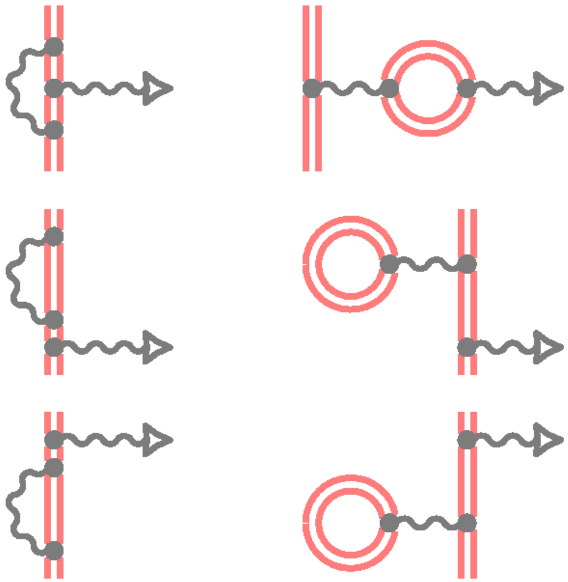
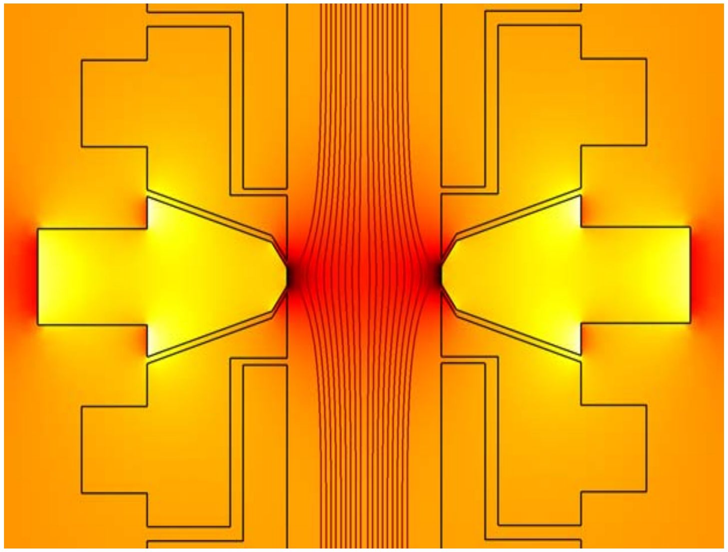
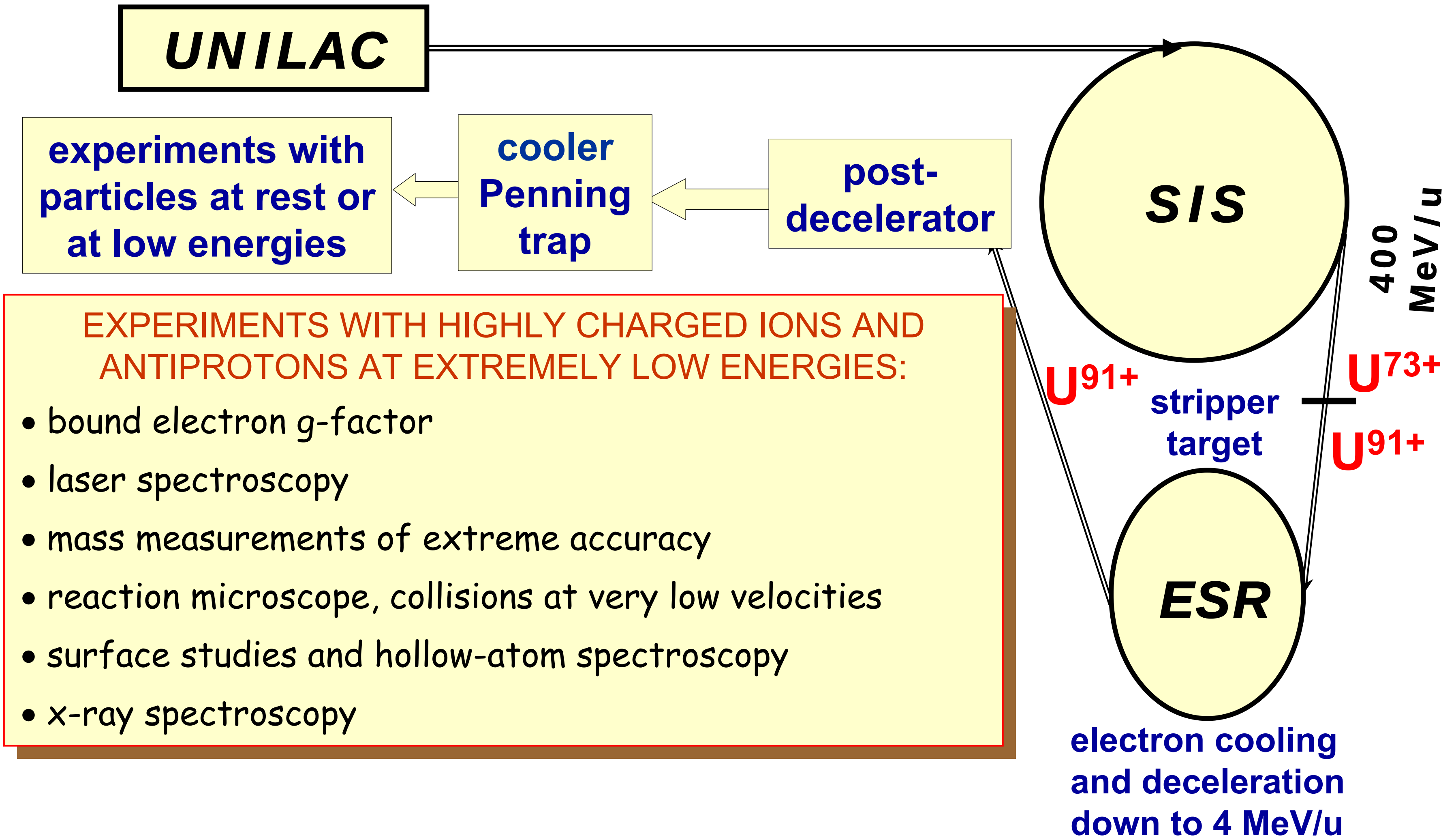
Precision Experiments with Cooled Highly Charged Ions in Penning Traps at HITRAP





Wolfgang Quint
GSI Darmstadt and Univ. Heidelberg

HITRAP at the ESR storage ring / GSI

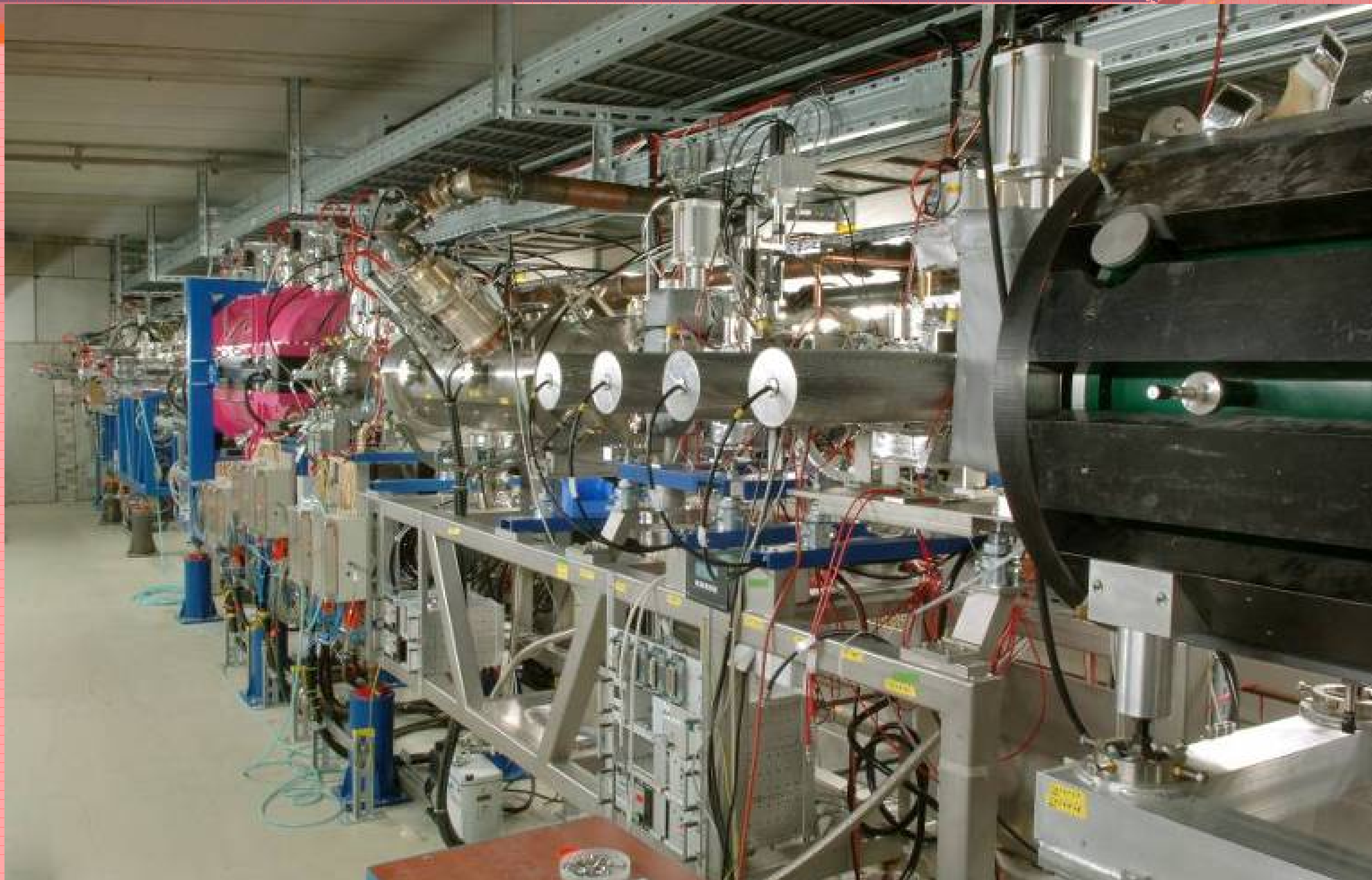


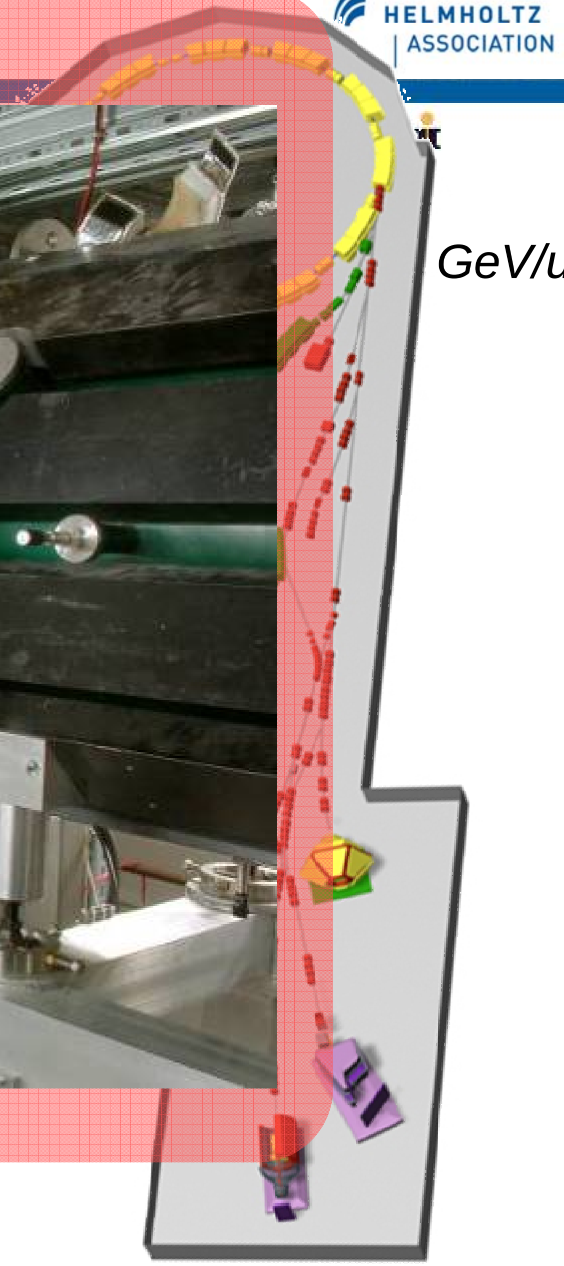
EXPERIMENTS WITH HIGHLY CHARGED IONS AND ANTIPROTONS AT EXTREMELY LOW ENERGIES:

- bound electron g-factor
- laser spectroscopy
- mass measurements of extreme accuracy
- reaction microscope, collisions at very low velocities
- surface studies and hollow-atom spectroscopy
- x-ray spectroscopy

