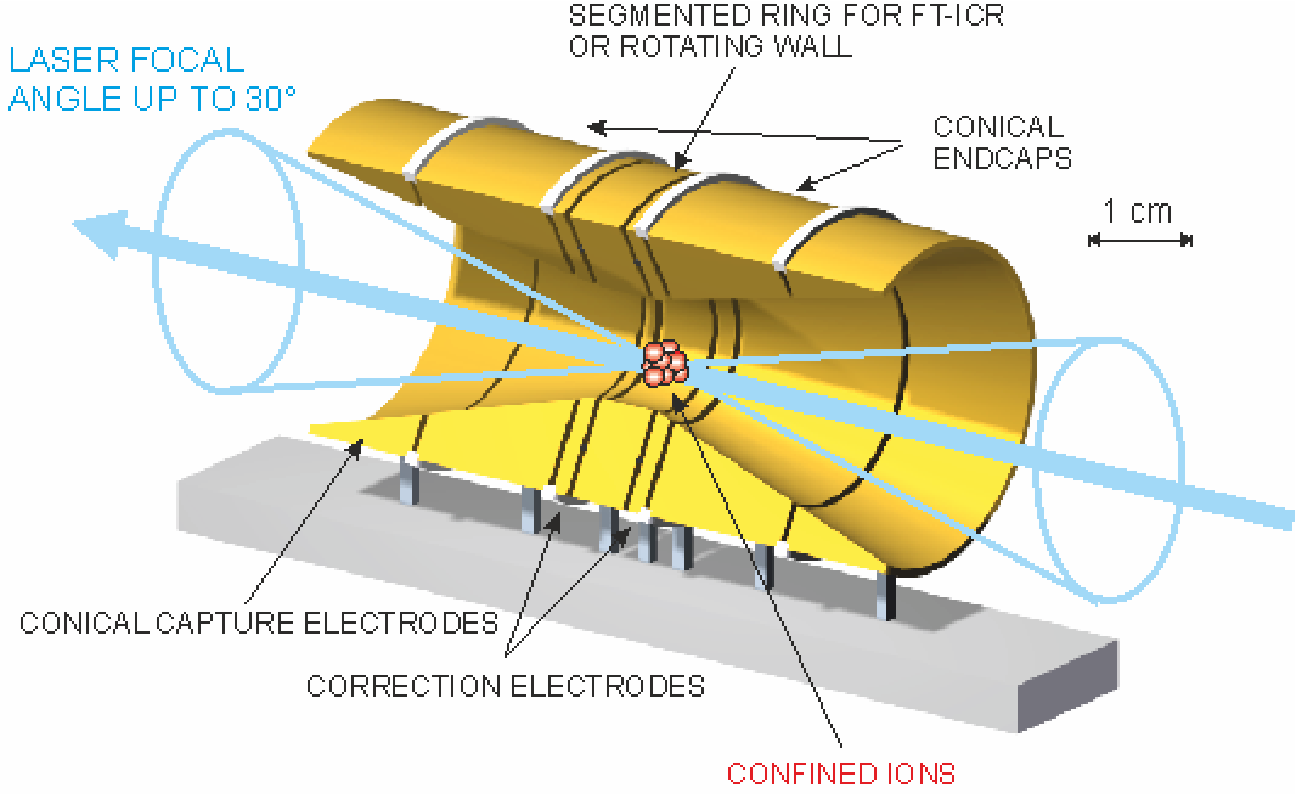
TRAP-ASSISTED STUDIES
@
A HIGH-INTENSITY LASER

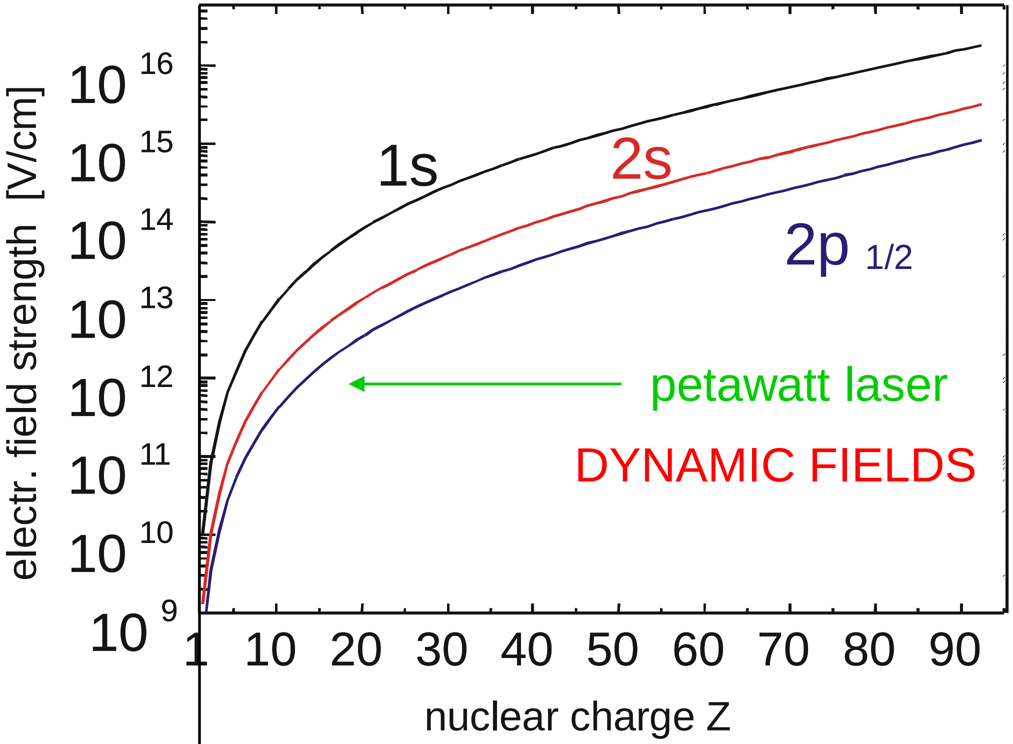


Helmholtz-Institut Jena
Schiller-Universität Jena

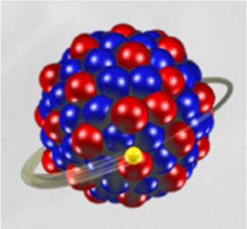
seit 1558

GSI

extreme fields



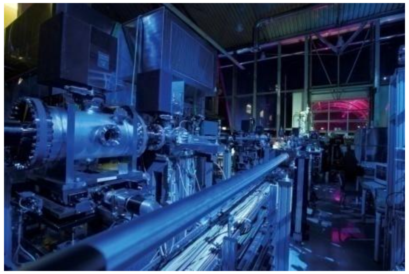
highly charged ions



STATIC FIELDS

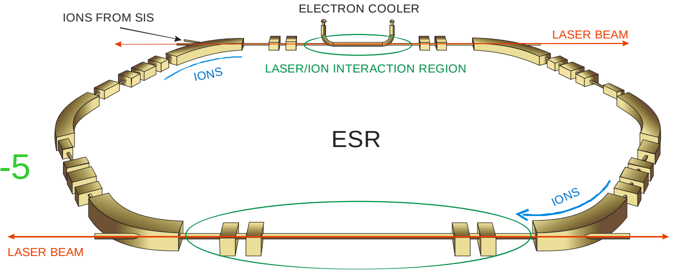
petawatt laser

DYNAMIC FIELDS



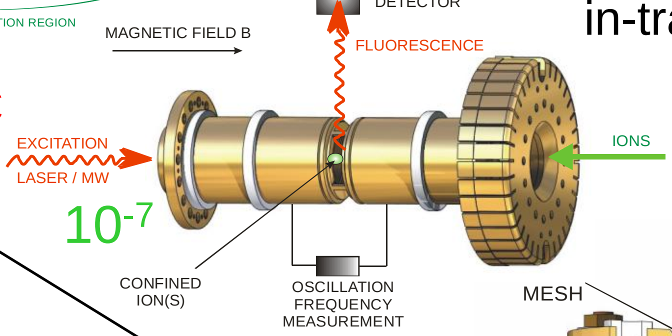
10^{4} lightning in air

our extreme field physics in traps



10^{-5}

in-ring experiments (e.g. LIBELLE)
(or EBIT)



