Implementing a Josephson Voltage Standard for the Nuclear Magnetic Moment Measurements of ^{2}D, ^{3}He and ^{7}Li in a Penning Trap

A. Kaiser[1], R. Behr[2], U. Beutel[1], S. Dickopf[1], M. Door[1], S. Eliseev[1], A. Kaushik[1], K. Kromer[1], M. Müller[1], L. Palafox[2], S. Ulmer[3,4], A. Mooser[1], and K. Blaum[1]

[1] Max-Planck-Institut für Kernphysik, Heidelberg (Germany), [2] Physikalisch Technische Bundesanstalt, Braunschweig (Germany),
[3] RIKEN, Ulmer Fundamental Symmetries Laboratory, Wako (Japan), [4] HHU Düsseldorf (Germany)

IN A NUTSHELL

PROBLEM

typical rel. stability of the electrostatic trapping potential: **4x10^{-8}** out of a few V over 2-4 min.

limits precision of **mass determinations** and makes spin-flip resolution for ***g*-factor determinations** of nuclei heavier than a proton impossible
→ requires **2x10^{-8}** and better for light nuclei

SOLUTION

implement a 20 V Josephson voltage standard to improve the trapping potential stability

MOTIVATION

Nuclear *g*-factor determination

test theory models for diamagnetic shielding of the nucleus by comparing measurements at different charge states with the unshielded nucleus

$$g_I^{\text{shielded}} = (1-\sigma)g_I$$

[V. A. Yerokhin *et al.*, Phys Rev A 85, 0225122 (2012)]

enable most accurate, absolute *B*-field calibration with ^{3}He NMR probes using the directly measured ^{3}He *g*-factor value
[M. Farooq *et al.*, Phys. Rev. Lett. 124, 223001 (2020)]
[A. Schneider *et al.*, Nature 606(7916) (2022)]

High-precision mass spectrometry

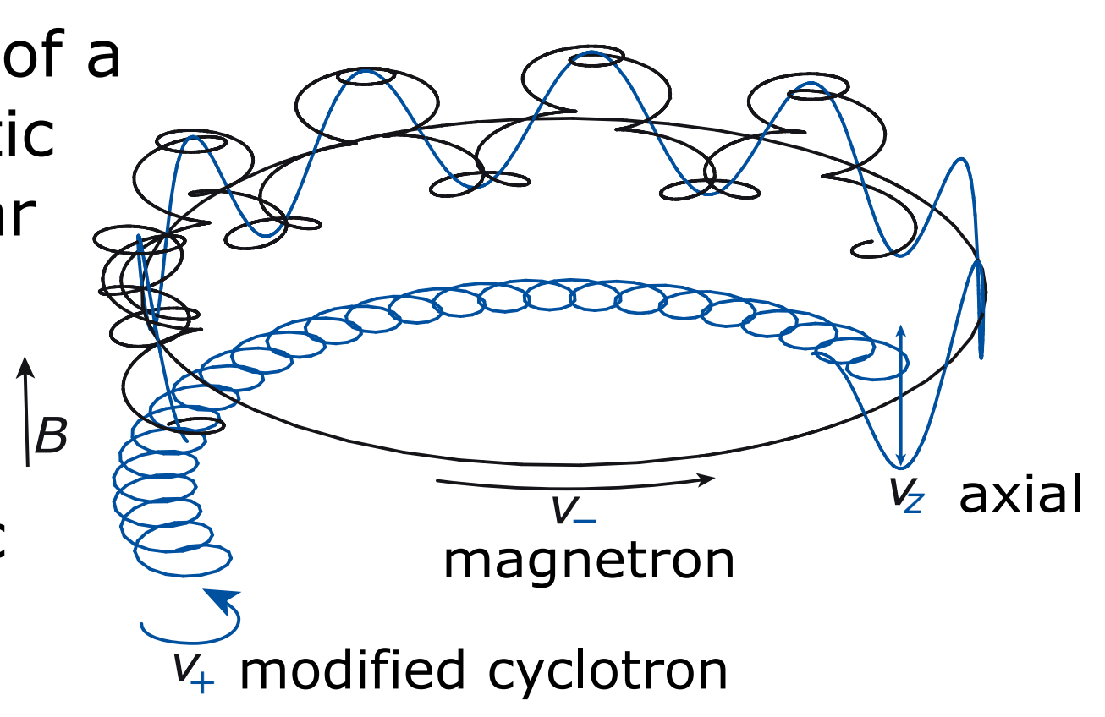
relevant to test fundamental theories:
e.g. quantum electrodynamics,
charge-parity-time invariance,
special relativity,
particle interactions and symmetries
or fifth force carriers