HITRAP

GSI accelerator facility

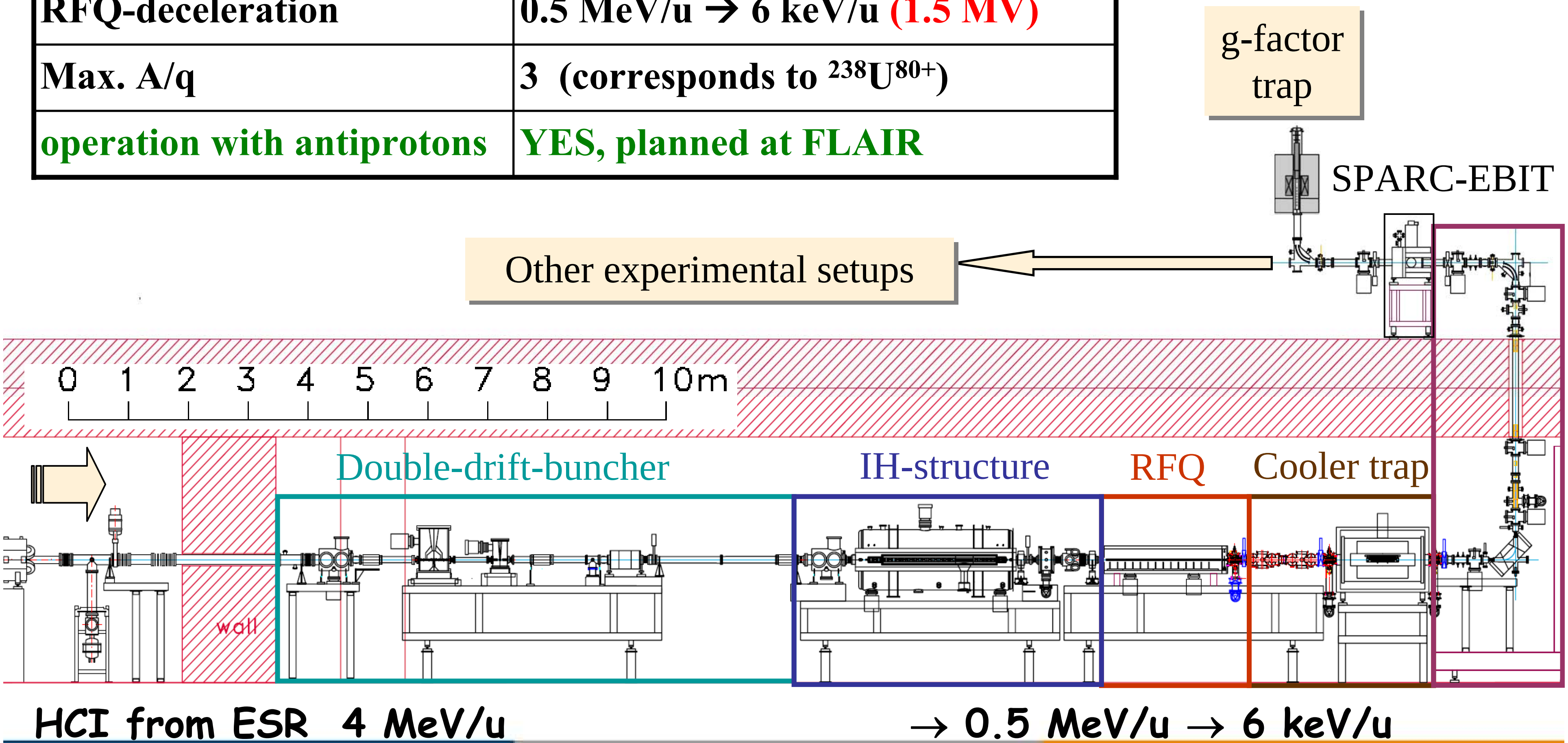




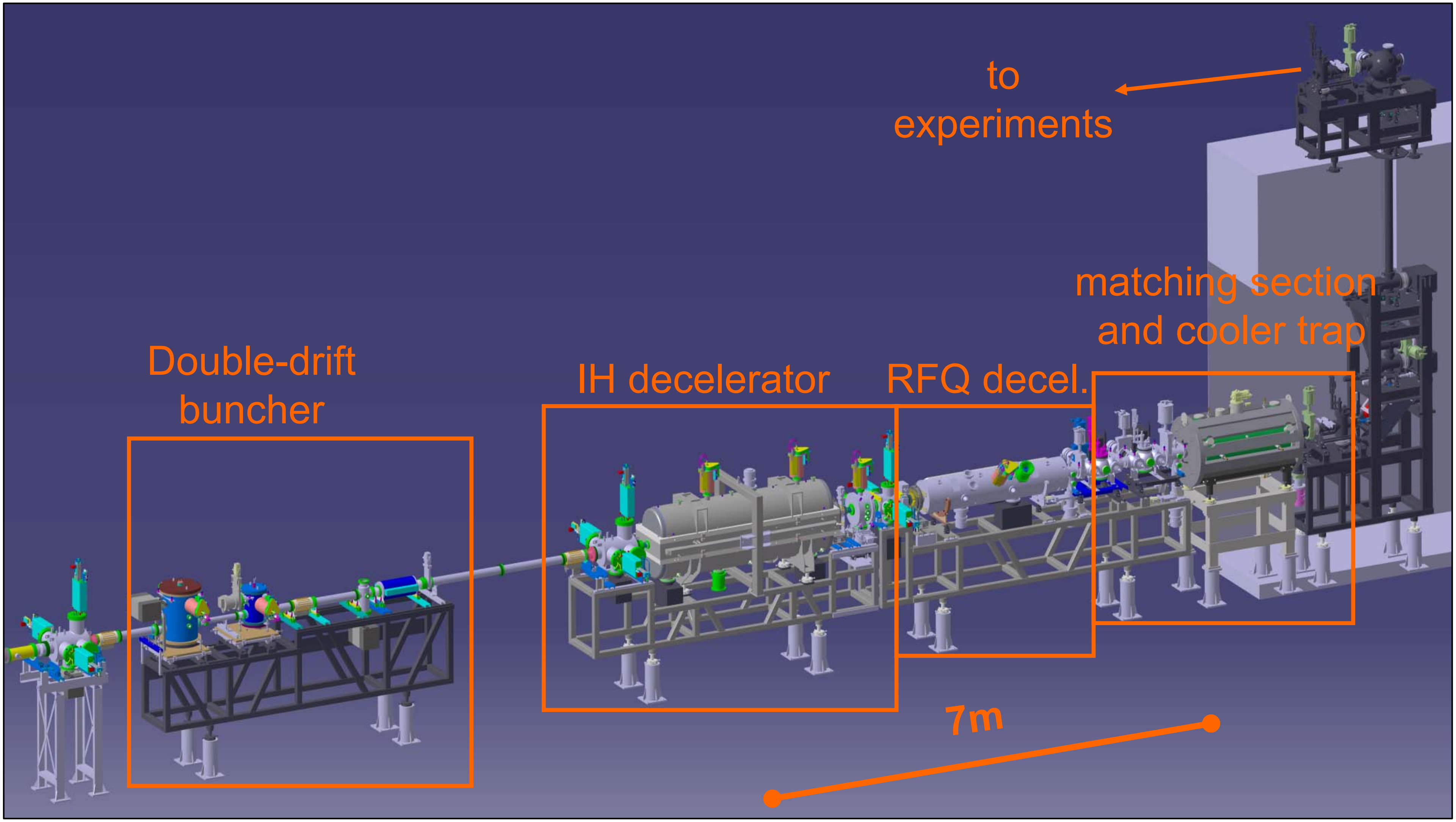
Ref.:
Frank Herfurth

HITRAP facility at ESR storage ring

Linac operation frequency	**108.408 MHz**
IH-deceleration	**4 MeV/u → 0.5 MeV/u (10.5 MV)**
RFQ-deceleration	**0.5 MeV/u → 6 keV/u (1.5 MV)**
Max. A/q	**3 (corresponds to $^{238}U^{80+}$)**
operation with antiprotons	**YES, planned at FLAIR**