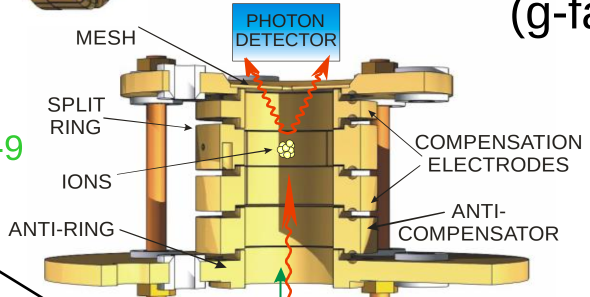
in-trap spectroscopy (SPECTRAP)

STATIC

DYNAMIC

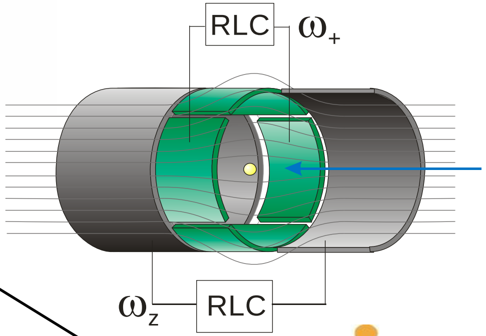
10^{-7}

double-resonance spectroscopy
(g-factor)

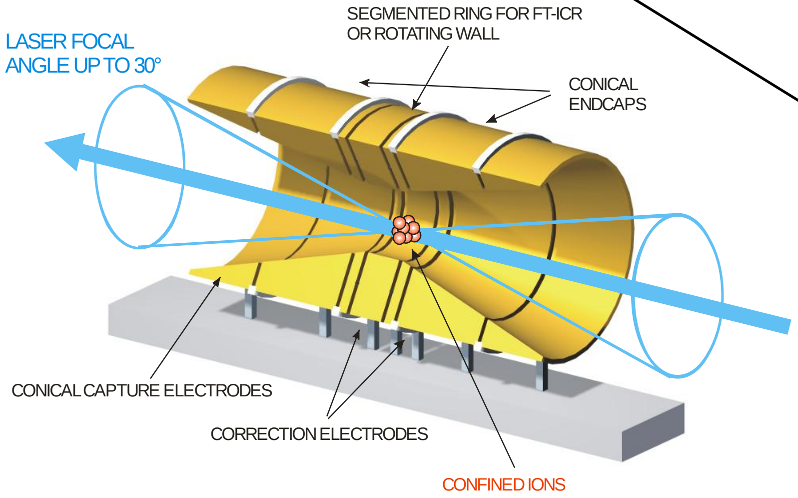


10^{-9}

blind spectroscopy



10^{-11}

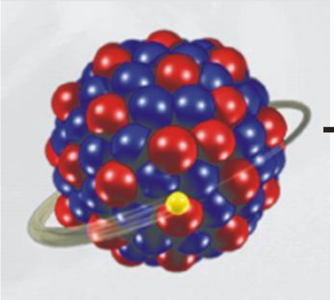


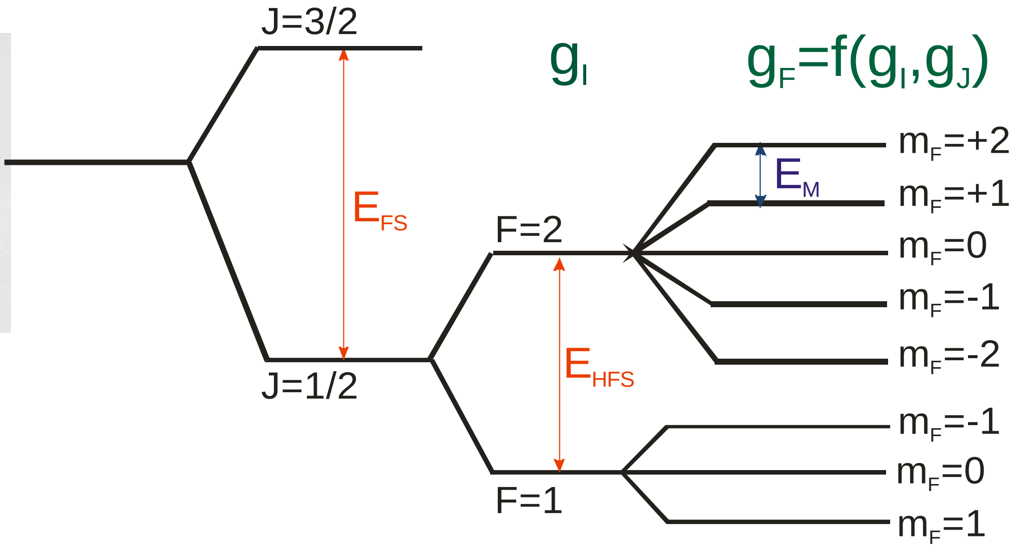
PHELIX
POLARIS
FLASH
JETI

precision spectroscopy of forbidden transitions in HCI (optical laser / MW)

Transition energy (frequency)	Z^2
Fine-structure (multiplet) splitting	$\alpha^2 Z^4$
Hyperfine splitting	$(m_e/m_p)\alpha^2 Z^3$
Lamb shift	$\alpha^5 Z^4$

