Recent results @ $\vec{\mu}$TEx

Annabelle Kaiser[a], Stefan Dickopf[a], Anton Gramberg[a], Philipp Justus[a], Ankush Kaushik[a], Marius Müller[a], Stefan Ulmer[b,c], Bastian Sikora[a], Vladimir A. Yerokhin[a], Zoltan Harman[a], Christoph H. Keitel[a], Andreas Mooser[a] und Klaus Blaum[a]

a - Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, Heidelberg, Germany

b - RIKEN, Ulmer Fundamental Symmetries Laboratory, 2-1 Hirosawa, Wako, Saitama, Japan

c - Institute for Experimental Physics, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany

PSAS Zürich, 10.06.2024 11:20-11:45

MAX-PLANCK-GESELLSCHAFT

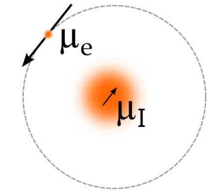
RIKEN

TC FS

hhu Heinrich Heine Universität Düsseldorf

Max-Planck-Institut für Kernphysik

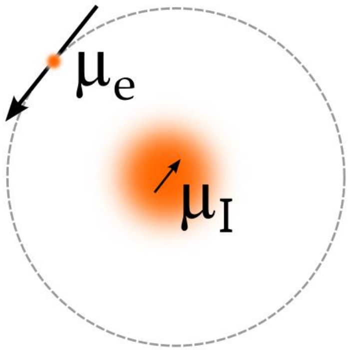
$\vec{\mu}$TEx = magnetic moment ($\vec{\mu}$) Trap Experiment



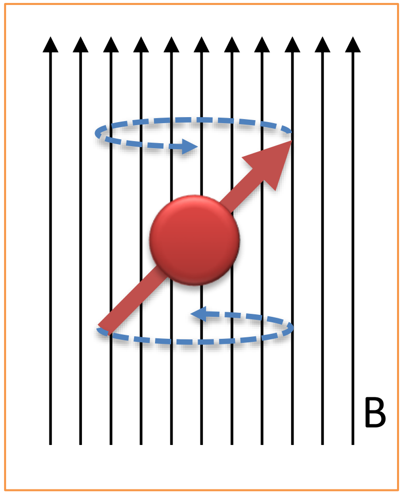
Max-Planck-Institute for Nuclear Physics

Content:

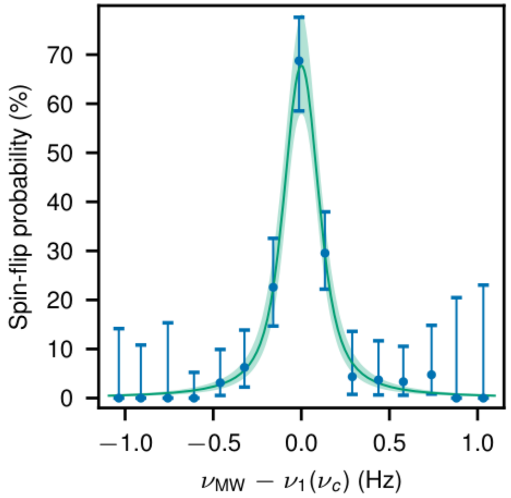
1. Ground-state Zeeman + hyperfine splittings



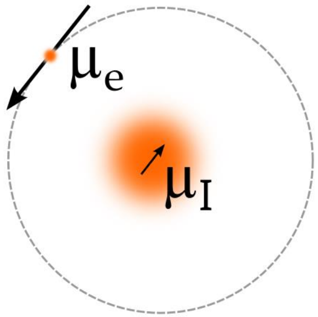
2. measurement principle



3. helium-3 campaign
beryllium-9 campaign
helium-4 campaign



Ground-state Zeeman/hyperfine splitting measurements (in a Penning trap)



14 GHz/Th

7.6 MHz/Th

$$H = -g_e\, \mu_B \boldsymbol{S}\cdot\boldsymbol{B} - g_I \mu_N \boldsymbol{I}\cdot\boldsymbol{B} - \Delta E_{\mathrm{HFS}} \boldsymbol{S}\cdot\boldsymbol{I}$$

$$\mu_B = \frac{e\hbar}{2m_e}$$

$$\mu_N = \frac{e\hbar}{2m_p}$$

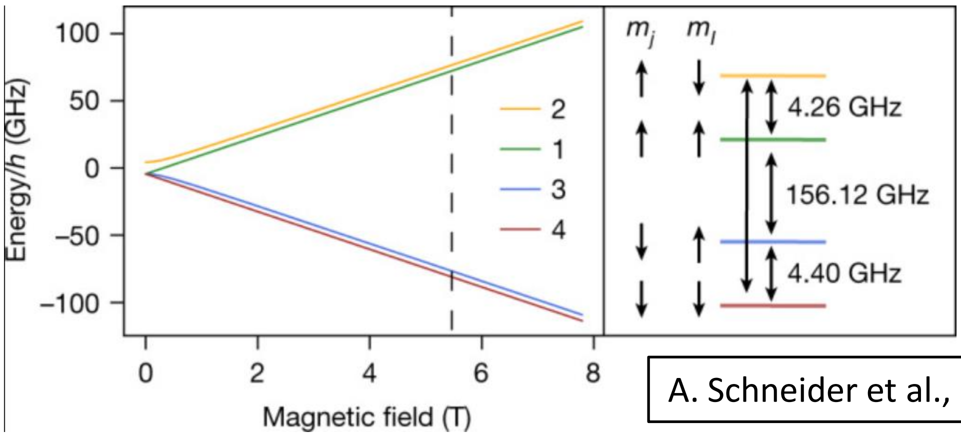
Transition frequencies $\nu_{ij}\ (g_e\mu_B, g_I\,\mu_N, \Delta E_{\mathrm{HFS}}; B)$

$\boldsymbol{g_e}$ – **Bound electron *g*-factor**

$\boldsymbol{g_I}$ – **Shielded nuclear *g*-factor**

$\boldsymbol{\Delta E_{HFS}}$ – **Zero field hyperfine-splitting**

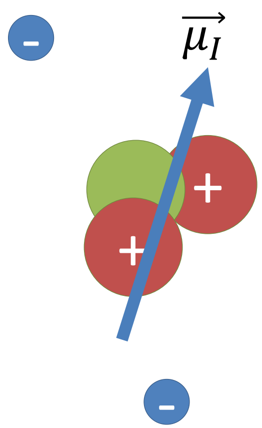
Ground-state Zeeman structure $^3He^+$



results @µTEx:

A. Schneider et al., Nature **606**, 878–883 (2022) → NMR probe

The diamagnetic shielding of nuclear magnetic moments



Orbiting electrons effectively reduce the magnetic moment

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

The transfer of magnetic moments from one charge state to another requires accurate theoretical calculations of shielding parameters!

Example

$$g'_I(^3\mathrm{He}^+) = -4.2550996069(35)$$

A. Schneider et al., Nature **606**, 878–883 (2022)

However, $g_I(^3\mathrm{He})$ is needed for accurate NMR magnetometry

$\sigma(^3\mathrm{He}^+) = 35.507427(10)$ ppm
$\sigma(^3\mathrm{He}) = 59.966512(24)$ ppm

M. Farooq et al, Phys. Rev. Lett. 124, 223001 (2020)

K. Pachucki, PRA. 108, 062806 (2023)

Currently no sufficiently accurate experimental test of shielding available…

Ideal candidate: ^{9}Be

$^9\mathbf{Be}^+$ magnetic moments and HFS via laser-microwave double resonance

N. Shiga et al., Phys. Rev. A 84, 012510 (2011)

- Shielding and HFS
- Extract $g_I(^9Be^{4+})$ with 30 ppb
- Calculation of E_{HFS} limited at ~ 500 kHz due to nuclear structure

