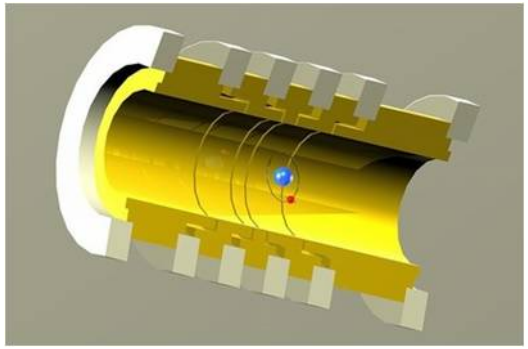
# The most stringent test of QED in strong fields: The g-factor of $^{28}Si^{13+}$



**Sven Sturm, Anke Wagner, Klaus Blaum**

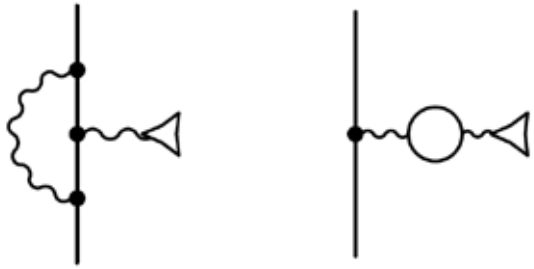
March 27th, 2012
PTB Helmholtz-Symposium

Max-Planck-Institut für Kernphysik

# *Quantum ElectroDynamics (QED)*

QED describes the quantum interaction of
***light*** (photons) and ***matter*** (charged particles)

through a series of simple fundamental interaction processes depicted by ***Feynman diagrams***

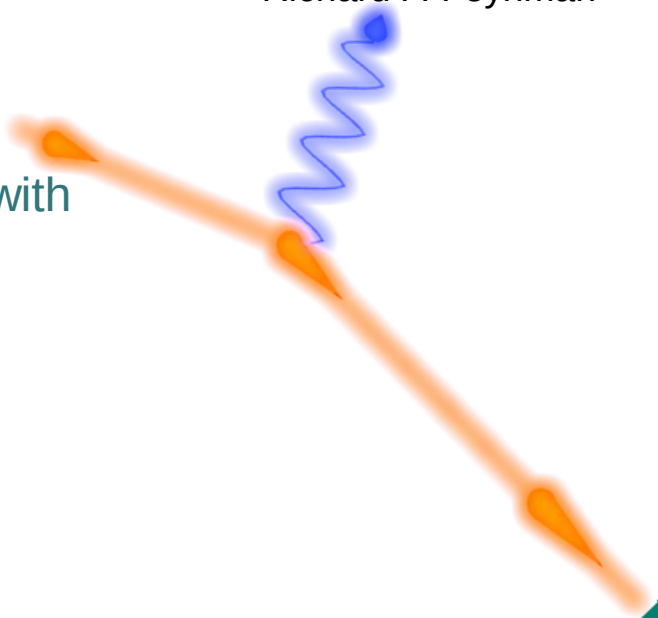


Richard P. Feynman

Calculated values are in impressive agreement with experimental results

QED is our <u>best tested</u> theory in weak fields

However: Lack of tests in extreme situations



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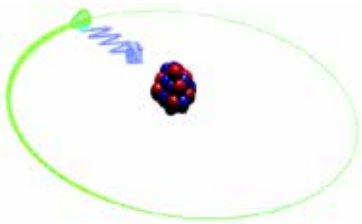
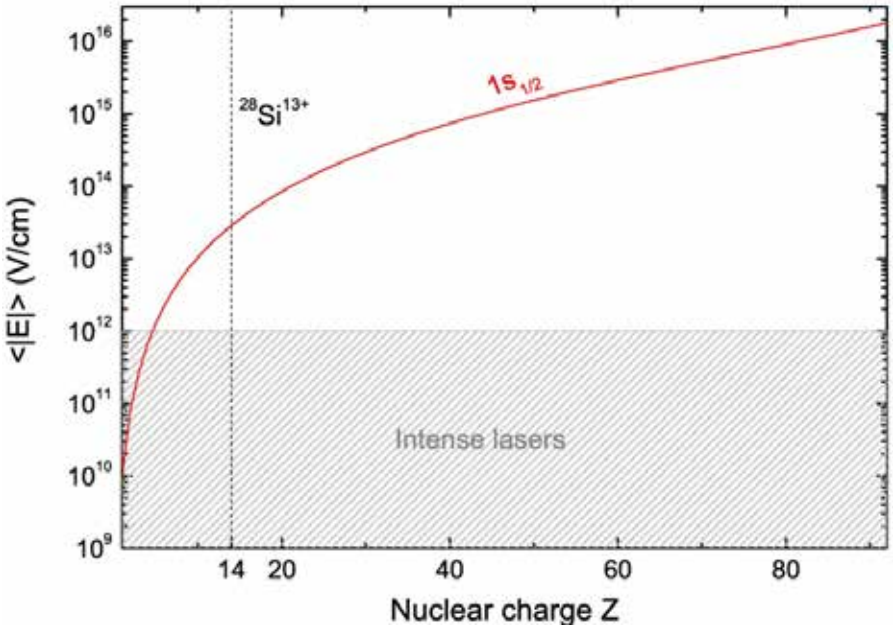
# bound state QED

How to provide ultra strong fields for a QED test ?

Highly charged ions provide strong binding fields for the remaining electron(s)

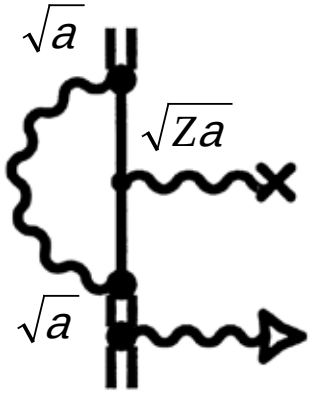





Few or single electron systems are <u>calculable</u> to very high accuracy in QED series solution

Free electron coupling ~ $\alpha^N = 0.007^N$

**BUT: Coupling to nucleus ~ $(Z\alpha)^N = 0.1^N$**

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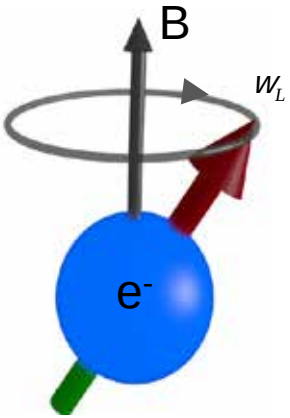
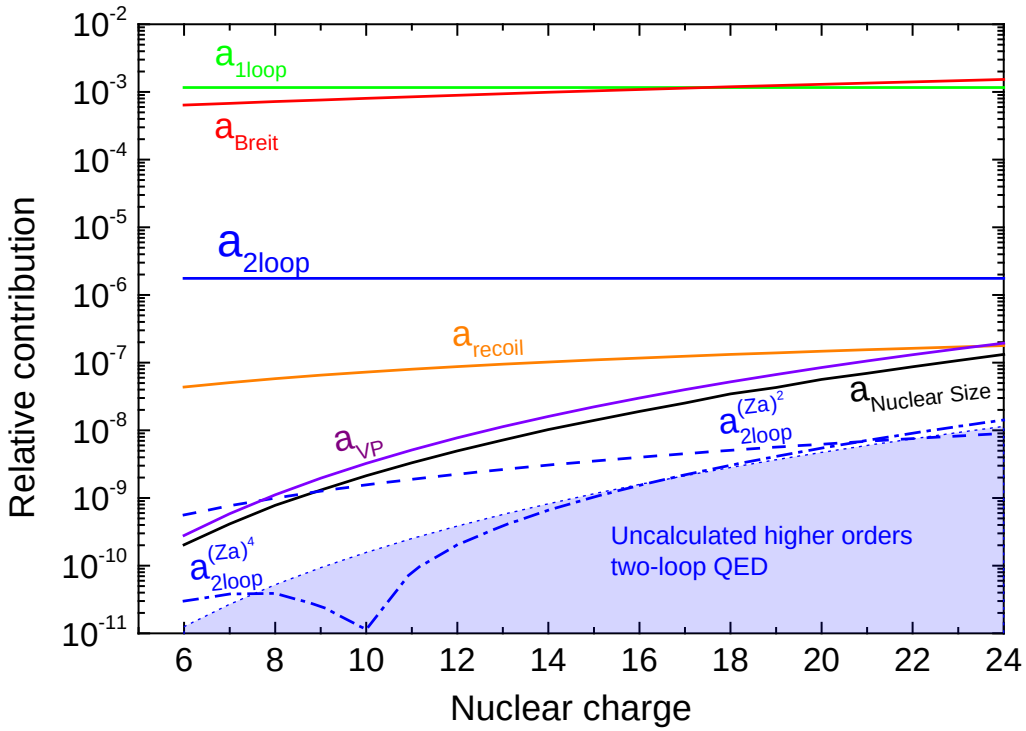
# g-factor ?