HCI

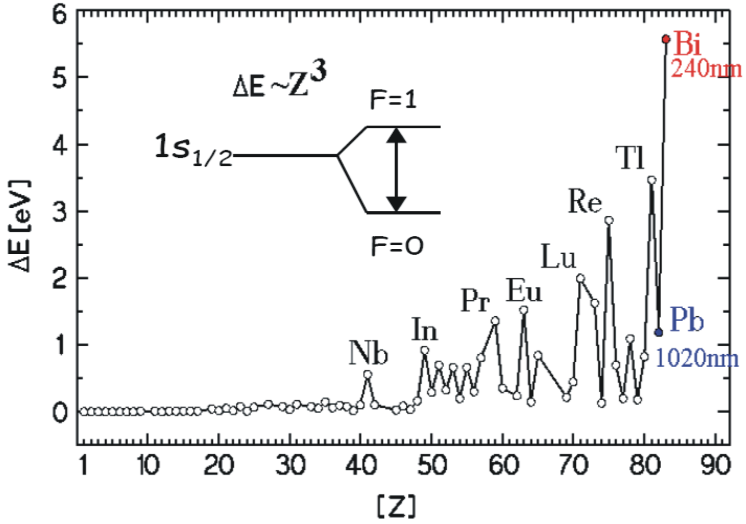




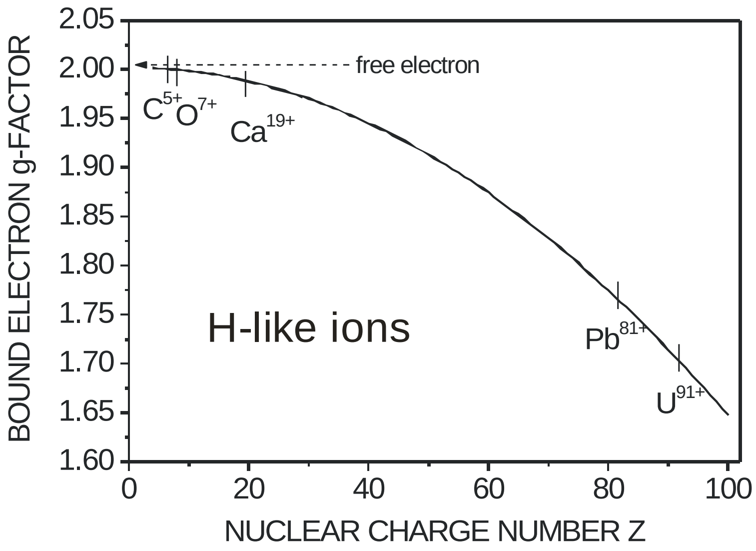
FINE STRUCTURE
J=L+S

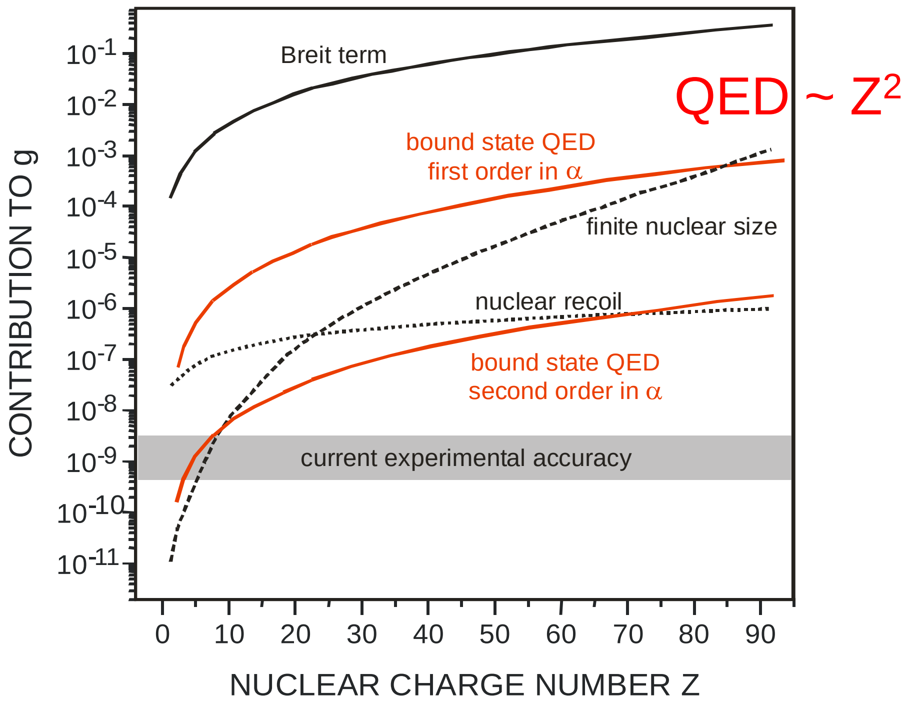
HYPERFINE STRUCTURE
F=I+J

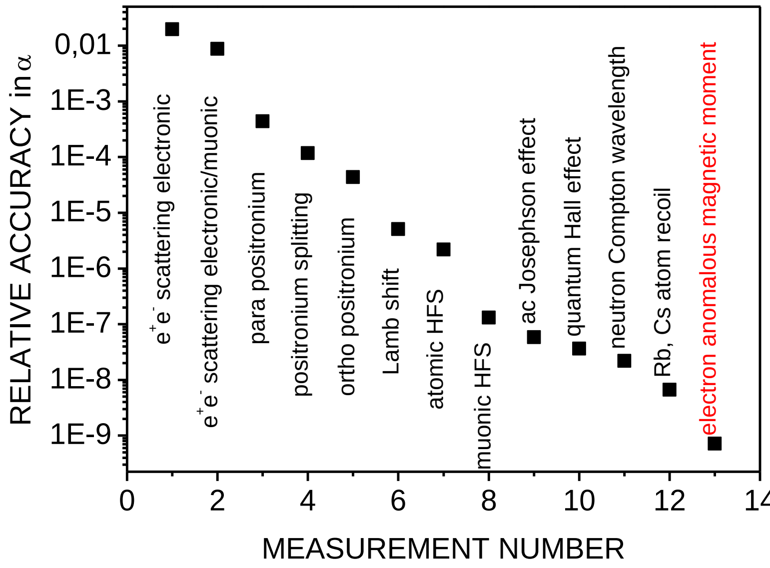
ZEEMAN
$m_F=-F...+F$

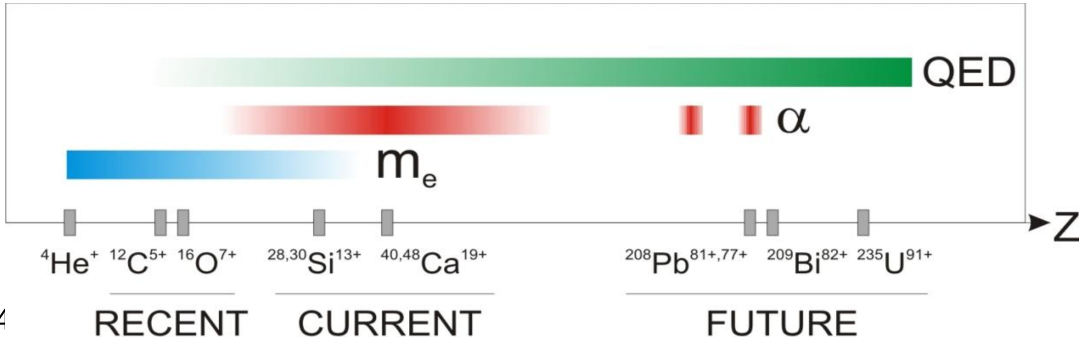


background: QED and fundamental constants



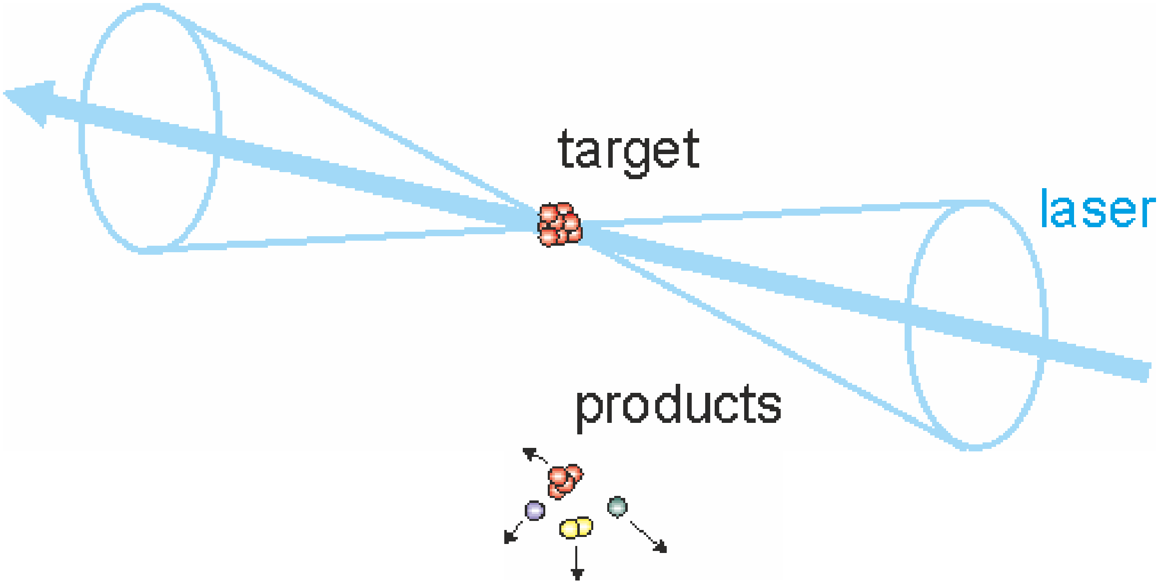






laser-induced reaction / analysis

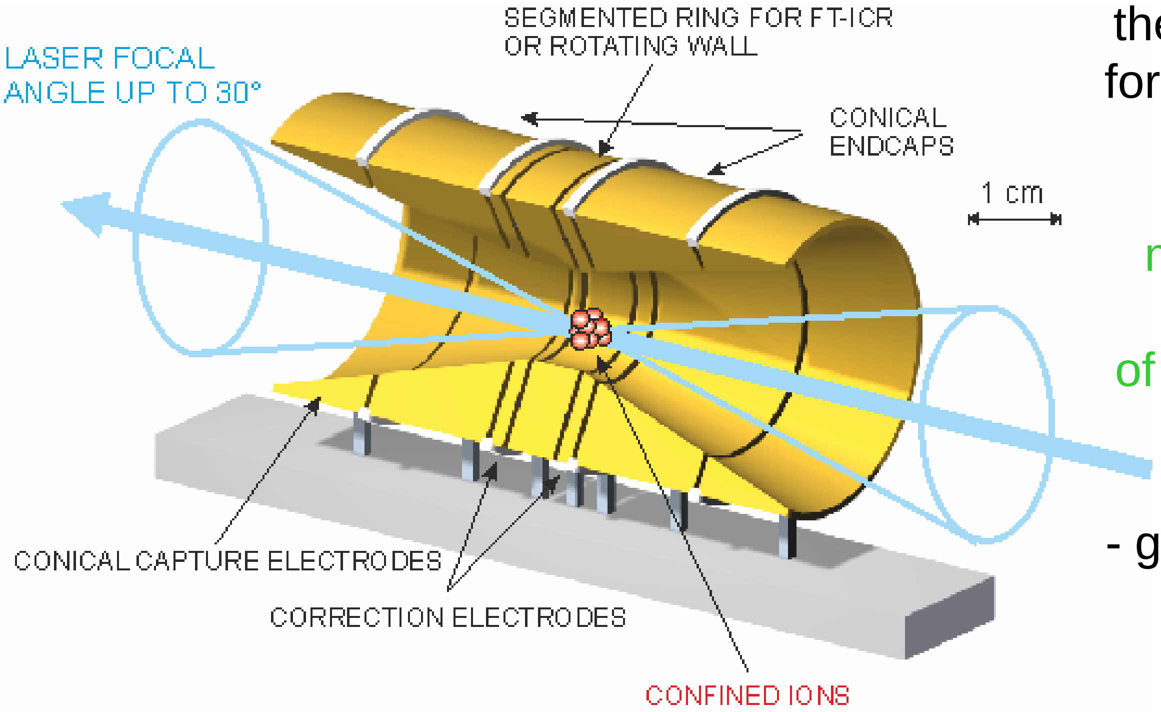
applications may be different but tools can be the same



