High precision **Penning Trap Measurements** of Magnetic Moments @ μTEx

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IMPRS
for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

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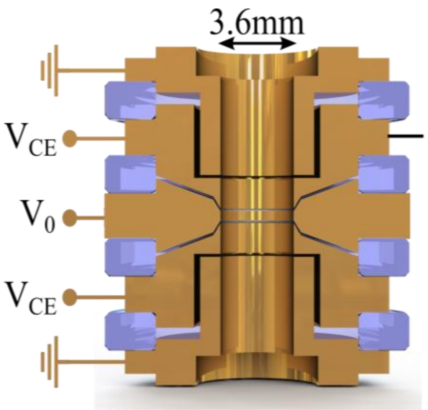
Content:

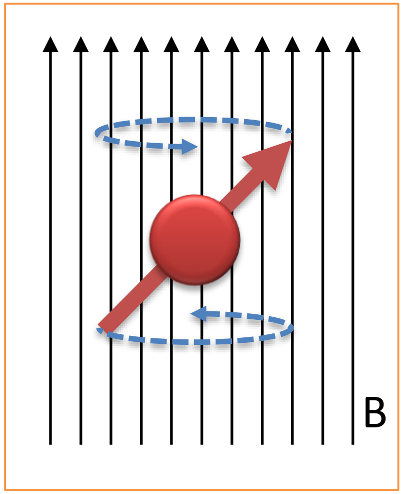
1.

Penning trap principles



2.

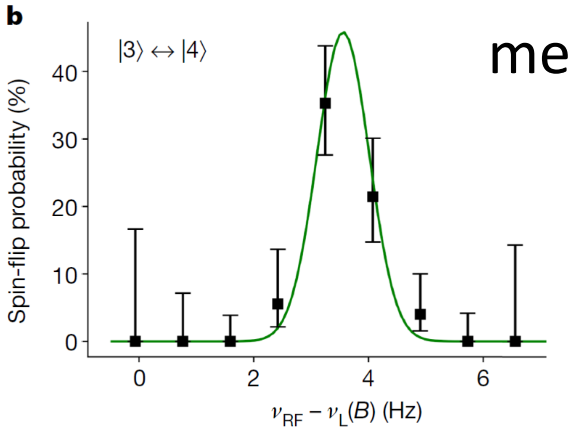
magnetic moment measurements



3.

$^{9}Be^{3+}$ campaign

$^{4}He^{+}$ campaign



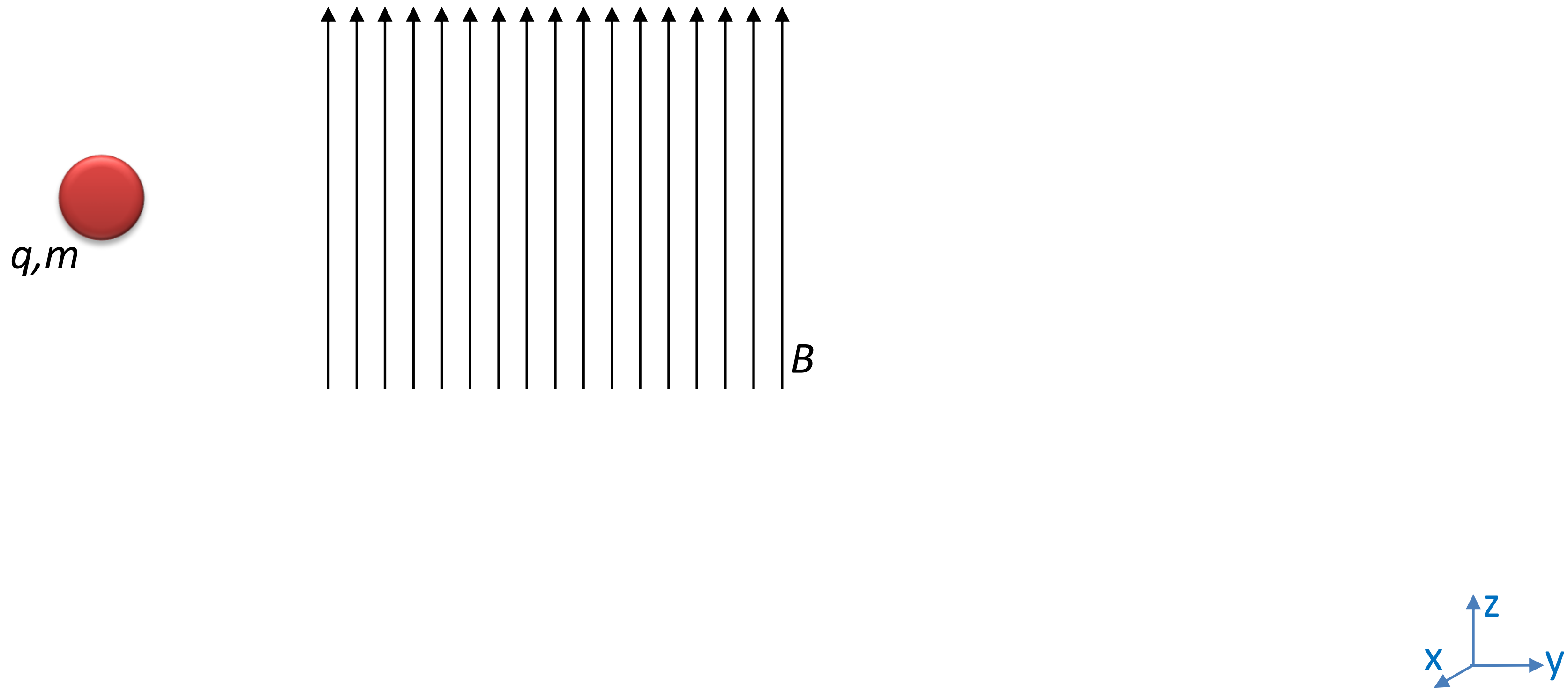
4.

nuclear magnetic moment measurements

ion rotates with free cyclotron frequency:

$$\nu_c = \frac{1}{2\pi} \cdot \frac{qB}{m}$$

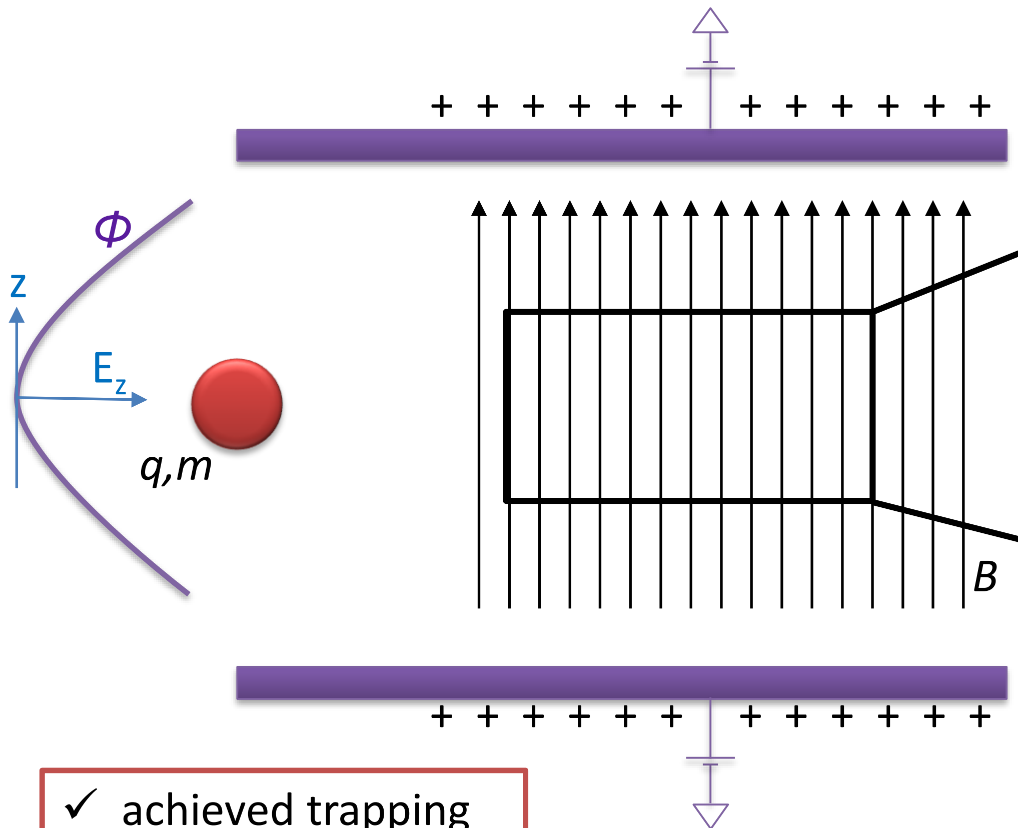
magnetic field *B*

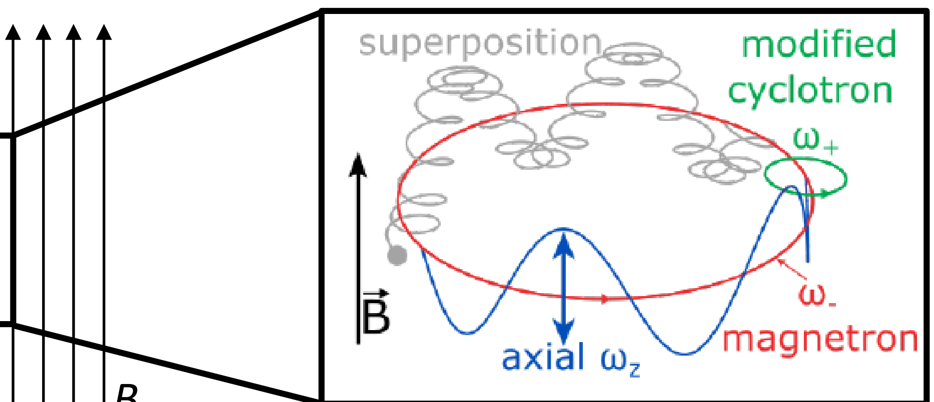


magnetic field B + electric field Φ

$$\nu_c = \frac{1}{2\pi} \cdot \frac{qB}{m}$$

$$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$$





Typical values:

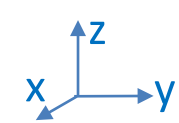
$\nu_+ = 30\ \mathrm{MHz}$

$\nu_z = 500\ \mathrm{kHz}$

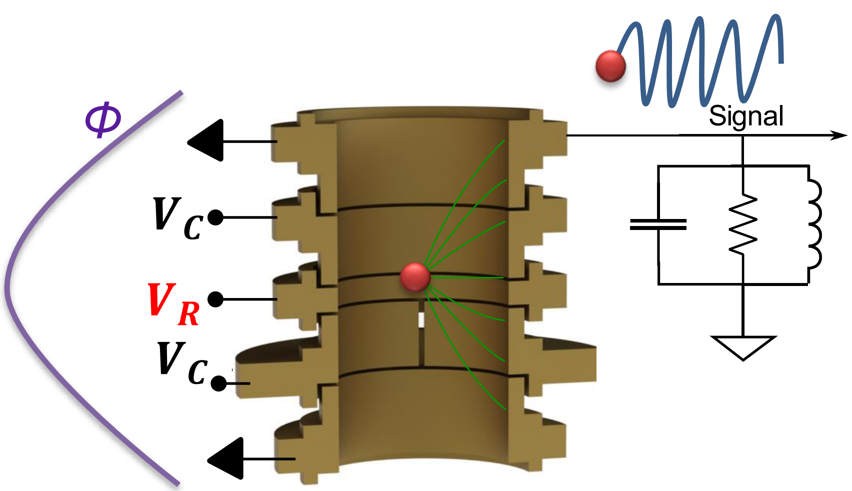
$\nu_- = 5\ \mathrm{kHz}$

✓ achieved trapping

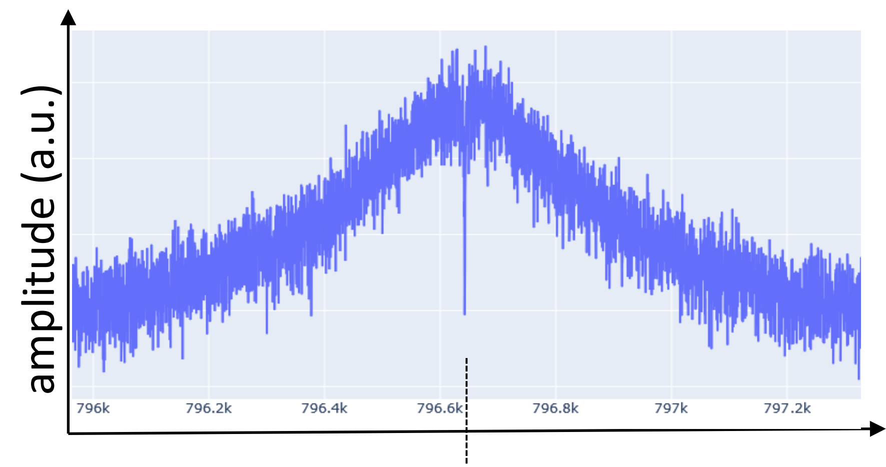
X able to measure ν_c



Detection system:

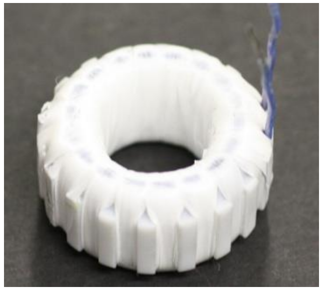


FFT spectrum:



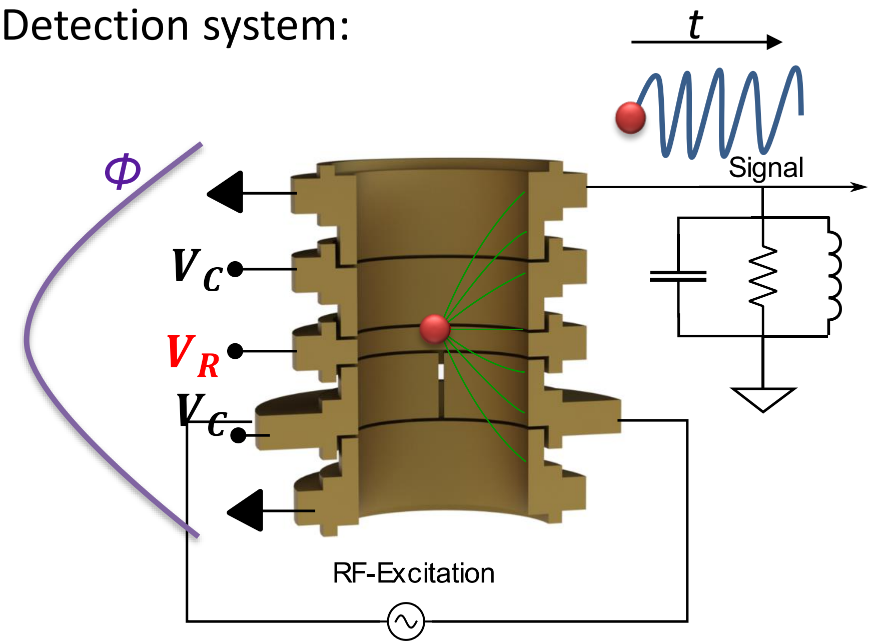
dip @ ν_z

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m}2V_R C_2}$$



resonant tank circuit (coil) amplifies the induced image charges

Detection system:

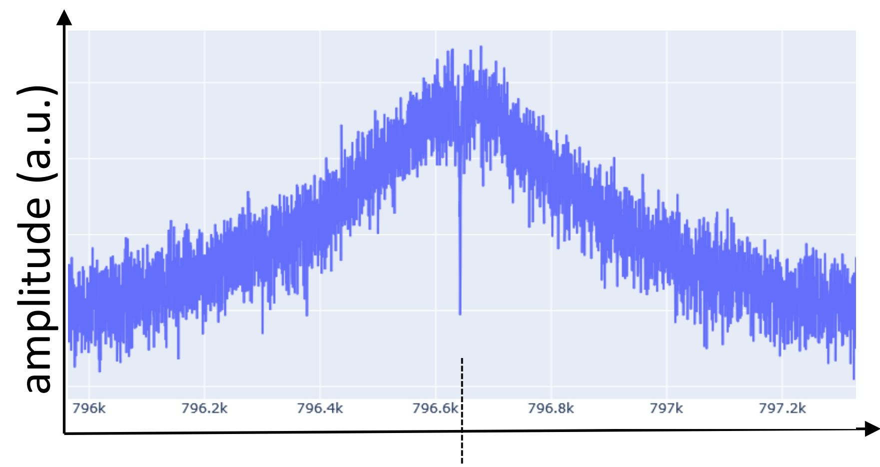


to couple and ν_z e.g. ν_+:

$$\nu_{RF} = \nu_z - \nu_+$$

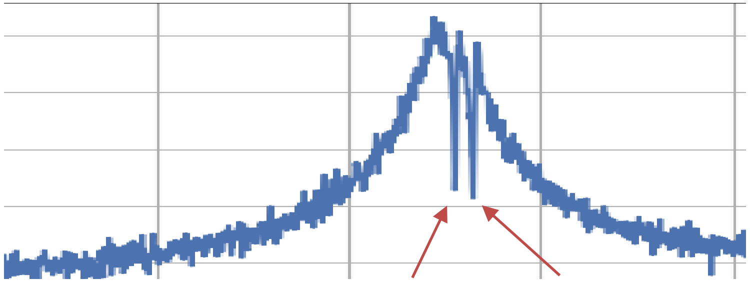
- ✓ achieved trapping
- ✓ able to measure $\nu_c \propto \frac{q}{m} B$

FFT spectrum:

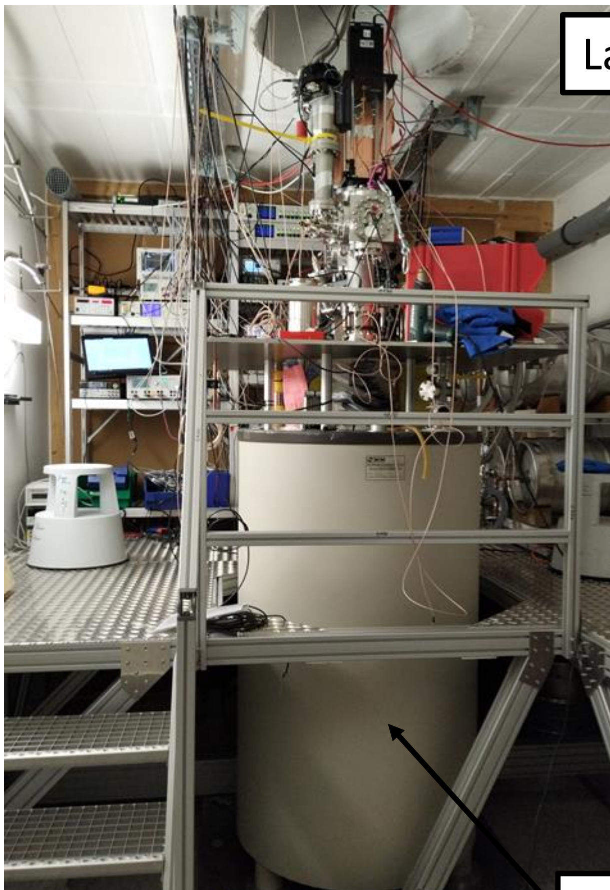


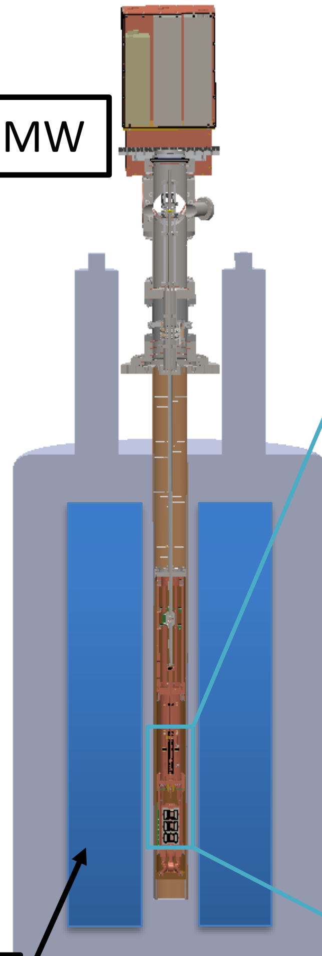
dip @ ν_z

double dip:

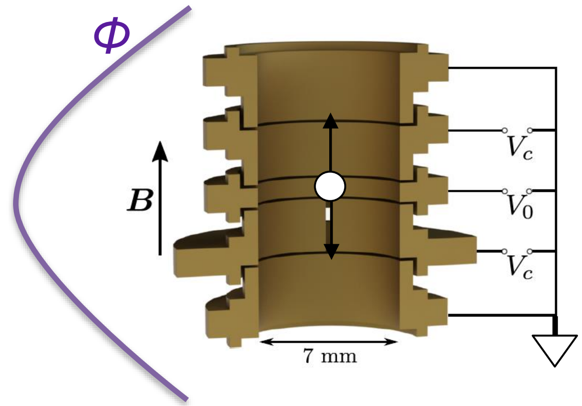


Experimental realization:

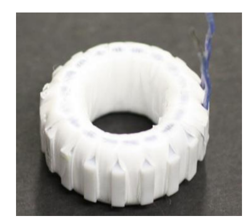




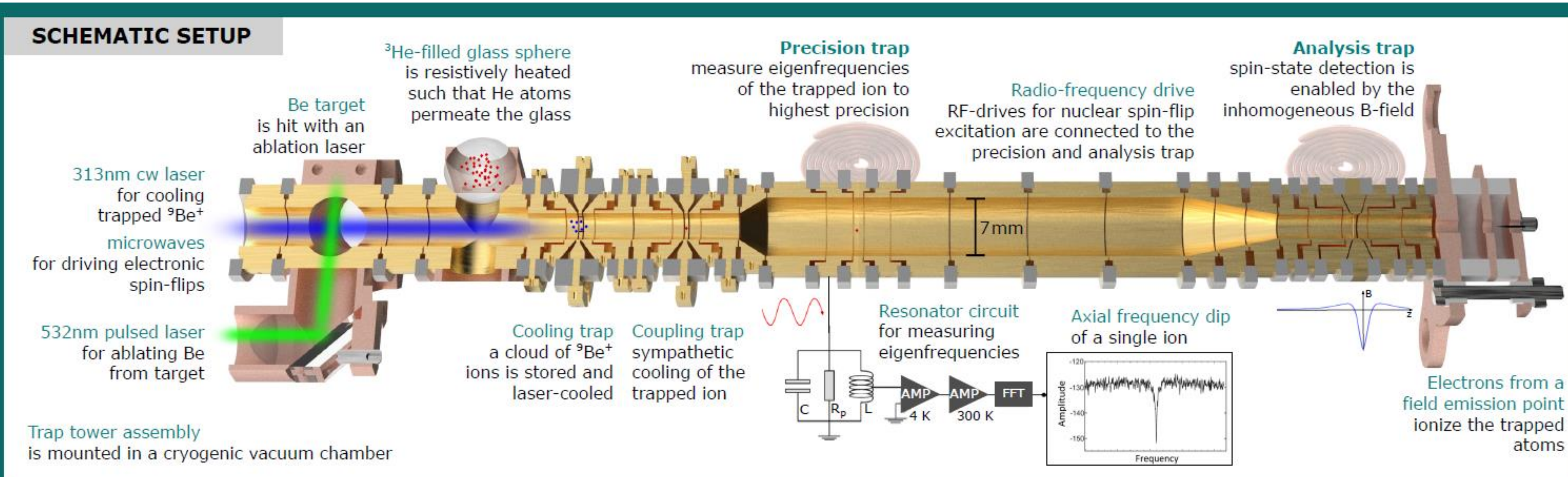
Trap tower:



Detection system:

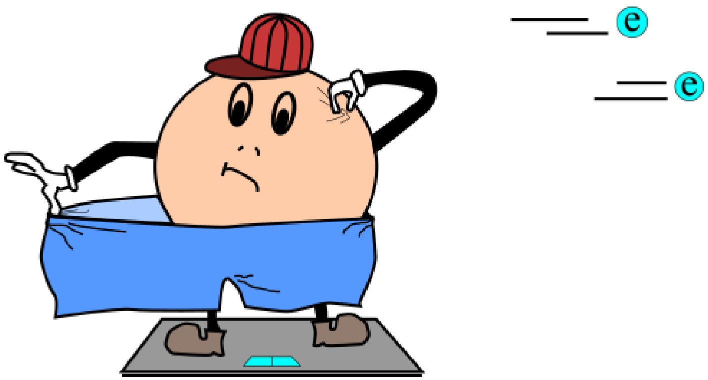


Loading and ionization:

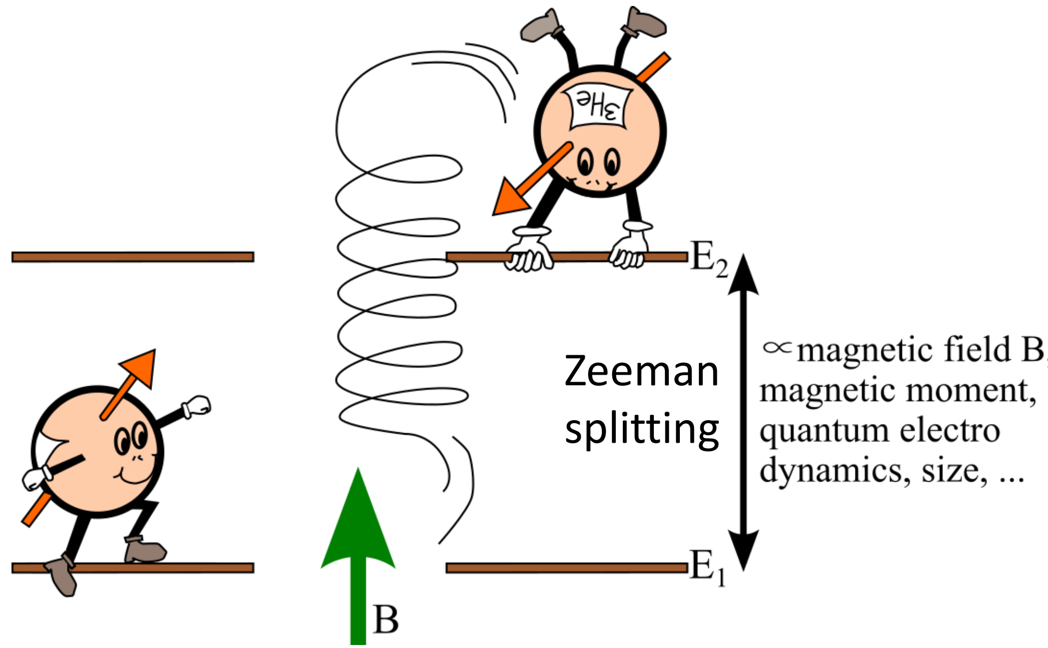


$$\nu_L = \frac{1}{2\pi} g \frac{q}{m} B \propto g\, \nu_c$$

independent mass determination @PENTATRAP:



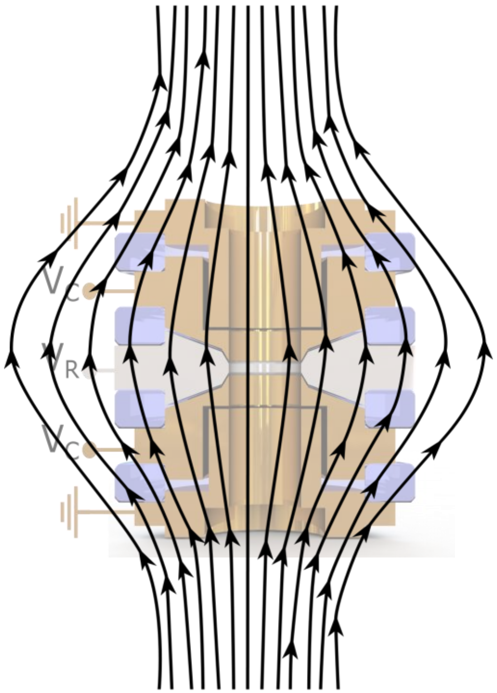
spin-flip resonance curve:



→ How to detect the spin-state?

$$\nu_L \propto g \frac{q}{m} B \propto g \nu_c$$

ferromagnetic ring electrode:

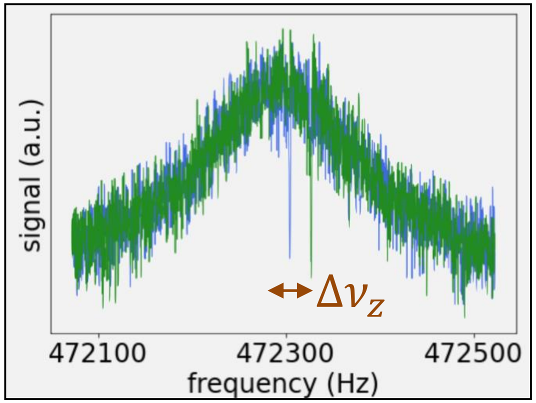


Addition of magnetic bottle inside separate trap:

$$B_z = B_0 + B_2 z^2$$
$$\rightarrow \Delta\nu_{z,SF} = \frac{B_2}{2\pi^2 m \nu_z}\left(g\mu_{B/N} I\right)$$

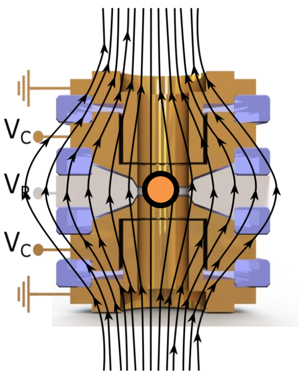
$\Delta\nu_{z,e} \approx$ 22Hz out of $\sim$500 kHz

$\Delta\nu_{z,p} \approx$ 100mHz $\approx \nu_z$ fluctuations

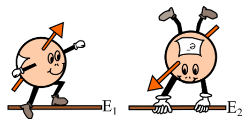


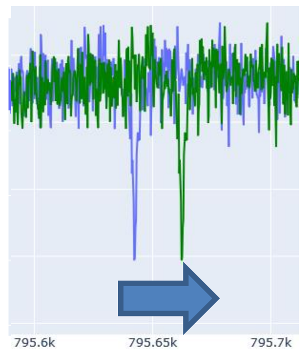
✓ observe electron spin-flips
X observe nuclear spin-flips

analysis trap

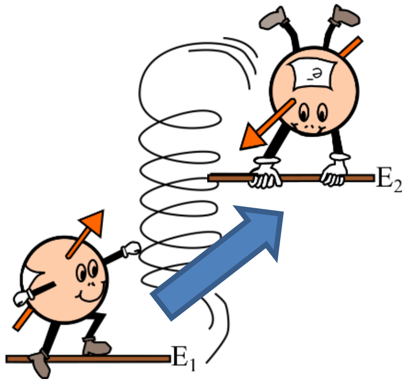


start with some state:

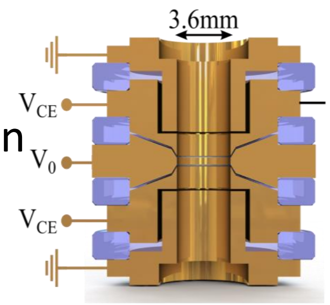


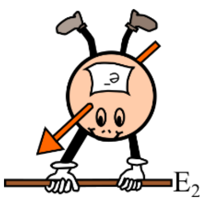


drive spin-flip @ ν_{RF} :



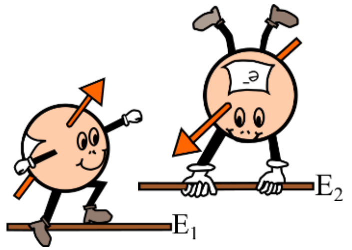
precision trap



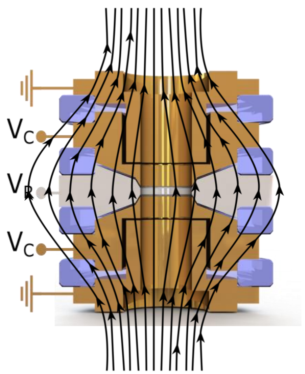


measure B via ν_c

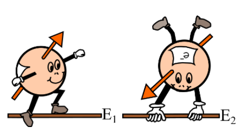
drive spin-flip

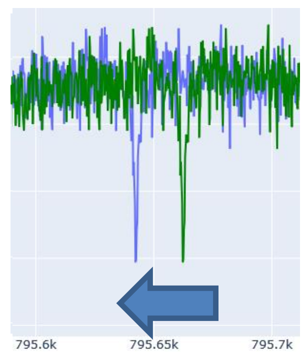


analysis trap

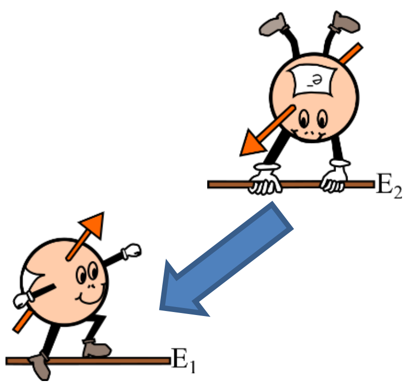


start with some state:



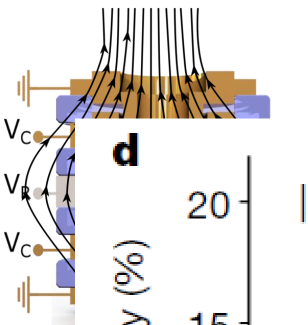


drive spin-flip @ ν_{MW} :