$$\vec{m} = -g\, m_B \frac{\vec{s}}{\hbar}$$




$$g = 2 + a_{Breit} + a_{1loop} + a_{NuclearSize} + a_{2loop} + a_{recoil} + \ldots$$




[J. Zatorski et al., 2011]

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# Measurement principle

Measurement of the Larmor frequency in a well-known magnetic field:

$$w_L = \frac{g}{2}\frac{e}{m_e}B$$

Measurement of the free cyclotron frequency to determine the magnetic field:

$$w_c = \frac{q_{ion}}{m_{ion}}B$$

$$g = 2\frac{w_L}{w_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e} = 2\,\mathrm{G}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

has to be determined

Measured by independent precision experiments

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# Experimental requirements

**Requirements of the experiment:**

§ Extremely homogeneous magnetic field (3.7 T)

§ **Single, cold** ion

§ Long storage times (months)

§ “Perfect“ vacuum

<u>Experimental conditions</u>

§ Cryogenic temperatures (**4.2K**)

§ Vacuum better than **$10^{-16}$ mBar**

§ less than 20 gas atoms in the trap volume !

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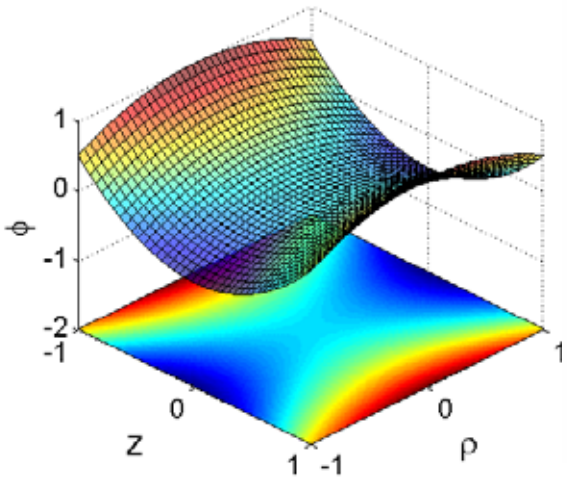
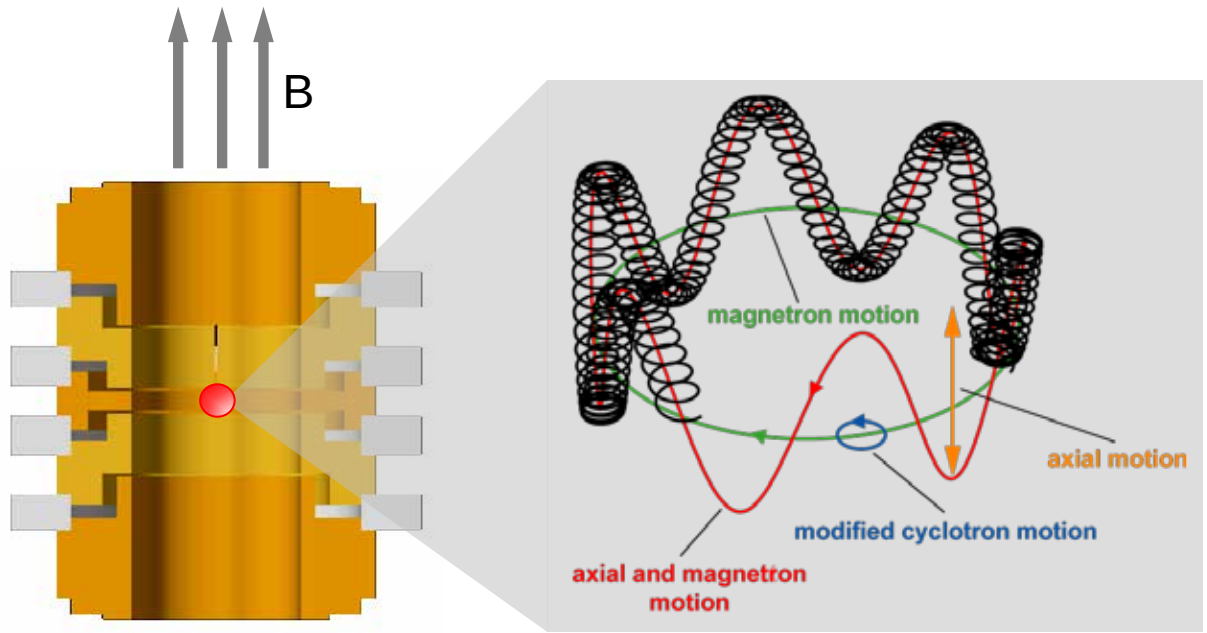
# Experimental requirements

Precision experiments with a single, trapped ion: The Penning trap




An ***invariance theorem*** saves the day:

$$w_c^2 = w_+^2 + w_-^2 + w_z^2$$

[L.S. Brown, G. Gabrielse, 1986]

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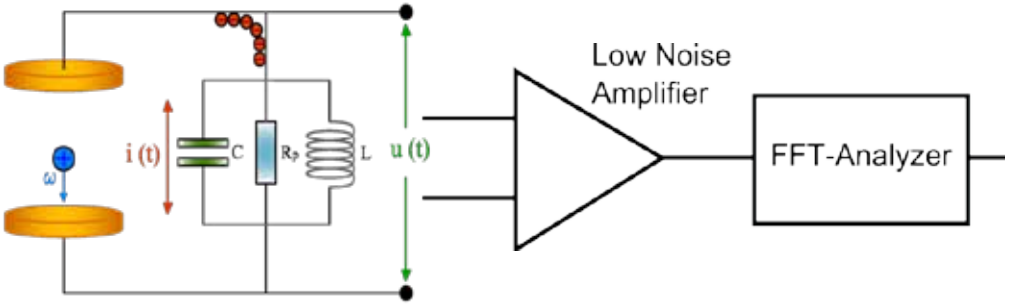
# Axial frequency detection

## Ion detection



Superconducting helical Resonator
$R_p$ = 50 MΩ @ 400 kHz
Q= 3200

Ultra-low noise cryogenic amplifier

$e_n$ = 400 pV/√Hz
$i_n$ ≤ 10 fA/ √Hz

- Oscillating ion induces mirror charges into the electrodes
- The resulting current is only fA
  - Tank circuit with high impedance is tuned to the ion frequency
- Voltage signal is amplified with cryogenic amplifiers featuring extremely low noise
- The frequency is determined with Fast Fourier Transformation

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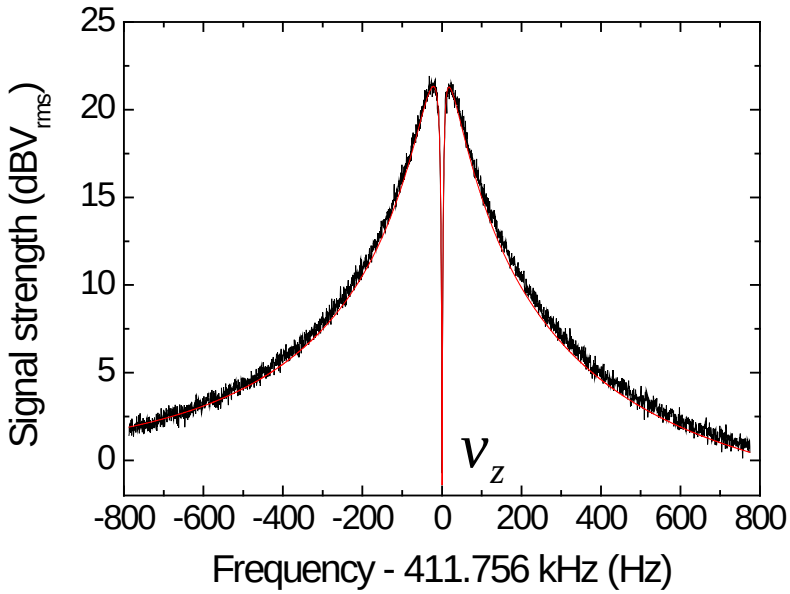
# Detection of motional frequencies