typical problems: what exactly was the target?
what exactly are the products?

for charged particles both can be controlled by use of a Penning trap

use of a Penning trap



non-linear photoionisation
giant resonances
strong-field effects

„transparent“ experiment

the Penning trap as a universal tool for the study of reactions induced by a high-intensity laser

main motivation: non-destructive real-time analysis of multiphoton ionization processes with high resolution

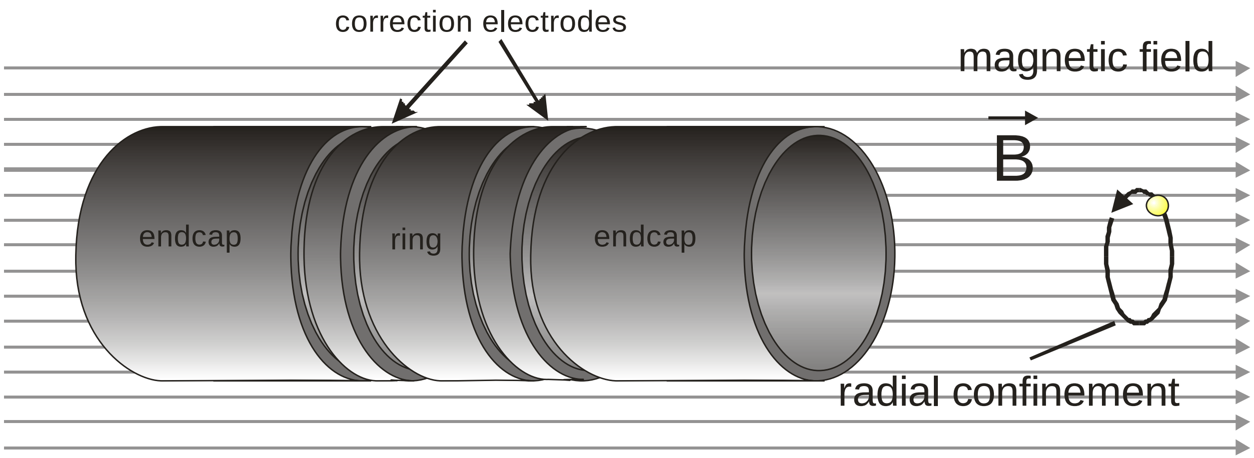
- good ion localization and extended storage times (minutes)

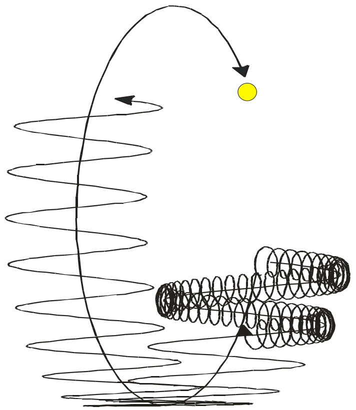
- well-controlled and clean environment for various reactions

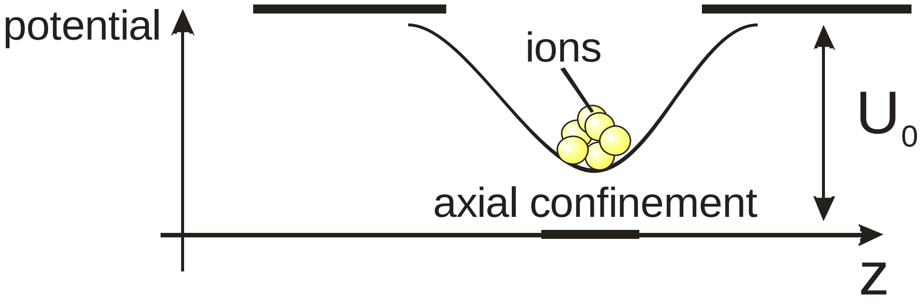
- numerous manipulation techniques

- non-destructive detection

Penning trap principles





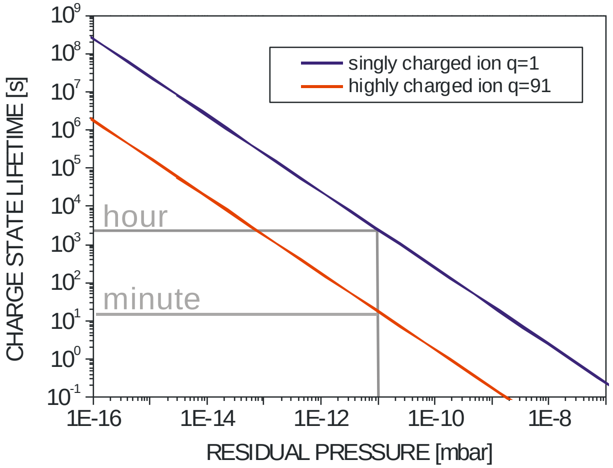


typical parameters: B = 6 T

U_0=100 V

d=20 mm

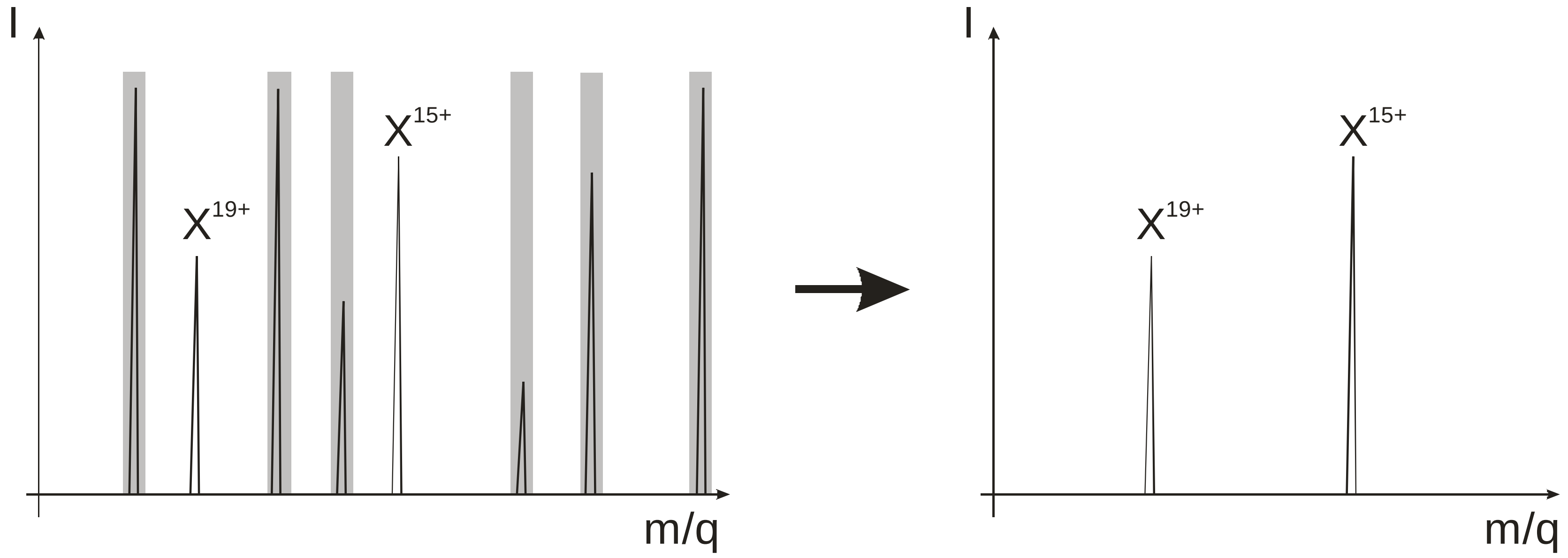
ω_- , ω_z, ω_+ = 10 kHz, 100 KHz, 10 MHz



techniques (1) : ion selection

selection of any mass to charge ratio combination
by resonant ejection of all unwanted ions

