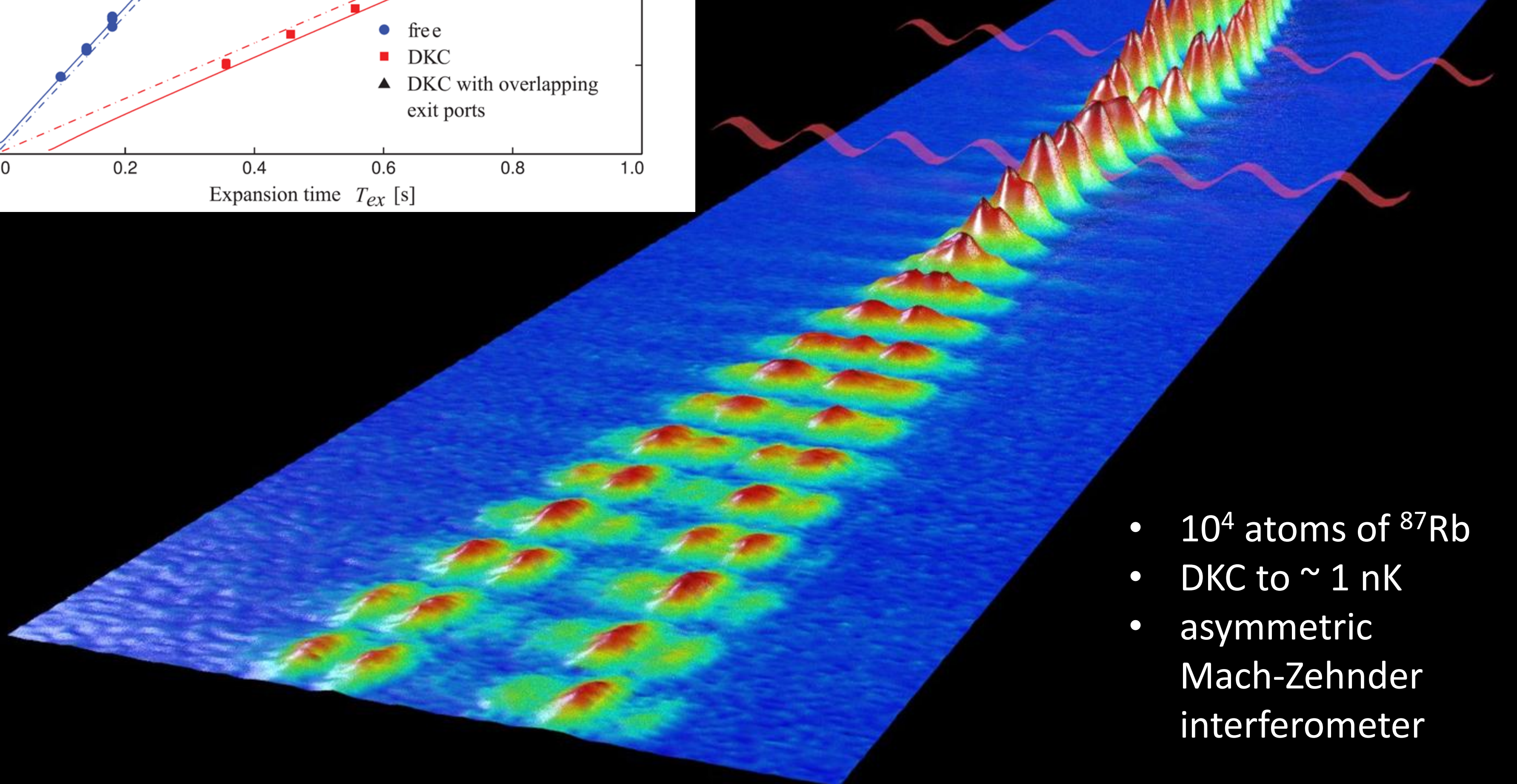
QUANTUS I – ^{87}Rb BEC, DKC & AI in µg

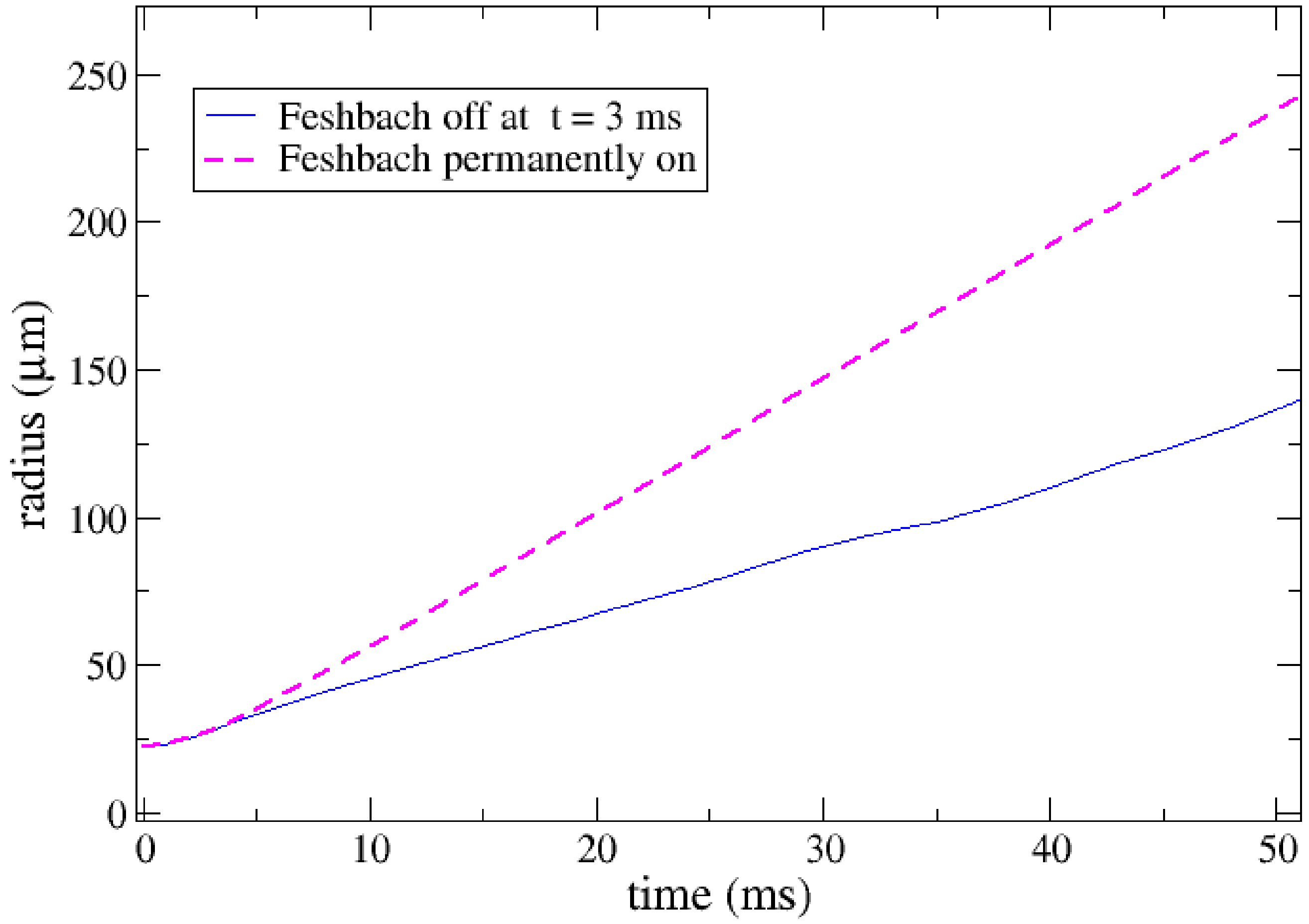




- 10^4 atoms of ^{87}Rb
- DKC to ~ 1 nK
- asymmetric Mach-Zehnder interferometer

[Physik Journal 05/2013; Müntinga et al., PRL 110, 093602 (2013)]