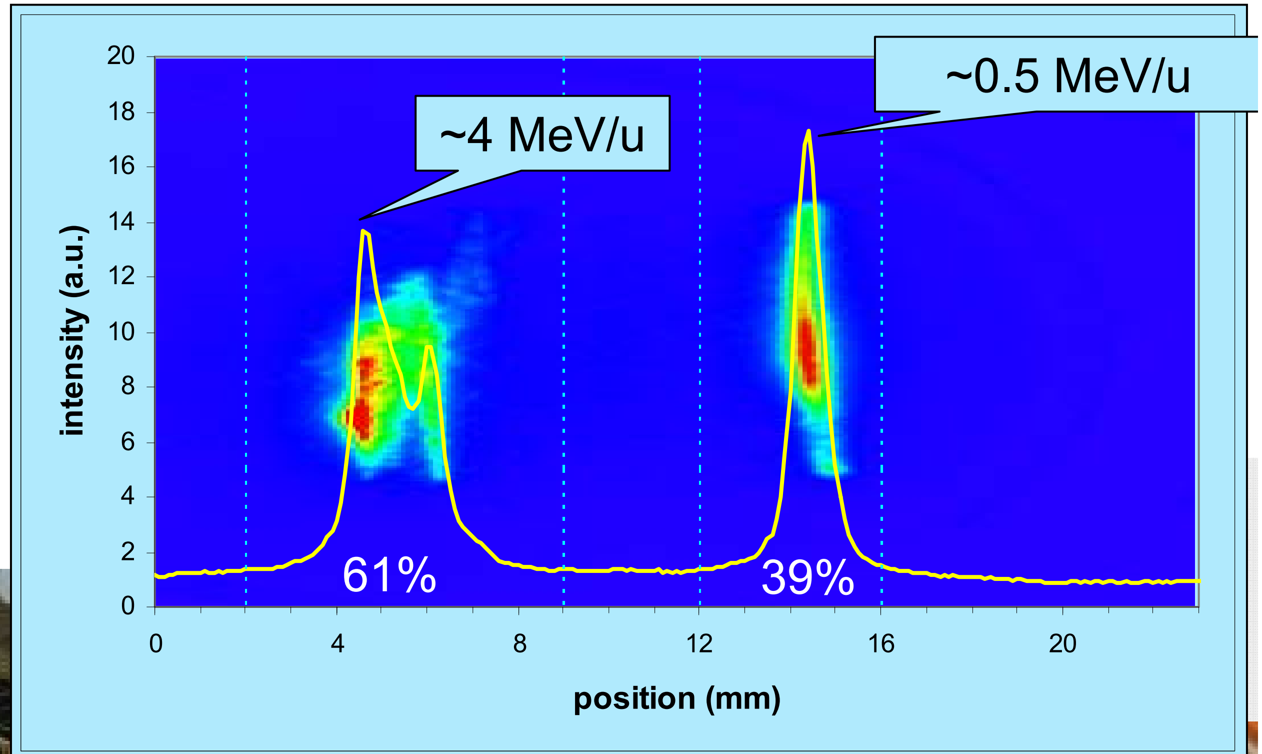


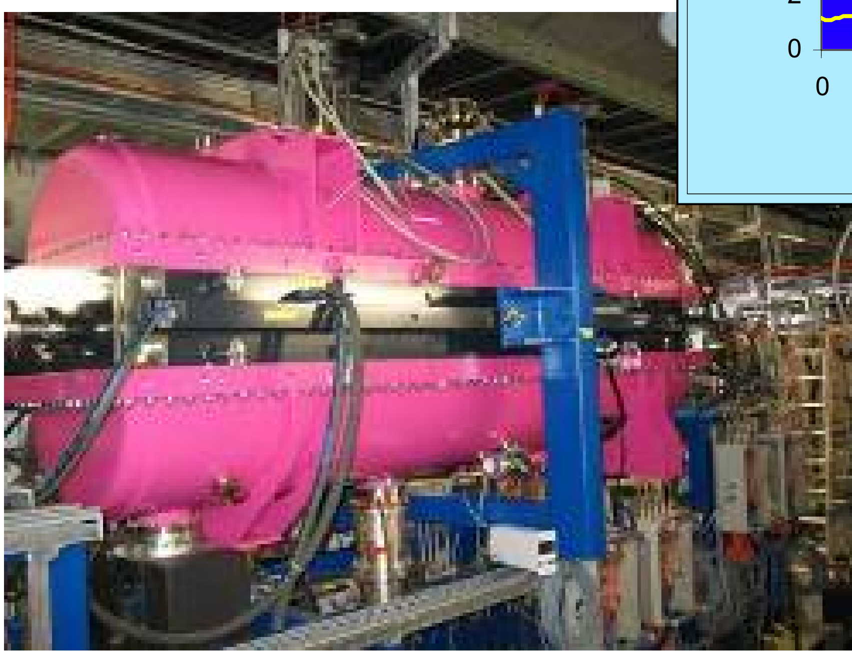
HITRAP: Technical design

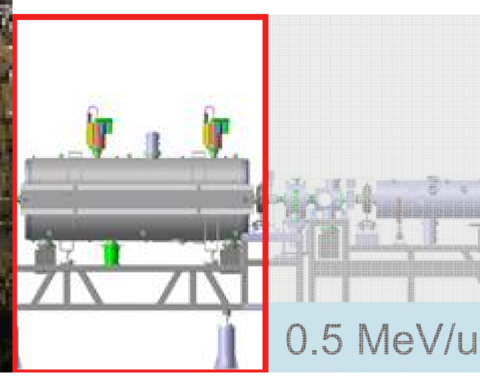


HITRAP – Linear decelerator

- Fraction of decelerated particles close to theory

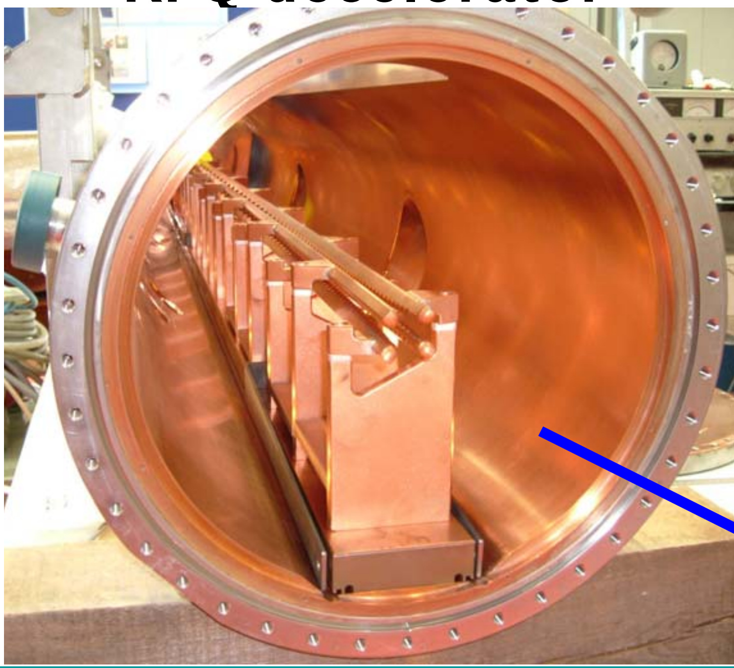




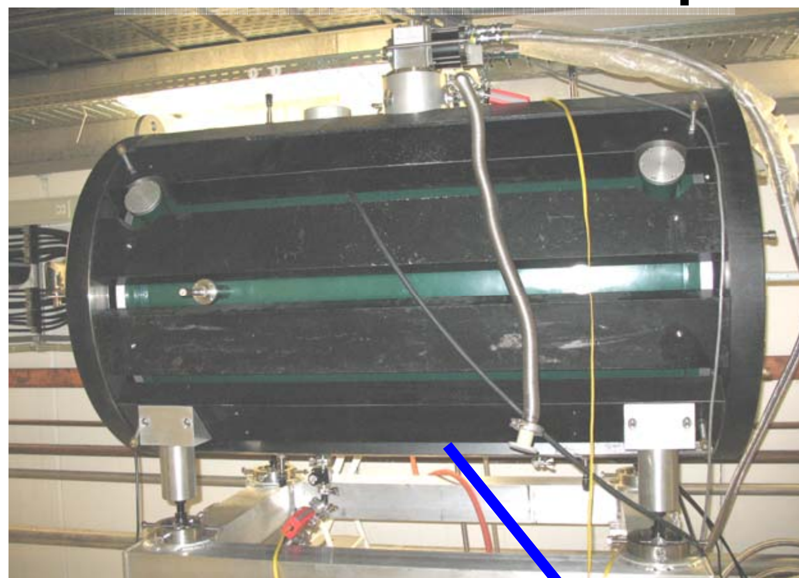


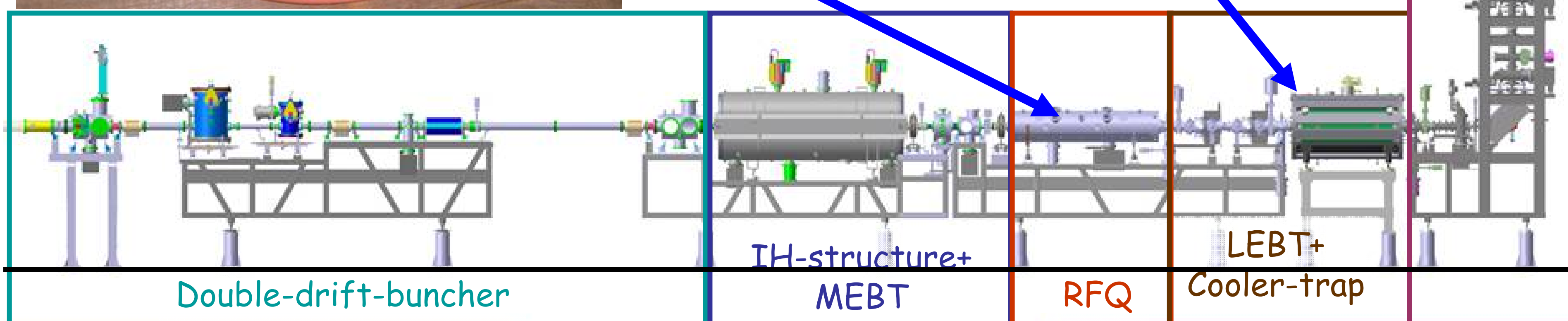
Commissioning of RFQ decelerator and of cooler trap in progress

RFQ decelerator



HITRAP cooler trap

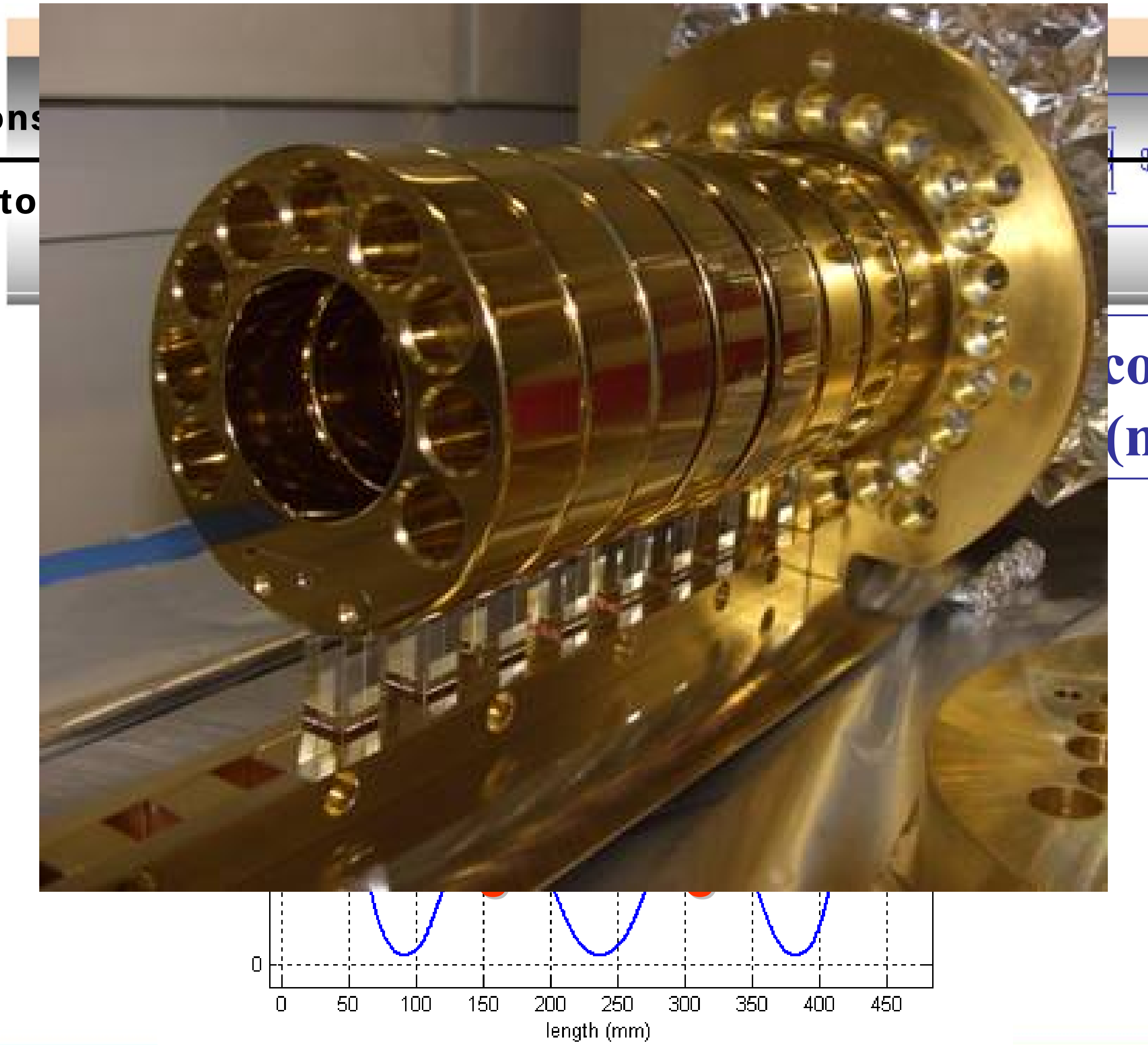




HITRAP Cooler Penning trap

● electron cooling ● resistive cooling to T = 4 K

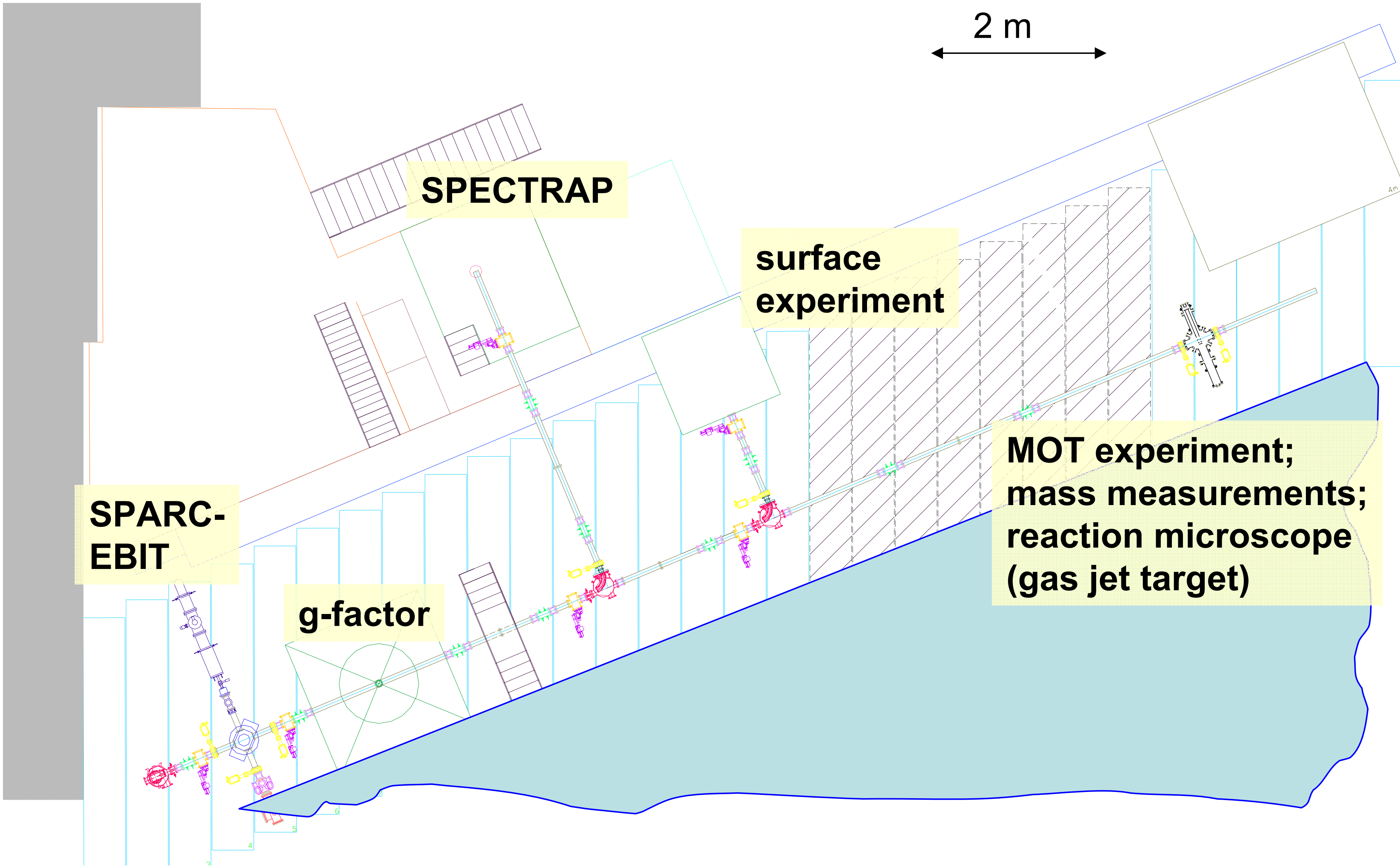
highly charged ions from HITRAP decelerato



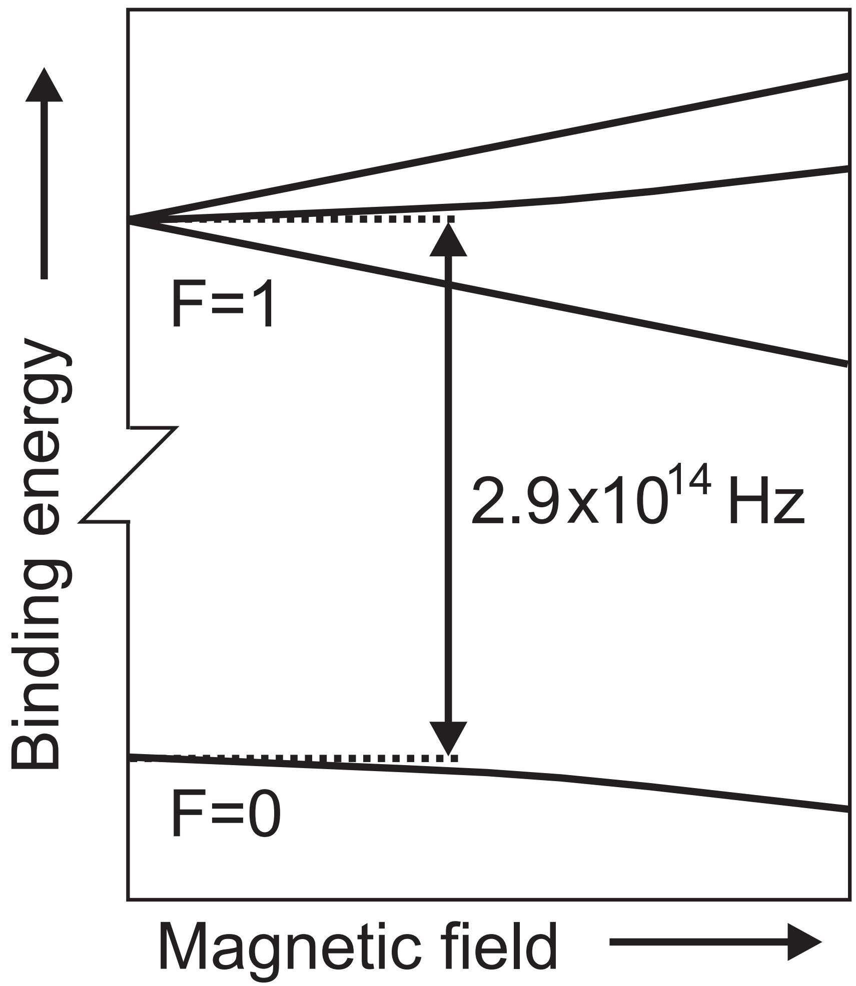
cooled HCI to HITRAP experiments

cooler trap:
(ms...sec)