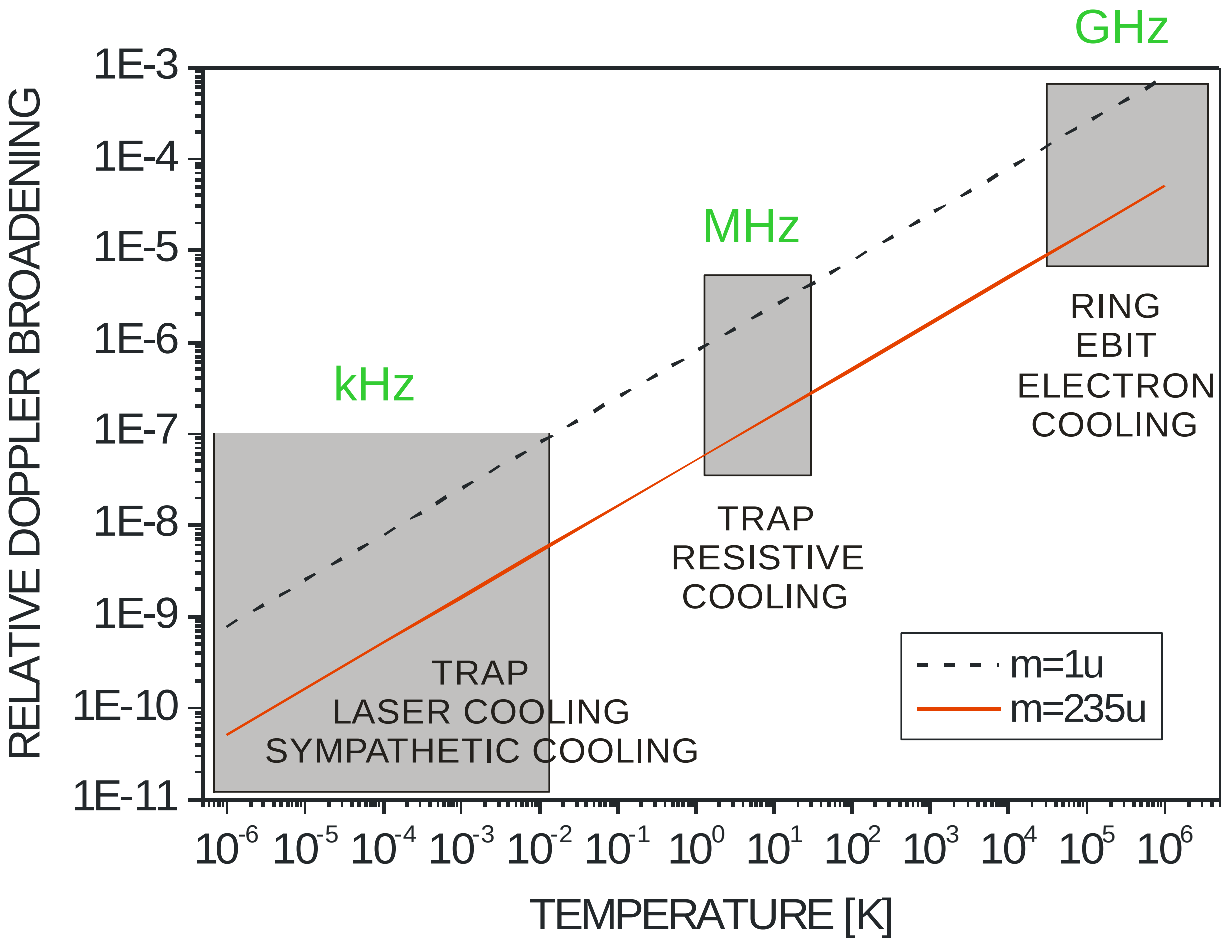
SWIFT (stored waveform inverse Fourier transform)



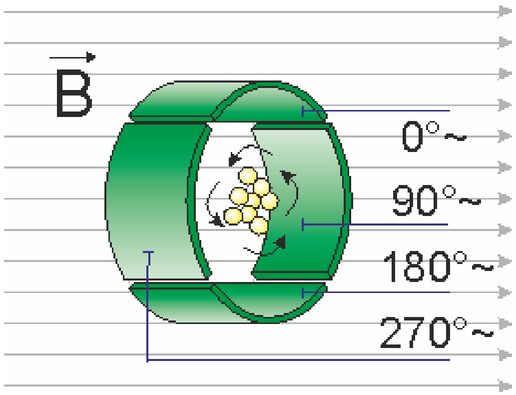
timescale: ms

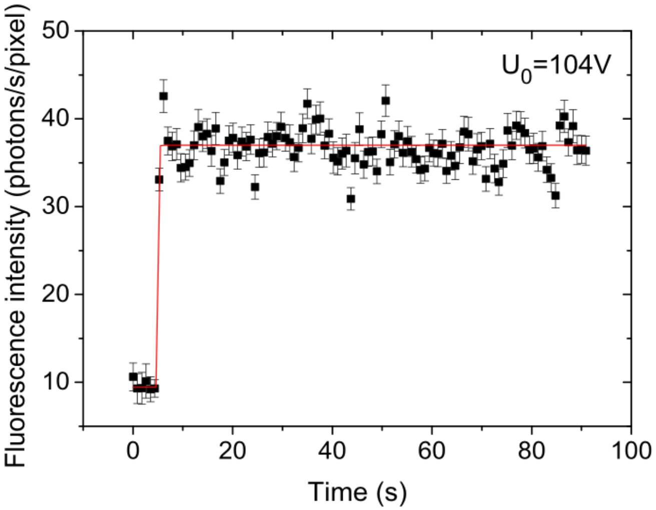
techniques (2) : ion cooling

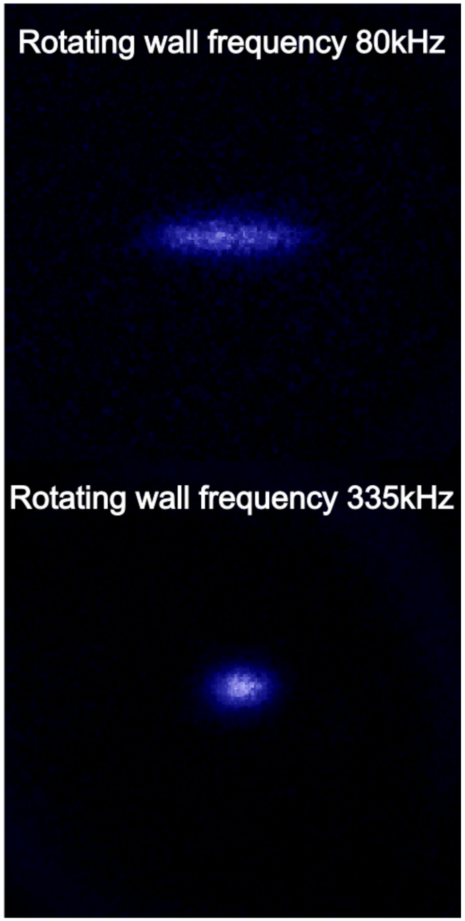
relative Doppler broadening of optical transitions