K. Pachucki, M. Puchalski, Opt. Commun. 283, 5 (2010)

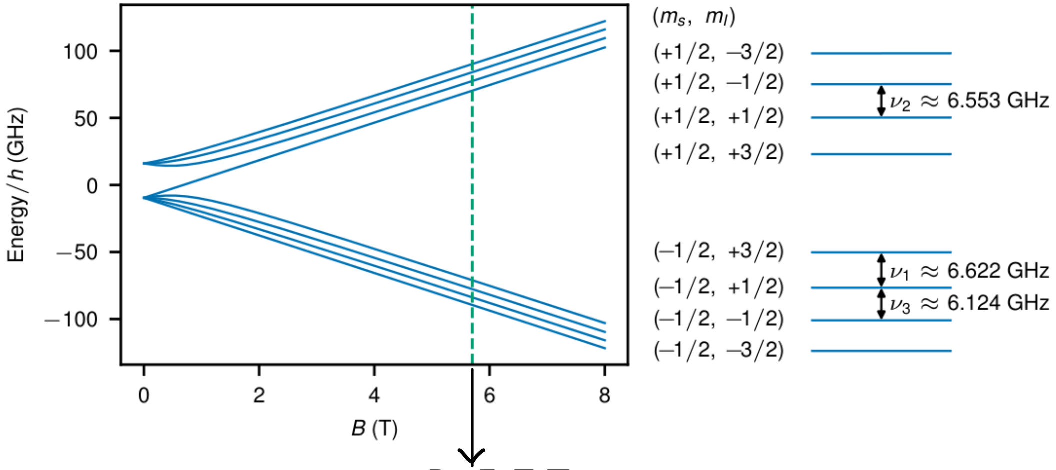
M. Puchalski et al., Phys. Rev. A 89, 032510 (2014)

$^9\mathbf{Be}^{3+}$ measurement @ $\vec{\mu}$TEx

- Measure ν_i transitions and extract

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

- Test of shielding via nuclear magnetic moments
- Test of HFS by specific difference



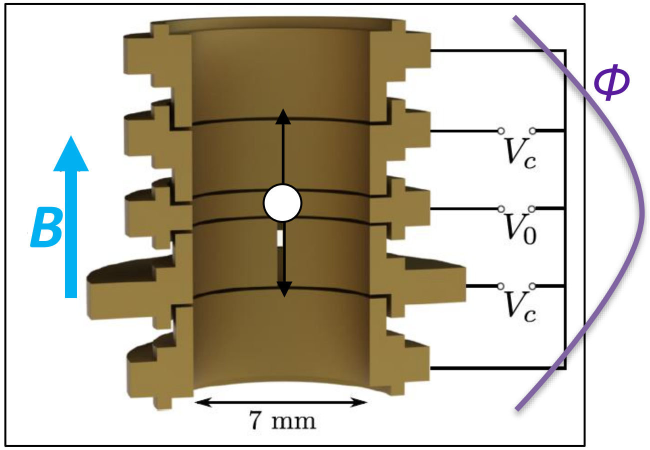
B=5.7 T

~140-160 GHz e$^-$ spin transitions

Penning trap measurements with single ions

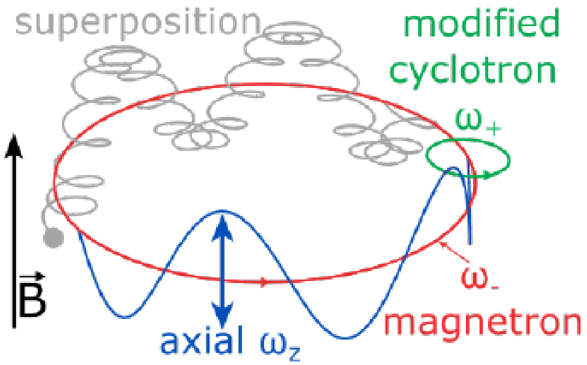
Radial confinement: $\boldsymbol{B} = B_0 \boldsymbol{e}_z$

Axial confinement: $\Phi(\rho, z) = V_0 C_2 (z^2 - \frac{\rho^2}{2})$



$$\nu_z = \sqrt{2 V_0 C_2 q/m}$$

$$\boldsymbol{\nu_c} = \sqrt{\nu_+^2 + \nu_-^2 + \nu_z^2} = \frac{1}{2\pi} \frac{q}{m} \boldsymbol{B}$$



Typical values:

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

Single-shot precision: $\sigma(\nu_c)$ ~50ppt
Measure all eigenfrequencies with image current detection method (10^{-9}) or phase sensitive method ($5\mathrm{x}10^{-11}$)

Penning trap spin-state detection

Magnetic bottle inside separate analysis trap:

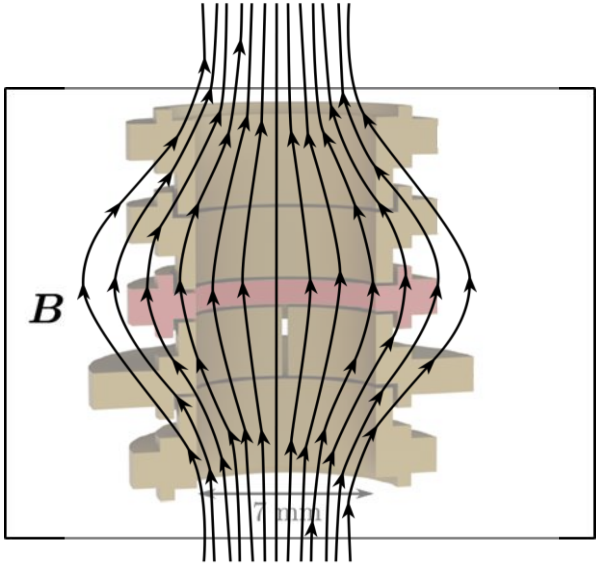
$$B_z = B_0 + B_2 z^2 \rightarrow \Delta\Phi(z) = -2\frac{B_2}{m}\mu_i z^2$$

→ Spin-state i dependent axial frequency

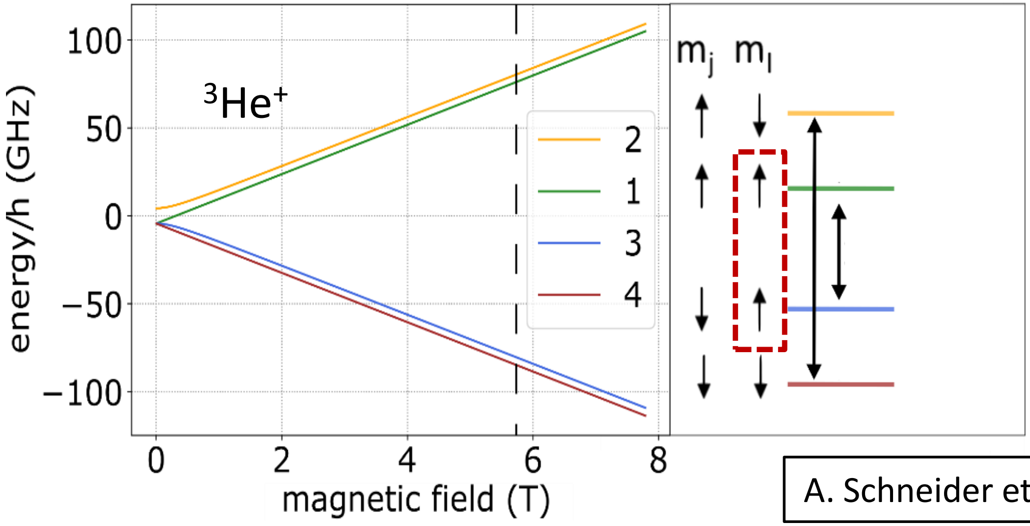
$\Delta\nu_{z,e} \approx 11\ \mathrm{Hz}$

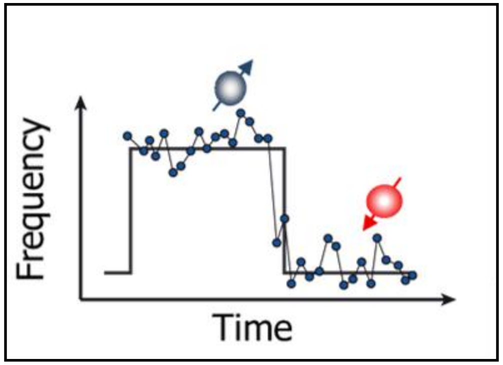
$\Delta\nu_{z,I} \approx 100\mathrm{mHz} \ll \nu_z$ fluctuations