Stability of ^{85}Rb



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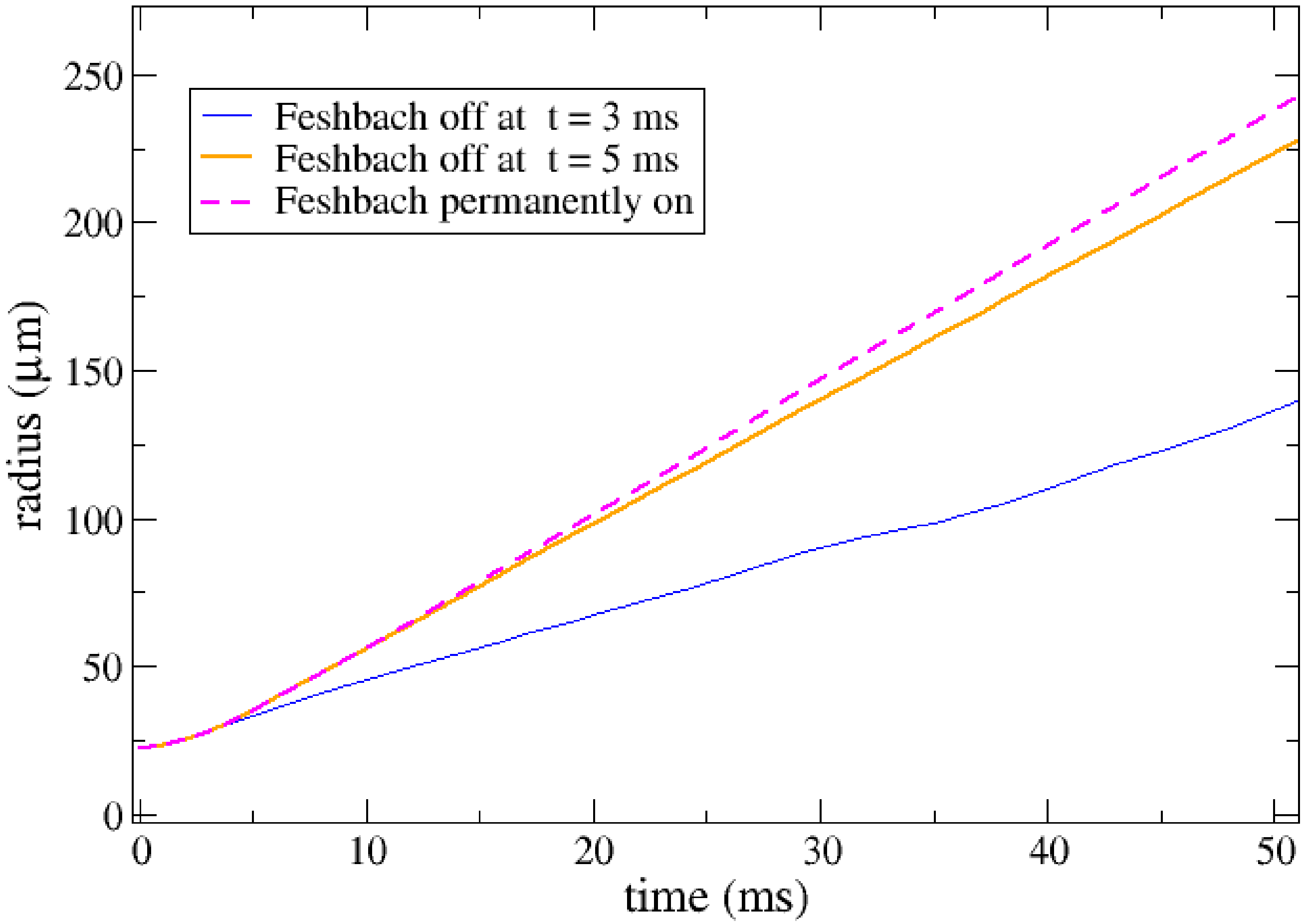