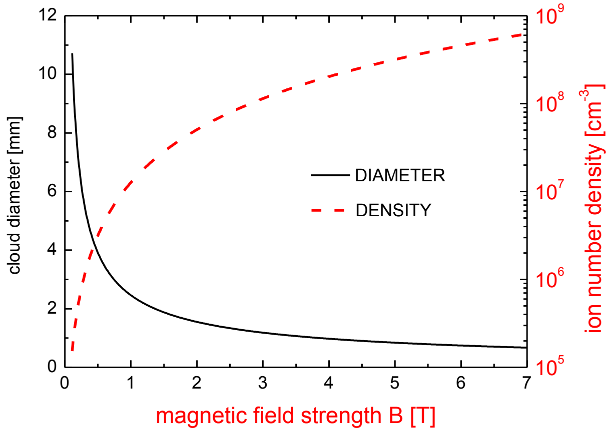
techniques (3) : compression by rotating wall

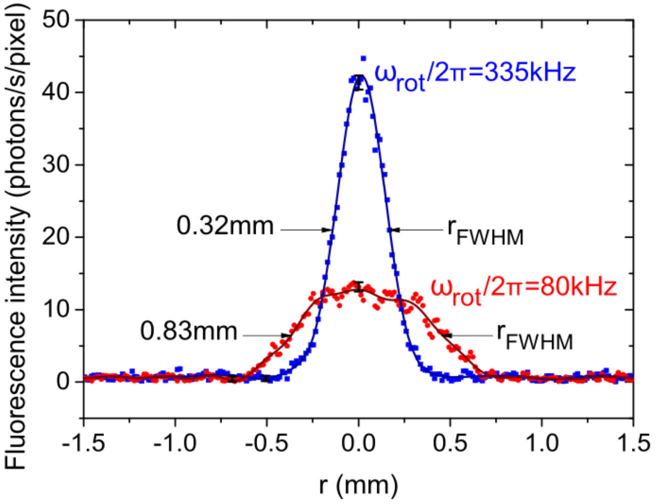




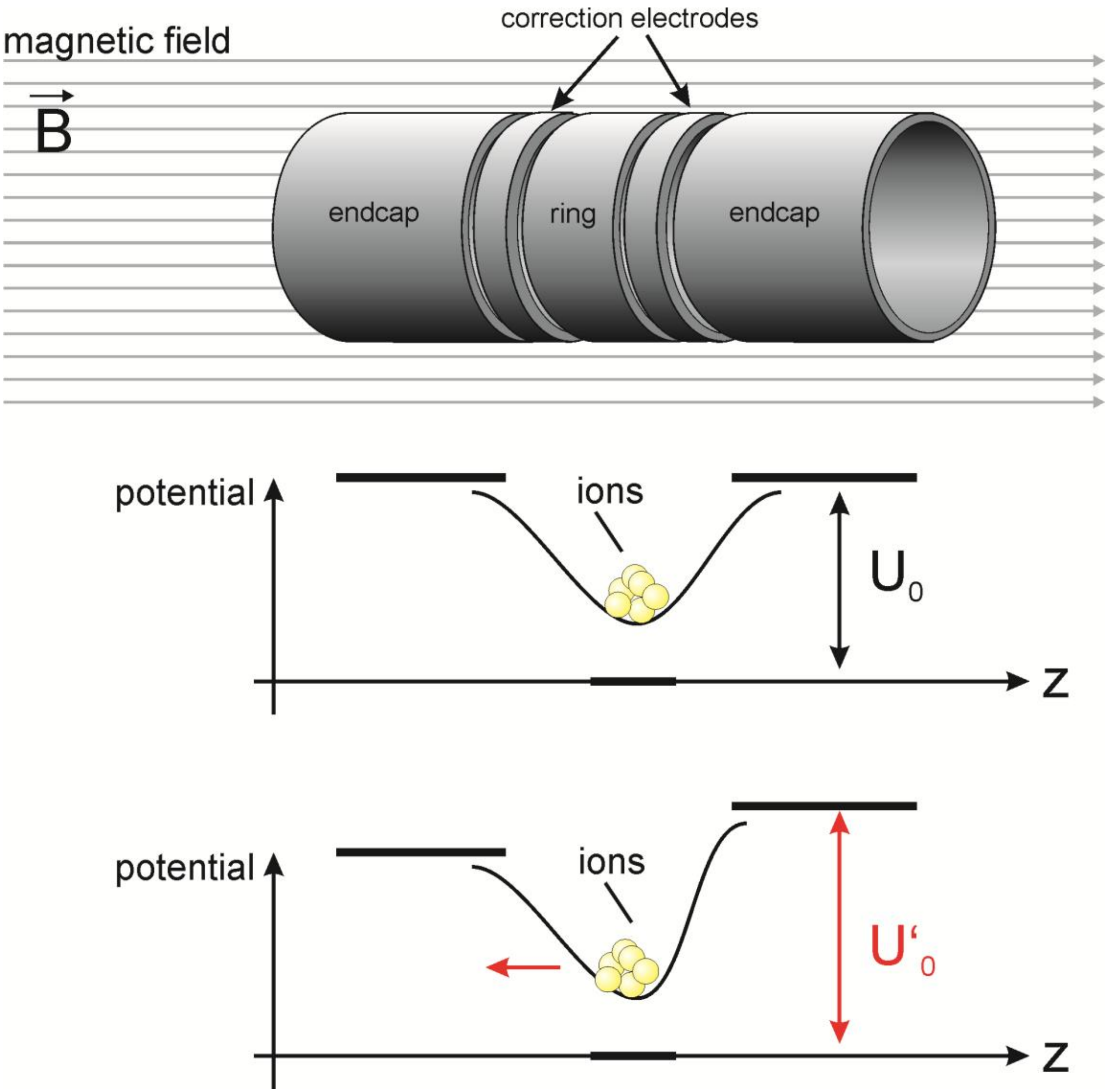

Rotating wall frequency 80kHz

Rotating wall frequency 335kHz





techniques (4) : ion positioning



ion position control
relative to laser focus
by potential asymmetry
ms, µm

shot-to-shot scan of
the effective laser
field strength

combination: experimental cycle (example)

0 s

- ion capture from external source or in-trap production
- possible ion cooling to 4 K or below
- ion selection („clean target“) e.g. by „SWIFT“
- ion centering / positioning and compression by „rotating wall“

PREPARATION

5 s

@ 10 Hz

- laser interaction, e.g. multiphoton ionisation
- non-destructive detection (charge state evolution)