HITRAP experimental area



SPECTRAP: Laser spectroscopy of hyperfine splitting in highly charged ions

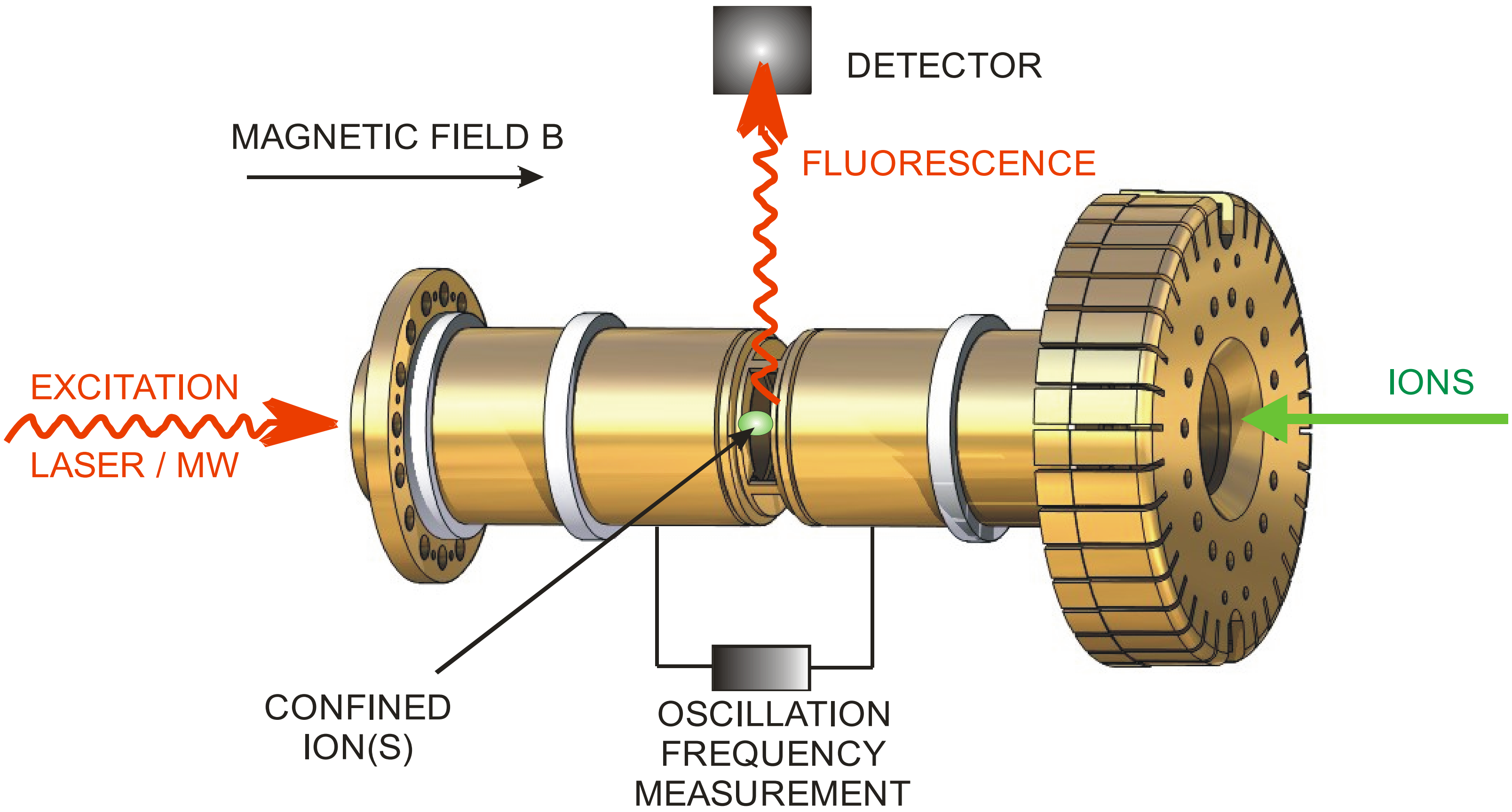


- example: H-like lead $^{207}Pb^{81+}$
- HFS wavelengths move into visible for Z>70
- very small Doppler width at T = 4 K
- relative wavelength accuracy ≤ 10^{-7}

Physics goals:

- test of QED in strong fields
- nuclear structure studies

SPECTRAP: Laser spectroscopy of HFS transitions in highly charged ions

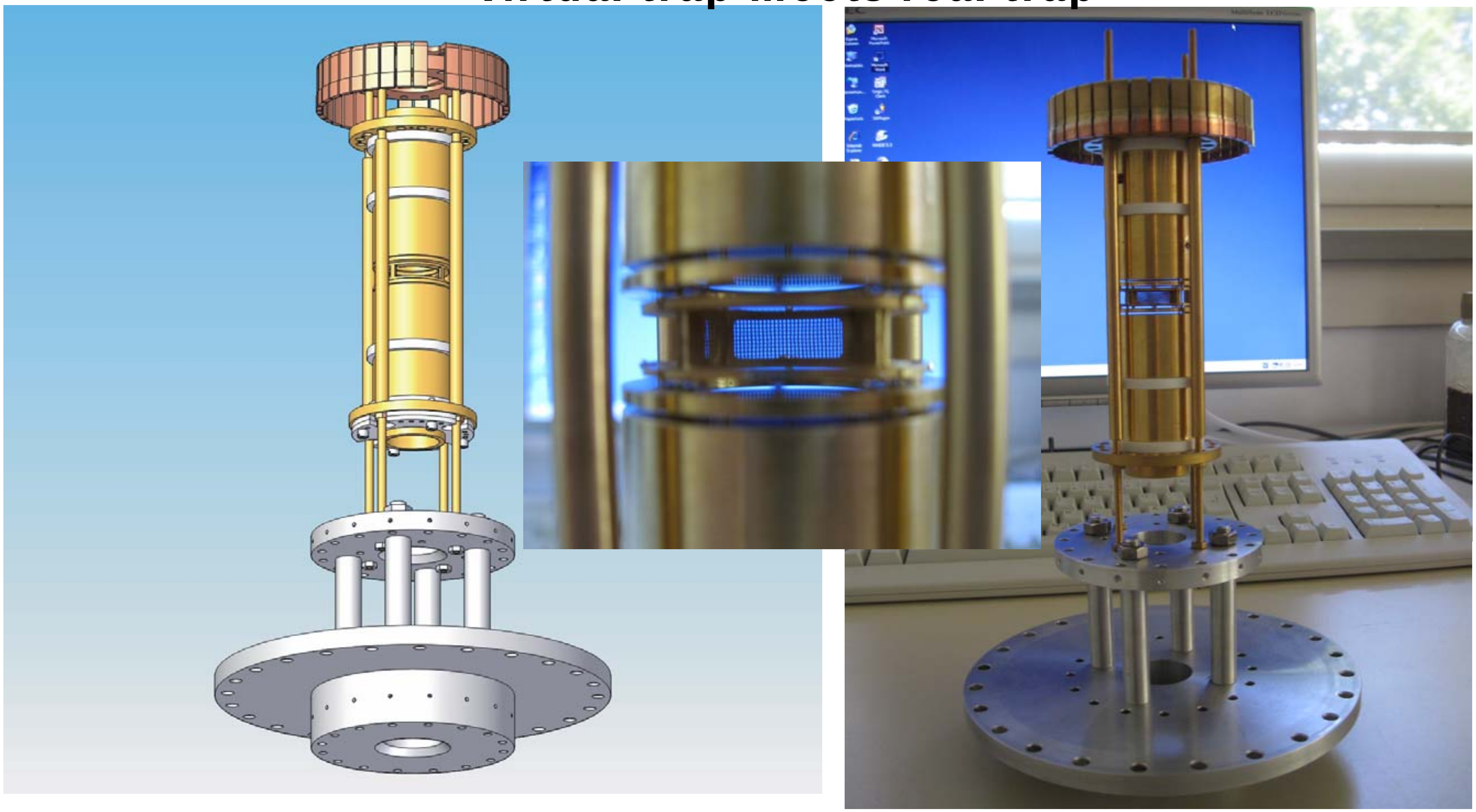


4 K ⟶ $\Delta E/E \sim 10^{-7}$

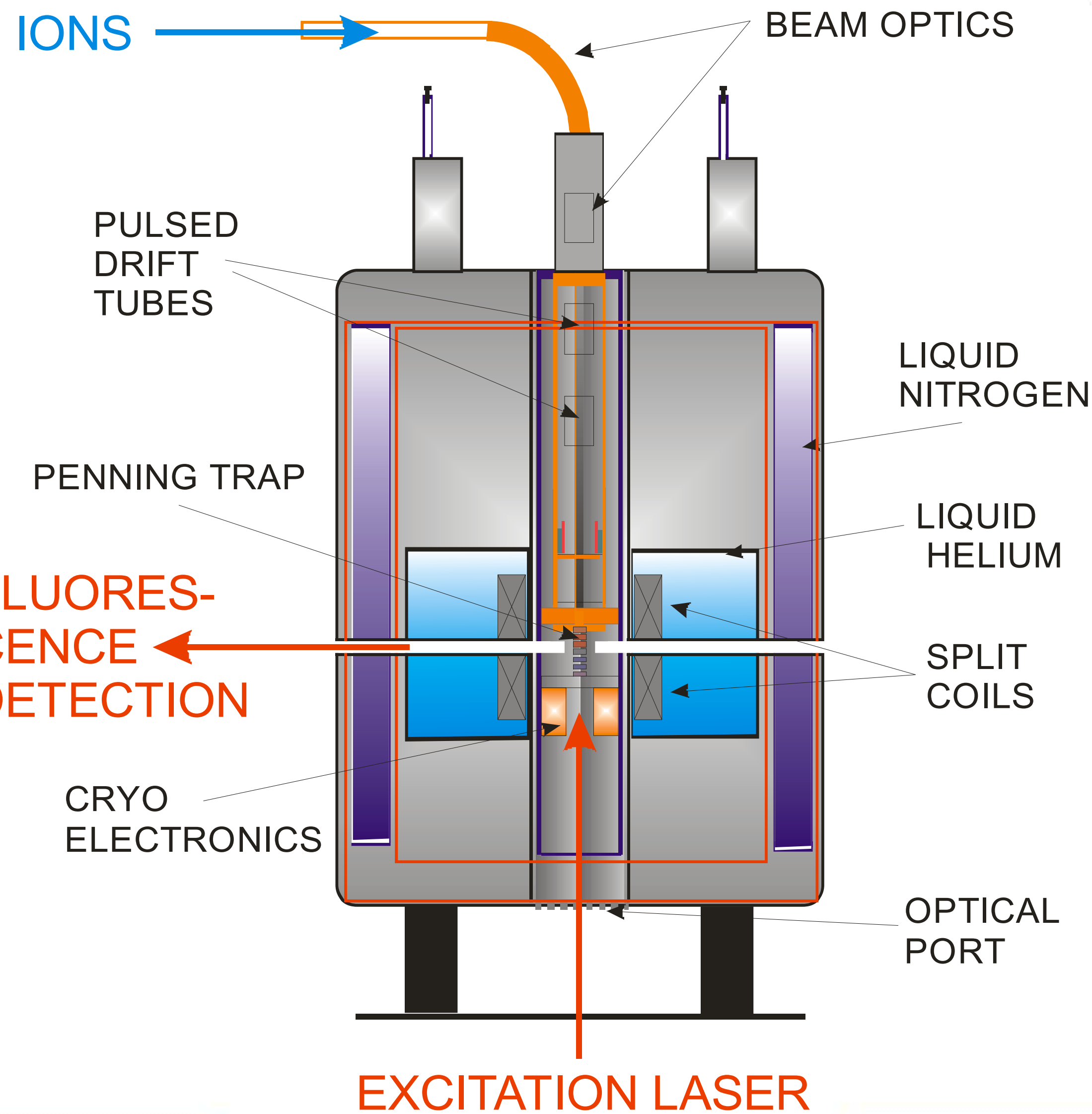
Ref.:
Wilfried Nörtershäuser et al.

SPECTRAP: Laser spectroscopy of HFS transitions in highly charged ions

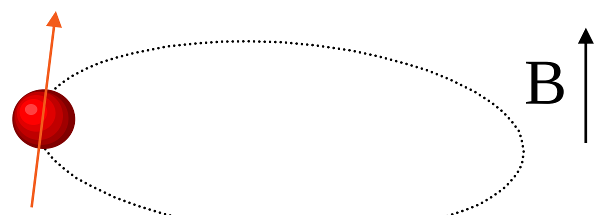
virtual trap meets real trap



SPECTRAP setup at the HITRAP facility



g-Factor of the electron



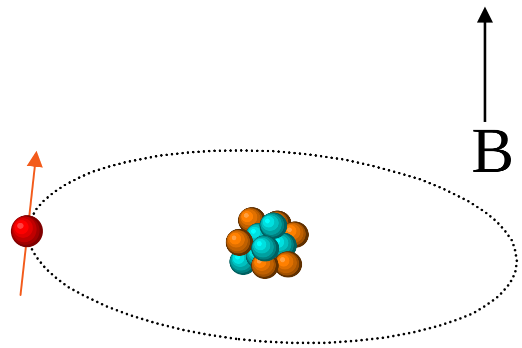
$$\mu = g \cdot \frac{e}{2m} J$$

m: magnetic moment
g: g-factor
e: charge
m: mass
J: angular momentum

g-Factor of the electron bound in a hydrogen-like ion

Larmor precession frequency of the bound electron:

$$\omega_L^{\ e} = \frac{g_J}{2}\frac{e}{m_e}B$$



Ion cyclotron frequency:

$$\omega_c^{\ ion} = \frac{Q}{M_{ion}}B$$

$$g_J = 2 \cdot \frac{\omega_L^{\ e}}{\omega_c^{\ ion}} \cdot \frac{m_e}{M_{ion}} \cdot \frac{Q^{ion}}{e}$$