[J. Morgner *et al.*, Nature 622, 53-57 (2023)]
[C. Smorra *et al.*, Nature 550, 371-374 (2017)]
[S. Rainville *et al.*, Nature 438, 1096-1097 (2005)]
[S. George *et al.*, Phys. Rev. Lett. 98, 162501 (2007)]
[I. Counts *et al*., Phys. Rev. Lett. 125, 123002 (2020)]

ION IN A PENNING TRAP

Eigenmotions of a trapped ion

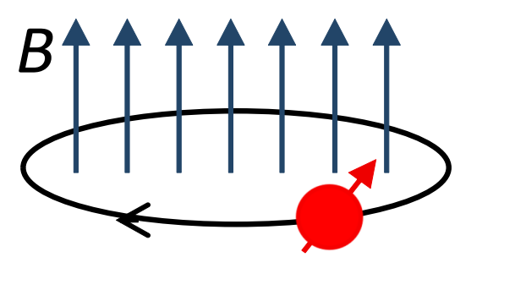
Penning traps confine an ion in a superposition of a homogeneous magnetic field and a quadrupolar electrostatic potential.
➜ particle motion composed of three independent harmonic oscillations



the free cyclotron frequency ω$_C$ follows from the measurement of the ion's eigenfrequencies

$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2}$$

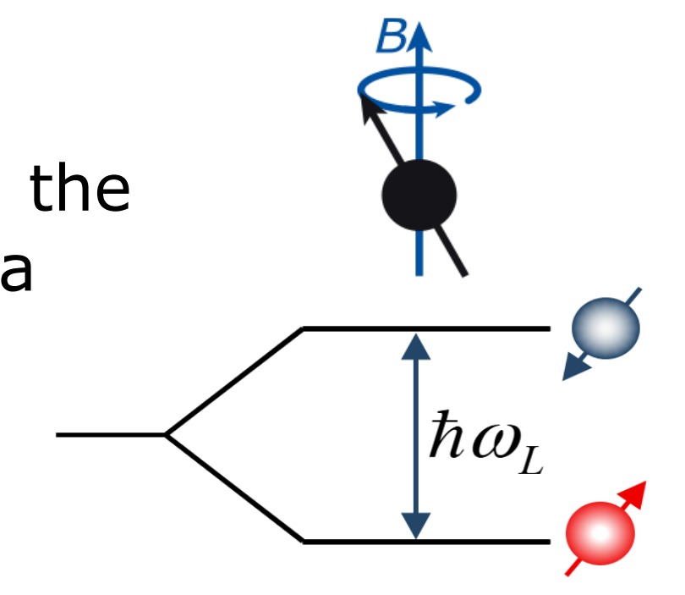
[L.S. Brown and G. Gabrielse *et al.* Rev. Mod. Phys. 58,233(1986)]



$$\omega_c = \frac{q}{m}B$$

the Larmor frequency ω$_L$ is determined from measuring the ion's spin-flip probability in a certain frequency range

$$\omega_L = 2\frac{\mu}{\hbar}B$$



g-FACTOR MEASUREMENT

a simultaneous measurement of the Larmor frequency with the free cyclotron frequency enables a *B*-field independent *g*-factor determination