→ Use electronic probe transitions to identify spin-state



Ferromagnetic ring electrode



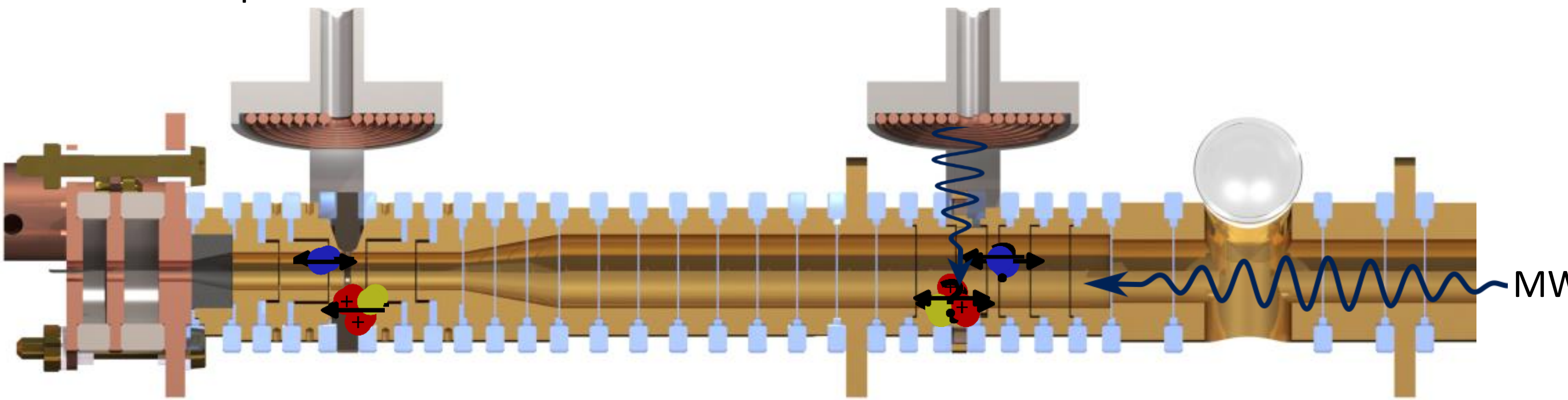


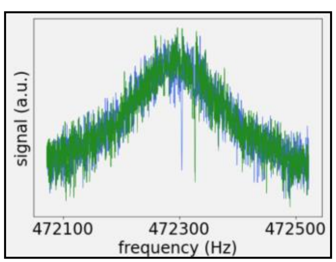
A. Schneider et al., Nature **606**, 878–883 (2022)

Measurement scheme

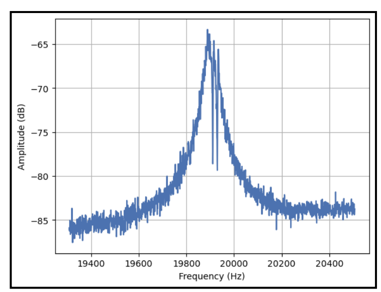
Analysis trap:
-spin state determination

Precision trap:
- measure eigenfrequencies, determine *B*
- drive nuclear spin transition

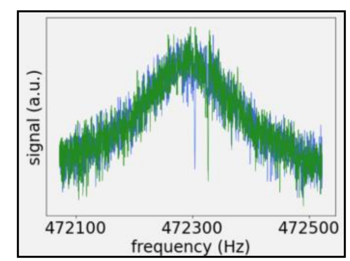




1. Spin-state determination in AT

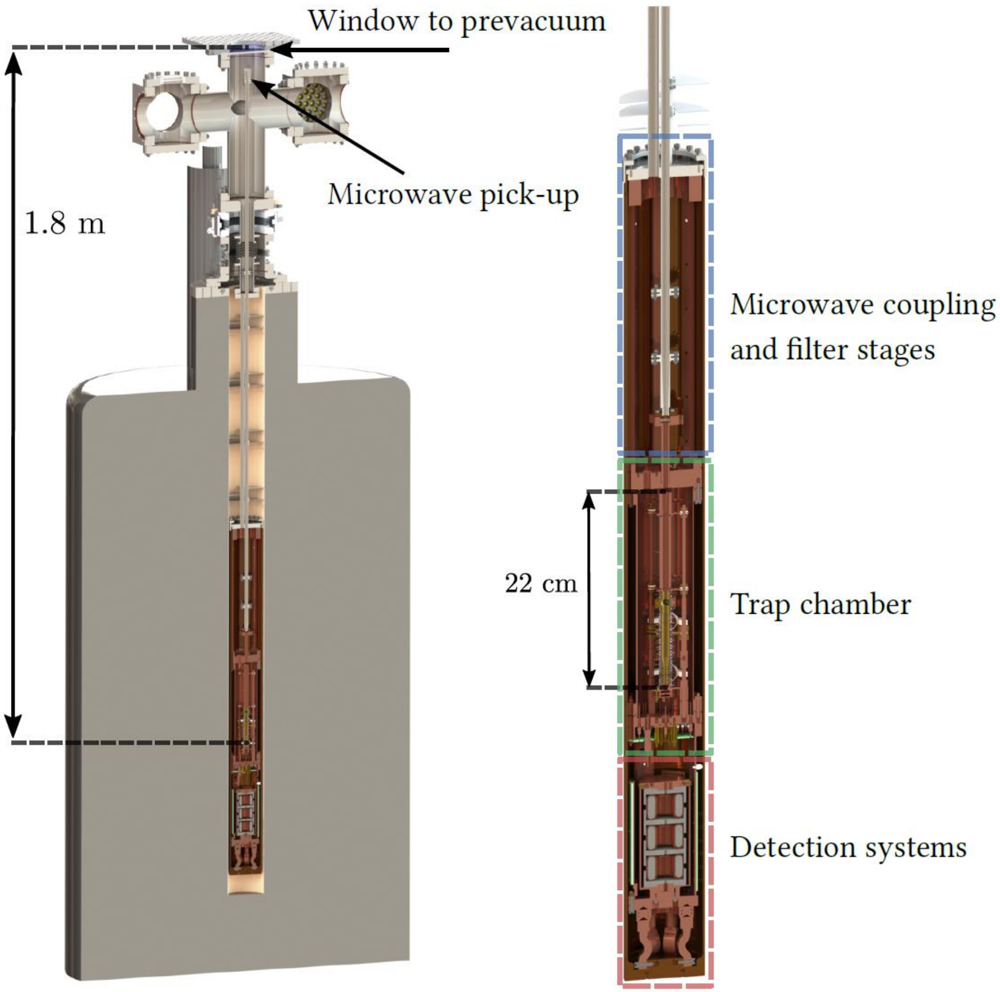


2. ν_c measurement and SF drive



3. Spin-state determination in AT

Experimental setup



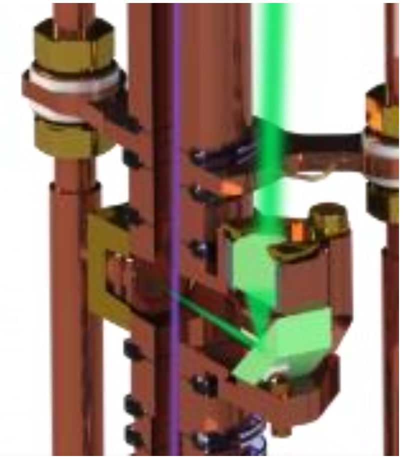
- Non-destructive detection of eigenfrequencies at 4 K
- MW with 140-170 GHz
- Nuclear transition can be driven at MHz-12 GHz
- Laser access
- Optical detection in progress
- Loading single ions (in-trap)
- Ionization up to 7+
- Magnetic field extremely stable
  dB/B/h = 3(2)ppt/h
  and 100ppt shot-to-shot
  [S. Dickopf, thesis 2024]
- ultra-high vacuum,
  ion lifetimes > 1y