→ 'experimental g-factor'
→ comparison with theory

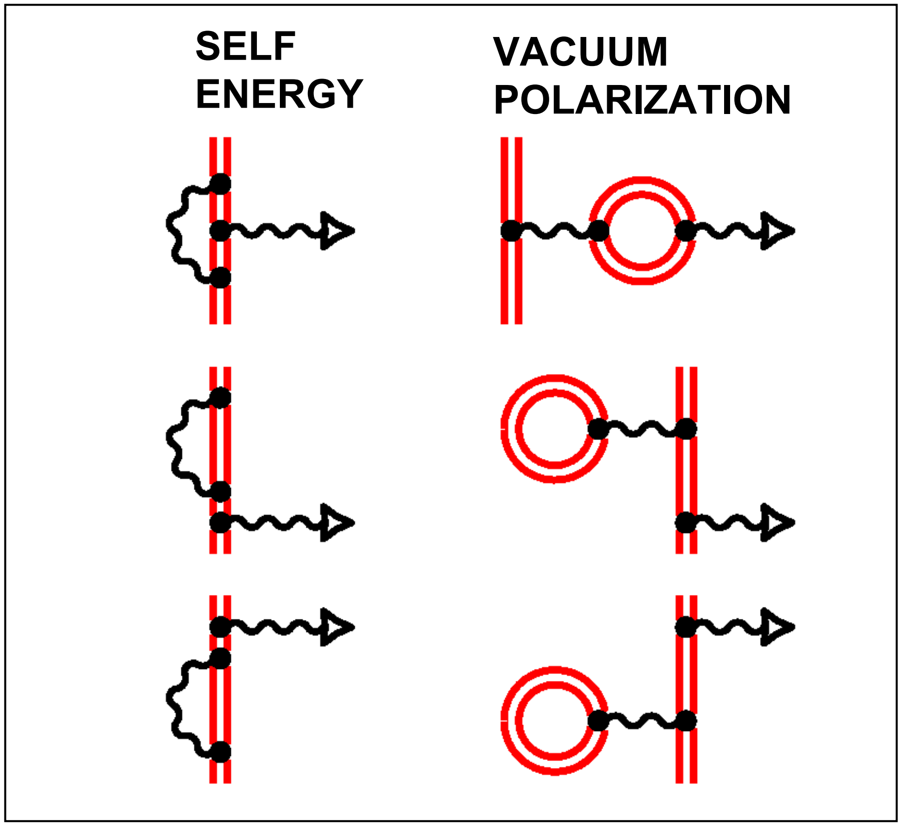
our measurement

external input parameter

Bound-electron g-factor:
Feynman graphs 1st order in α/π

$$g_{bound}/g_{free} \approx 1 - (Z\alpha)^2/3 + \alpha(Z\alpha)^2/4\pi + \ldots$$

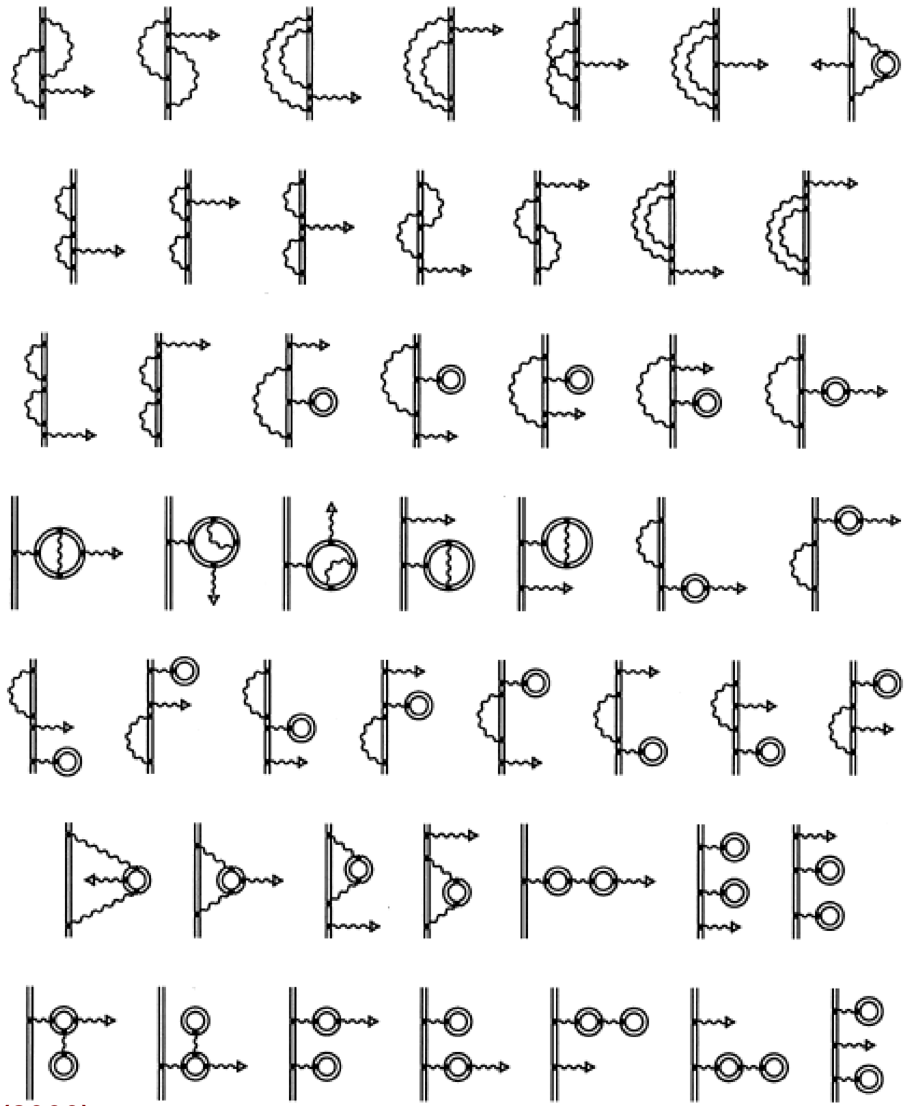
Dirac theory — bound-state QED



Ref.:
T. Beier, Physics Reports 339, 79 (2000)

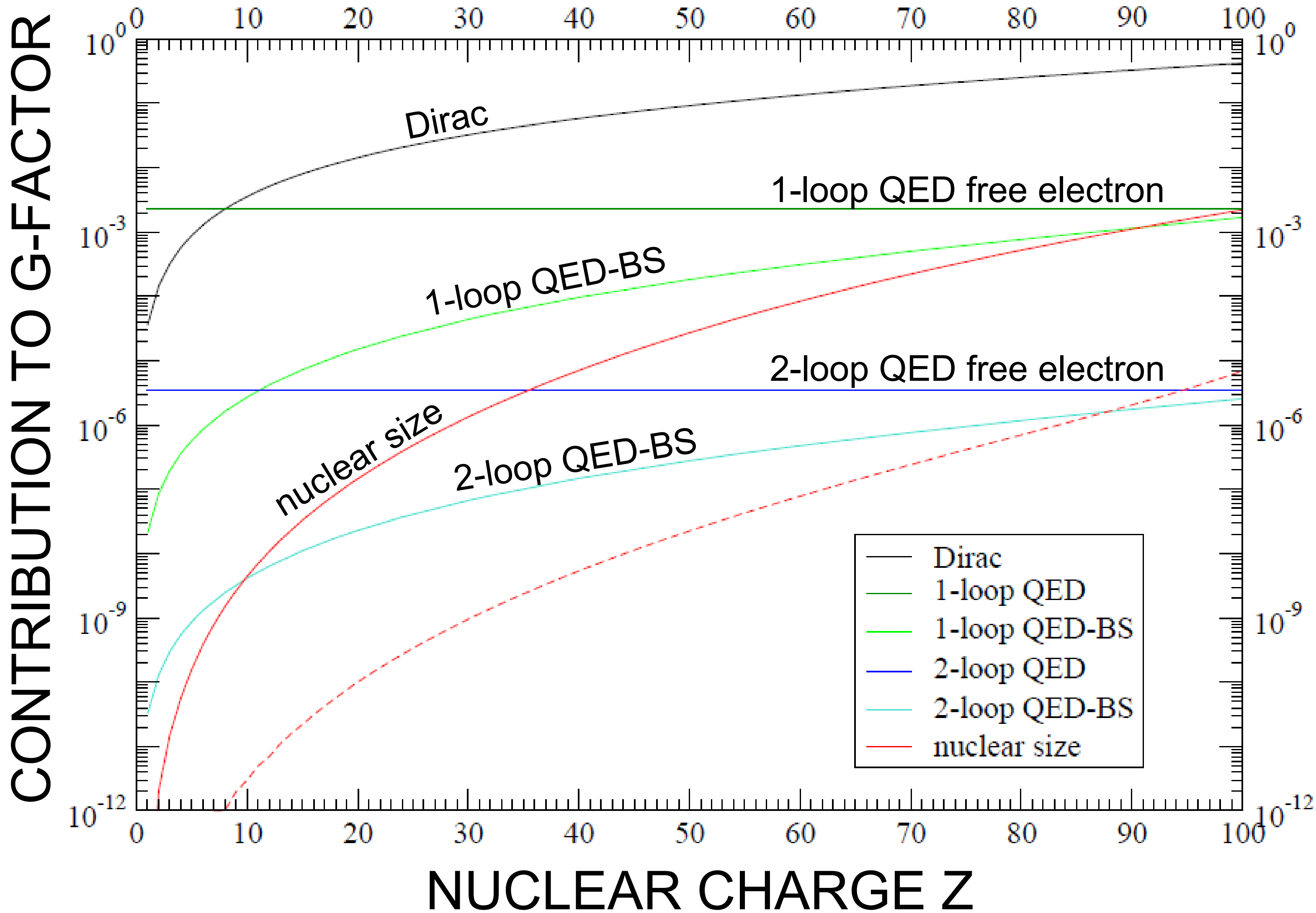
Bound-electron g-factor:
Feynman graphs 2nd order in α/π

50 graphs



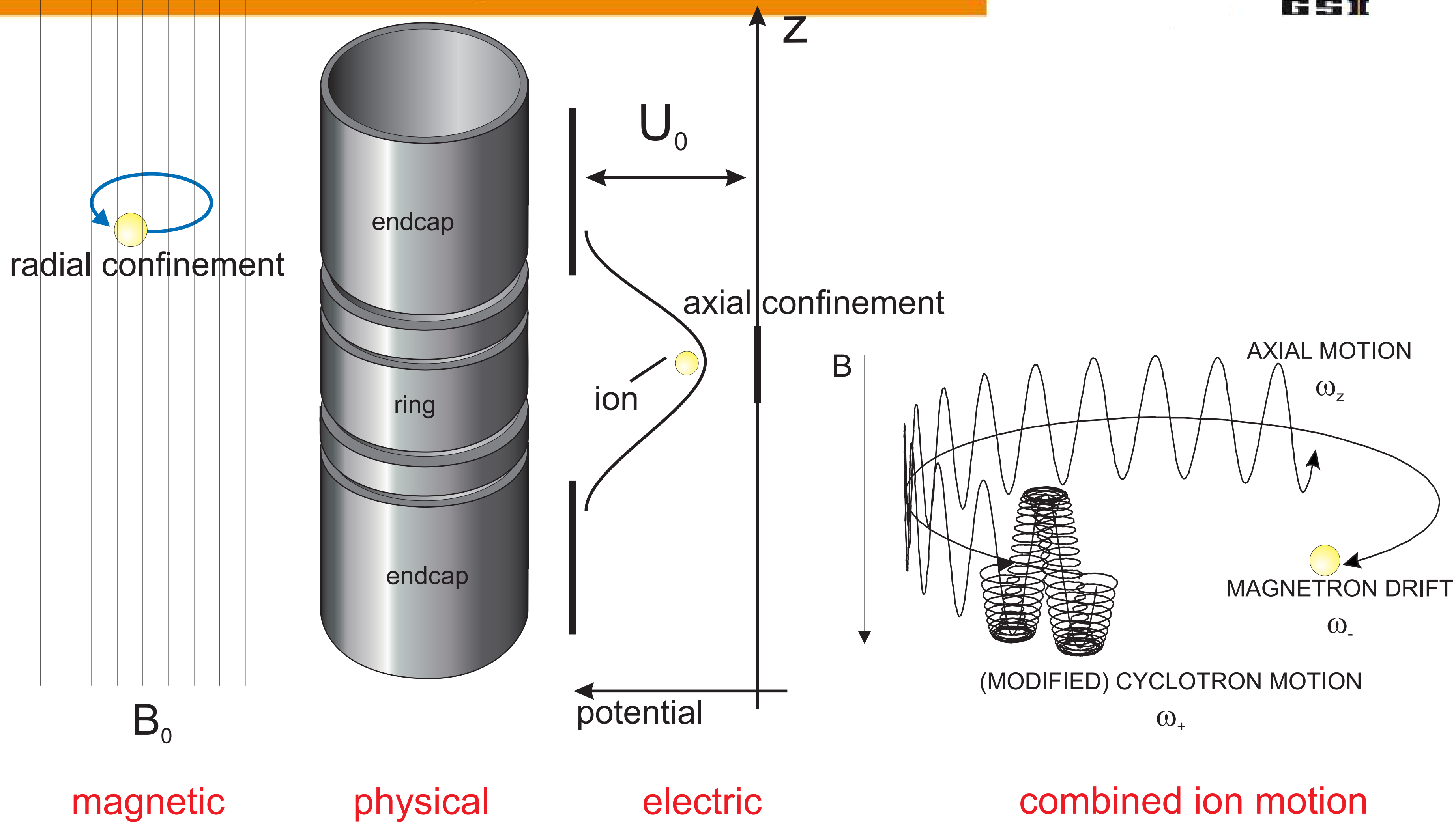
Ref.:
T. Beier, Physics Reports 339, 79 (2000)