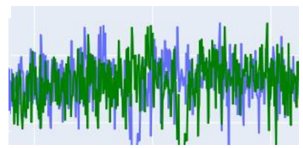


→ no spin-flip in precision trap

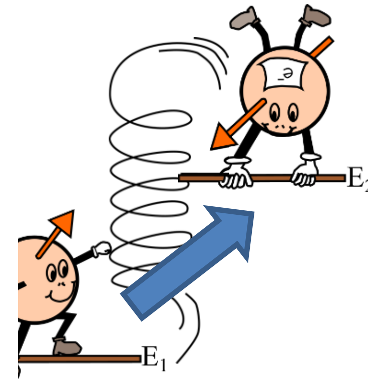
analysis trap

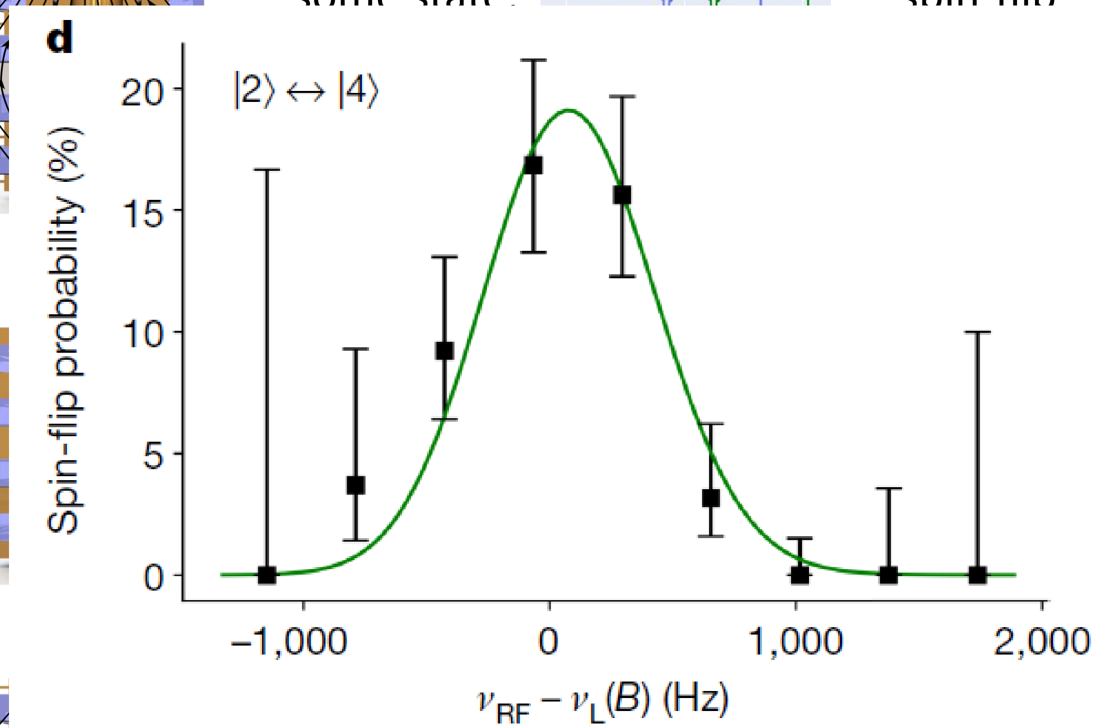


start with some state:

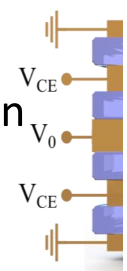


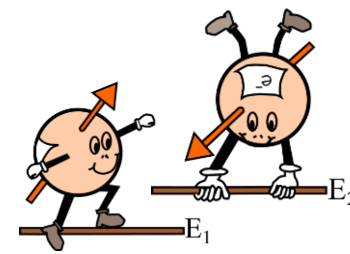
drive spin-flip



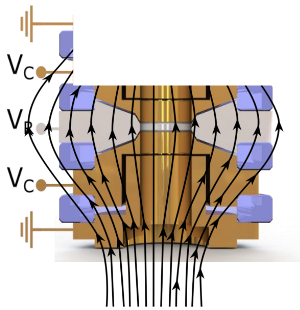


precision trap

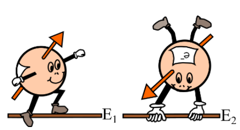


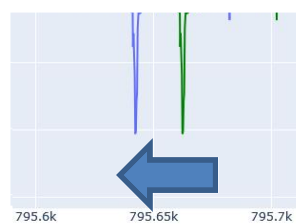


analysis trap

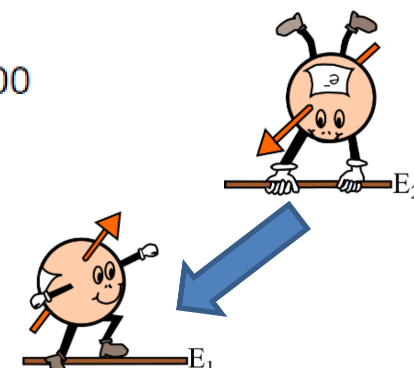


some state:





spin-flip @ ν_{MW} :

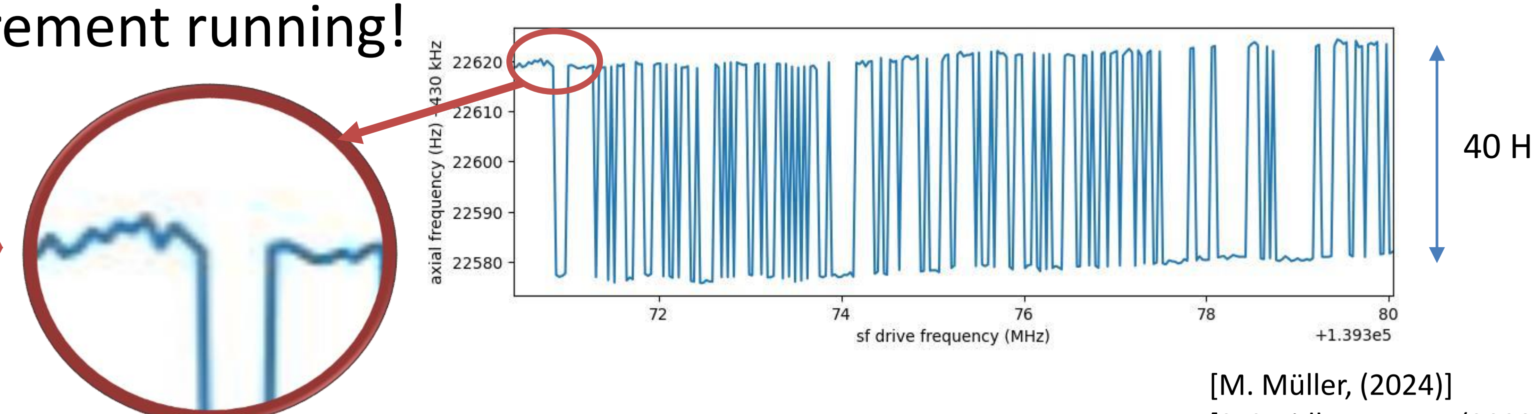


→ no spin-flip in precision trap

$^4He^+$ campaign at  TEx

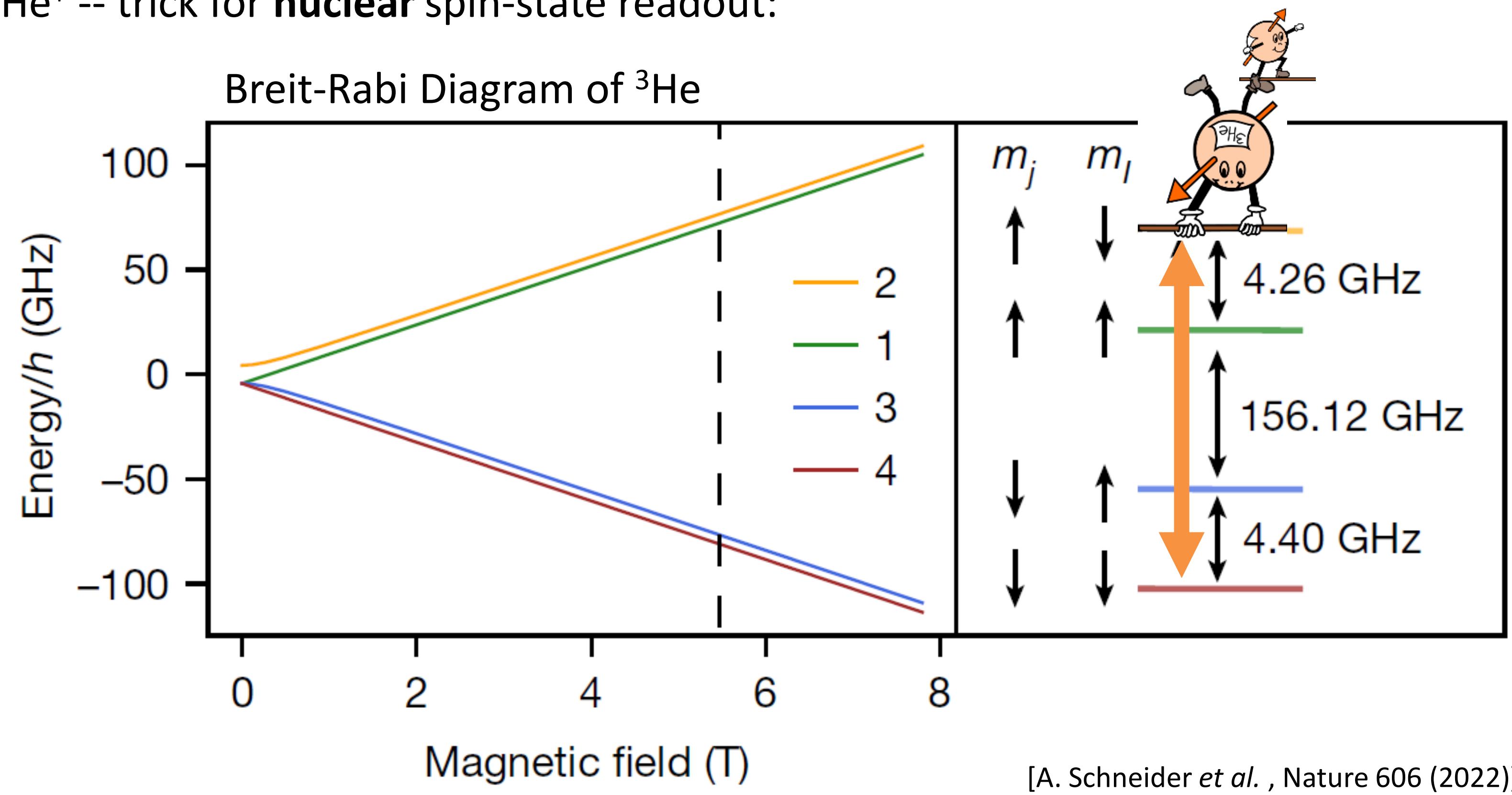
- one transition (nuclear spin $I = 0$)
- easy in-trap production (^{4}He in quartz-glass)
- mass known to 13ppt; might be improved by PENTATRAP
- uncertainty of the g_e theory is around 0.2 ppt
- extract e mass with highest precision $m_e = \frac{g_e}{2}\frac{e}{q}\frac{\nu_c}{\nu_L}m_{ion}$
- measrement running!