§ Axial frequency directly detected as narrow "dip"

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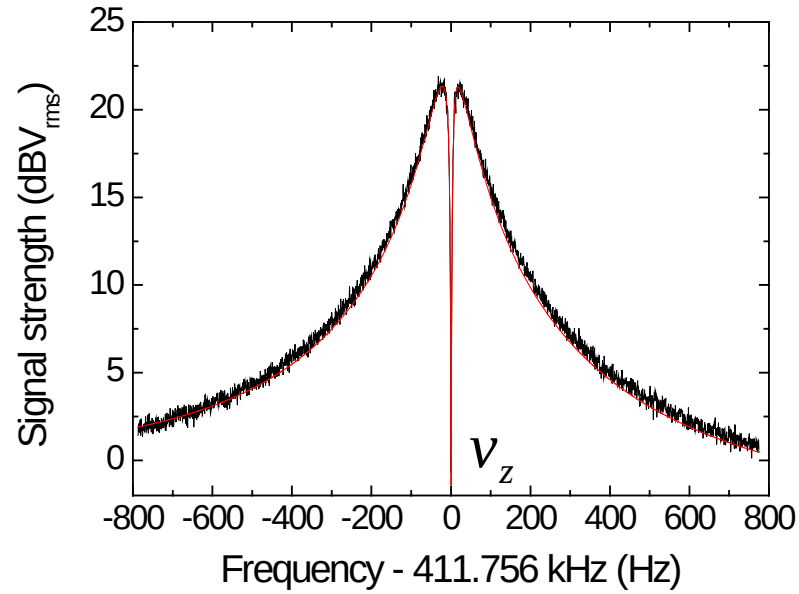


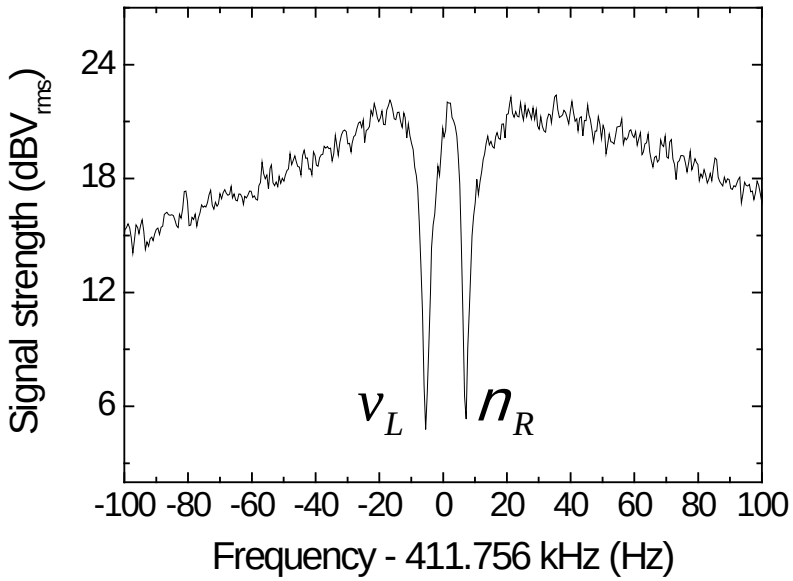


§ Axial frequency directly detected as narrow "dip"

§ Other modes can be coupled to axial motion via *rf*-sideband coupling

Ø Splitting of the axial frequency allows to deduce radial eigenfrequencies

$$\nu_+ = n_L + n_R - n_z + n_{rf}$$

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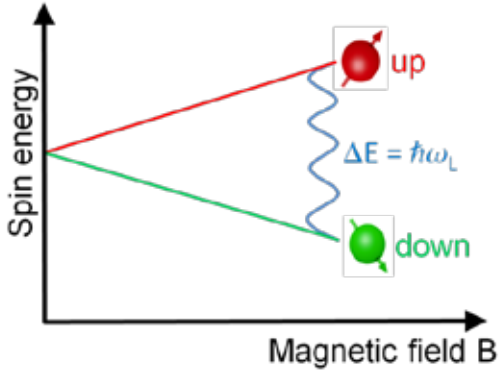
# Continuous Stern-Gerlach effect

§ Larmor frequency cannot be detected directly

§ Microwaves probe spin transition

**How to detect a successful spinflip ?**



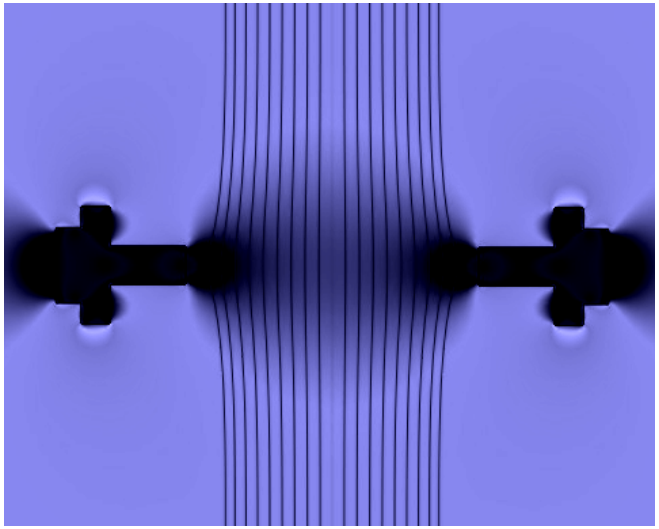

§Magnetic inhomogeneity results in a spin-dependent potential

§ Tiny axial frequency difference between spin up and down

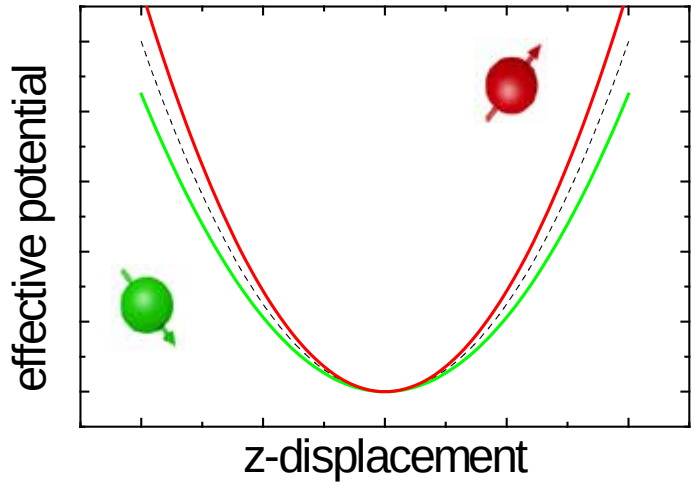
$$\Delta\nu_z = \frac{g\,\mu_B\,B_2}{4\,\pi^2\,m_{ion}\nu_z} = 240\ mHz$$

$$\delta U \approx 300\,\mathrm{nV} @ 3\mathrm{V}$$

$$\delta E_+ \approx 35\,\mu\mathrm{eV}$$



Ferromagnetic ring produces a magnetic bottle

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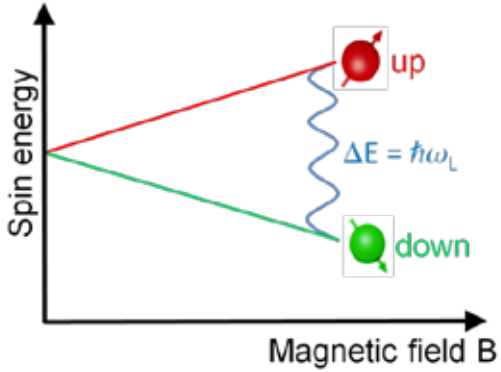


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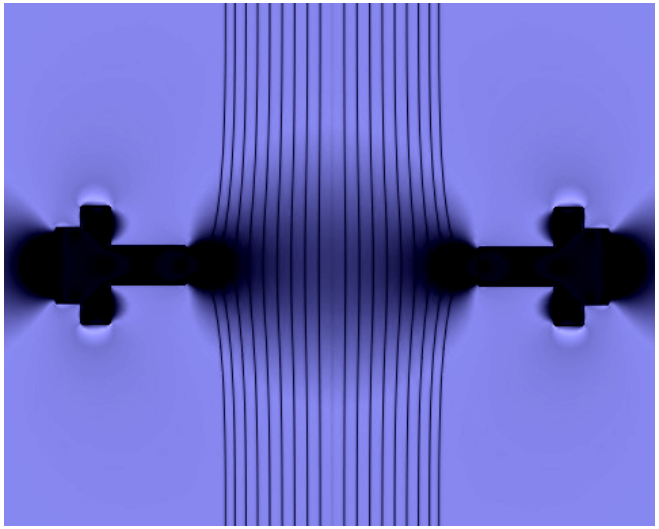
$dU$ £ 300 nV @ 3V