Bound-electron g-factor

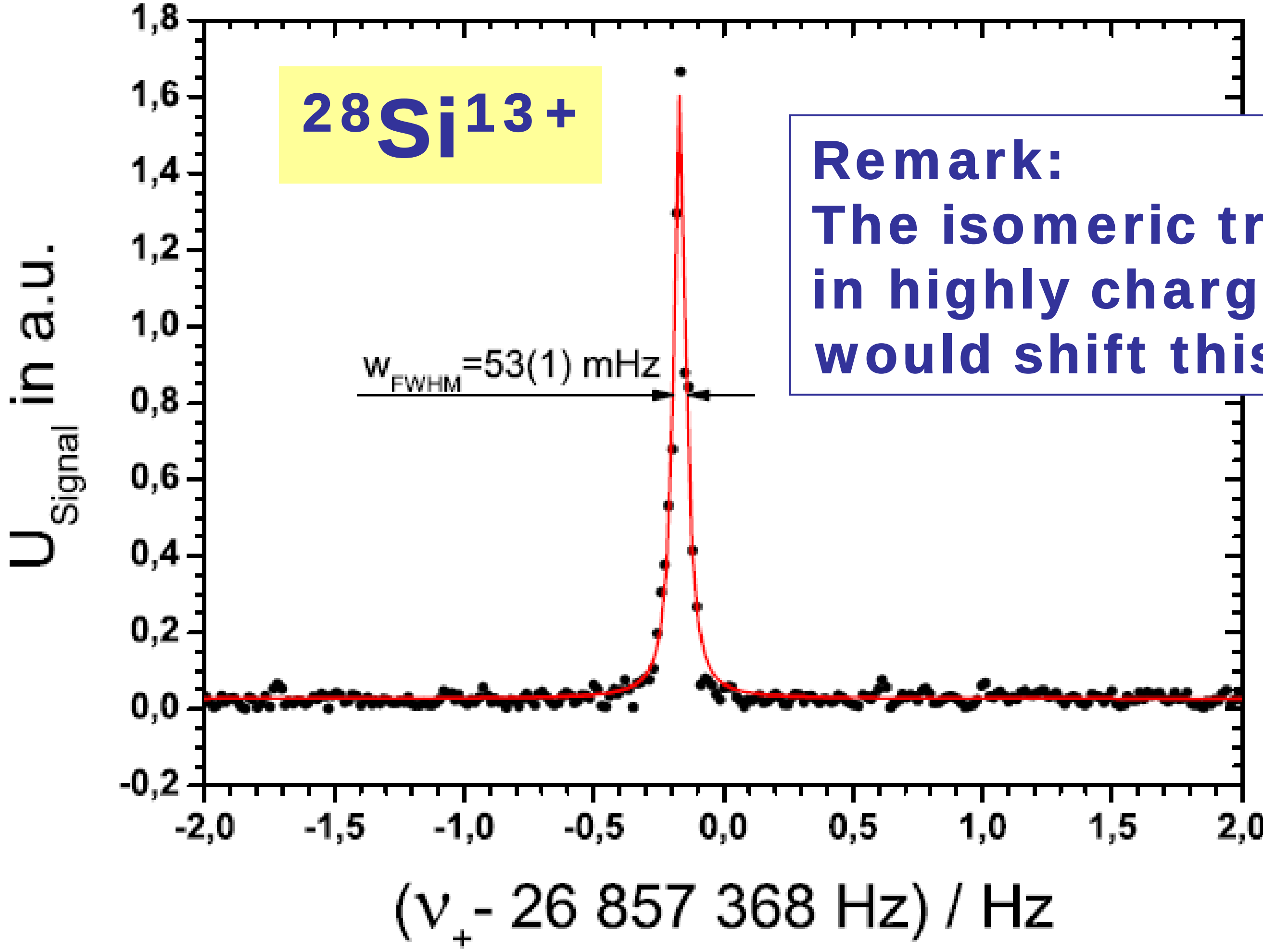


Ref.:
D. Glazov

A single HCI stored in a Penning trap



High-resolution cyclotron frequency measurement of a single highly charged silicon ion by Schottky detection

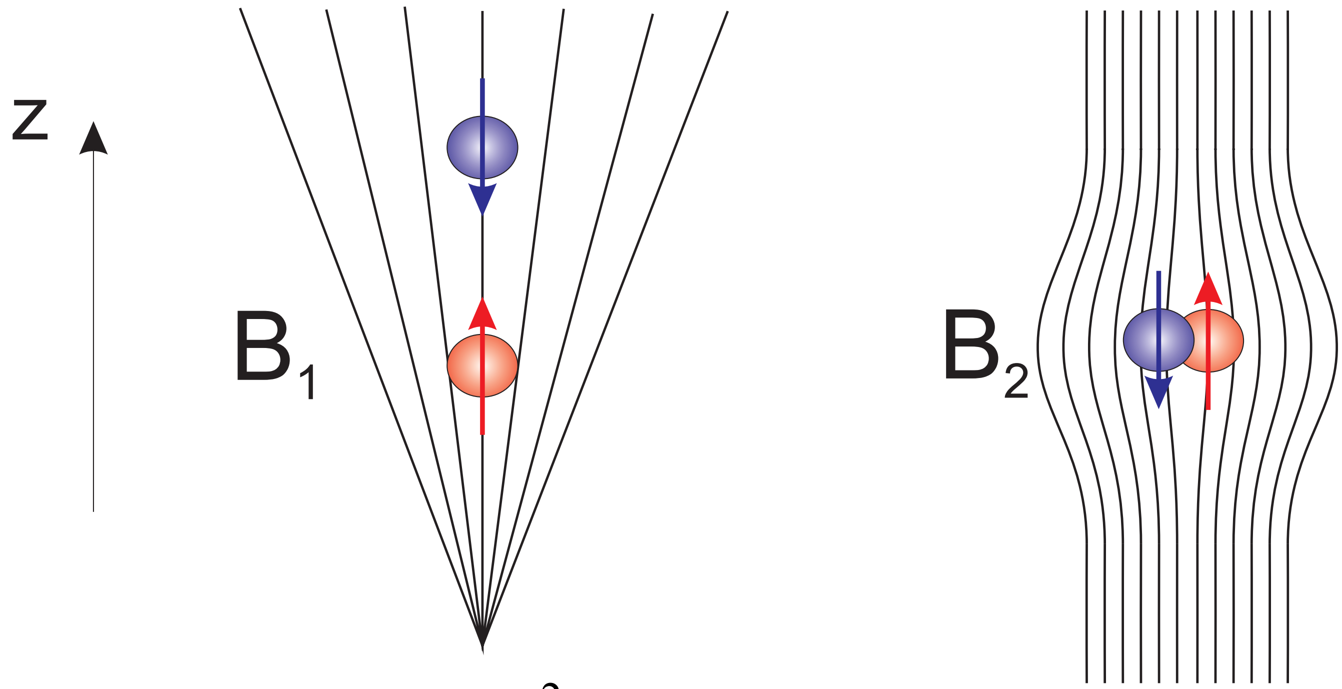


Remark:
The isomeric transition in highly charged thorium would shift this line by 1 mHz.

Ref.:
Birgit Schabinger, Sven Sturm, Anke Wagner

Continuous Stern-Gerlach effect: Determination of spin direction

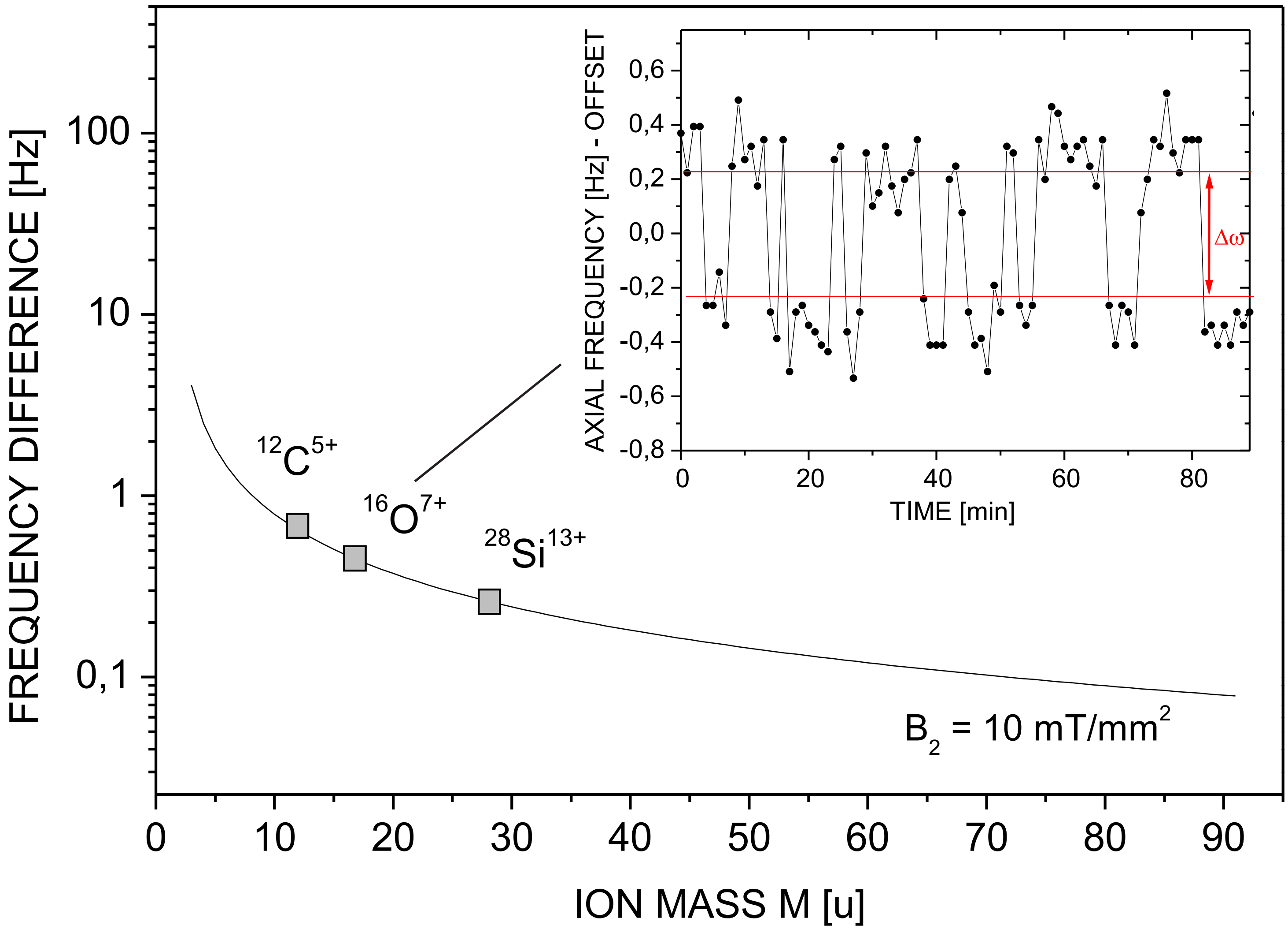
CLASSICAL STERN-GERLACH	CONTINUOUS STERN-GERLACH
SEPARATION IN POSITION SPACE	SEPARATION IN FREQUENCY SPACE



$$\Delta z = \frac{\mu L^2}{2KE} B_1$$

$$\Delta \omega_z = \frac{\mu}{m\omega_z} B_2$$

Quantum jumps of a single HCI in a Penning trap



Bound electron magnetic moment measurement on hydrogen-like silicon $^{28}Si^{13+}$

PRL **107**, 023002 (2011) PHYSICAL REVIEW LETTERS week ending 8 JULY 2011

g Factor of Hydrogenlike $^{28}Si^{13+}$

S. Sturm,[1,2] A. Wagner,[1] B. Schabinger,[1,2] J. Zatorski,[1] Z. Harman,[1,3] W. Quint,[4] G. Werth,[2] C. H. Keitel,[1] and K. Blaum[1]

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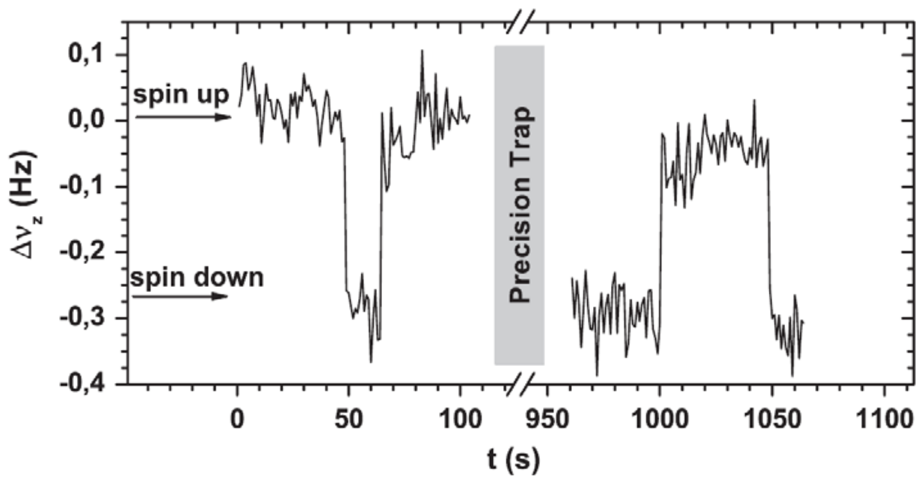
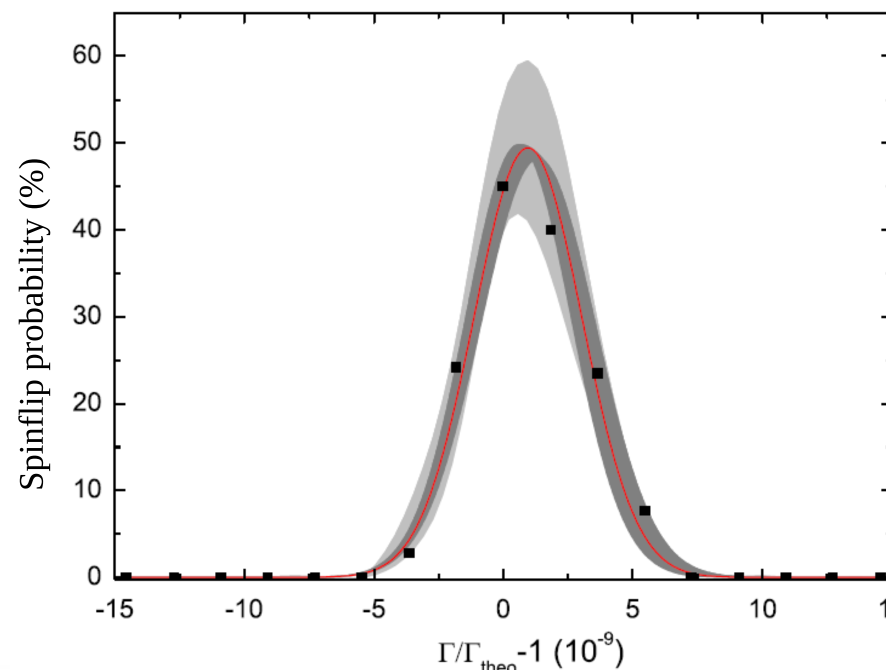
[4]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt, Germany*

(Received 6 May 2011; published 7 July 2011)

We determined the experimental value of the g factor of the electron bound in hydrogenlike $^{28}Si^{13+}$ by using a single ion confined in a cylindrical Penning trap. From the ratio of the ion's cyclotron frequency and the induced spin flip frequency, we obtain $g = 1.995\,348\,958\,7(5)(3)(8)$. It is in excellent agreement with the state-of-the-art theoretical value of $1.995\,348\,958\,0(17)$, which includes QED contributions up to the two-loop level of the order of $(Z\alpha)^2$ and $(Z\alpha)^4$ and represents a stringent test of bound-state quantum electrodynamics calculations.