nuclear transitions would be ~ 40 mHz ($^3He^{2+}$)

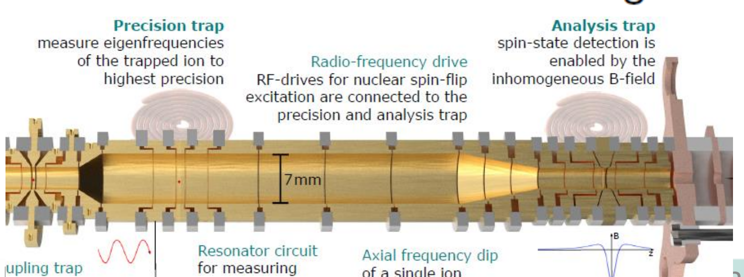


[M. Müller, (2024)]
[S. Sasidharan, PRL (2023)]

$^3He^+$ -- trick for **nuclear** spin-state readout:



[A. Schneider *et al.* , Nature 606 (2022)]



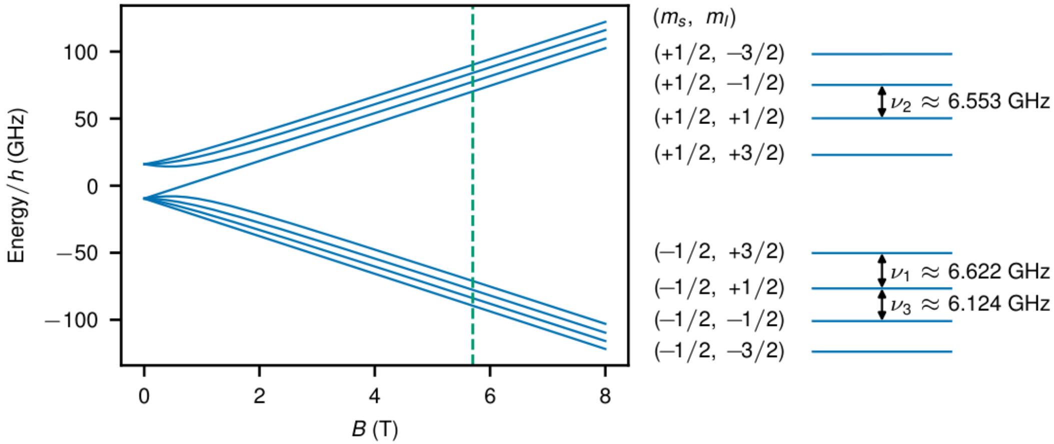
→ this only works because of the remaining electron bound to the nucleus

$^{9}Be^{3+}$ campaign

- many transitions (nuclear spin $I = 3/2$)

extract:

- ΔE_{HFS} zero-field hyperfine-splitting
- mass



$$\nu_i \left(g_e \mu_B, g_I\, \mu_N, \Delta E_{\mathrm{HFS}}; B\right)$$

$$\mu_B = \frac{e\hbar}{2m_e} \simeq -9 \cdot 10^{-24} J/T$$

$$\mu_N = \frac{e\hbar}{2m_p} \simeq -5 \cdot 10^{-27} J/T$$

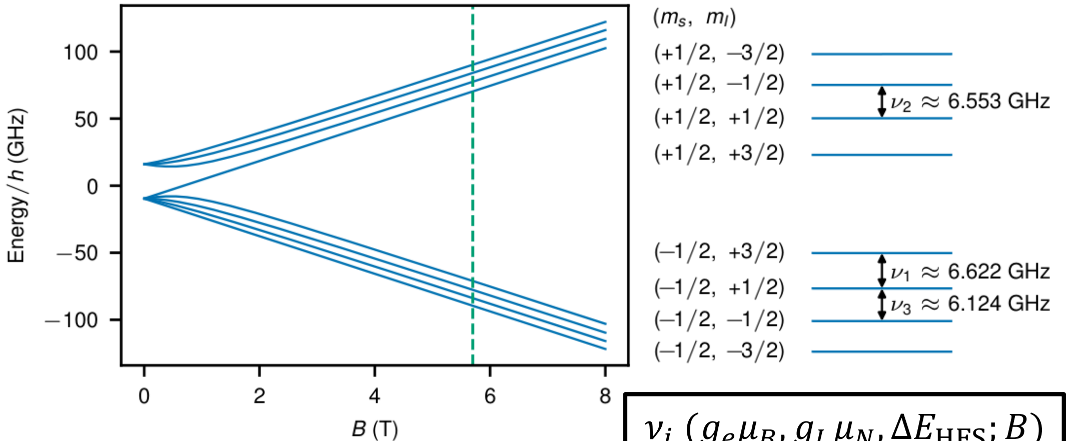
[S. Dickopf, (2024)]

$^{9}Be^{3+}$ campaign

- many transitions (nuclear spin $I = 3/2$)

extract:

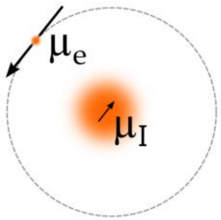
- ΔE_{HFS} zero-field hyperfine-splitting
- mass
- g_I' shielded nuclear magnetic moment
- test diamagnetic shielding by comparing $^{9}Be^{3+}$ and $^{9}Be^{+}$ [N. Shiga et al., Phys. Rev. A 84, 012510 (2011)]
- Test of HFS by specific difference (canceling nuclear structure effects): $\Delta\nu_{HFS} = \nu_{\mathrm{HFS,1+}} - \xi\nu_{HFS,3+}$



$\nu_i\ (g_e\mu_B, g_I\,\mu_N, \Delta E_{\mathrm{HFS}}; B)$

Orbiting electrons reduce the magnetic moment

$$g_I \rightarrow g'_I = g_I(1-\sigma)$$

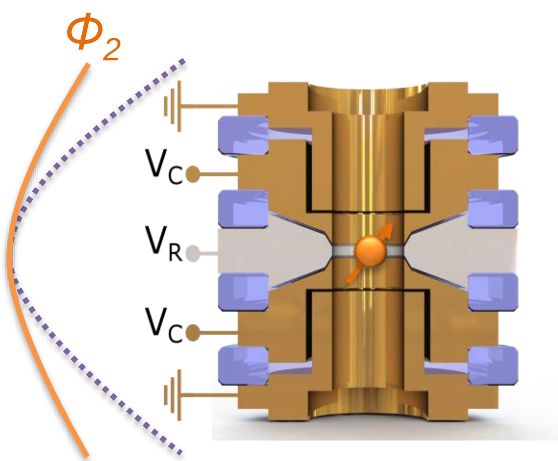


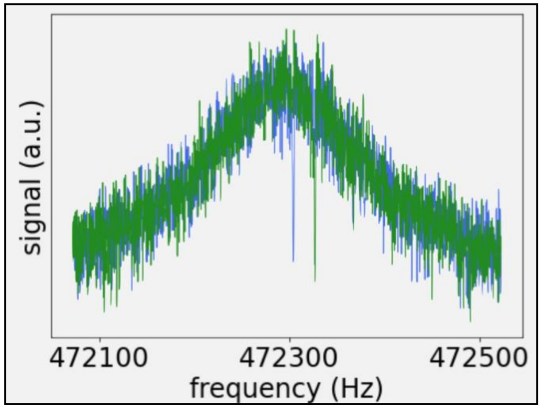
[S. Dickopf, (2024)]

Future: direct determination of nuclear spin-flips

how to resolve $\Delta\nu_{z,I}$ for nuclear spin-flips?

1. eliminate noise sources (like voltage fluctuations)
2. cool the ion to low motional amplitudes





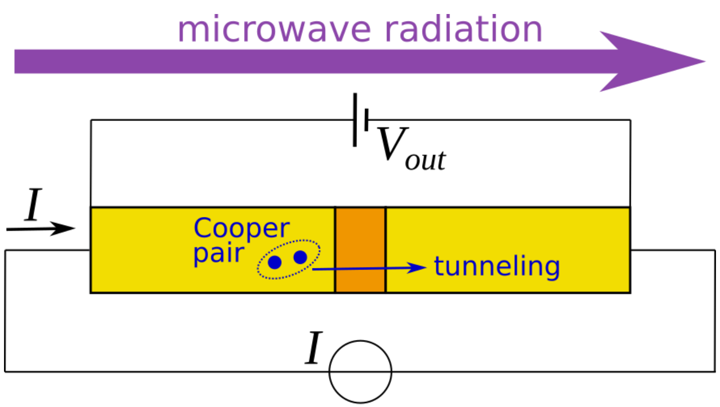
$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m}2\boldsymbol{V_R}C_2}$$

$$\rightarrow \frac{\sigma_{\nu_z}}{\nu_z} = \frac{1}{2}\frac{\sigma_{V_R}}{V_R}$$

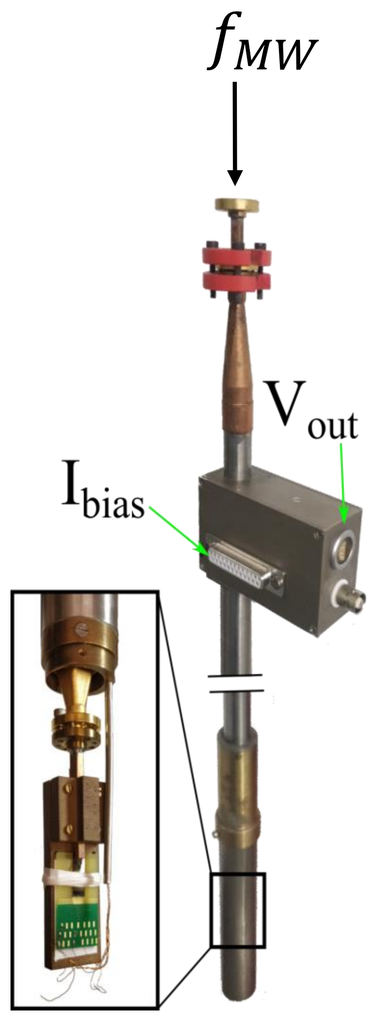
$\Delta\nu_{z,I}(^1H^+) \approx 100\text{mHz}$ → 80nV/V_0 to detect a spin flip with a fidelity of 80%
$\Delta\nu_{z,I}\ (^3He^{2+}) \approx 25\text{mHz}$ → 20nV/V_0