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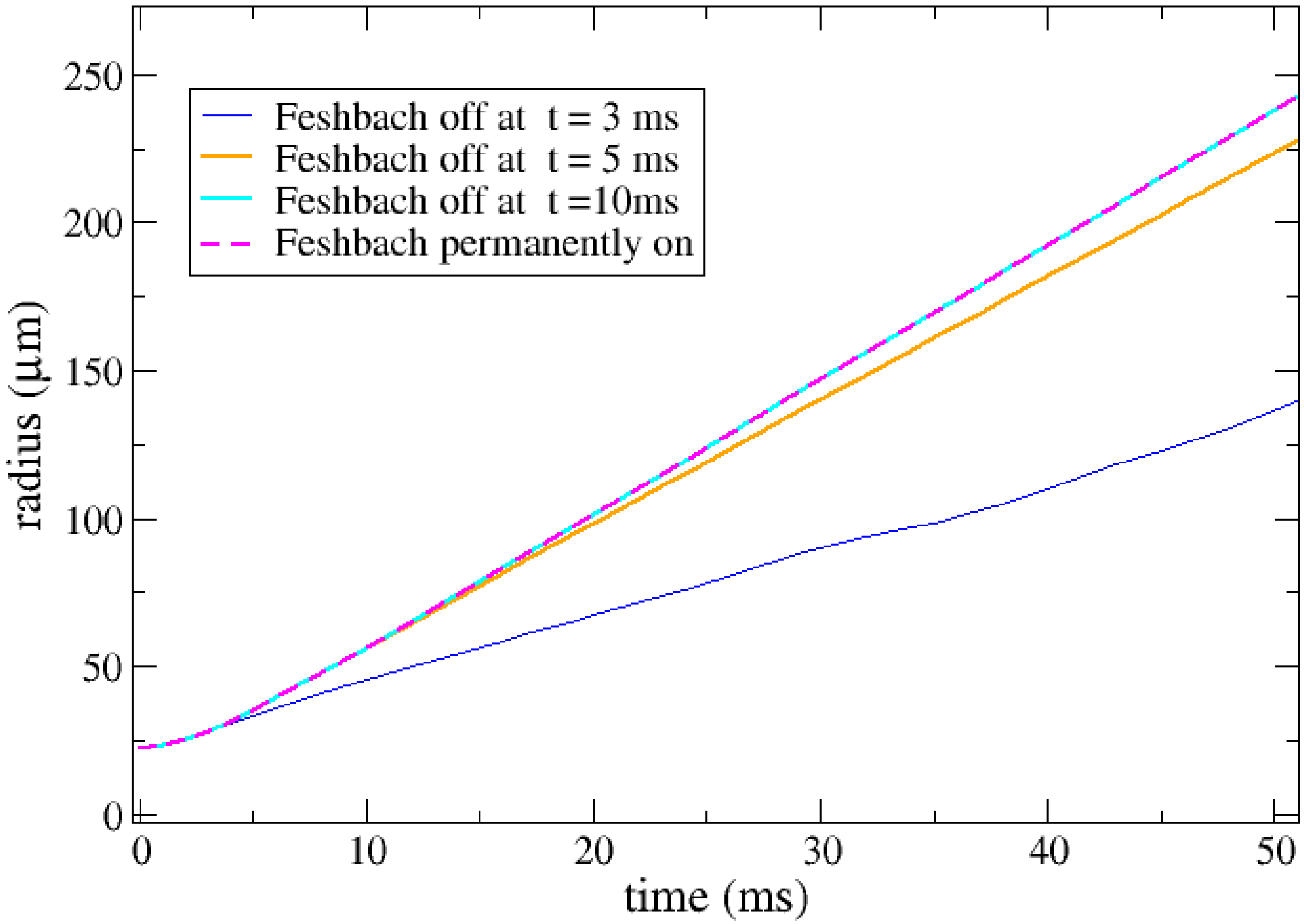
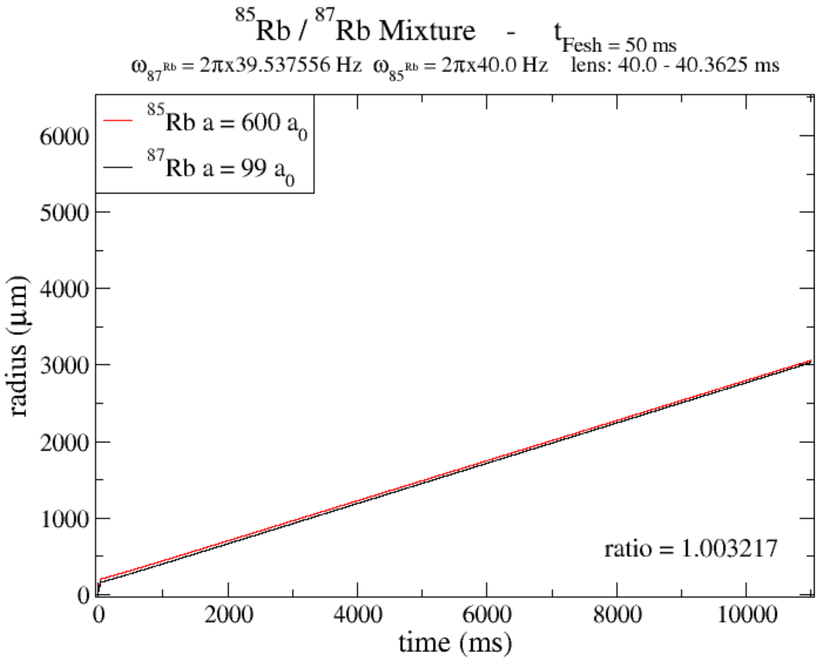
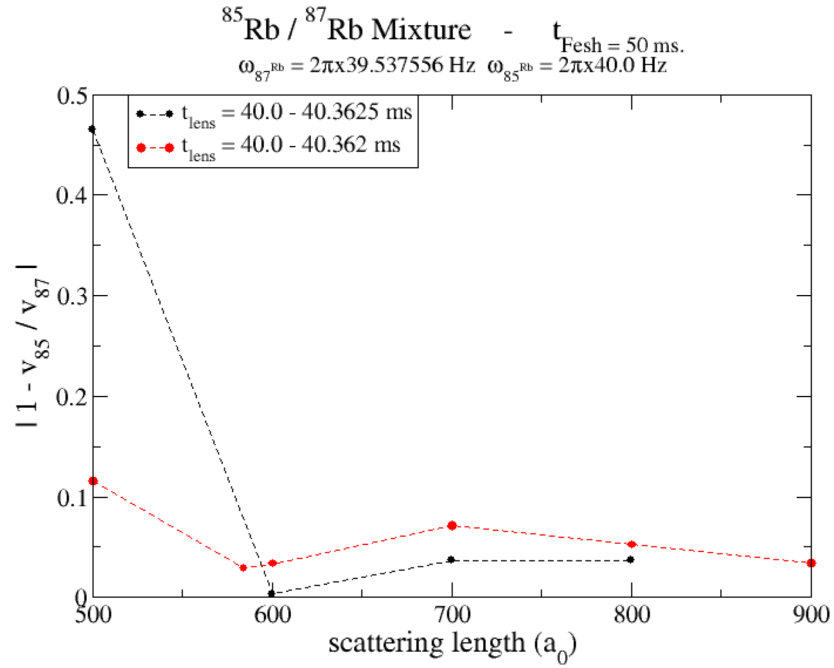