Comparison of theory and experiment: g-Factor of the bound electron in H-like carbon $^{12}C^{5+}$, oxygen $^{16}O^{7+}$ and silicon $^{28}Si^{13+}$

$g_J(^{12}C^{5+})$ = 2.001 041 590 18 (3) theoretical value
$g_J(^{12}C^{5+})$ = 2.001 041 596 4 (10)(44) our measurement

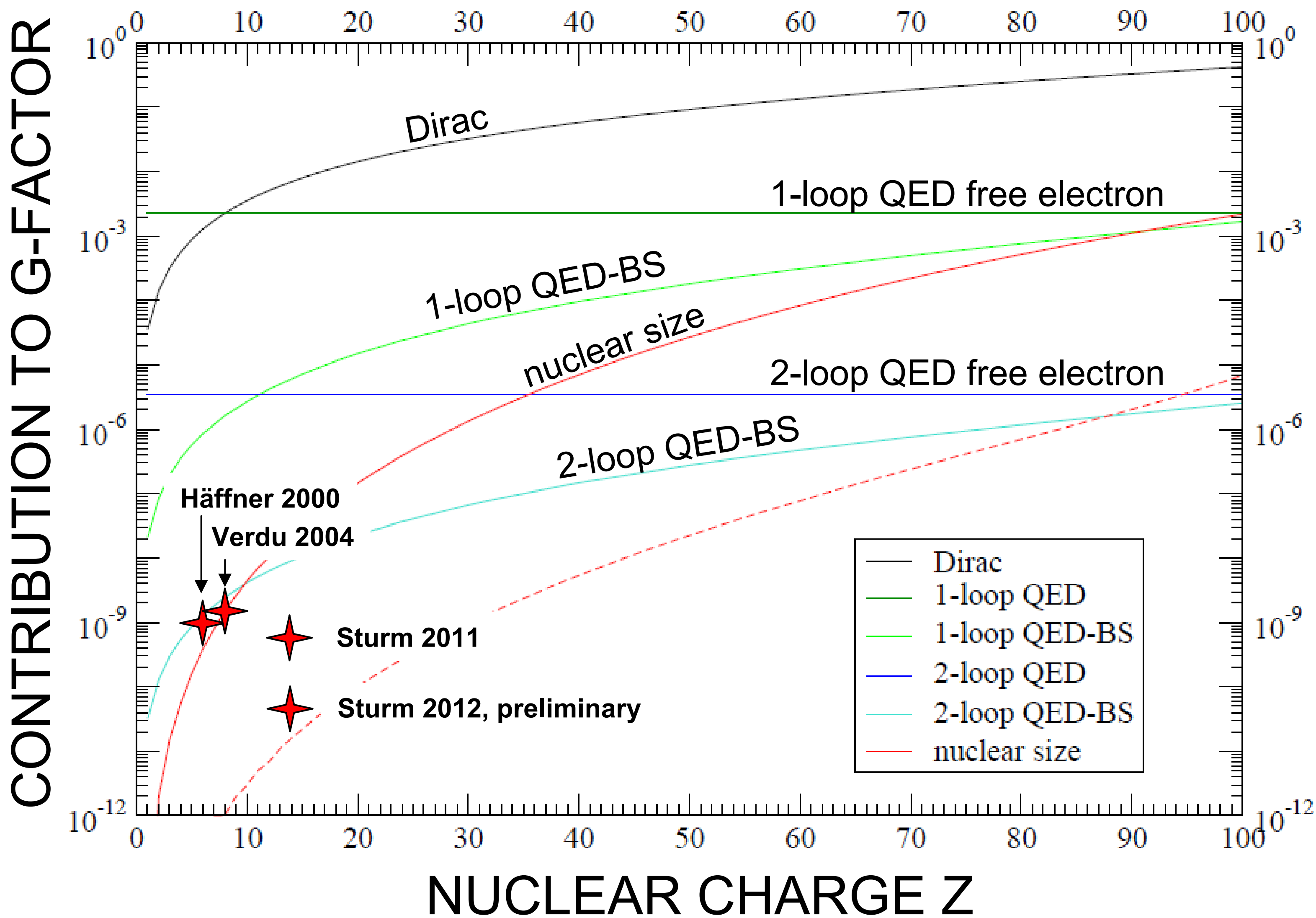
$g_J(^{16}O^{7+})$ = 2.000 047 020 32 (11) theoretical value
$g_J(^{16}O^{7+})$ = 2.000 047 025 4 (15)(44) our measurement

$g_J(^{28}Si^{13+})$ = 1.995 348 958 0 (17) theoretical value
$g_J(^{28}Si^{13+})$ = 1.995 348 958 7 (5)(3)(8) our measurement

Lit.:

T. Beier et al., PRL 88, 011603 (2002)
V. Shabaev et al., PRL 88, 091801 (2002)
V. Yerokhin et al., PRL 89, 143001 (2002)
K. Pachucki, V. Yerokhin et al., PRA 72, 022108 (2005)
S. Sturm et al., PRL 107, 023002 (2011)

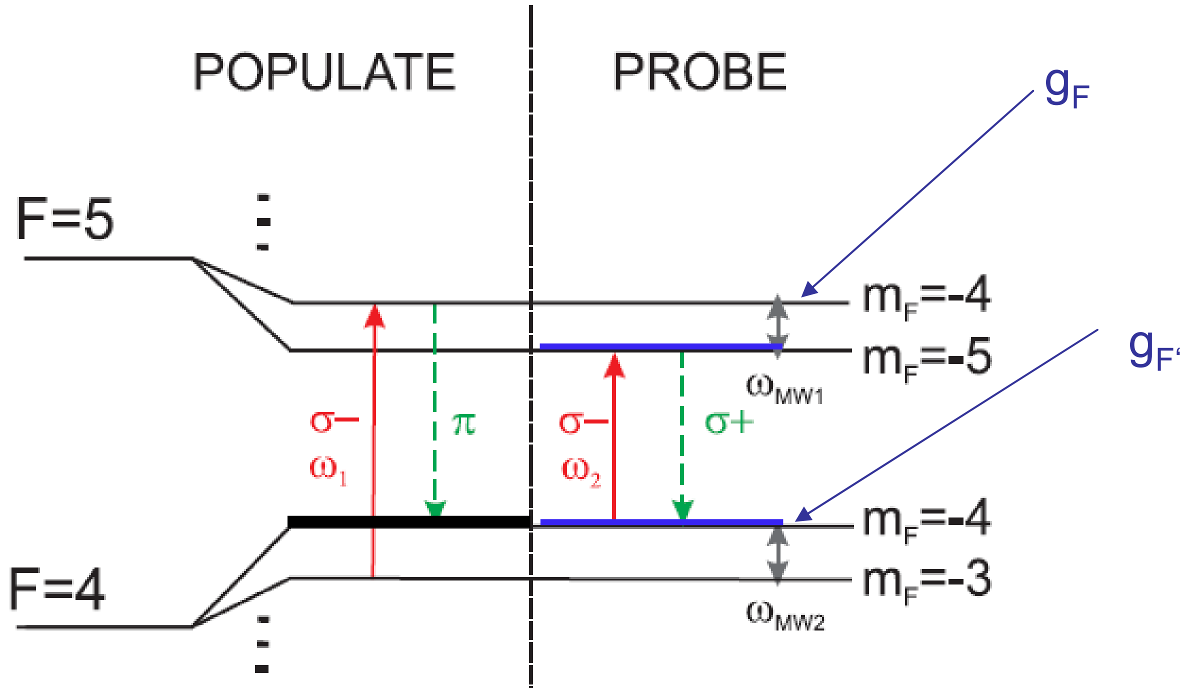
Bound-electron g-factor



Ref.:
D. Glazov

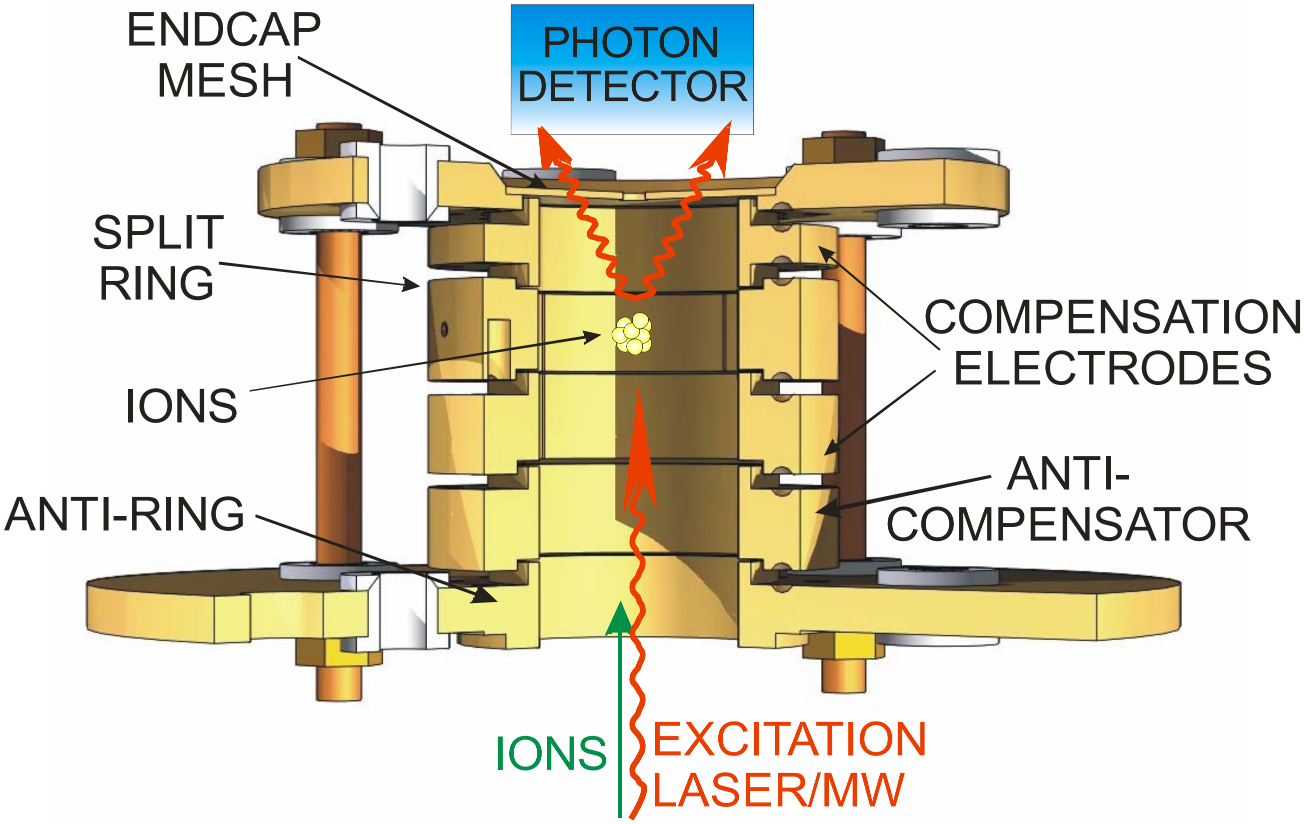
Laser-microwave double resonance spectroscopy for bound electron g-factor measurements in $^{209}Bi^{82+}$

idea:
use the light from the optical transition as a probe for the Zeeman transitions



Alternative to quantum jump spectroscopy by continuous Stern-Gerlach effect

Half-open Penning trap for laser-microwave double resonance spectroscopy: ARTEMIS



Ref.:
David von Lindenfels, Marco Wiesel, Manuel Vogel

Determination of electron g-factor g_J and nuclear g-factor g_I from two g_F-factors *(thanks to Moskovkin, Shabaev)*

if g_F is measured for two different F levels,
then we can simultaneously and independently get

$$g_J = (I+1)g_{F'} - I g_F - \delta_Q Q \left(\frac{m_e c}{\hbar}\right)^2 \frac{2(I+1)}{2I-1}$$