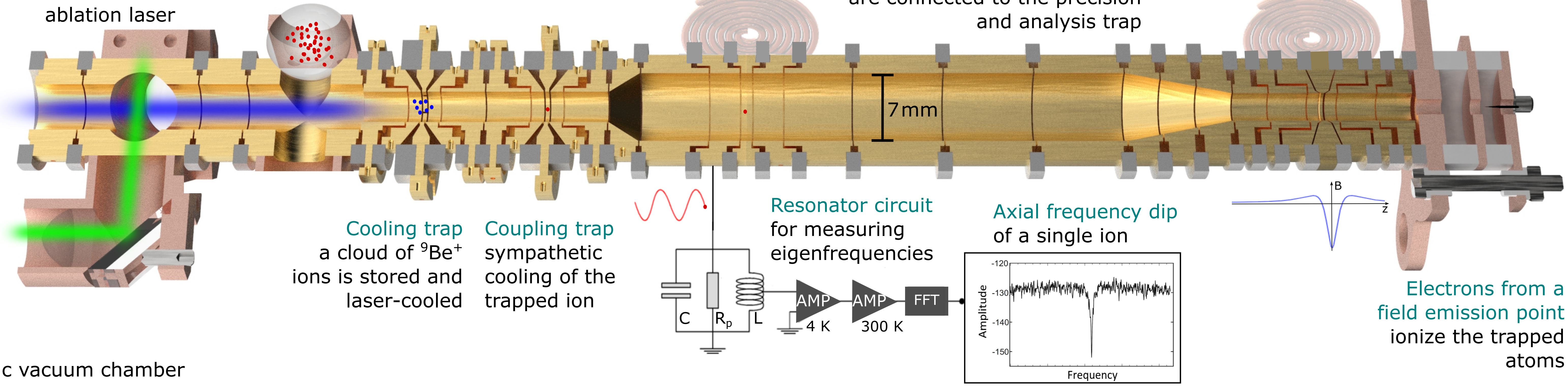
$$\boxed{\frac{\omega_L}{\omega_C} = \frac{g\,m}{2\,m_p}}$$

MASS SPECTROMETRY

mass measured independently of *B*-field using the ratio of cyclotron frequencies

$$\boxed{\frac{\omega_{c,1}}{\omega_{c,2}} = \frac{q_1\,m_2}{q_2\,m_1}}$$

SCHEMATIC SETUP



^{3}He-filled glass sphere
is resistively heated such that He atoms permeate the glass

Be target
is hit with an ablation laser

313 nm cw laser
for cooling trapped ^{9}Be^{+}

microwaves
for driving electronic spin-flips

532 nm pulsed laser
for ablating Be from target

Trap tower assembly
mounted in a cryogenic vacuum chamber

Cooling trap
a cloud of ^{9}Be^{+} ions is stored and laser-cooled

Coupling trap
sympathetic cooling of the trapped ion

Precision trap
measures eigenfrequencies of the trapped ion to highest precision

Radio-frequency drives
for nuclear spin-flip excitation are connected to the precision and analysis trap

Analysis trap
spin-state detection is enabled by the inhomogeneous B-field

Resonator circuit
for measuring eigenfrequencies

Axial frequency dip
of a single ion

Electrons from a field emission point
ionize the trapped atoms

SPIN-FLIP DETECTION

use ferromagnetic ring electrode to create strong magnetic inhomogeneity B$_{2,AT}$= 100 kT/m^2 in the Analysis trap
[A. Schneider *et al.*, Ann. Phys. 532,1800485 (2019)]

$$B_z = B_0 + \boldsymbol{B_2}\left(z^2 - \frac{\rho^2}{2}\right)$$

$$\Delta\omega_{z,e/N} = \frac{\boldsymbol{B_2}}{m_{ion}\omega_z}\cdot\left(\frac{E_+}{B_0} \pm \underbrace{\frac{g_{e/N}e\hbar(2I)}{2m_{e/p}}}_{\text{electronic / nuclear spin-flip}}\right) = \begin{matrix} > 10\ \text{Hz} \\ < 0.1\ \text{Hz}\end{matrix}$$