DKC – fine tuning





Simulated expansion rate match: 0.3 % @ 600 a_0 for ^{85}Rb

Mitigation techniques

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Temperature ~ 70 pK

- Beam splitting efficiency ~ 100 %
- Contrast loss due to gravity gradients and spurious rotations prevented: C > 60 %
- Wave front bias terms proportional to atomic temperature: < 10^{-15} m/s^2

^{87}Rb / ^{85}Rb matched effective wave vectors ~ 10^{-9}, Rabi frequencies ~ 10^{-4}, pulse timing

- High differential suppression ratio for vibrations / inertial bias terms: $2.5 \cdot 10^{-9}$
- Terms dependent on initial overlap / differential velocity remain: ~ 1 nm / 0.3 nm/s

Alternation of interferometer input states for subsequent cycles + µ-metal shield

- Relaxes the bias phase shift due to magnetic field gradients
- Gradients still affect initial overlap / differential velocity: have to be < $3 \cdot 10^{-6}$ G/m

Double diffraction (Mach-Zehnder) interferometer

- Beam splitter laser phase lock loop noise negligible
- Suppression of AC-Stark shift

Sensitivity to the Eötvös ratio

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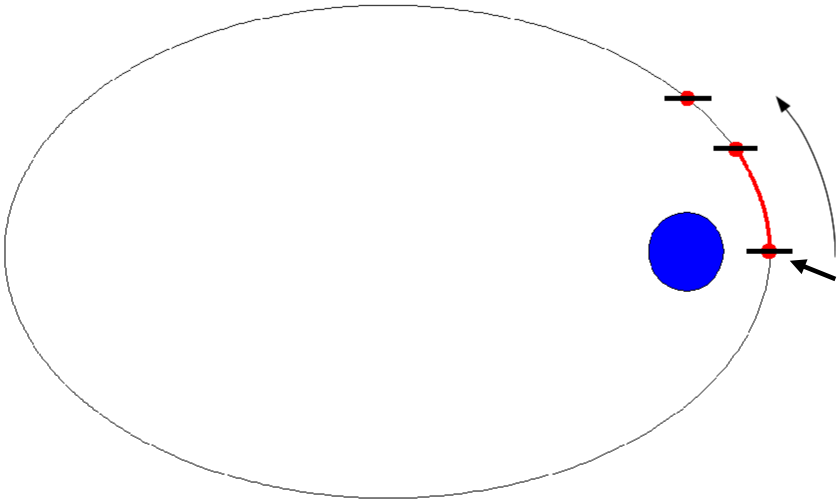
- Orbit duration: 16 h
- 5 years correspond to 2840 orbits
- ATI science operation at perigee, 100 cycles corresponds to 0.5 h per orbit