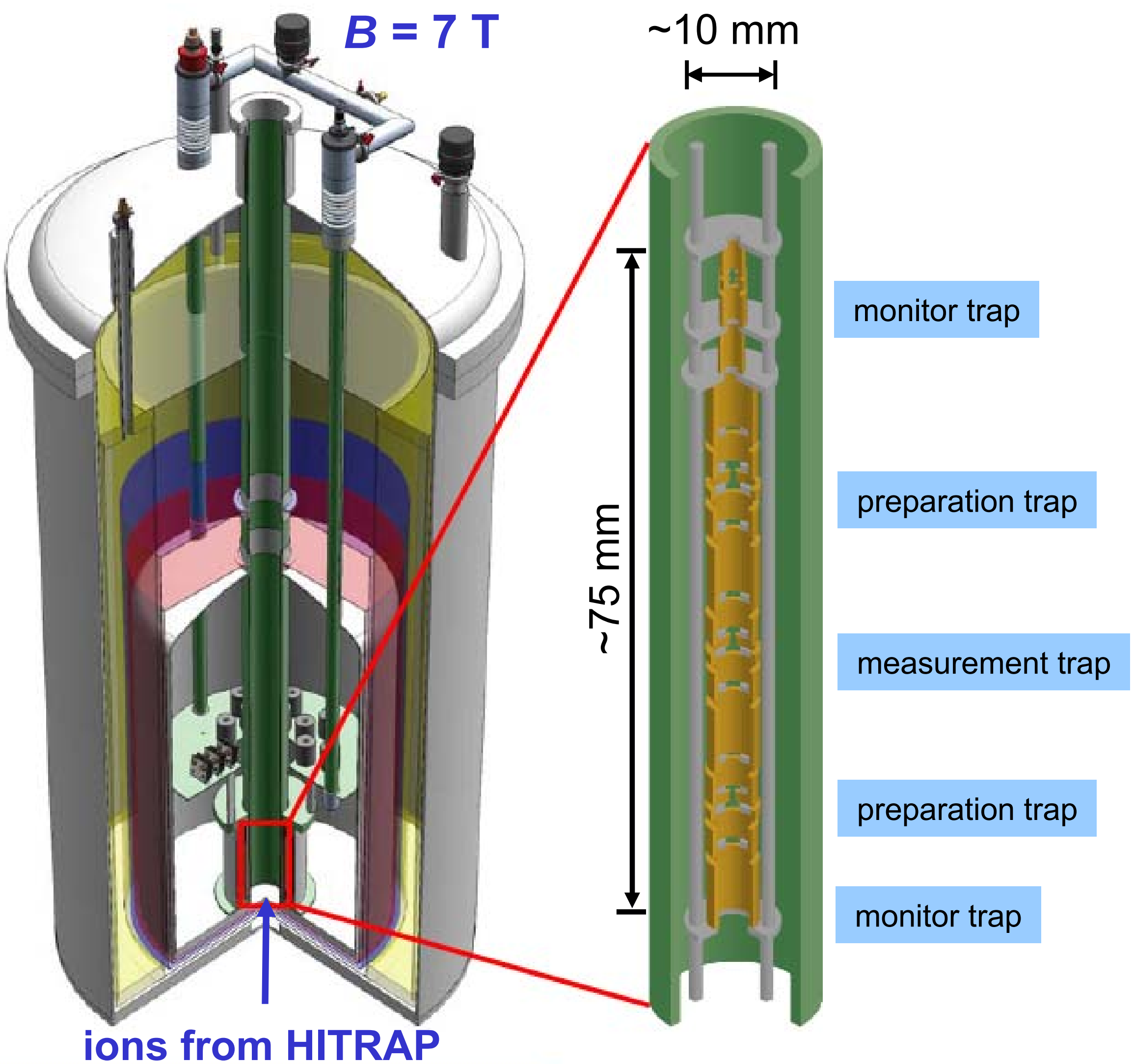
theoretical uncertainty: 1.5×10^{-10}

$$g_I = -\frac{m_p}{m_e} \frac{g_{F'} + g_F + \delta_Q Q \left(\frac{m_e c}{\hbar}\right)^2 \frac{3}{I(2I-1)}}{2(1-\delta_\mu)} .$$

Remark:
We are **independent** of **diamagnetic shielding**,
i.e. shielding effects can for the first time be measured and theory can be tested.

High-accuracy mass measurements with heavy HCI

PENTATRAP: novel five-fold Penning trap mass spectrometer



- measurement of cyclotron frequency in different charge states
- determination of atomic and nuclear binding energies

$\delta m/m < 1 \cdot 10^{-11} \rightarrow$
$\delta mc^2 \approx 2$ eV $\rightarrow$
'weighing' of Lamb shift or isomeric excitation energy

Ref.:
MPIK Heidelberg, Klaus Blaum

Determination of the proton g-factor

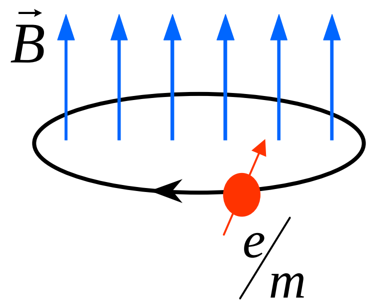
$$\omega_c = \frac{e}{m_p} B$$

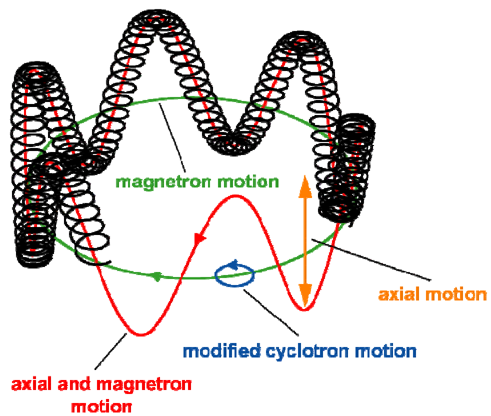
Cyclotron frequency

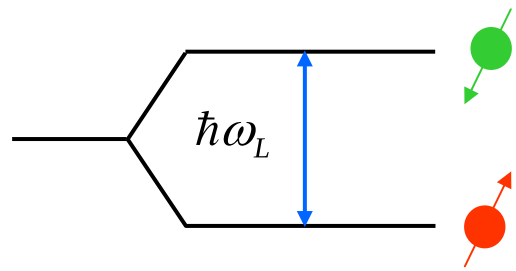
$$g = 2\,\frac{\omega_L}{\omega_c}$$

$$\omega_L = g\,\frac{e}{2m_p} B$$

Larmor frequency



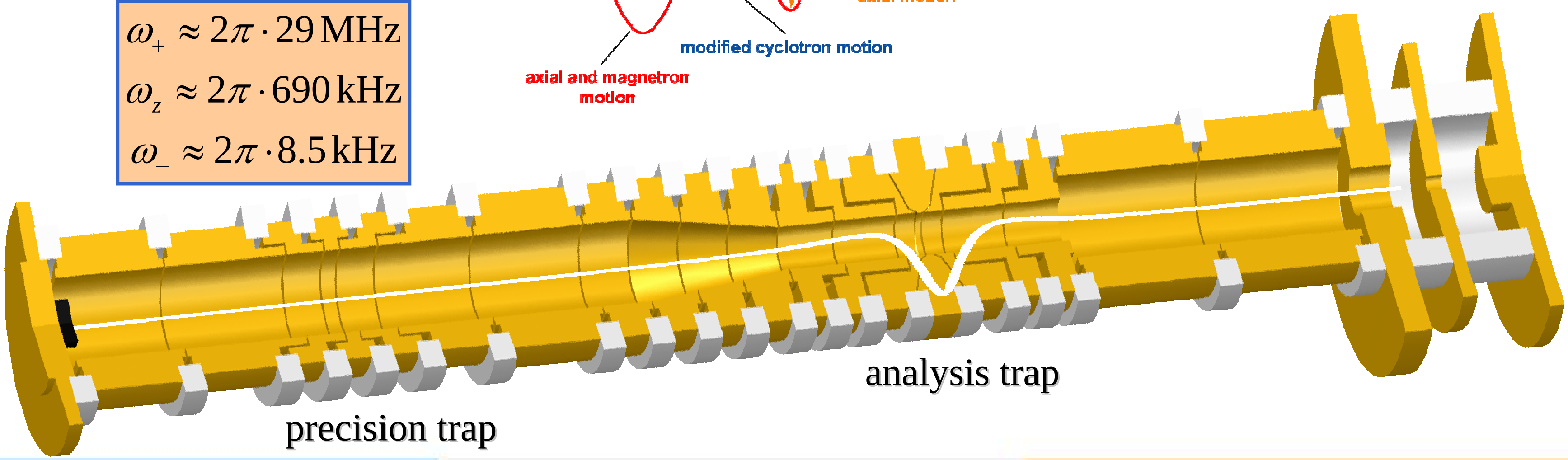




$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2}$$

$$\omega'_z(\uparrow) - \omega'_z(\downarrow) = \Delta\omega_z$$

$$\omega_+ \approx 2\pi \cdot 29\,\mathrm{MHz}$$
$$\omega_z \approx 2\pi \cdot 690\,\mathrm{kHz}$$
$$\omega_- \approx 2\pi \cdot 8.5\,\mathrm{kHz}$$



A single trapped proton and the continuous Stern-Gerlach effect

HELMHOLTZ ASSOCIATION

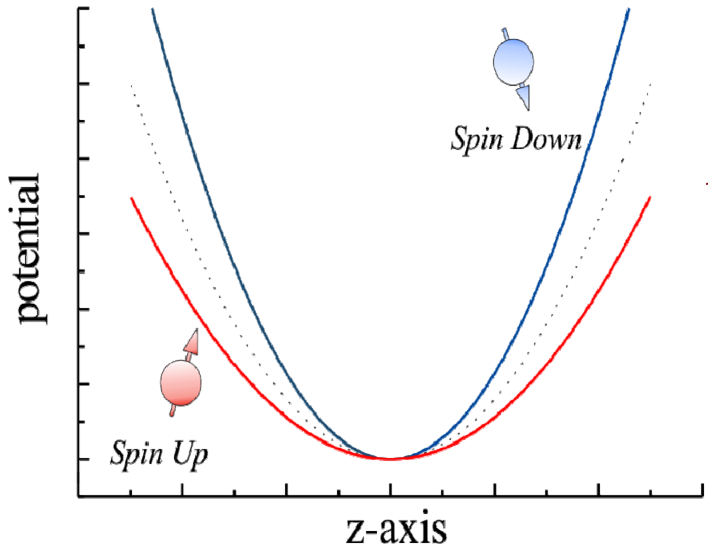
GSI

axial frequency shift due to spinflip:

$$\Delta\nu_z \approx \frac{1}{2\pi^2}\frac{\mu_z B_2}{m\nu_z}$$

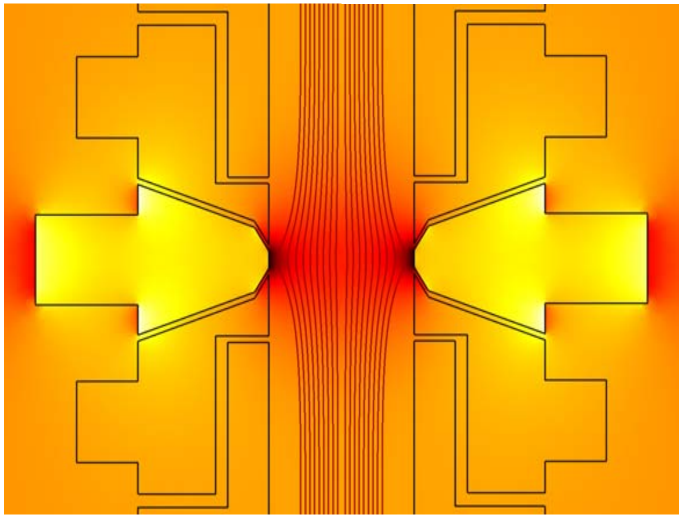
⇓

Proton measurement is 10 000 times harder compared to electron g-2 measurement.



***B_2* = 0.3 T/mm²**

***$\Delta\nu_z$*= 190 mHz**



First Larmor resonance curve of a single proton in the Penning trap

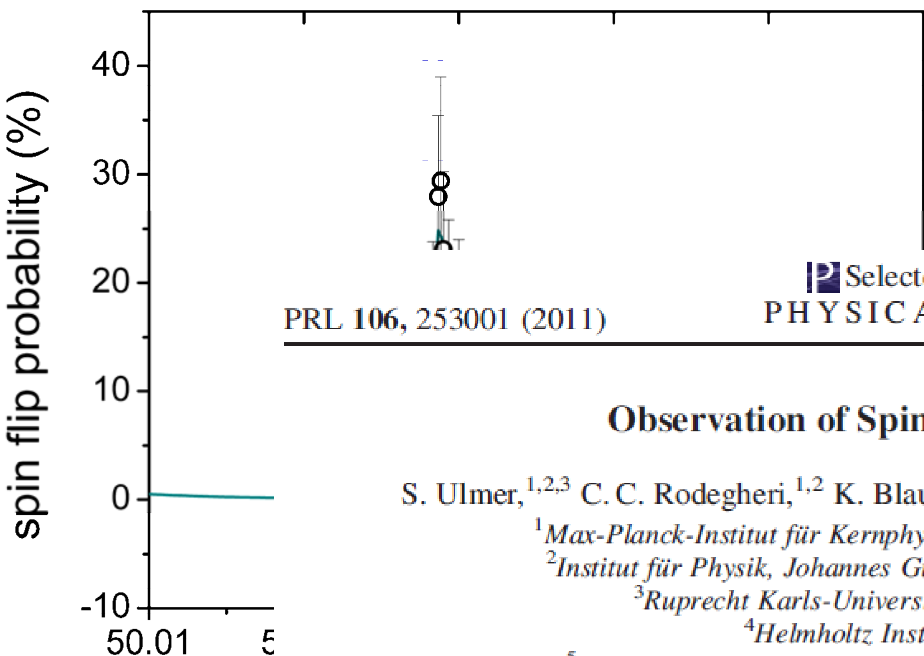
HELMHOLTZ ASSOCIATION

GSI

✓ Axial temperature reduced
✓ Larmor resonance narrower

$$\frac{\Delta \nu_L}{\nu_L} = 1.2 \cdot 10^{-6}$$

$$g = 2\frac{\nu_L}{\nu_c}$$



Next steps:

- Reduce axial frequency fluctuations further

Selected for a Viewpoint in *Physics*

PRL **106,** 253001 (2011) PHYSICAL REVIEW LETTERS week ending 24 JUNE 2011

Observation of Spin Flips with a Single Trapped Proton

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(Received 28 February 2011; published 20 June 2011)

Radio-frequency induced spin transitions of one individual proton are observed. The spin quantum jumps are detected via the continuous Stern-Gerlach effect, which is used in an experiment with a single proton stored in a cryogenic Penning trap. This is an important milestone towards a direct high-precision measurement of the magnetic moment of the proton and a new test of the matter-antimatter symmetry in the baryon sector.

Acknowledgements

- ✓ Atomic Physics Division at GSI Darmstadt
- ✓ Group at the institute of physics - Mainz
- ✓ Group of at MPIK Heidelberg

VH-NG-037

Helmholtz-Institut Mainz

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

Thank you for your attention !