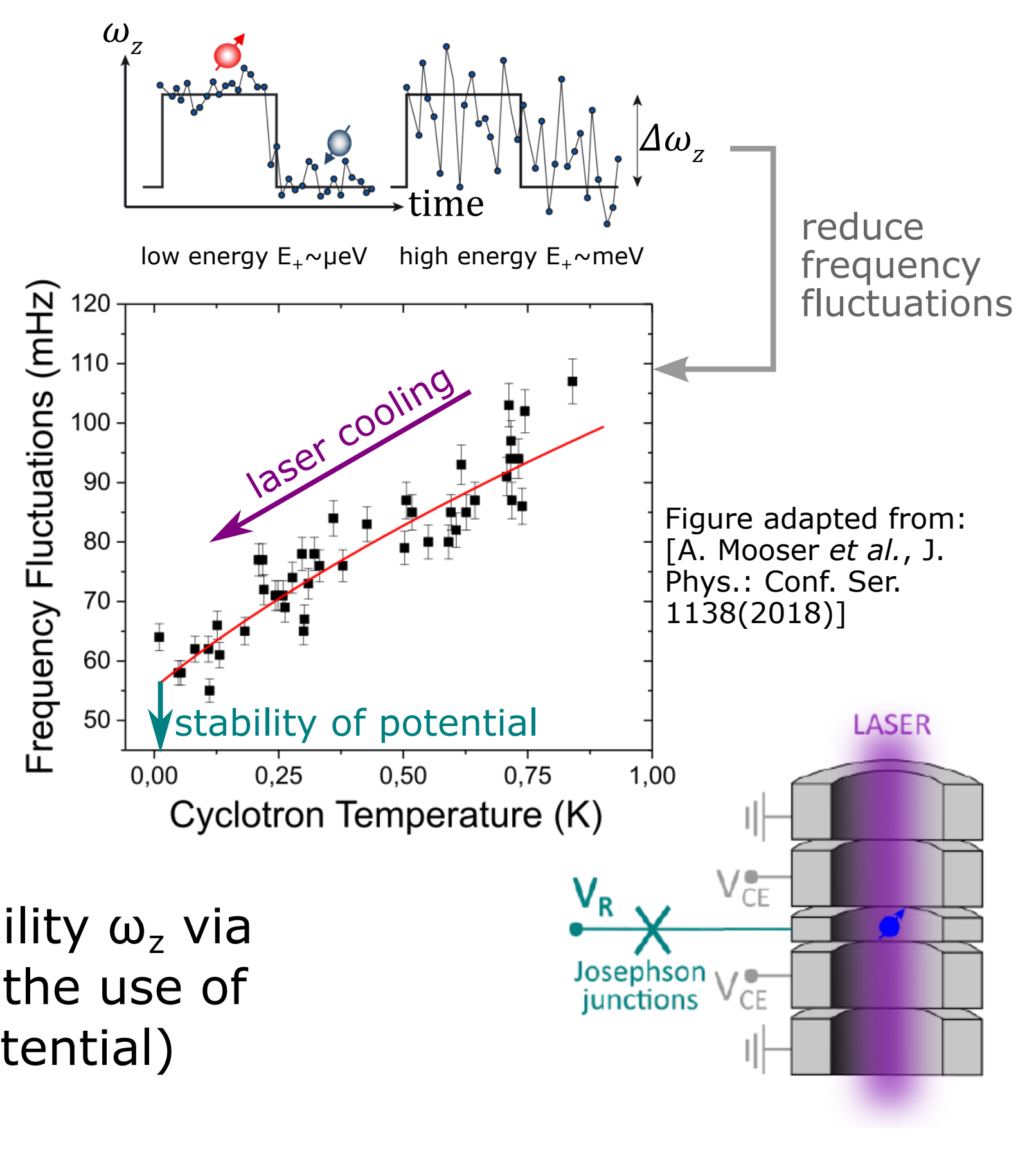
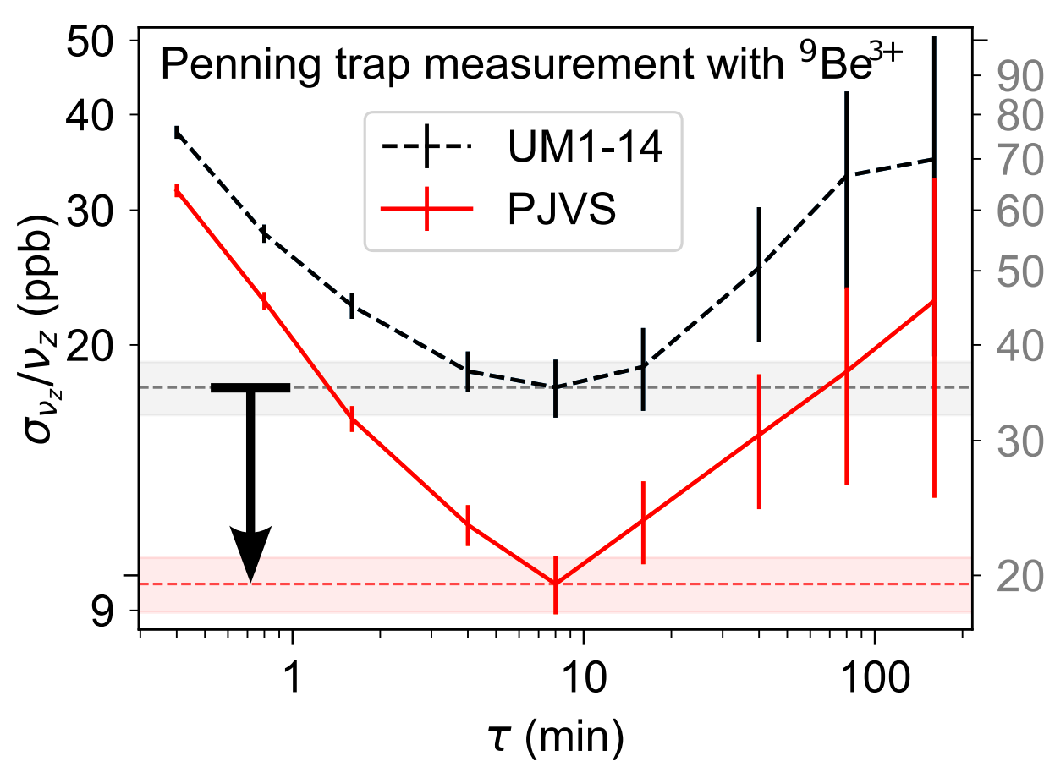