$dE_+$ £ 35 µeV



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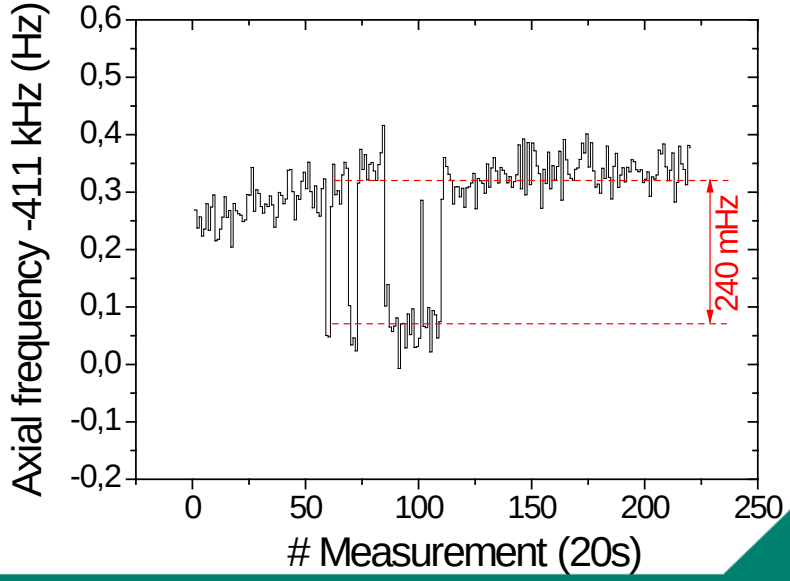


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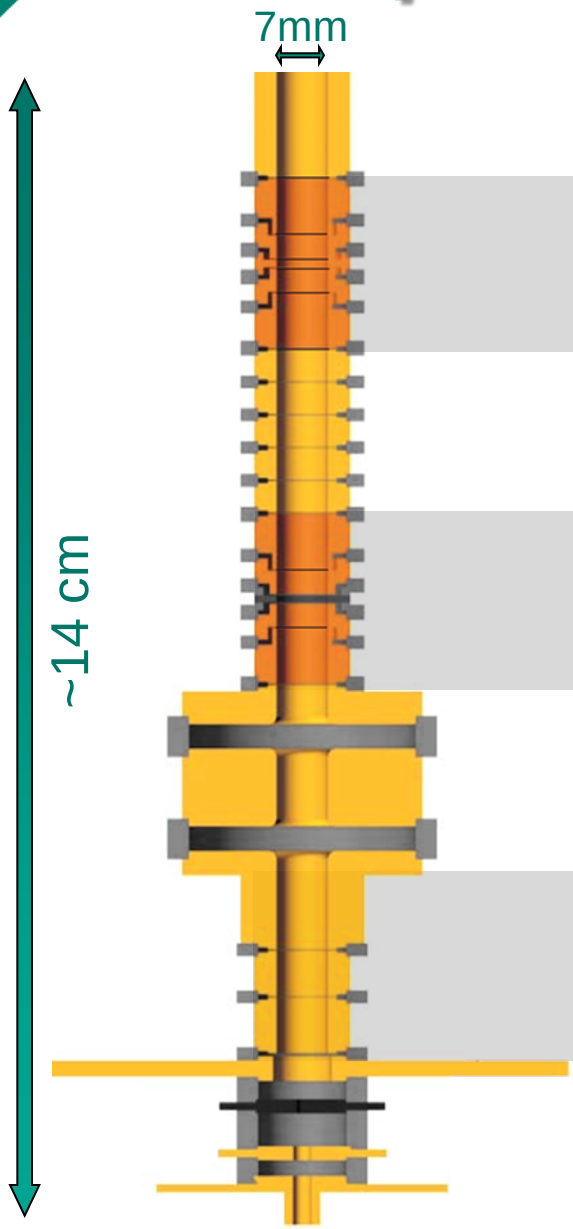
# Setup: triple Penning trap system




**Precision trap (PT)**
§ Very homogeneous magnetic field

**Analysis trap (AT)**
§ Magnetic bottle for spin detection

**Creation trap (CT)**
§ In-trap ion creation of highly-charged ions

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# Setup: triple Penning trap system

**Precision trap (PT)**
§ Very homogeneous magnetic field

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§ Magnetic bottle for spin detection

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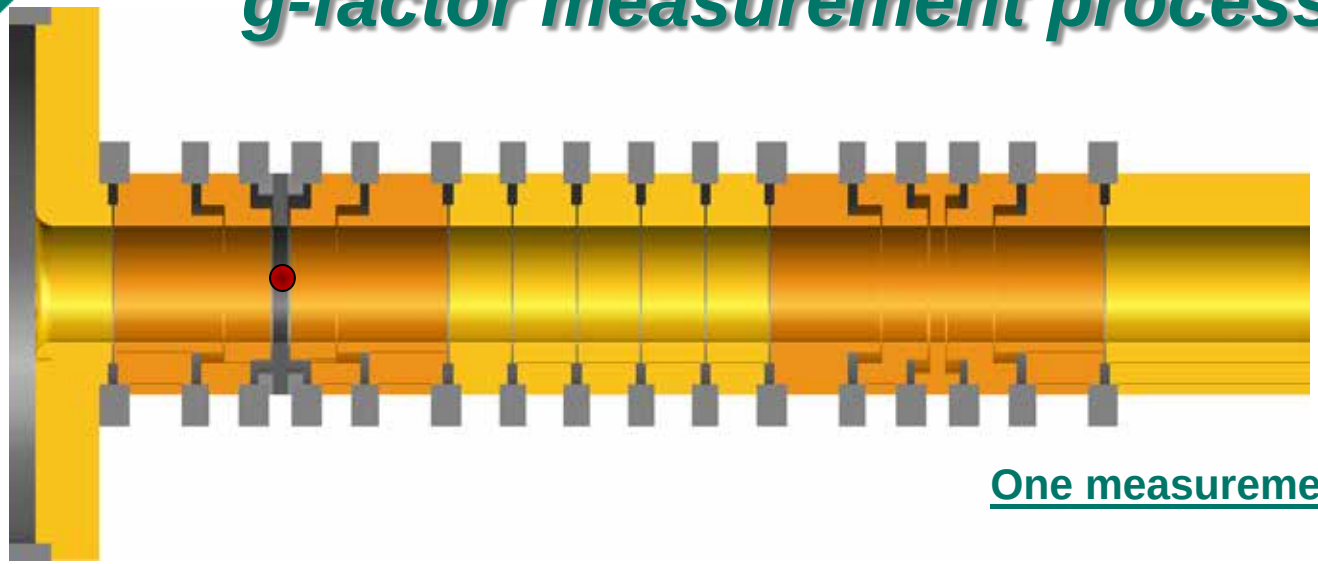
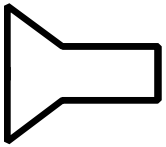
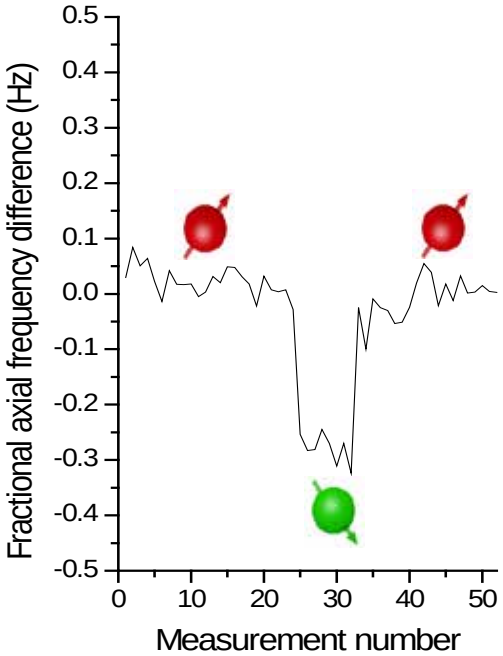
# g-factor measurement process