Experimental upgrades for $^{9}Be^{3+}$

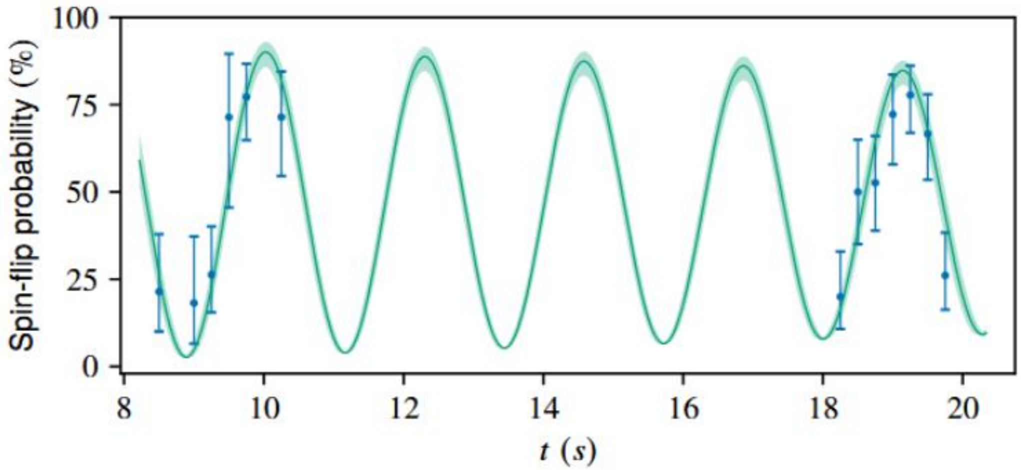
Production of $^{9}Be^{3+}$ ions

- In-trap Laser ablation produces $^{9}Be^{+}$
- Subsequent ionization by electron beam
- Can be used for other targets

U. Beutel, Bachelor thesis (2024)

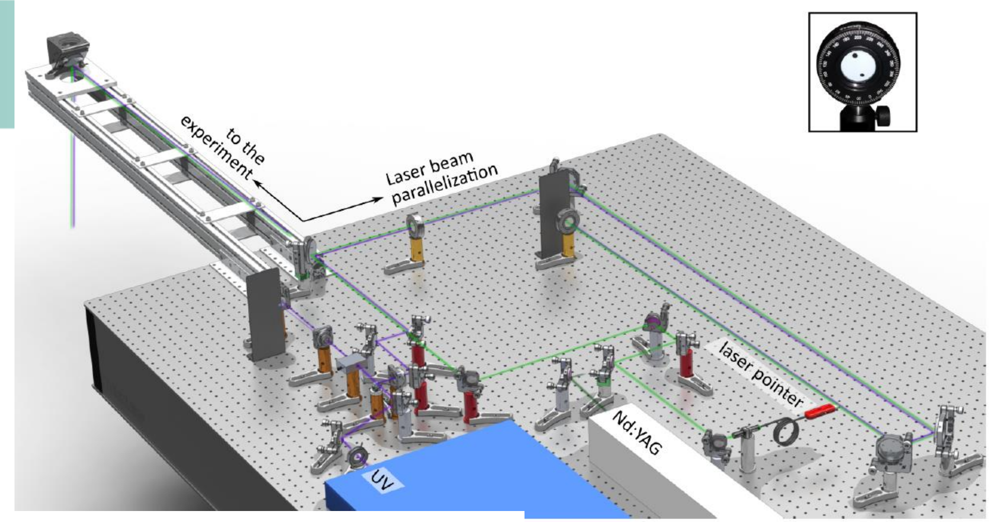


Coherent drive of nuclear transitions



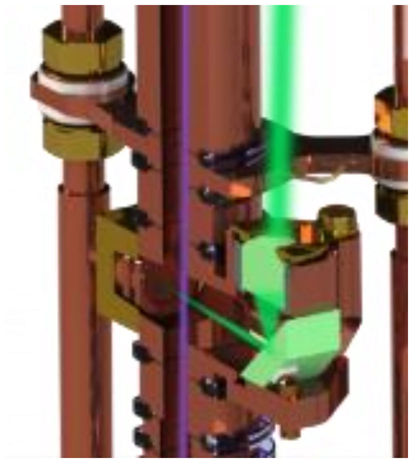
S. Dickopf et al., submitted (2024)

Experimental upgrades for $^9Be^{3+}$



Production of $^9Be^{3+}$ ions

- In-trap Laser ablation produces $^9Be^+$
- Subsequent ionization by electron beam
- Can be used for other targets

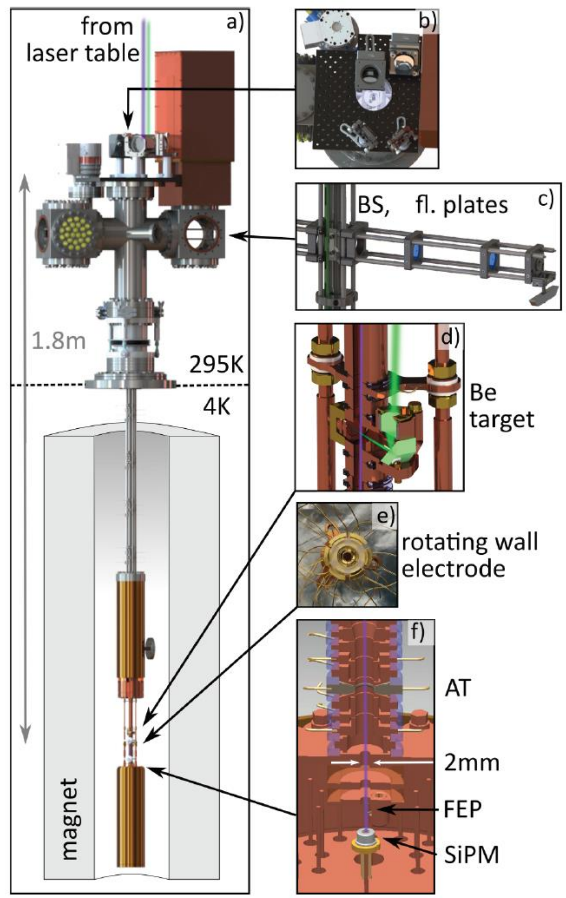


Coherent drive of nuclear transitions

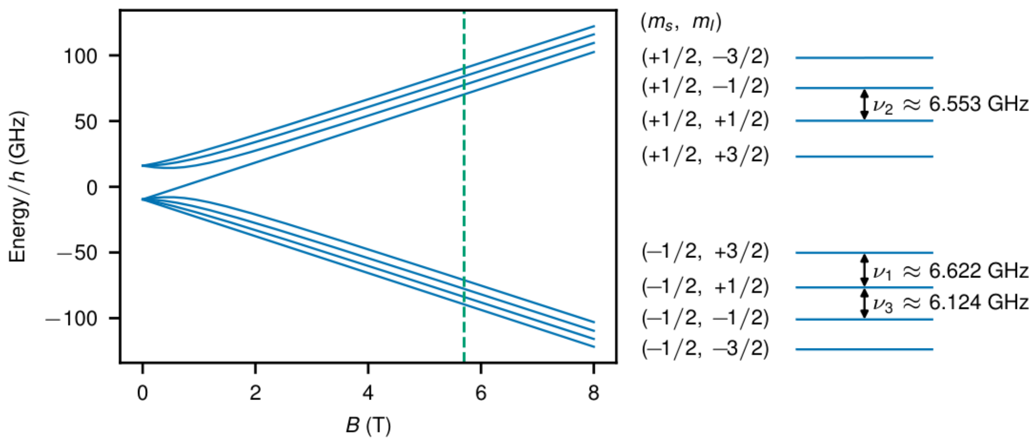
7-pole Penning trap for compensation of higher order electrostatic field inhomogeneities