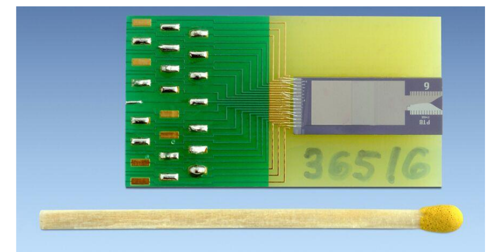
Use most stable voltage source – a JVS

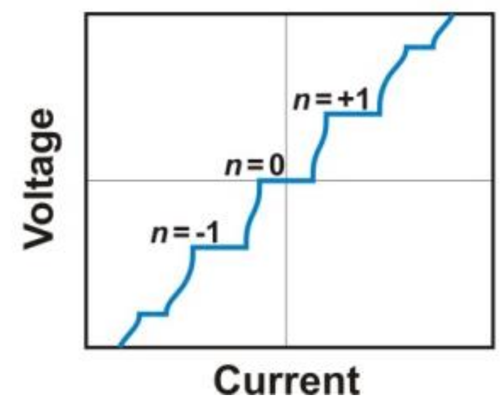
collaboration with PTB and PENTATRAP



superconductor
normal conductor







$$V \propto n\, M\, f_{MW}$$

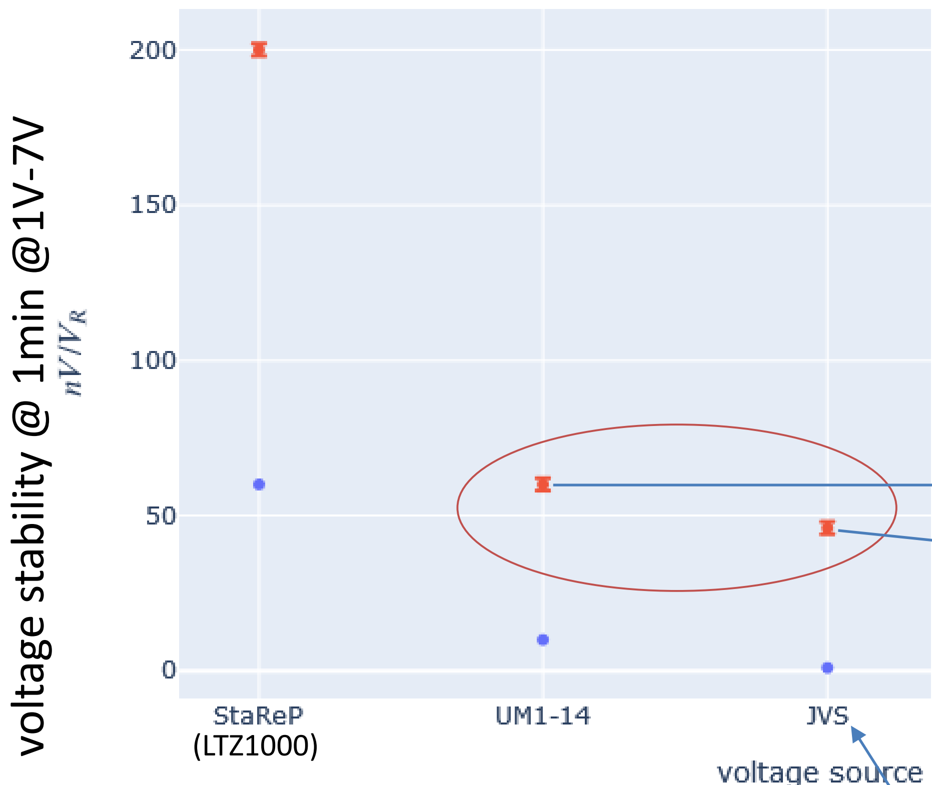
f_{MW} = 69-75 GHz
$n = \pm 1$
$M = 10^3$ junctions in series

[DOI: 10.5772/17031]

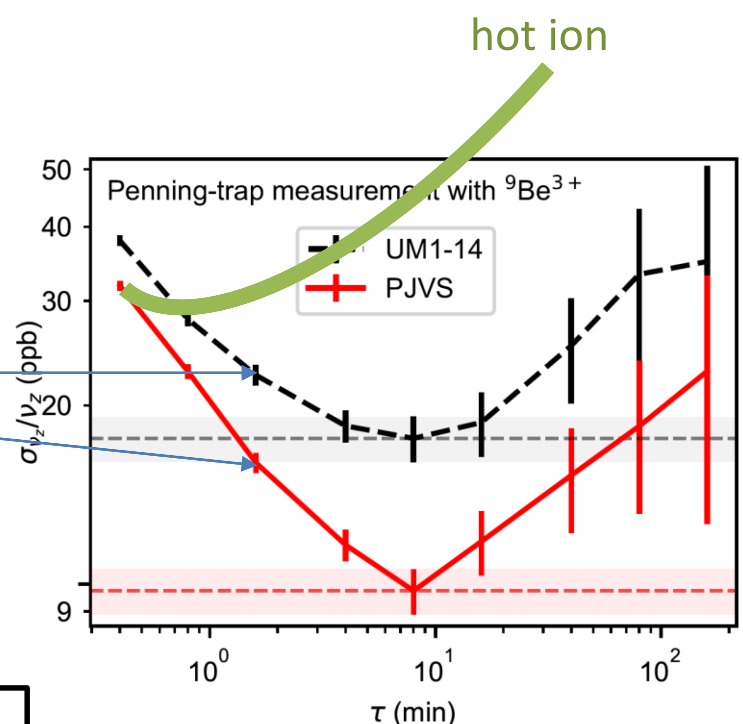
measured on nanovoltmeter

measured on trapped ion via $\nu_z \propto \sqrt{V_R}$

this was done for an extremely cold ion ($T_+ \simeq 2.2\ K$)!



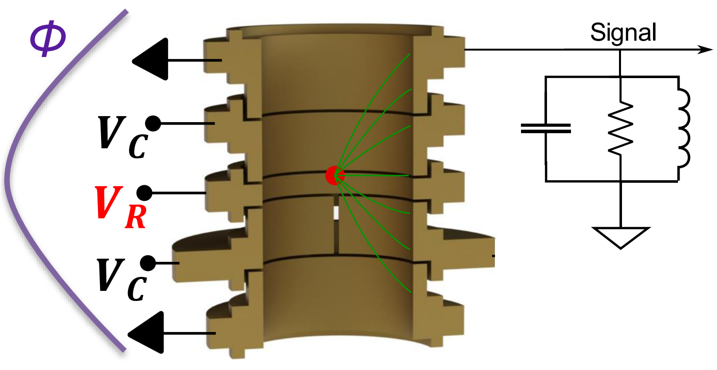
most stable voltage source



[https://www.stahl-electronics.com/devices]
[https://doi.org/10.1016/j.nima.2016.05.044]

[A. Kaiser, submitted (2024)]

Limitations



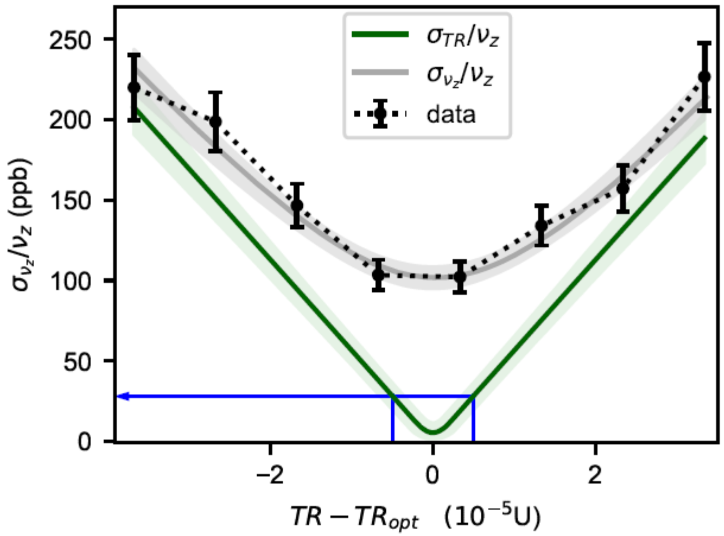
$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{q}{m}2V_R C_2}$$

potential $\Phi = V_0(1 + C_2 z^2 + C_4 z^4 + \ ...)$

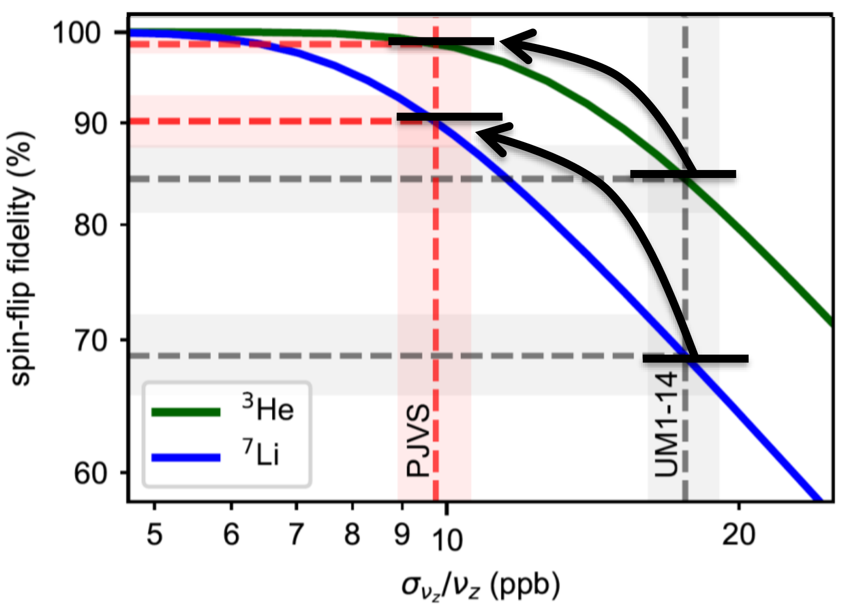
$$\nu_z \propto \frac{C_4}{C_2}\ r_z^2$$

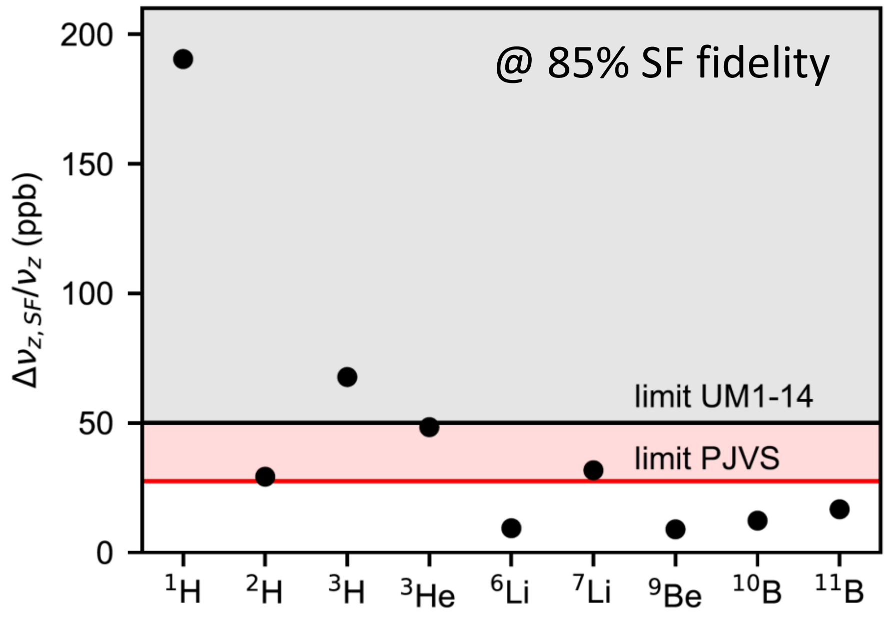
noise source	UM1-14 (ppb)	PJVS (ppb)
trap anharmonicity	28(8)	28(8)
voltage fluctuations on ring electrode	16.6(2.2)	2.2 (2.2)
readout jitter and thermal radius distribution	10.5(2.0)	10.5(2.0)
measured shot-to-shot noise	37.9(7)	31.8(6)

also relevant: cyclotron energy



nuclear spin-flip measurements with the JVS:



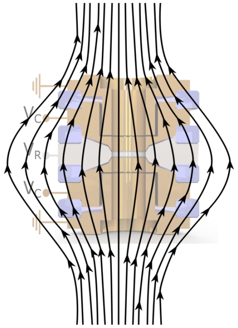


- ✓ observe spin-flips (of light ions)
- ✓ able to measure $\nu_L \propto g\nu_c$

Future: direct determination of nuclear spin-flips

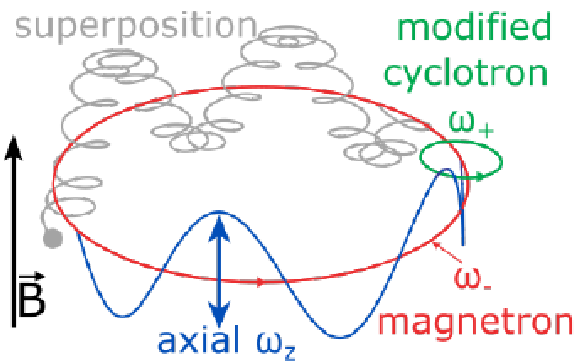
how to resolve $\Delta\nu_{z,I}$ for nuclear spin-flips?