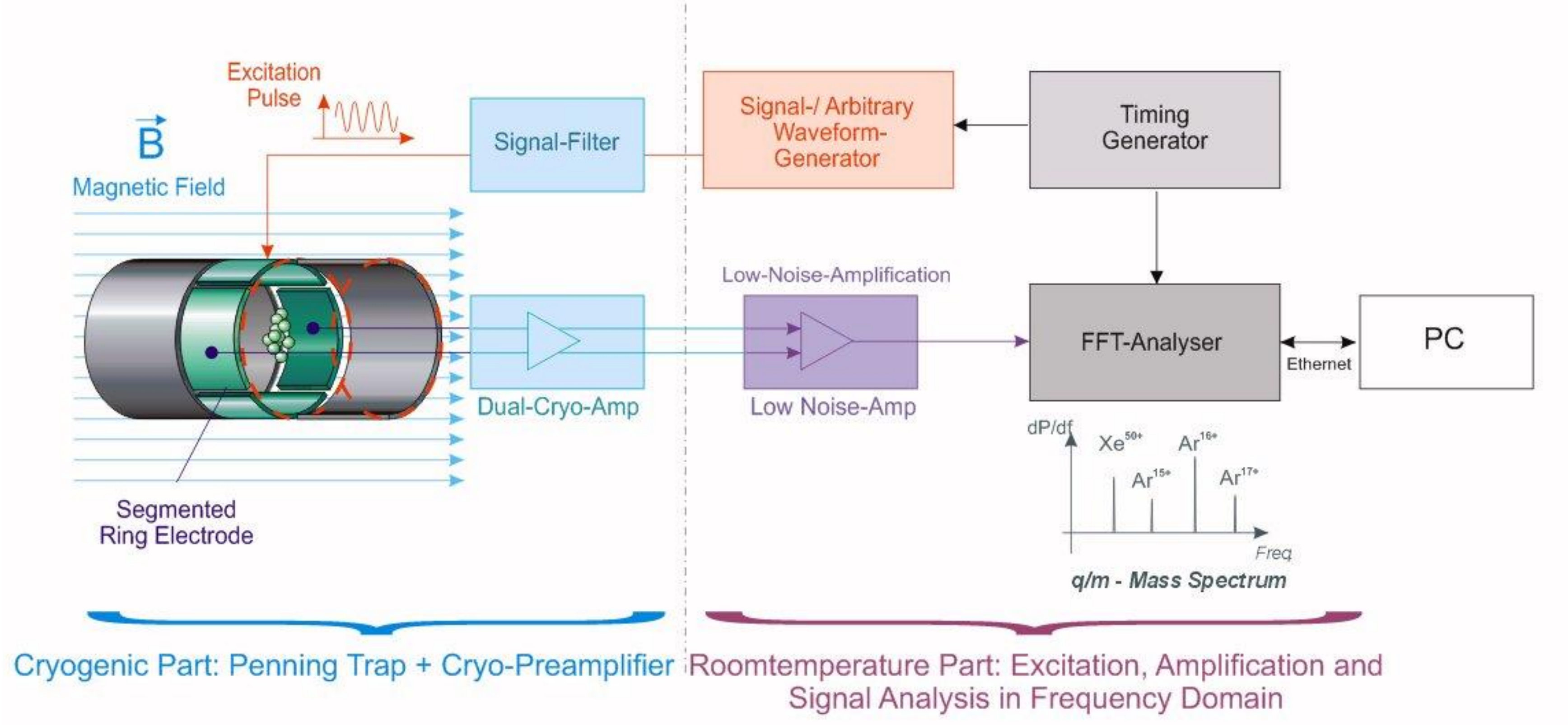
INVESTIGATION

- product ions still in trap for further measurements...

FTICR mass spectrometry

limit: of order 1000 charges (broad band), single ion (resonant)

10 Hz seconds

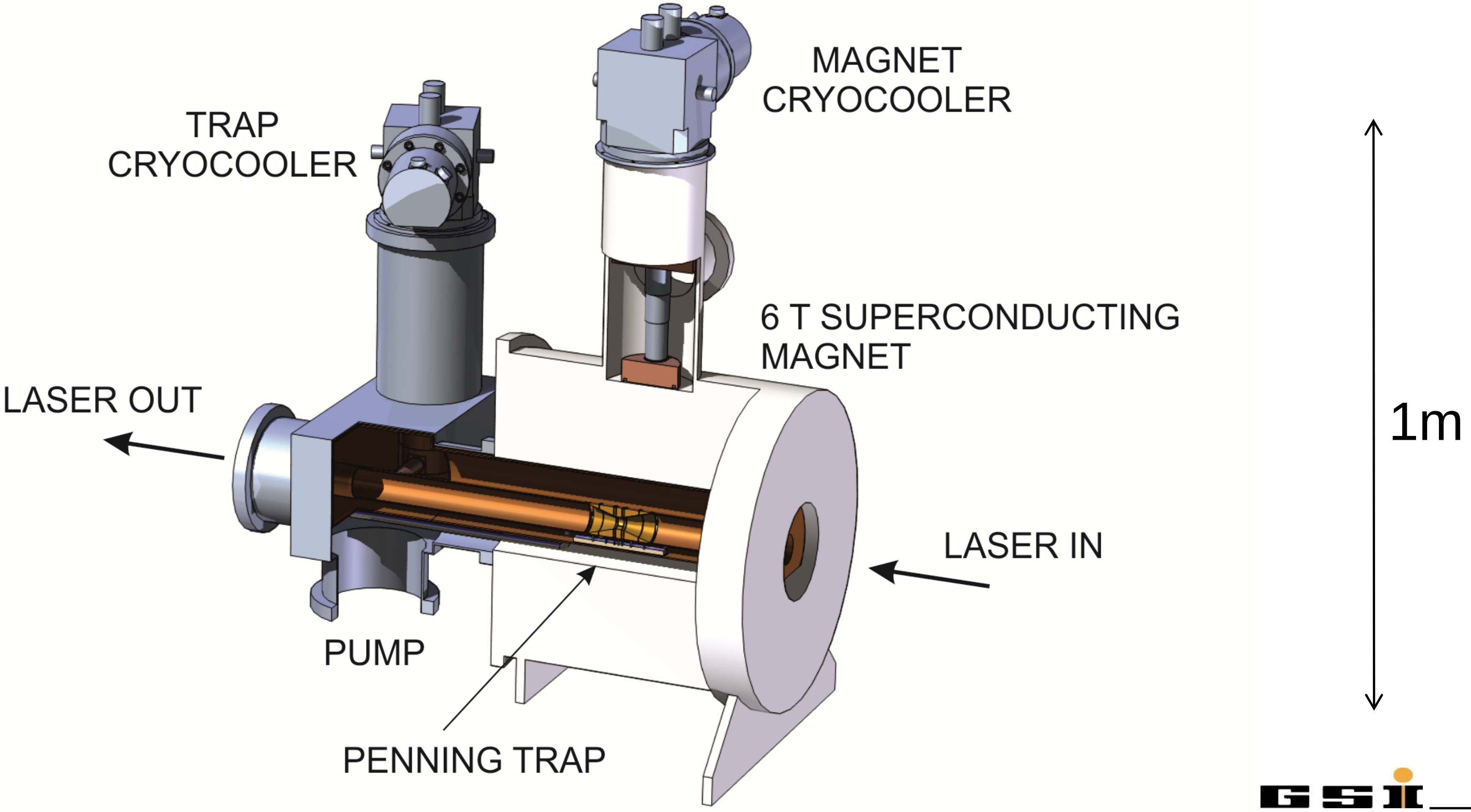


non-destructive detection

setup schematic

Penning trap in a dry superconducting magnet:
high operation stability, high resolution, yet easy transport and flexible use

@ PHELIX, FLASH (II), JETI, POLARIS,...



Determination of the Proton g-Factor

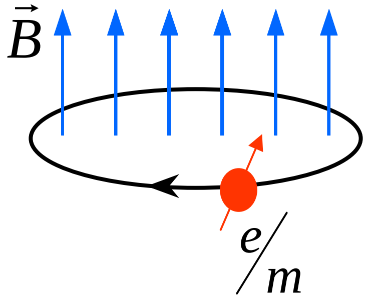
$$\omega_c = \frac{e}{m_p} B$$

Cyclotron frequency

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

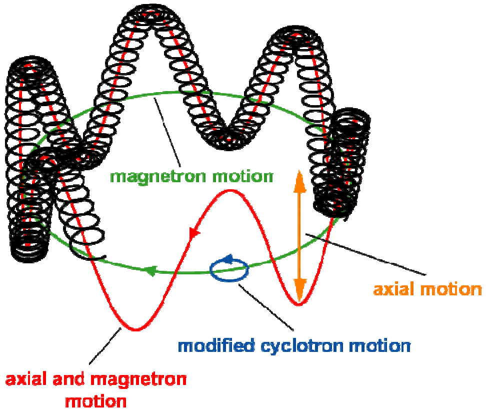
$$\omega_L = g\,\frac{e}{2m_p} B$$

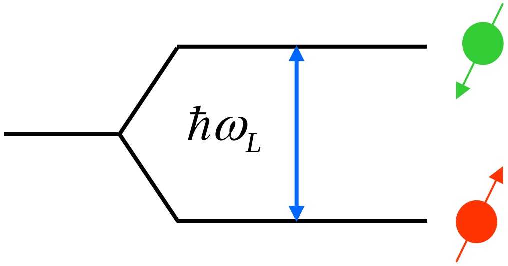
Larmor frequency



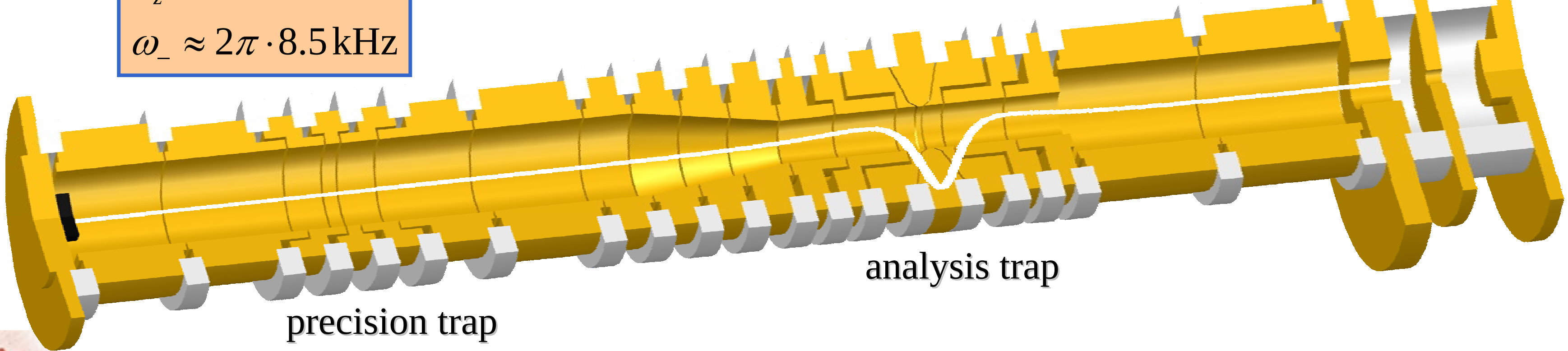
$$\omega_c = \sqrt{\omega_+^2 + \omega_-^2 + \omega_z^2}$$