UV laser incoupling for laser cooling $^9Be^+$

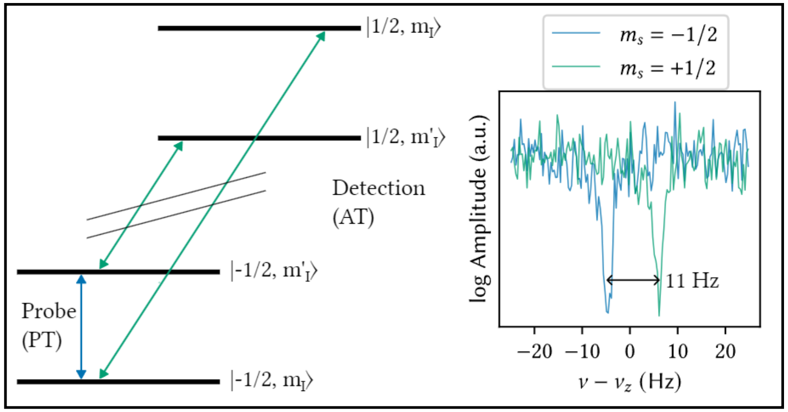
Magnetic shielding coils

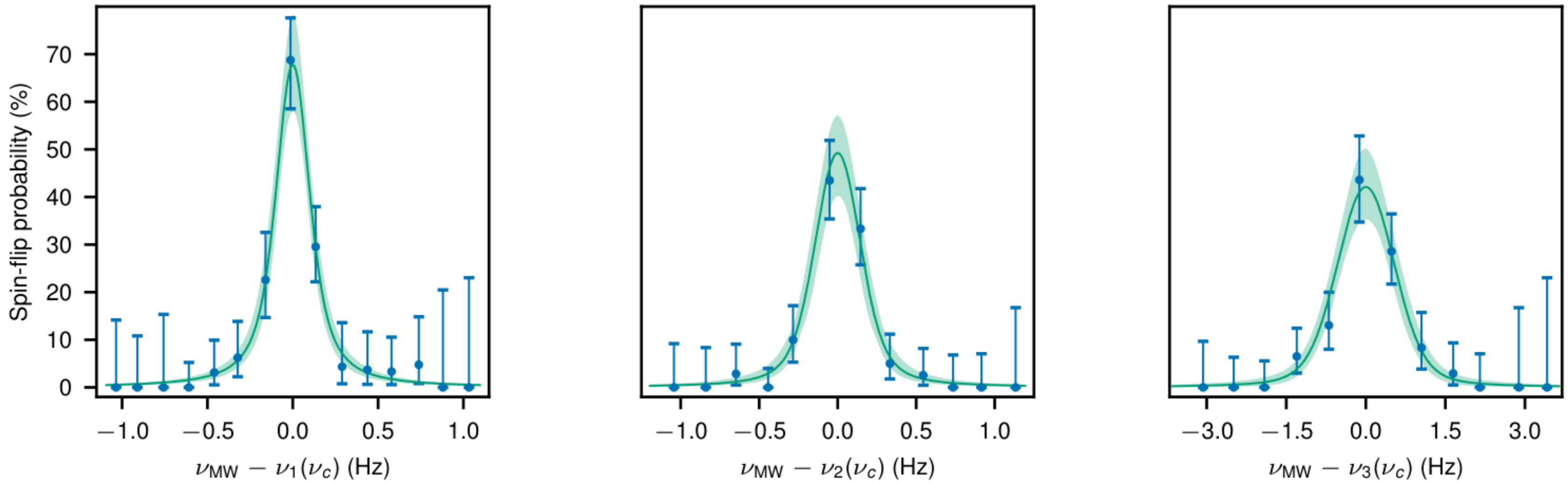


Measurement of nuclear transitions



Detection via electron spin transitions





S. Dickopf *et al.*, submitted (2024)

Systematics budget

$$\Gamma_e(^9\mathrm{Be}^{3+}) = \frac{g_e(^9\mathrm{Be}^{3+})}{2}\frac{e}{q}\frac{m(^9\mathrm{Be}^{3+})}{m_e}, \qquad \Gamma_I(^9\mathrm{Be}^{3+}) = \frac{g_I(^9\mathrm{Be}^{3+})}{g_e(^9\mathrm{Be}^{3+})}\frac{m_e}{m_p}$$

$$\nu_{MW} - \nu_i(\nu_c|\Gamma_e, \Gamma_I, \nu_{HFS}) = 0, \qquad i = \{1,2,3\}$$

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

	Γ_e	Γ_I	ν_{HFS}
Statistical result	−5479.86334[redacted](11)	2.13547538[redacted](11)x10^{-4}	−12796971342.5[redacted](50) Hz
Systematic shifts	/10^{-7}	/10^{-14}	/mHz
Field imperfections	−1(< 1)	0(< 1)	0(< 1)
Relativistic	0(< 1)	0(1)	50(3)
Image charge	−5(< 1)	-	-
Dip	0(19)	-	-
Time reference	0(1)	0(3)	0(15)
Quadrupole moment	−5(< 1)	−15(< 1)	11(< 1)
Total shifts	−11(19)	−15(3)	61(15)
Corrected result	−5479.86334[redacted](22)	2.13547538[redacted](11)x10^{-4}	−12796971342.6[redacted](52) Hz
Fractional uncertainty	0.39 ppb	0.54 ppb	4.0 ppt

Simultaneous extraction requires careful treatment of correlations/covariances!

S. Dickopf et al., submitted (2024)

Results derived from the nuclear transitions

$$\Gamma_e(^9\mathrm{Be}^{3+}) = \frac{g_s(^9\mathrm{Be}^{3+})}{2}\frac{e}{q}\frac{m(^9\mathrm{Be}^{3+})}{m_e}, \qquad \Gamma_\mathrm{I}(^9\mathrm{Be}^{3+}) = \frac{g_I(^9\mathrm{Be}^{3+})}{g_s(^9\mathrm{Be}^{3+})}\frac{m_\mathrm{e}}{m_p}$$

$$E_{HFS}(^9\mathrm{Be}^{3+}) = \mathrm{E_F}(\mathrm{A_{1S}} - 2\alpha Z\, r_Z + \delta_{\mathrm{recoil},1S} + \delta_{\mathrm{QED},1S})$$

	Accepted value	**Our value**
$\boldsymbol{g_I(^9\mathrm{Be}^{4+})}$	$-0.784\,954\,39(2)_{theo}$	$-0.784\,954\,422\,xx(45)_{exp}(11)_{theo}$
$\boldsymbol{r_Z}$	$4.03(5)\mathrm{fm}$	$4.04x(2)$ fm
$\boldsymbol{m(^9\mathrm{Be})}$	$9.012\,183\,06(8)\mathrm{u}$	$9.012\,183\,03xx(35)\mathrm{u}$

Profit from improved theory for hydrogen-like ions to gain orders of magnitude in precision

S. Dickopf et al., submitted (2024)

Direct comparison with $^{9}Be^{1+}$ cancels nuclear structure

Test of shielding

$$1-\sigma(^{9}\mathrm{Be}^{1+}) = (1-\sigma(^{9}\mathrm{Be}^{3+}))\frac{\Gamma_I(^{9}\mathrm{Be}^{1+})}{\Gamma_I(^{9}\mathrm{Be}^{3+})}\frac{g_s(^{9}\mathrm{Be}^{1+})}{g_s(^{9}\mathrm{Be}^{3+})}$$

Our work: $\sigma(^{9}\mathrm{Be}^{1+}) = 141.8xxx(12)(10)\cdot 10^{-6}$

Theory: $\sigma(^{9}\mathrm{Be}^{1+}) = 141.85(3)\cdot 10^{-6}$

First high-precision test of multi-electron shielding

Specific difference of zero-field splitting

$$E_{HFS}(^{9}\mathrm{Be}^{3+}) = \mathrm{E}_{\mathrm{F,1S}}(\mathrm{A}_{1\mathrm{S}} - 2\alpha Z\, r_Z + \delta_{\mathrm{recoil},1S} + \delta_{\mathrm{QED},1S})$$

$$E_{HFS}(^{9}\mathrm{Be}^{+}) = \mathrm{E}_{\mathrm{F,2S}}(\mathrm{A}_{2\mathrm{S}} - 2\alpha Z\, r_Z + \delta_{\mathrm{recoil},2S} + \delta_{\mathrm{QED},2S})$$

Directly cancel nuclear structure contributions

$$\Delta\nu_{HFS} = \nu_{HFS}(^{9}\mathrm{Be}^{+}) - \xi\nu_{HFS}(^{9}\mathrm{Be}^{3+})$$

Our work: $\Delta\nu_{HFS} = -274.xxxxxx(12)$ kHz
Theory : $\Delta\nu_{HFS} = -271.x(3.6)$ kHz

Complementary to $^{209}Bi^{80/82+}$

High Z: Fully relativistic l.o. with expansion of electron-correlation and h.o. effects