**One measurement cycle**

§ Detection of spin-orientation in analysis trap 2-3min

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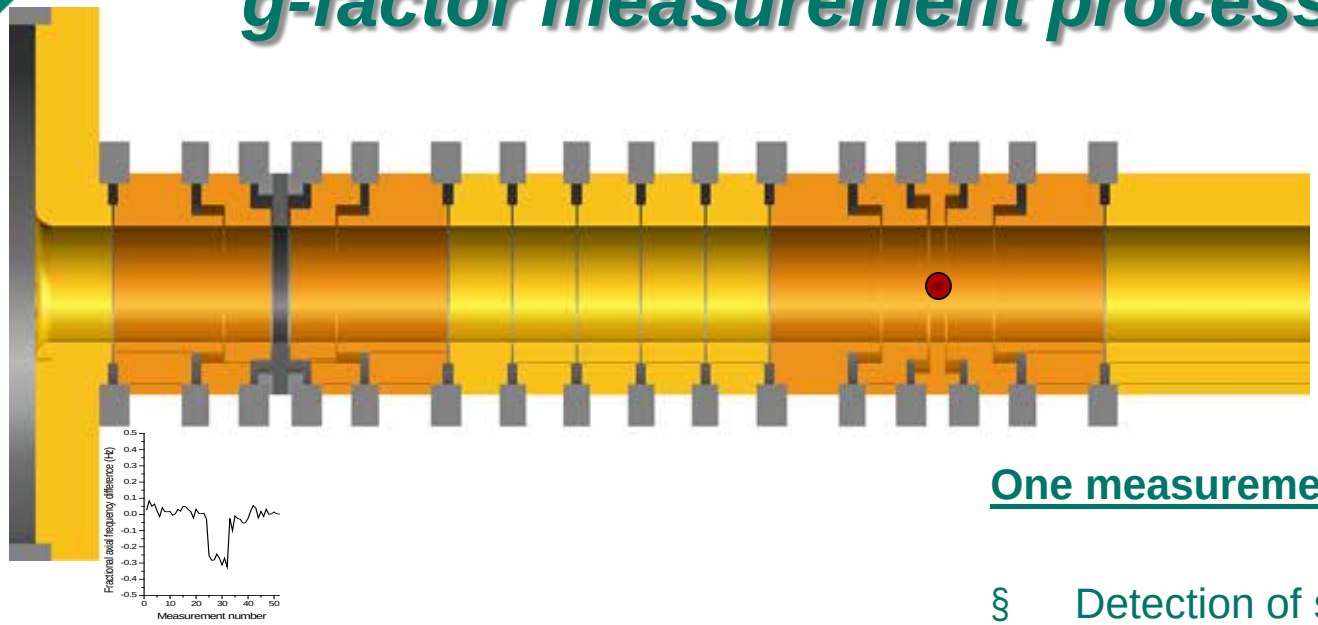


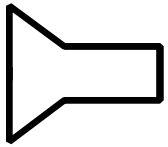

**One measurement cycle**

§ Detection of spin-orientation in analysis trap 2-3min

§ Transport to precision trap 20s

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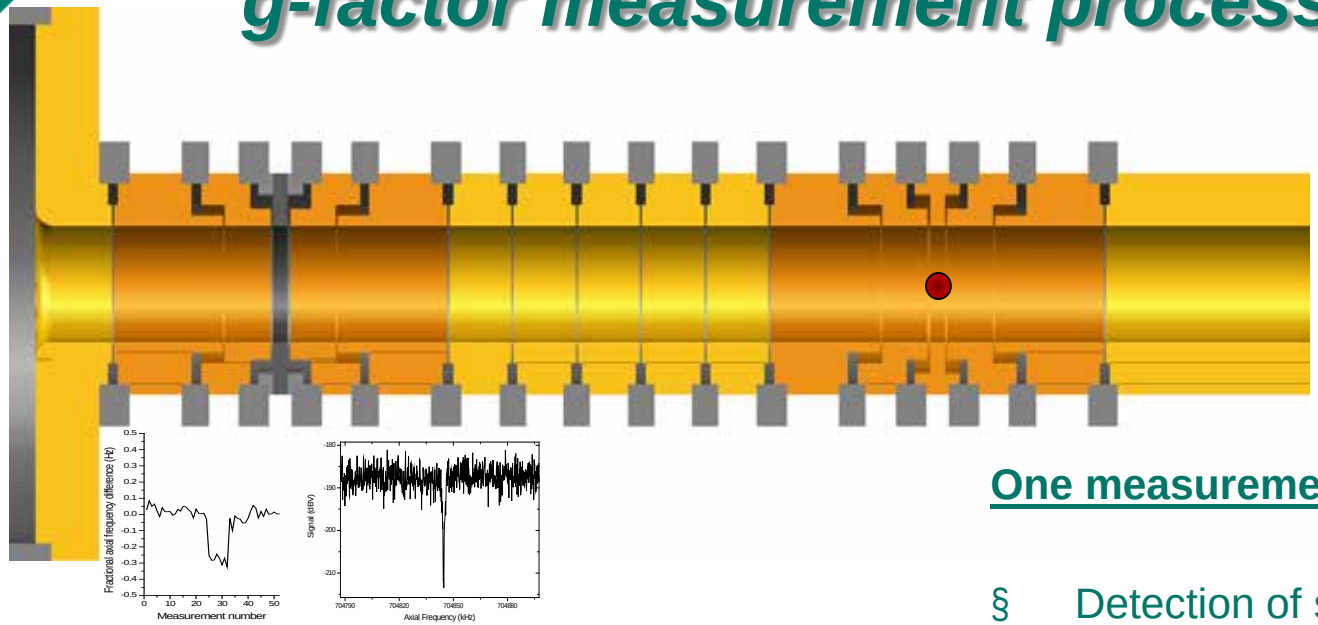


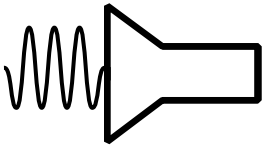

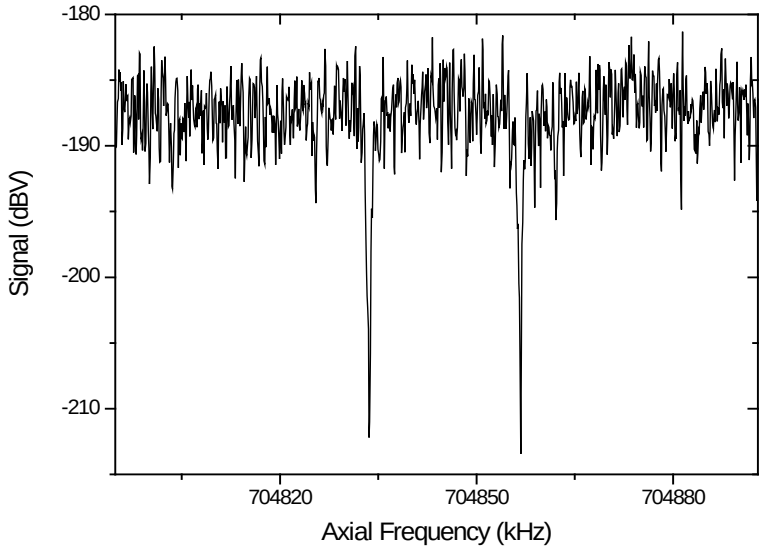


**One measurement cycle**

- Detection of spin-orientation in analysis trap 2-3min
- Transport to precision trap 20s
- Measurement of eigenfrequencies and simultaneous irradiation with microwaves 10min