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





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



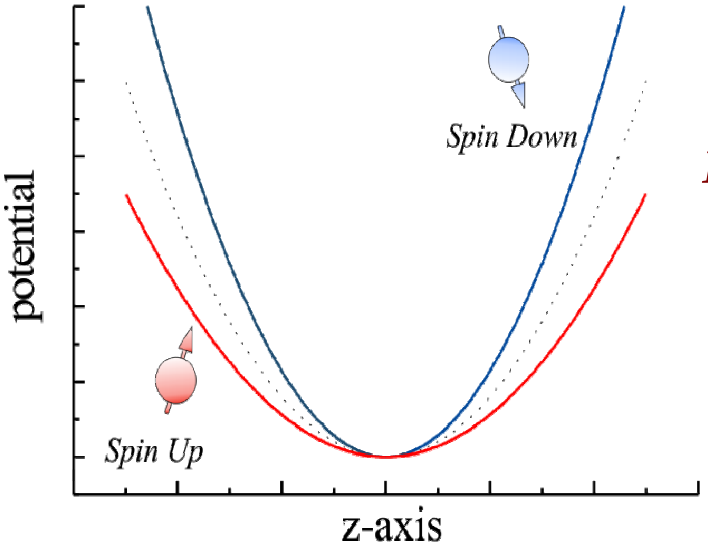
A Single Trapped Proton and the Continuous Stern-Gerlach Effect

axial frequency shift
due to spinflip:

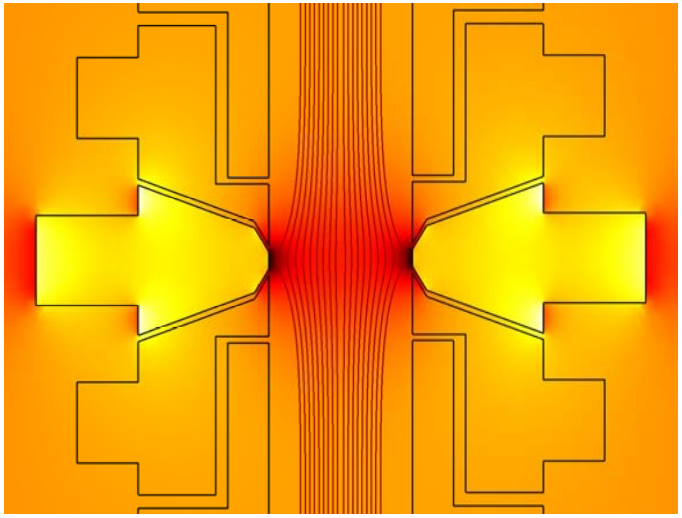
$$\boxed{\Delta\nu_z \approx \frac{1}{2\pi^2}\frac{\mu_z B_2}{m\nu_z}}$$

⇓

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



B_2 = 0.3 T/mm^2
$\Delta\nu_z$= 190 mHz

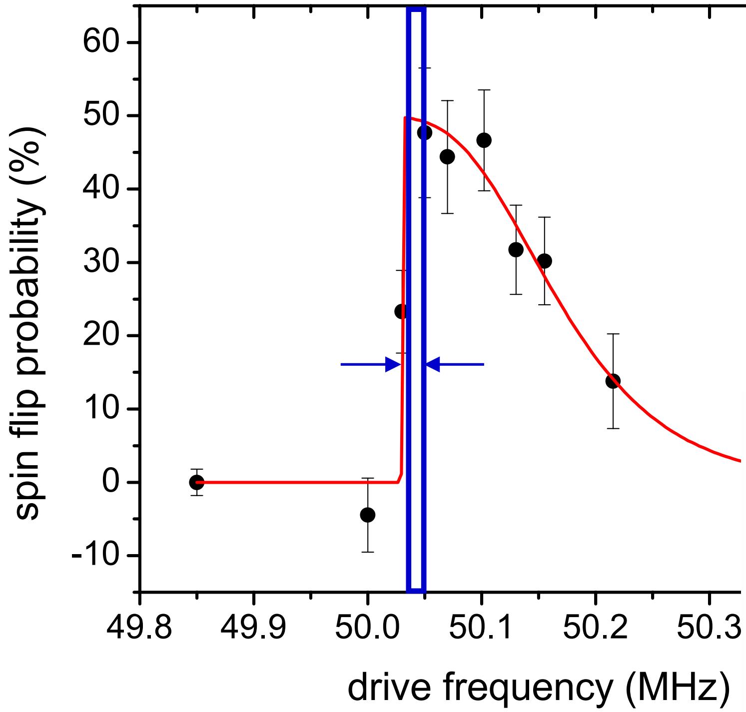


First Larmor Resonance Curve of a Single Proton in the Analysis Trap

- ✓ Axial frequency fluctuation reduced
- ✓ Larmor resonance curve measured

$$\boxed{\frac{\Delta g}{g} = 6\cdot 10^{-4}}$$

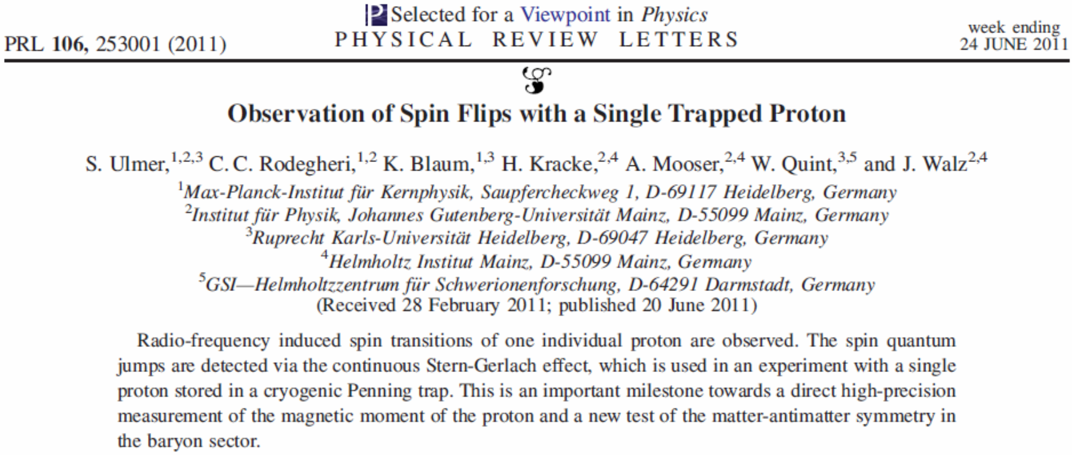
$$\boxed{g = 2\frac{\nu_L}{\nu_c}}$$



Next step: Apply double-trap method.
Magnetic field in precision trap is more homogeneous by 4 orders of magnitude → improvement to

$$\boxed{\frac{\Delta g}{g} = 10^{-9}}$$

expected



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

S. Ulmer,[1,2,3] C. C. Rodegheri,[1,2] K. Blaum,[1,3] H. Kracke,[2,4] A. Mooser,[2,4] W. Quint,[3,5] and J. Walz[2,4]

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[2]*Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
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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.

The Ion g-Factor Team in Mainz
(before spinflip)

Birgit Schabinger

Sven Sturm

Anke Wagner

The Ion g-Factor Team (after spinflip)

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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(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.