Low Z: Fully correlated l.o. with expansion of relativistic and h.o. effects

Next candidate: helium-4

$$\mu_B = \frac{e\hbar}{2m_e}$$

$$H = -g_e\,\mu_B \boldsymbol{S}\cdot\boldsymbol{B} - g_I\mu_N \boldsymbol{I}\cdot\boldsymbol{B} - \Delta E_{\mathrm{HFS}}\boldsymbol{S}\cdot\boldsymbol{I}$$

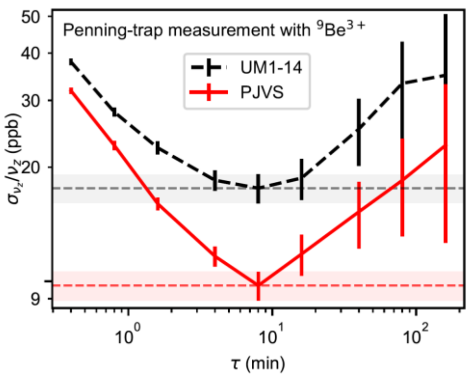
- Most precise m_e measurement reached 3×10^{-11} [1]
- Our magnet more stable
- m_e fundamental constant
- Used for the determination of the fine-structure constant α in atomic recoil experiments[2]

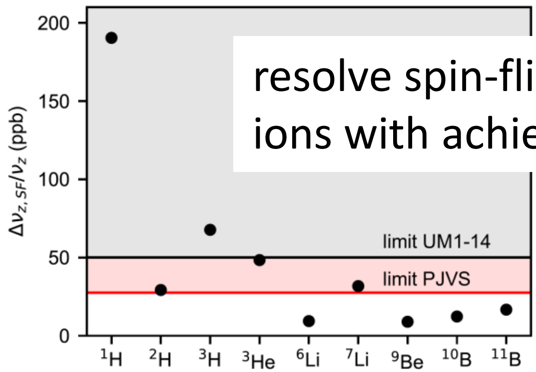
$$\alpha^2 = \frac{2R_\infty}{c}\frac{m}{m_e}\frac{h}{m}$$

[1]S. Sturm et al., Nature 506, 467 (2014), F. Köhler, PhD thesis (2015)
[2] L. Morel, et al., Nature 588, 61 (2020)

Future measurements: nuclear *g*-factor of helium-3

- Integrate Josephson voltage standard for creating the trap potential → higher axial stability

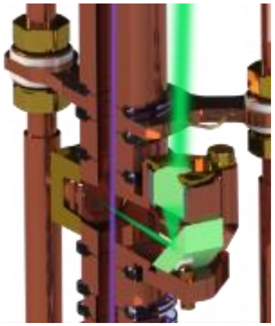


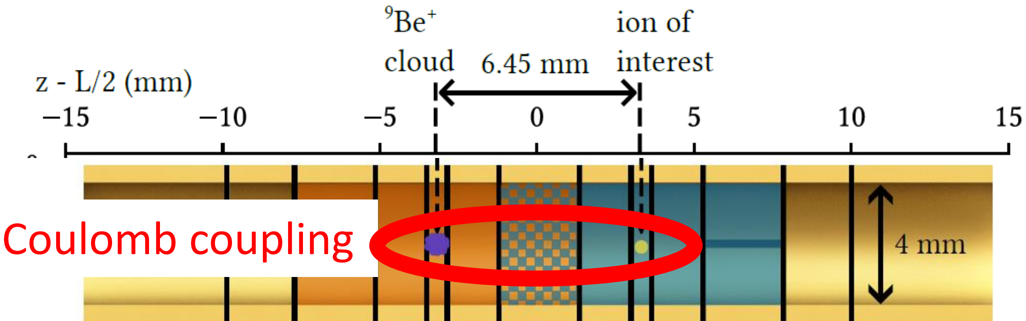


resolve spin-flips of light ions with achieved stability

A. Kaiser *et al.*, APL 124,22 (2024)

- Sympathetic laser cooling to reduce ion cyclotron energy

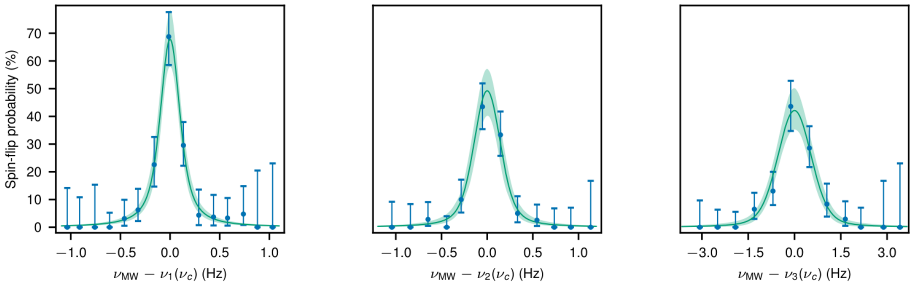




SUMMARY

Beryllium-9

measure 3 nuclear transitions of $^{9}Be^{3+}$



extract $g_I, \Delta\nu_{HFS}, g_e$

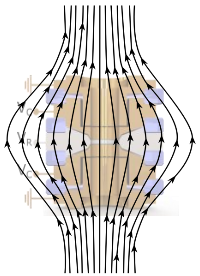
compare to $^{9}Be^{+}$ for first experimental, high precision shielding test for multiple electrons

cancel nuclear structure uncertainties with specific difference for $\Delta\nu_{HFS}$

helium-4

most stable magnet

improve precision for more stringent tests of QED



bare helium-3

implement sympathetic laser cooling scheme

implement Josephson voltage standard

Thank you!
Questions?

Thank you for your attention and thanks to all collaborators!

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

µTEx:

- Annabelle Kaiser
- Stefan Dickopf
- Marius Müller
- Andreas Mooser
- Anton Gramberg
- Ankush Kaushik
- Philipp Justus
- Klaus Blaum

PTB:

- Ralf Behr
- Luis Palafox

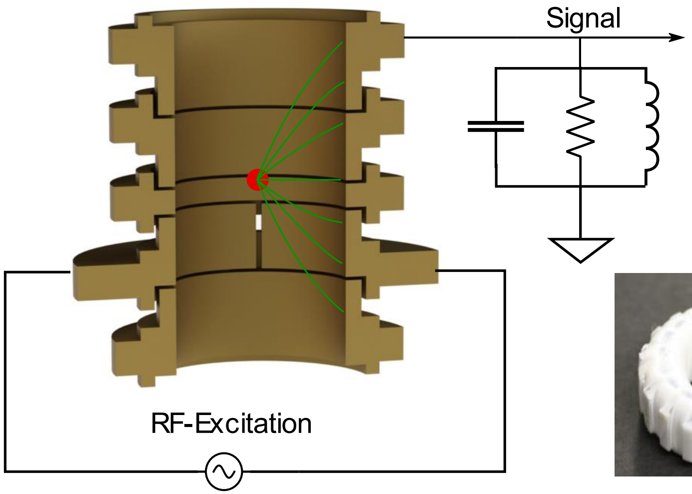
Pentatrap:

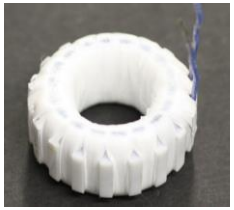
- Menno Door
- Kathrin Kromer
- Sergey Eliseev

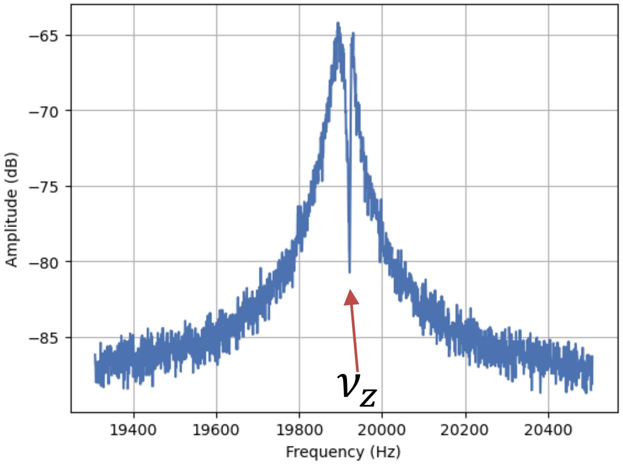
Theory:

- Bastian Sikora
- Zoltan Harman
- Vladimir A. Yerokhin
- Christoph H. Keitel

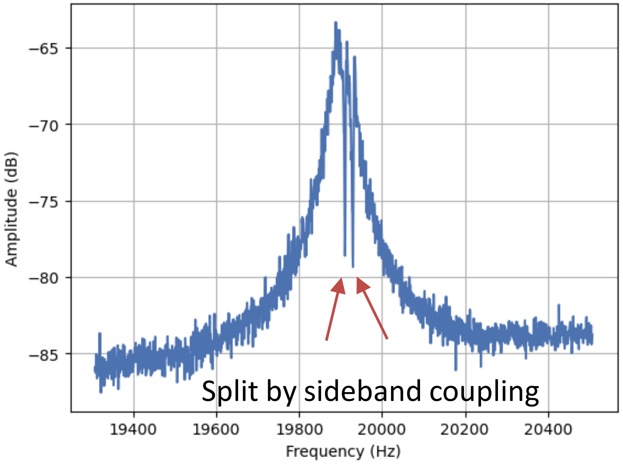
Penning trap frequency detection







Thermalised ion

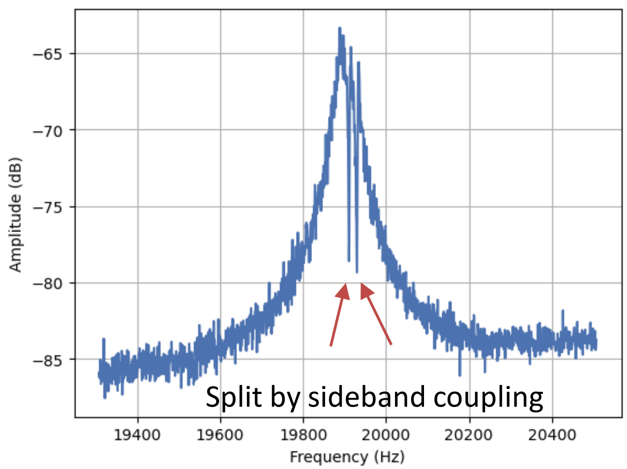


Ion thermalised with sideband drive at

$$\nu_{\mathrm{rf}} = \nu_+ - \nu_z$$

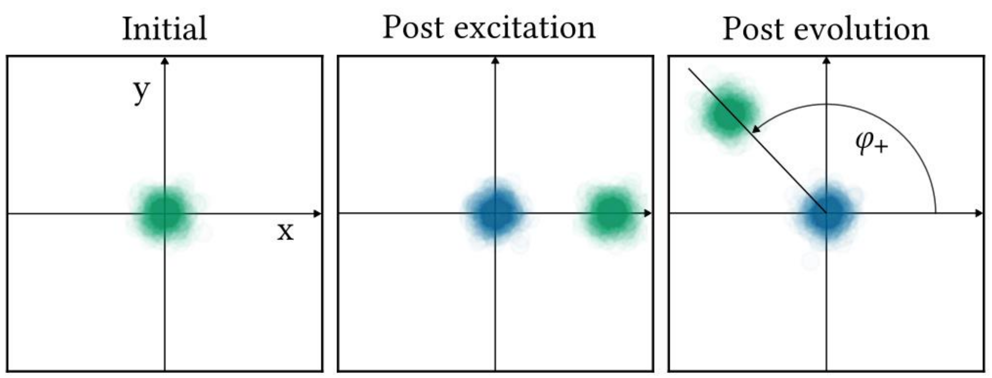
Modified cyclotron frequency detection

Thermal detection: Double dip



$$\sigma(\nu_+) \propto 1/\sqrt{T}$$

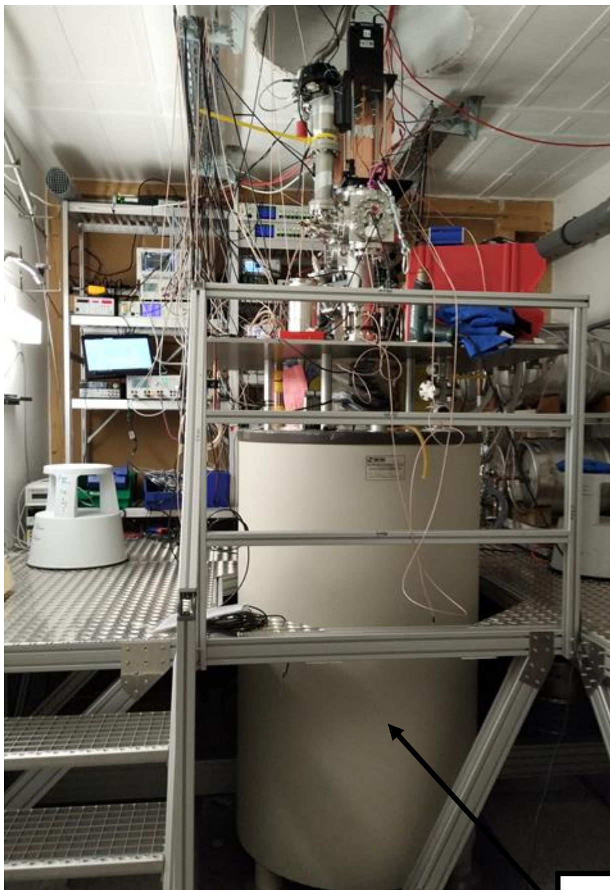
Phase-sensitive detection

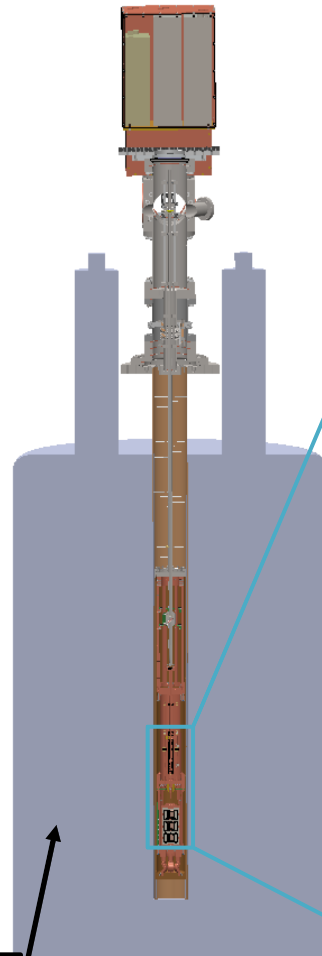


Phase space distribution for many realizations

$$\sigma(\nu_+) \propto 1/T$$

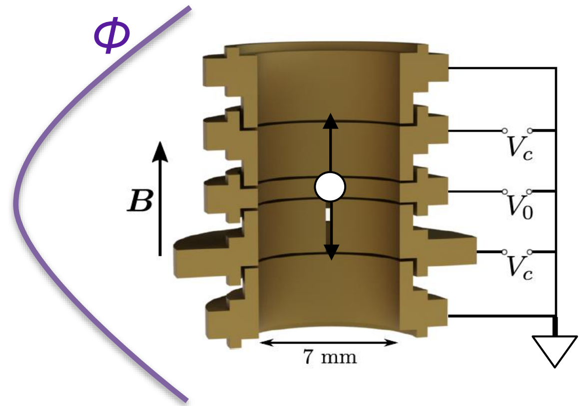
Experimental realization:





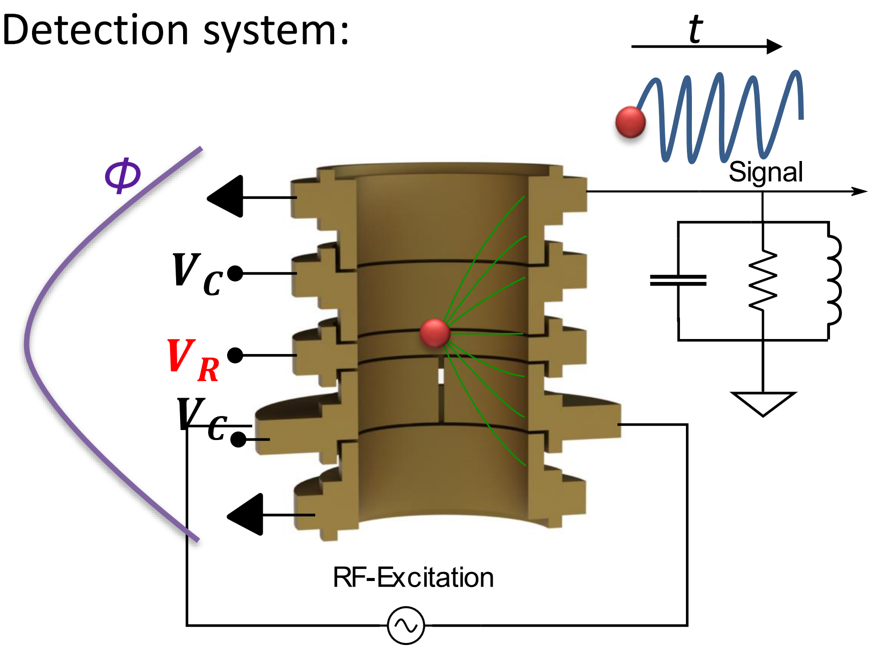
magnet

Trap tower:



Detection system:

Detection system:

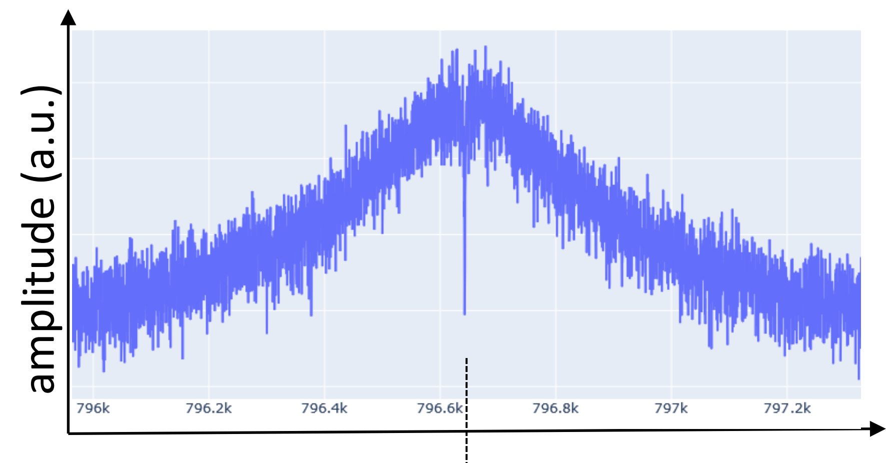


to couple and ν_z e.g. ν_+:

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

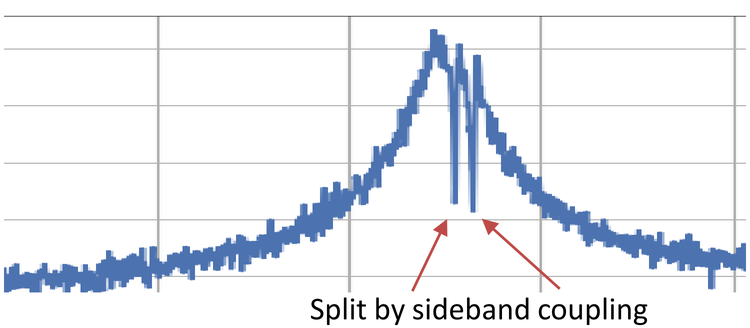
- ✓ achieved trapping
- ✓ able to measure $\nu_c \propto \frac{q}{m} B$

FFT spectrum:

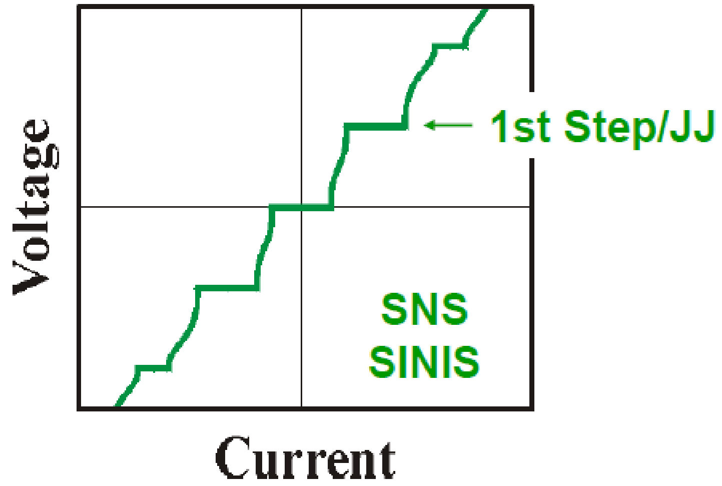


dip @ ν_z

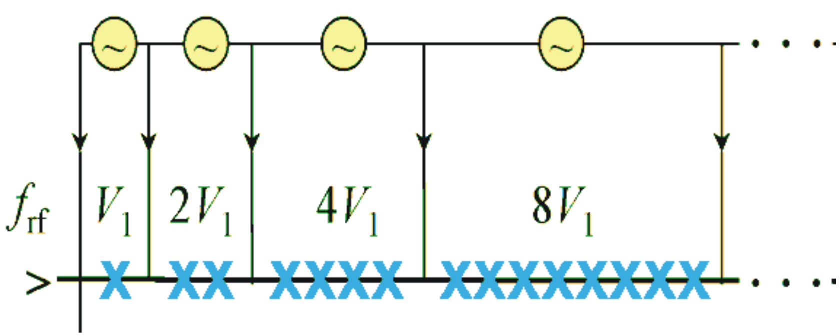
double dip:

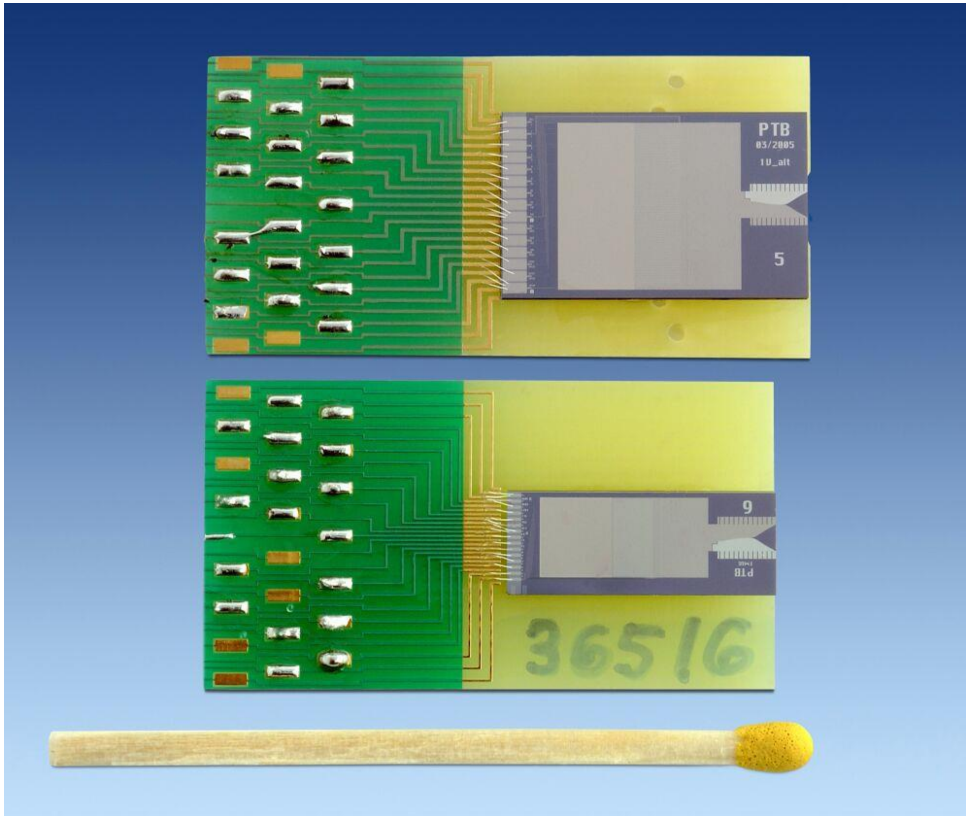


Josephson Array as programmable voltage reference



≈ 70 000 JJ @ 70 GHz





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