1. eliminate noise sources (like voltage fluctuations)
2. cool the ion to low motional amplitudes

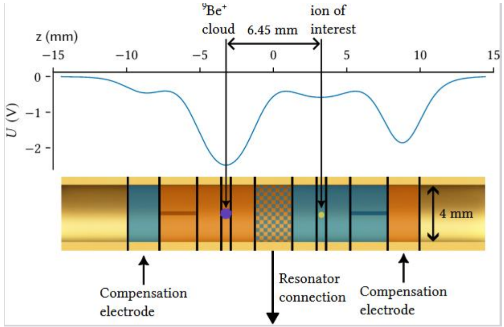


$$B_z = B_0 + B_2 z^2$$

$$\rightarrow \Delta\nu_{z,SF} = \frac{B_2}{2\pi^2 m\nu_z}\left(g\mu_{B/N} I\right) + \frac{B_2}{4\pi^2 m\nu_z}\left(\frac{\Delta E_+(T_+)}{B_0}\right)$$



→ cyclotron quantum jumps mimick spin-flips
→ sympathetic laser cooling



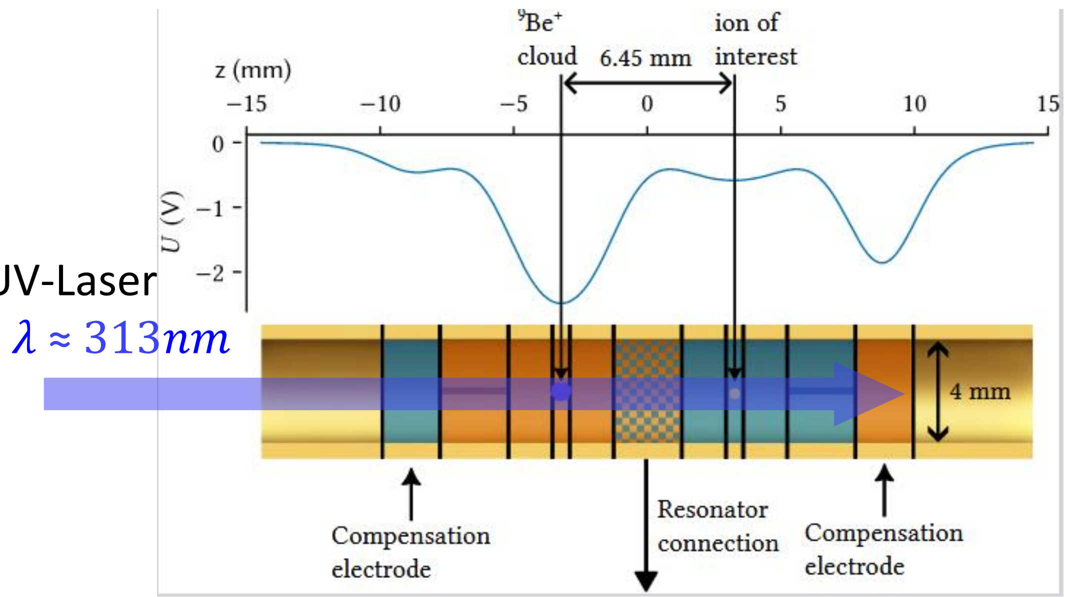
Typical values:

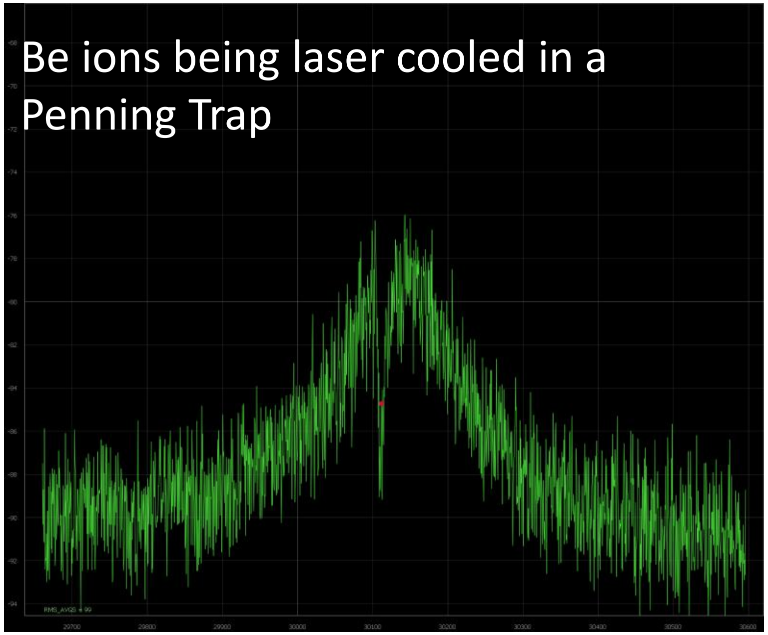
$\nu_+ = 30\ \mathrm{MHz}$
$\nu_z = 500\ \mathrm{kHz}$
$\nu_- = 5\ \mathrm{kHz}$

[S. Dickopf, (2024)]

sympathetic laser cooling

- use $^9Be^+$ cloud (easy to laser cool)
- cool ion of interest via Coulomb coupling
  [thesis S. Dickopf, 2024]





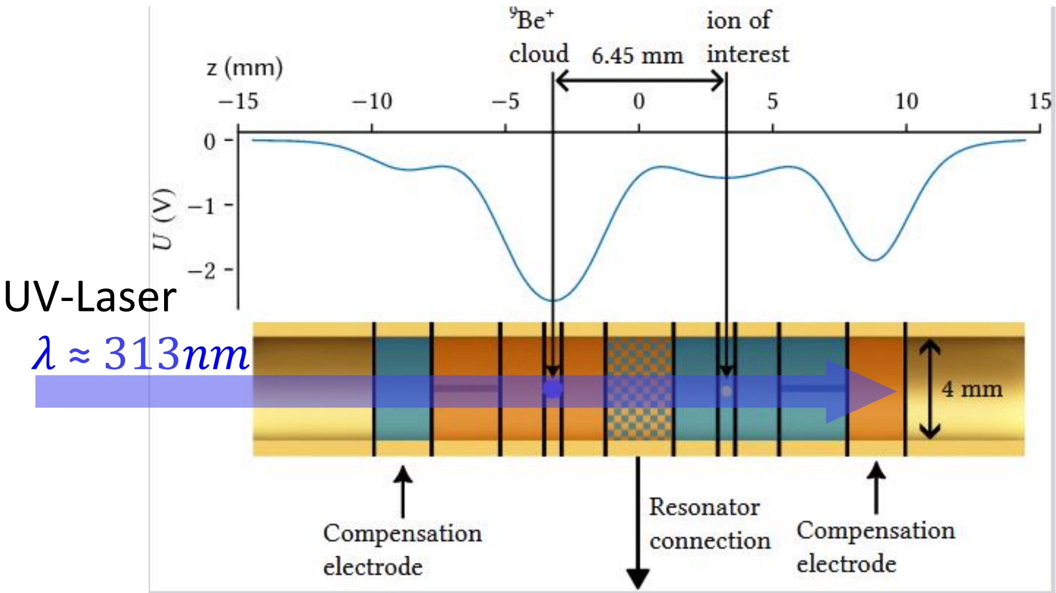
$f_{transition}$ = 957. 316 75 THz (σ^-)

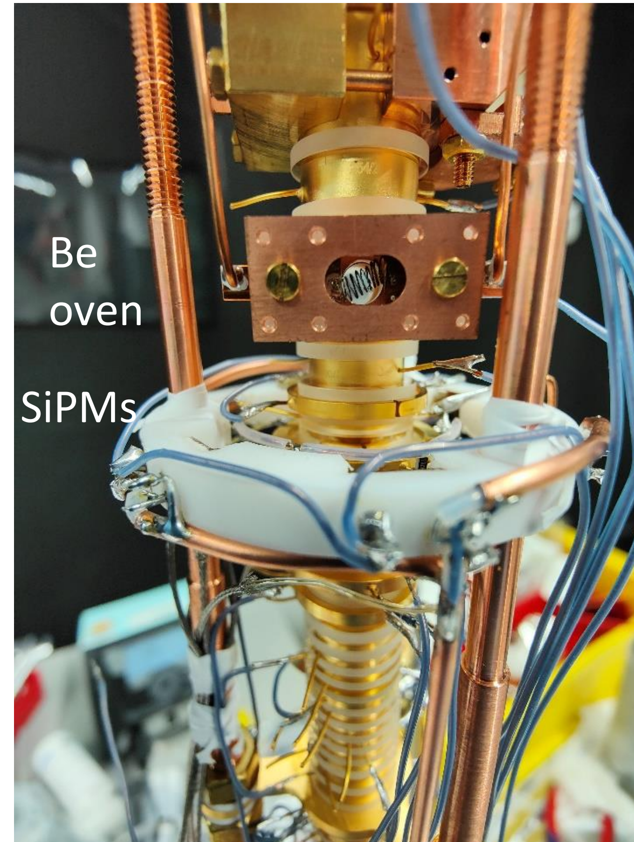
[S. Dickopf, (2024)]

sympathetic laser cooling

- use $^9Be^+$ cloud (easy to laser cool)
- cool ion of interest via Coulomb coupling

[thesis S. Dickopf, 2024]





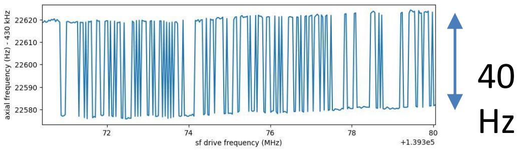

[S. Dickopf, (2024)]

- what is next? testing new coupling traps, fluorescence detection, sympathetic cooling of ion of interest

SUMMARY

$^4He^+$ and $^9Be^{3+}$

- extract most precise electron mass

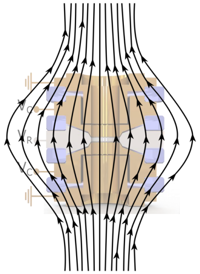


- probe diamagnetic shielding
- test HFS via specific difference

$$\Delta\nu_{HFS} = \nu_{\mathrm{HFS},1+} - \xi\nu_{HFS,3+}$$

difficulties with nuclear spin-flip observations

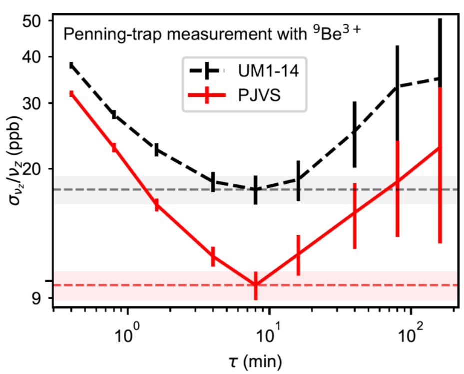
use magnetic bottle to get spin-state dependent frequency:

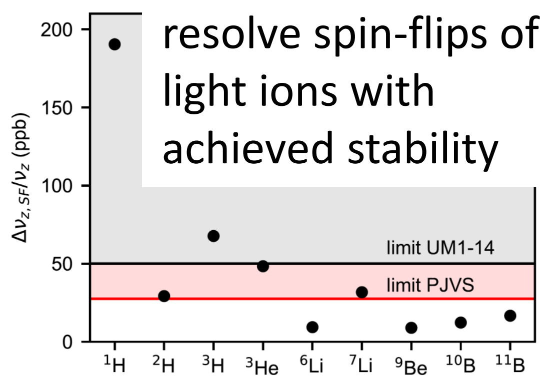


$$\rightarrow \Delta\nu_{z,SF} = \frac{B_2}{2\pi^2 m\nu_z}\left(g\mu_{B/N}I + \frac{\Delta E_+}{2B_0}\right)$$

$$\rightarrow \frac{\sigma_{\nu_z}}{\nu_z} = \frac{1}{2}\frac{\sigma_{V_R}}{V_R} \qquad \rightarrow \frac{\sigma_{V_R}}{V_R} < 2\cdot 10^{-8}$$

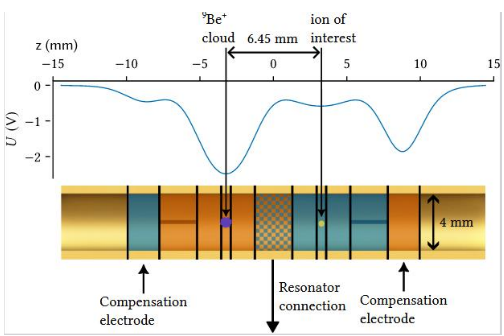
use most stable voltage source for V_R:
Josephson voltage standard





resolve spin-flips of light ions with achieved stability

sympathetic laser cooling with ^9Be
→ more to come, stay tuned ☺



Thank you for your attention!

Klaus Blaum

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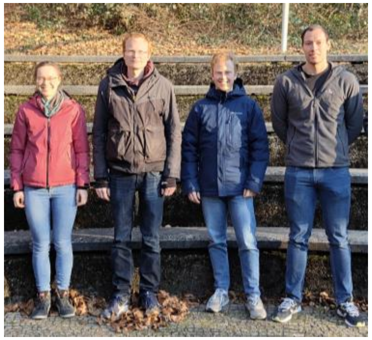
- Marius Müller
- Ute Beutel
- Andreas Mooser



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- Luis Palafox

RIKEN:
- Stefan Ulmer

IMPRS for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

typical g-factor resonance (3He):

Direct measurement of the $^3He^+$ magnetic moments

https://doi.org/10.1038/s41586-022-04761-7
Received: 1 March 2021

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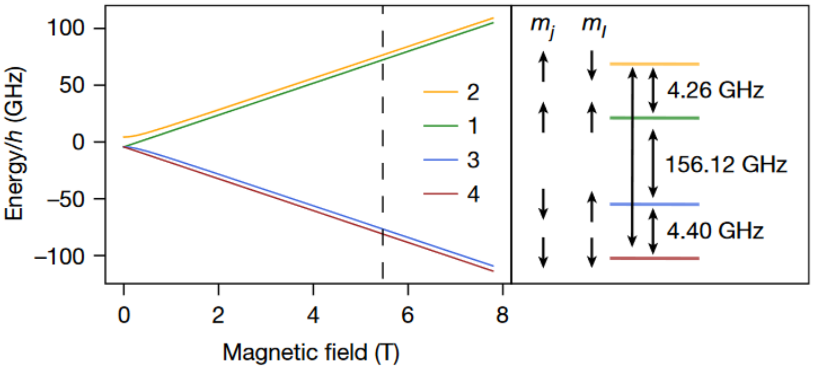
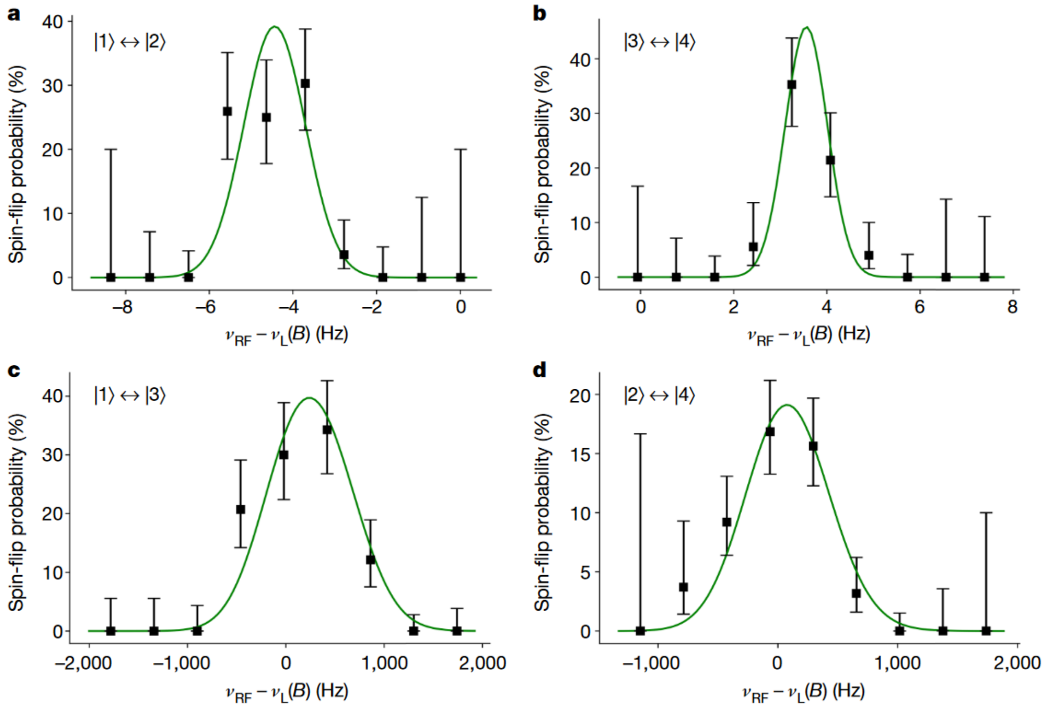
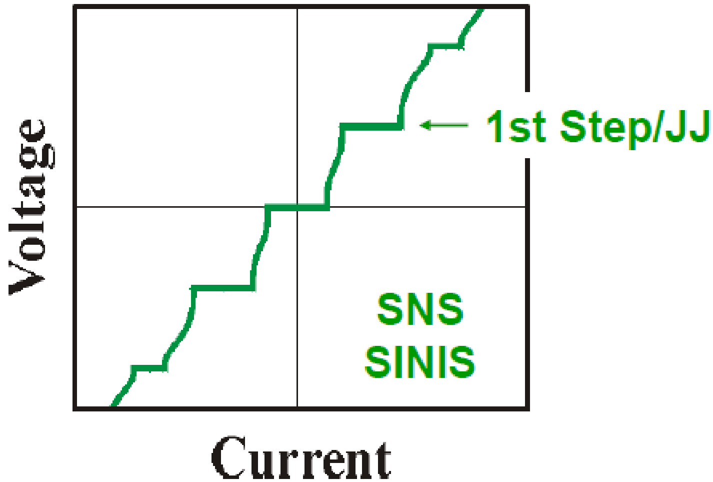
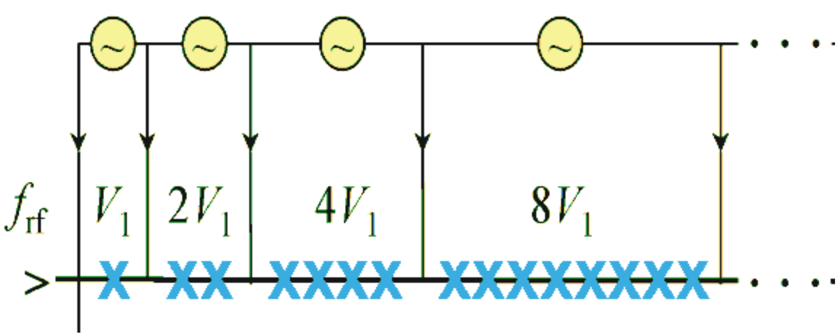


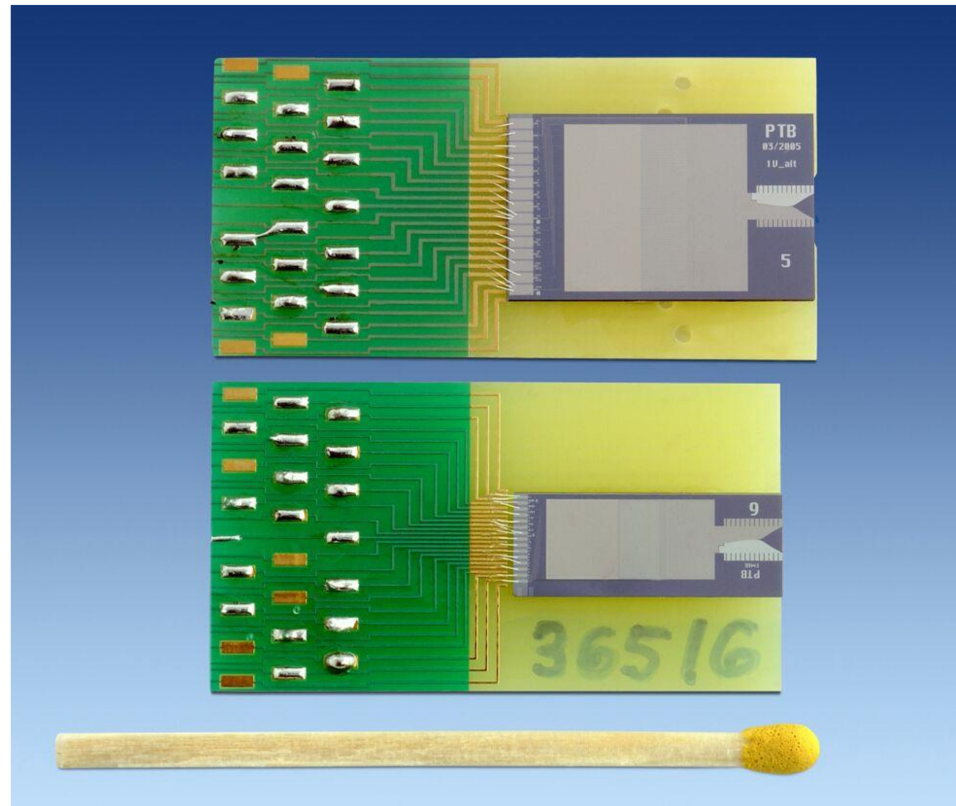


Josephson Array as programmable voltage reference



≈ 70 000 JJ @ 70 GHz





Taken from talk by Luis Palafox (PTB) @ MPIK 2020