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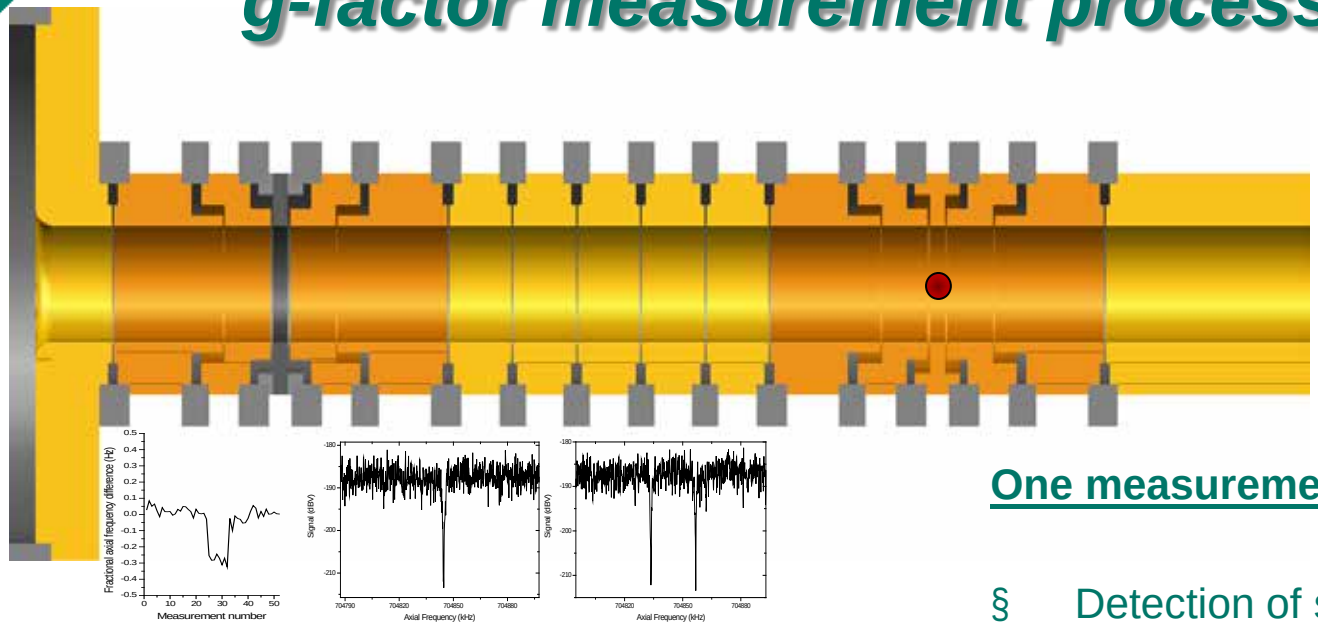
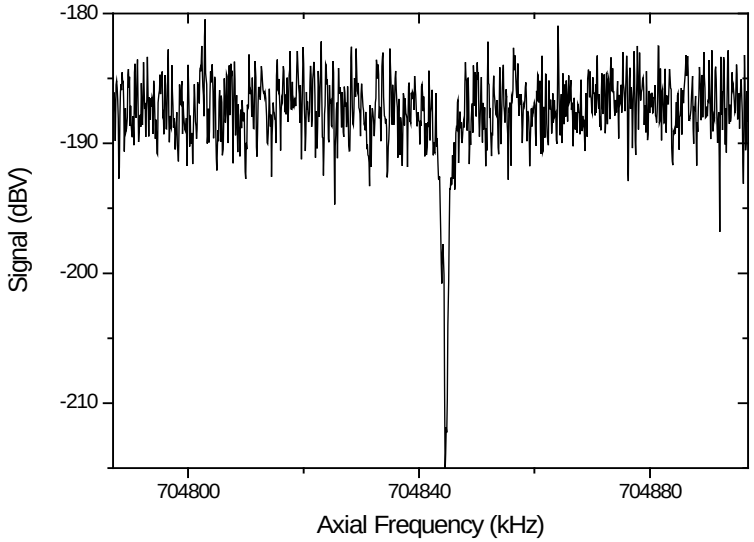
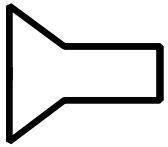
# g-factor measurement process



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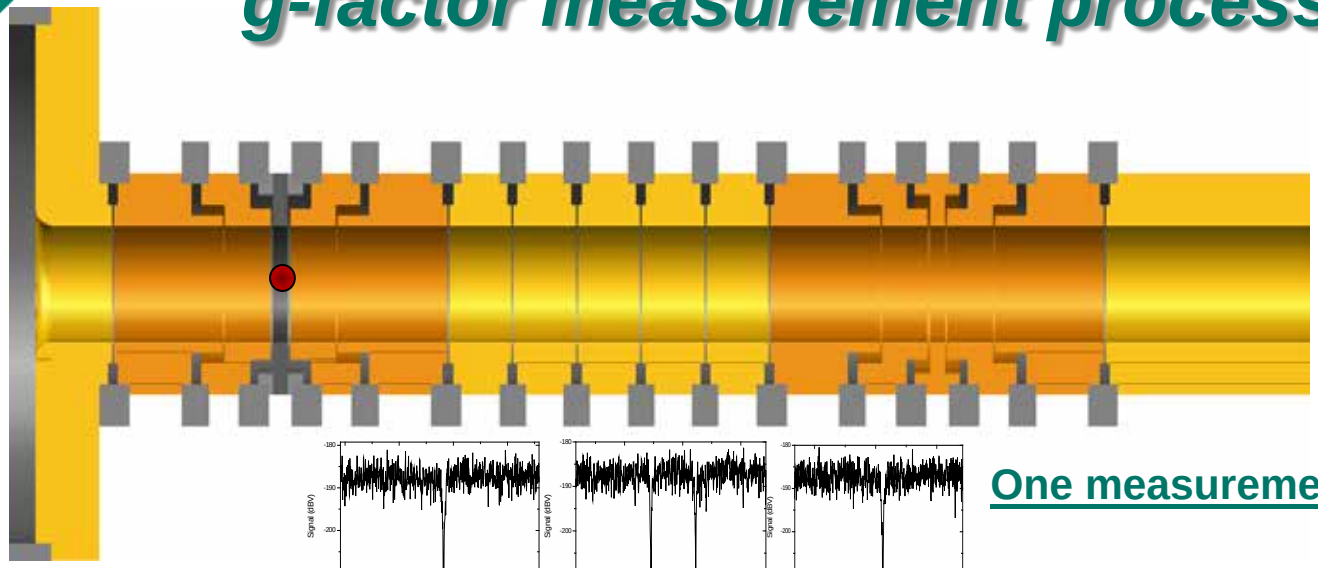

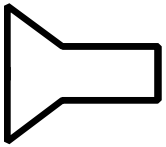

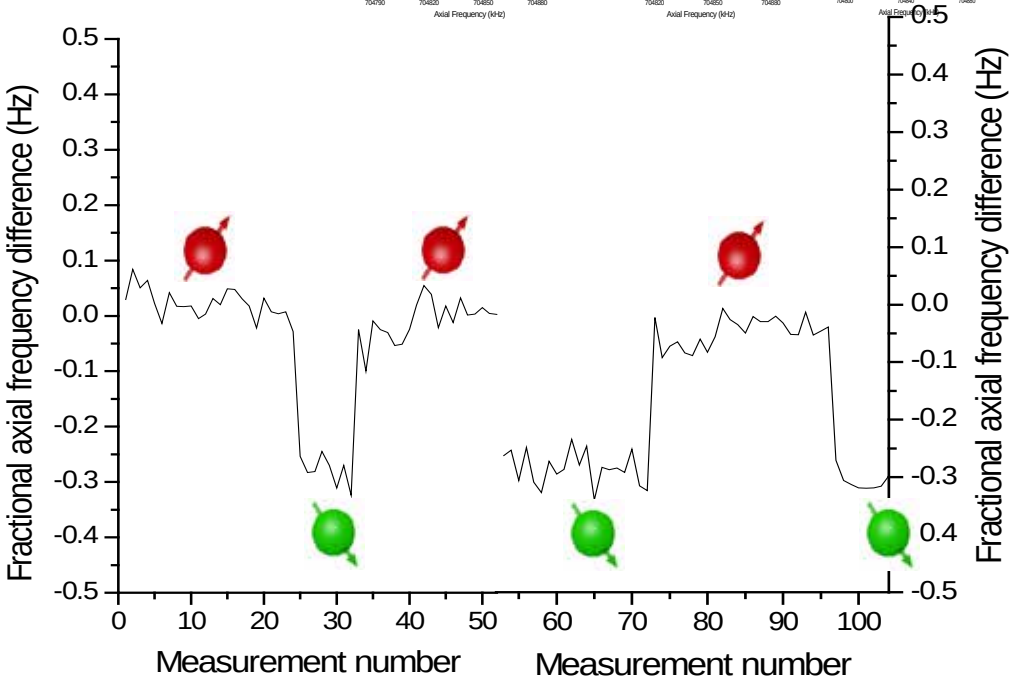


## One measurement cycle

- § Detection of spin-orientation in analysis trap 2-3min
- § Transport to precision trap 20s
- § Measurement of eigenfrequencies and simultaneous irradiation with microwaves 10min
- § Transport to analysis trap 20s
- § Detection of spin orientation in analysis trap
  - Ø Spin flip in the precision trap?