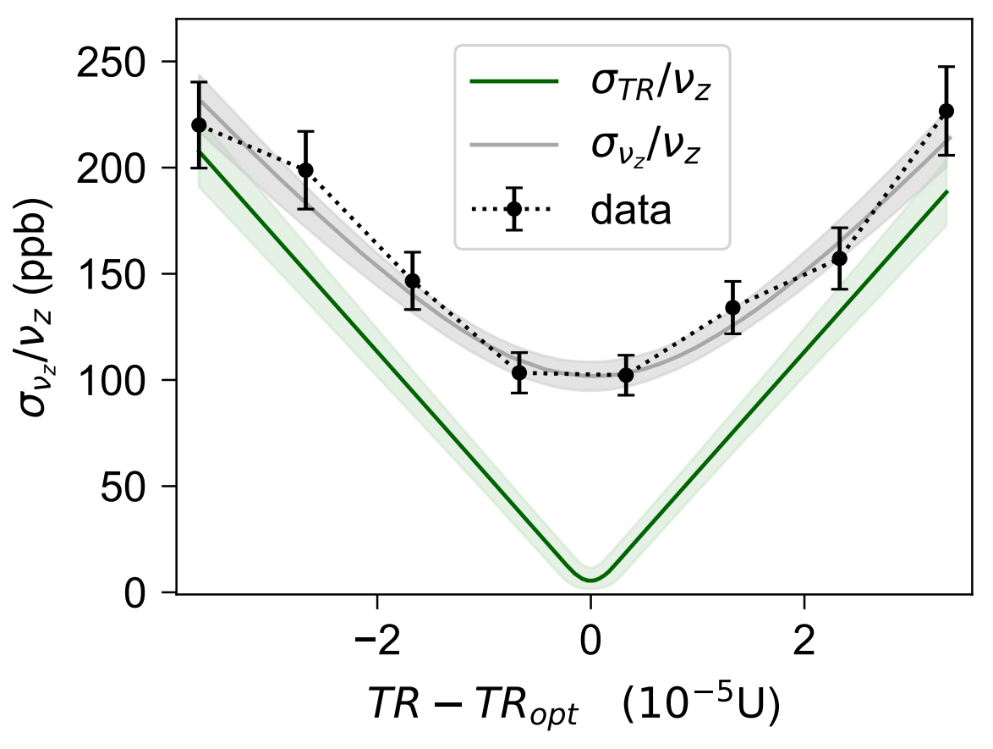