Perigee:

- $g = 3 – 4.5\ m/s^2$
- rotation rate $1 \cdot 10^{-6}$ rad/s
- Contrast > 0.6 with T = 5 s

Dependencies on the position of the satellite:

- g and projection of g onto the sensitive axis
- Interferometer contrast – gravity gradient causes dephasing
- Eötvös sensitivity per orbit: **$5 \cdot 10^{-14}$** – **$5.2 \cdot 10^{-14}$**
  → **2500** orbits to reach **$1 \cdot 10^{-15}$**, corresponding to **4.75 years**

Preliminary budget: statistical errors

Noise source	Conditions	Corresponding limit in m/s^2	Comment
Shot noise	10^6 atoms, C = 0.6	$2.93 \cdot 10^{-12}$	Contrast changes
Linear vibrations	k matched to 10^{-9}, Rabi frequency matched to 10^{-4}	~ 10^{-12}	
Magnetic field	B_0 = 1 mG, ∇B = 83 µG/m	$1.1 \cdot 10^{-13}$	
Other inertial contributions	10 % fluctuation per cycle in spatial overlap / differential velocity	< 10^{-13}	
Mean field	Delay 1 s after release, effective ODT frequency 1 Hz, beam splitting jitter 0.001 per cycle	~ 10^{-17}	
Sum		$3.1 \cdot 10^{-12}$	

Preliminary budget: systematic errors

Error source	Conditions	Corresponding limit in m/s^2	Comment
Gravity gradient	$\Delta z = 1.1 \cdot 10^{-9}$ m $\Delta v_z = 3.1 \cdot 10^{-10}$ m/s	$2.5 \cdot 10^{-15}$ $3.5 \cdot 10^{-15}$	Connected to magnetic field gradient and distance to center of mass
Coriolis acceleration	$\Delta v_x = 3.1 \cdot 10^{-10}$ m/s $\Delta v_y = 3.1 \cdot 10^{-10}$ m/s	$6.2 \cdot 10^{-16}$ $6.2 \cdot 10^{-16}$	Connected to magnetic field gradient and distance to center of mass
Other inertial terms depending on differential displacement / velocity	$\Delta x = 1.1 \cdot 10^{-9}$ m, $\Delta y = 1.1 \cdot 10^{-9}$ m others	$5.5 \cdot 10^{-17}$ $1.6 \cdot 10^{-18}$ $4.6 \cdot 10^{-17}$	Connected to magnetic field gradient and distance to center of mass
Photon recoil	$T_{zzz} = 6GM_e/R^4$	$3.9 \cdot 10^{-17}$	
Static magnetic fields	$\nabla B < 0.1$ nT/m	10^{-15}	Mitigation: alternate input states
Raman lasers wave front	Retro reflection R = 250 km Collimation ~400 m, $T_{at} = 0.07$ nK	$6.3 \cdot 10^{-16}$ $2.8 \cdot 10^{-16}$	Mitigation: expansion rate lock
Mean field	Delay 1 s after release, effective ODT frequency 1 Hz	$-1 \cdot 10^{-17}$	
Spurious accelerations	Suppression ratio $2.5 \cdot 10^{-9}$, $4 \cdot 10^{-7}$ m/s^2	10^{-15}	
Detection efficiency	$\lvert \eta - 1 \rvert < 0.003$	$< 10^{-15}$	Possibly calculated from Bayesian fit
Sum		$1.1 \cdot 10^{-14}$	

Outlook

Source performance

- Anharmonicities of the trap
- Miscibility criterium
- Anisotropic trap
- Optimized evaporation
- Crossed dipole trap and vibrations

Consolidation of error budgets / calibration techniques

- e.g. Rabi frequency match to 10^{-4}
- Experimental verification of the estimated error budget / basic assumptions
- Impact of self-gravity has yet to be determined

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Thank you for your attention!

LUH team: E.M. Rasel, N. Gaaloul, J. Hartwig, H. Ahlers, K. Posso-Tiujillo

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