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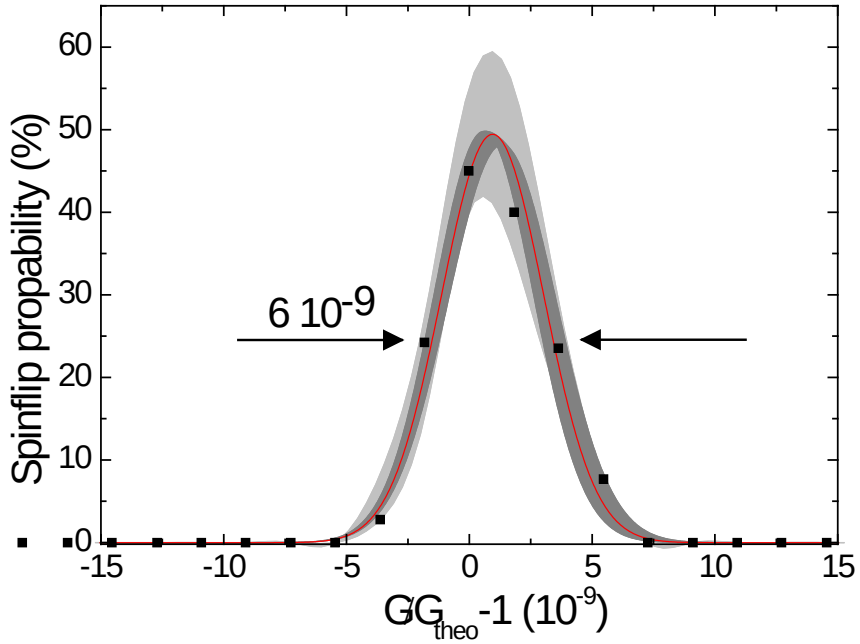
# *g*-factor resonance

§ Many repetitions for random frequencies

Ø *g*-factor resonance

§ Γ is extracted from fit

§ *g*-factor is calculated $$g = 2\,\mathrm{G}\frac{q}{e}\frac{m_e}{m_{Ion}}$$

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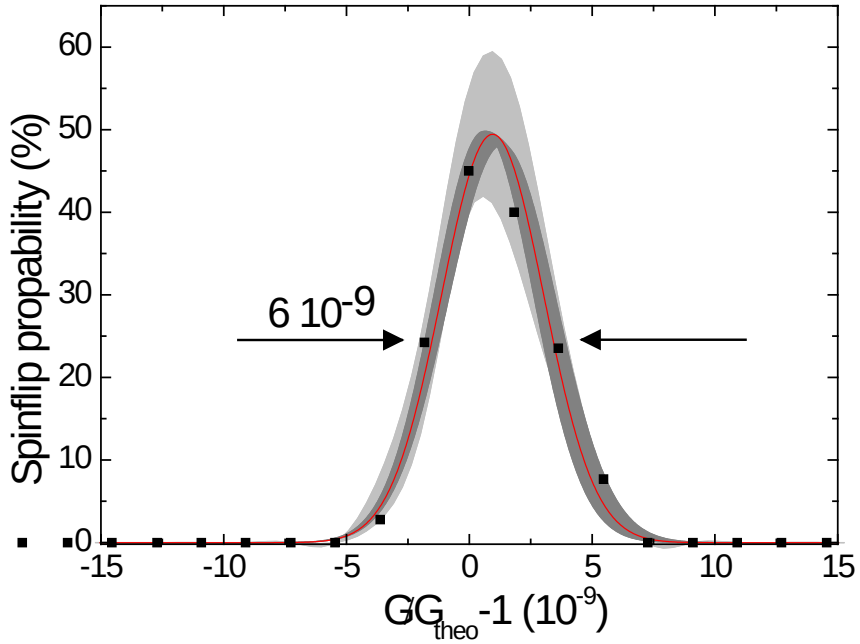


$g_{exp}$ = 1.995 348 958 7 (5)(3)(8)
$g_{theo}$ = 1.995 348 958 0 (17)

Error dominated by uncertainty of electron mass

Theoretical value by:
[Z. Hamann, J. Zatorski, C. Pachucki et al. 2011]

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# The mass of the electron

§ Experimental uncertainty limited by knowledge of the electron mass

**CODATA 2011: $\delta m_e/m_e=4.2\ 10^{-10}$**

§ Reversing the argument:

$$m_e = \frac{g_{theo}}{2\,\Gamma}\frac{e}{q_{ion}}\,m_{ion}$$

§ Special system:

$^{12}C^{5+}$

§ Field strength low, QED very likely correct
§ (Atomic) Mass is known per definition
§ Theory precision reaches **$dg/g=1.5\ 10^{-11}$** !

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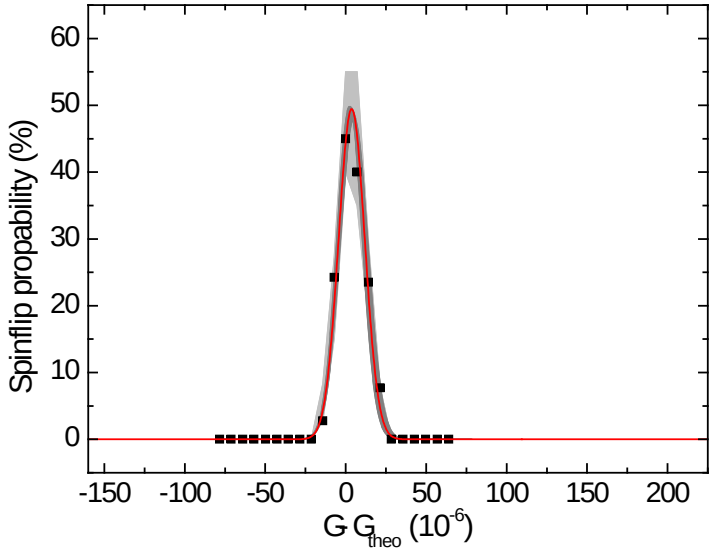
# Going even further…

New measurement method developed

- ü Phase sensitive, coherent detection of the modified cyclotron frequency
  - ü Allows rapid cyclotron frequency measurements at the Cramér-Rao information bounds
  - ü Energy dependent systematic shifts on $10^{-13}$ scale
  - ü Statistical measurement noise is reduced by an order of magnitude

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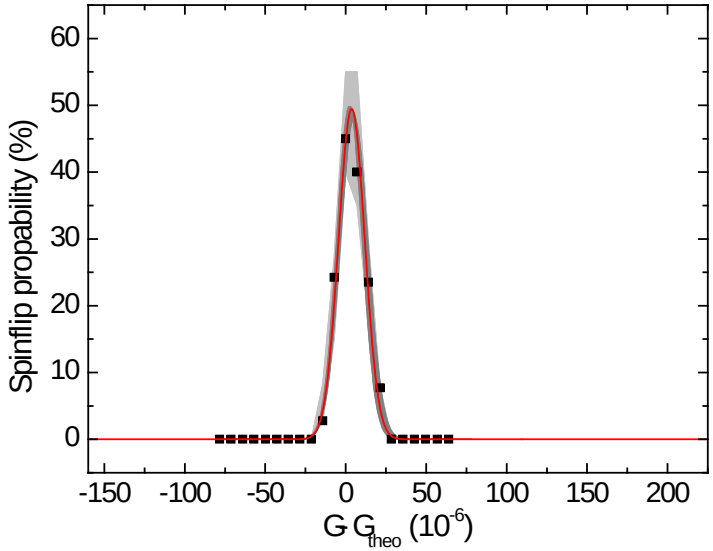
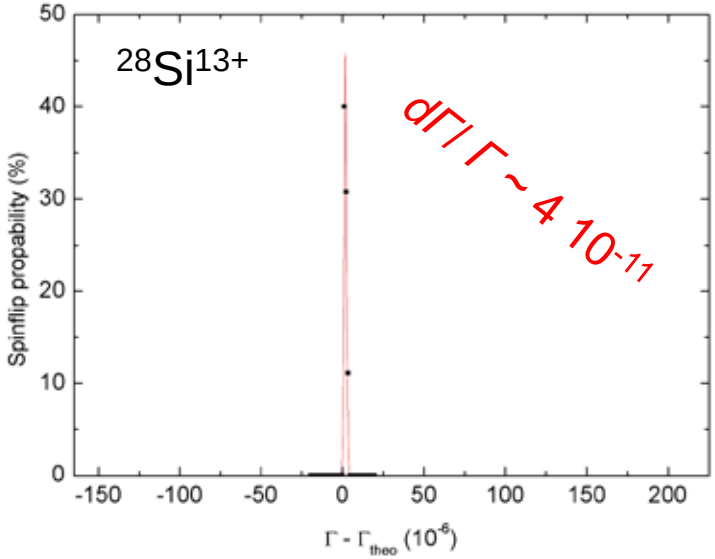
  - ü Statistical measurement noise is reduced by an order of magnitude