Figure adapted from: [A. Mooser *et al.*, J. Phys.: Conf. Ser. 1138(2018)]

for nuclear spin-flip detection: improve axial stability ω$_z$ via implementation of sympathetic laser cooling and the use of Josephson voltage standards (for the trapping potential)

RESULTS





test Josephson voltage standard on a trapped ^{9}Be^{3+} ion:
Phase sensitive measurement of the axial frequency stability of a trapped ^{9}Be^{3+} ion using two voltage sources on the ring electrode.

$$\nu_z = \frac{\phi_l - \phi_s}{2\pi(t_l - t_s)}$$

The implementation of a 20 V programmable Josephson voltage standard (PJVS) improves the stability of the axial frequency by a factor of 2 compared to a conventional highly-stable voltage source UM1-14.

The main limitation in shot-to-shot noise is a non-optimal tuning ratio TR = V$_{CE}$/V$_R$.

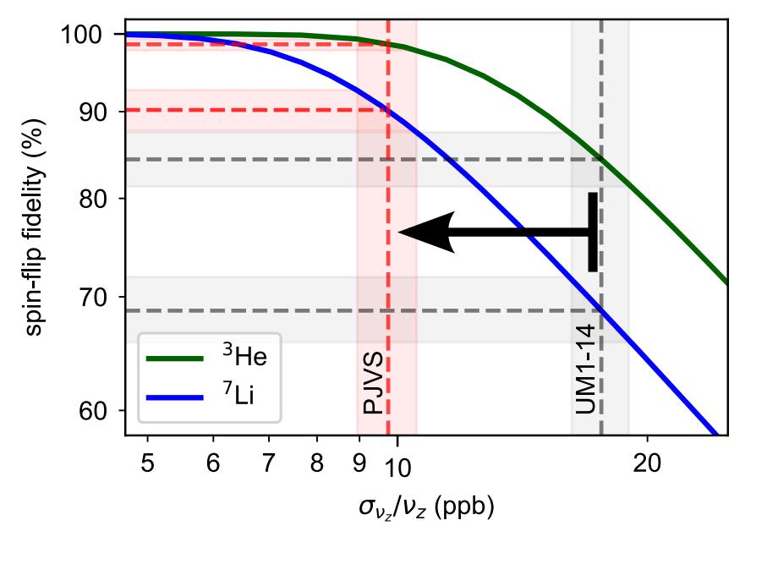
The TR was optimized to 5 µV/V. An offset of only 5 µV on V$_{CE}$ leads to a frequency uncertainty of 28(8) x10^{-9}, well in agreement with the observed shot-to-shot noise in the ^{9}Be^{3+} measurement and thus the largest noise contribution.

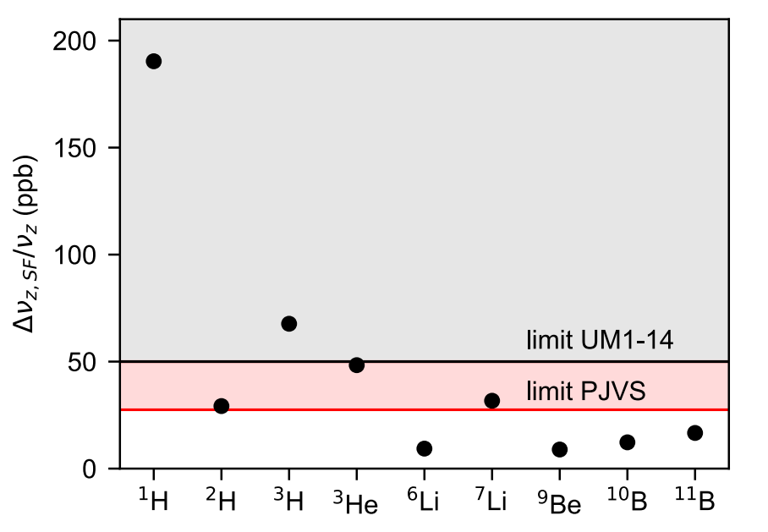
[A. Kaiser *et al.*, APL, accepted (2024)]

OUTLOOK

High-precision mass spectrometry:
The implementation of a Josephson voltage standard potentially enables mass measurements with unprecedented precision below 2x10^{-12}.

g-factor measurements:
The improved axial frequency stability allows the unambigous resolution of spin-flip induced frequency shifts as small as 3x10^{-8}. This enables first direct nuclear *g*-factor measurements of ^{2}D, ^{3}He and ^{7}Li in a Penning trap.





[A. Kaiser *et al.*, APL, accepted (2024)]

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