*g*-factor measurements to $\delta\Gamma / \Gamma \approx 4\ 10^{-11}$ performed

Electron mass accuracy improvement by a factor of ~20 if repeated with $^{12}C^{5+}$

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# Results

§ *g*-factor measurement of the electron bound in $^{28}Si^{13+}$ with a precision of

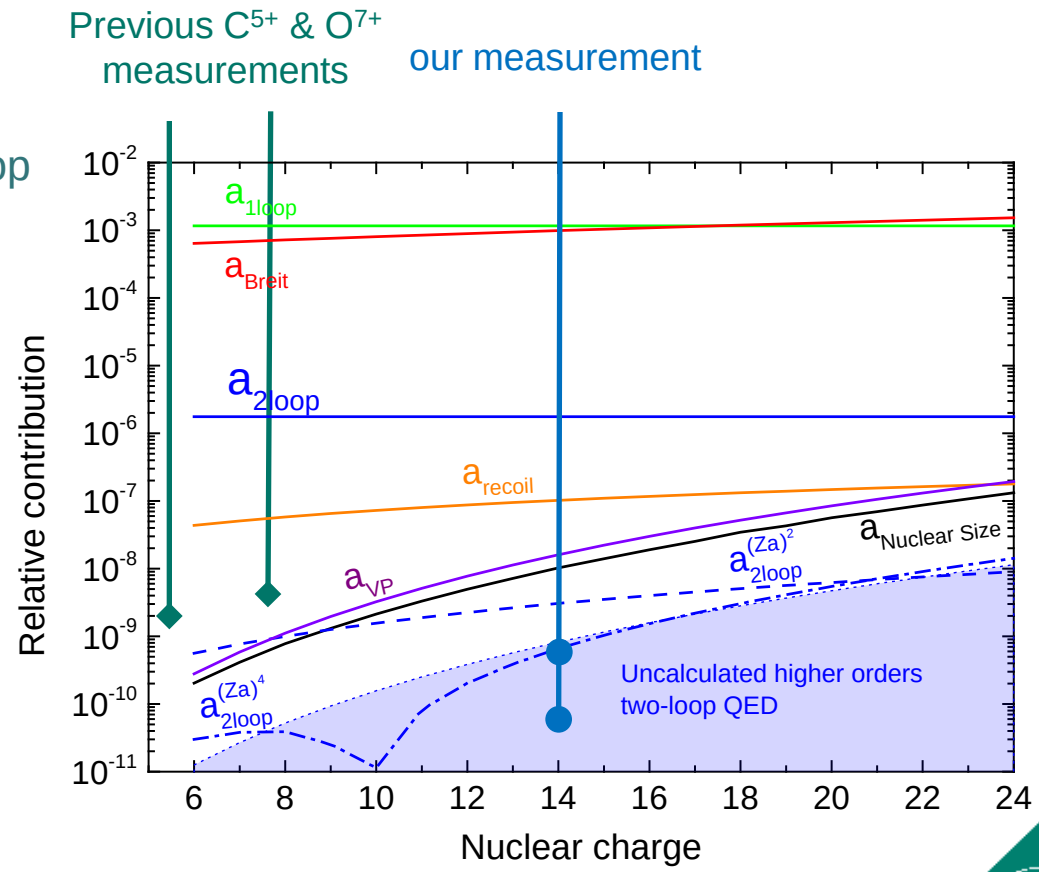
$\delta g/g = 5\cdot 10^{-10}$ (experimental precision 4 $10^{-11}$ !)
**Most stringent test of BS-QED in strong fields**

§Higher order contributions to two-loop theory are relevant for the first time

§ Vacuum polarization tested

§ Nuclear size effect tested for the first time, nuclear charge radius extracted:

$\langle r^2\rangle^{1/2} = 3.18\ (15)$ fm

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# Fascinating perspectives ...

Multi electron systems:

Exploring electron correlations with lithiumlike ions:

$^{28}Si^{11+}$ (in progress), $^{40,48}Ca^{17+}$

Hunt for fundamental constants:

§ Electron mass from *g*-factors of light ions: $^{12}C^{5+}$

$$m_e = \frac{g_{theo}}{2\,\Gamma}\,\frac{e}{q_{ion}}\,m_{ion}$$

Improvement factor over current CODATA value: 20 !

Even stronger fields with heavier ions:

$^{40,48}Ca^{19+}$, …

Fine structure constant □ from heavy systems:

$^{207}Pb^{81+,77+}$

@ HITRAP (GSI) or MPI-K

Max-Planck-Institut für Kernphysik

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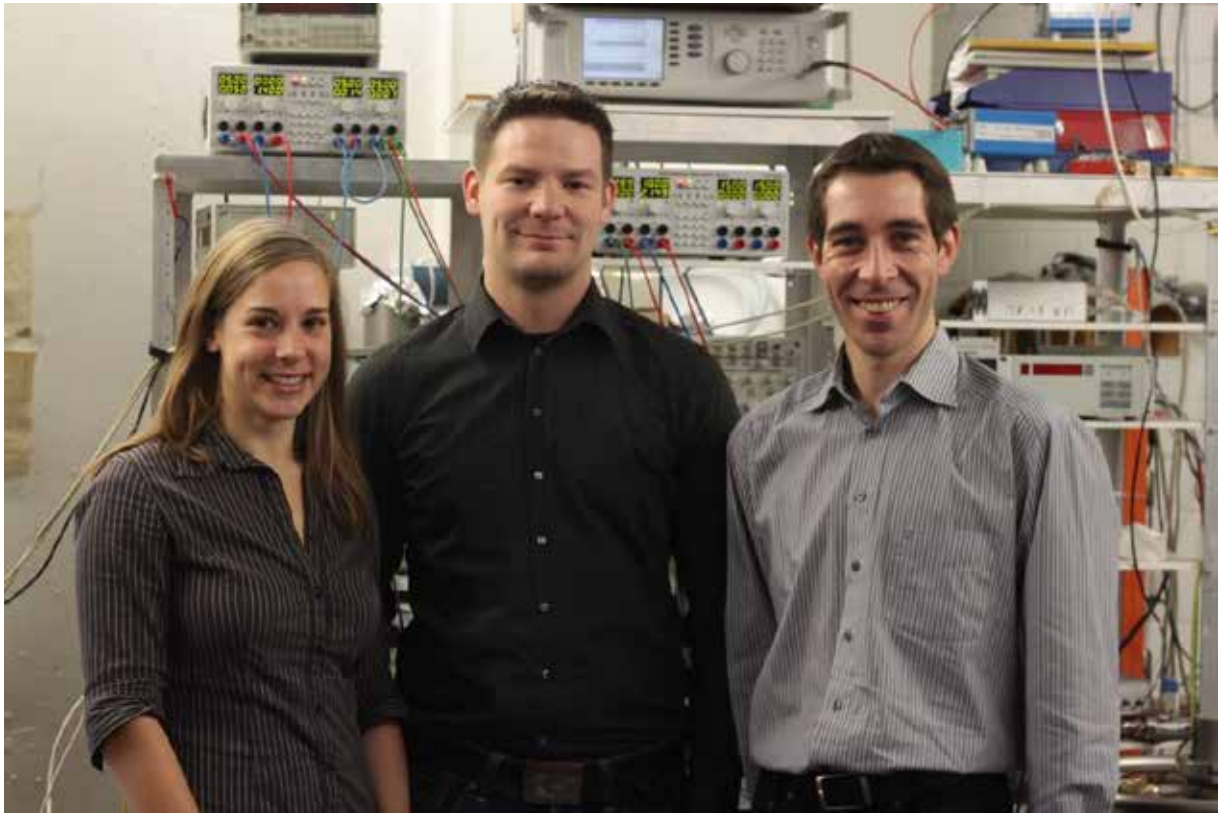

*We are honored to receive the Helmholtz Award 2012.*
*It is an outstanding recognition of our work and keeps us going.*
*Thank you very much.*

**Thanks a lot for your attention !**