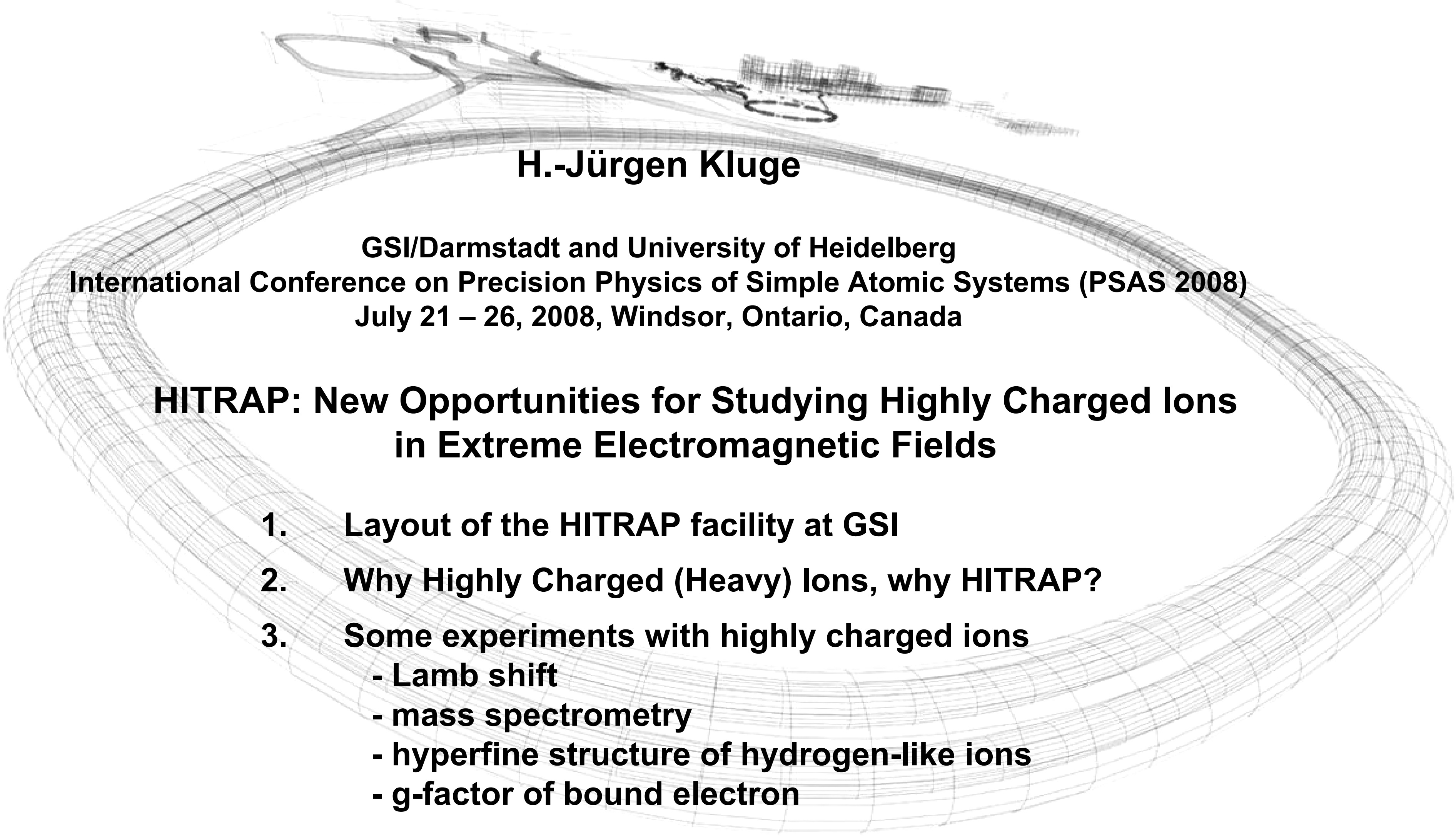


H.-Jürgen Kluge

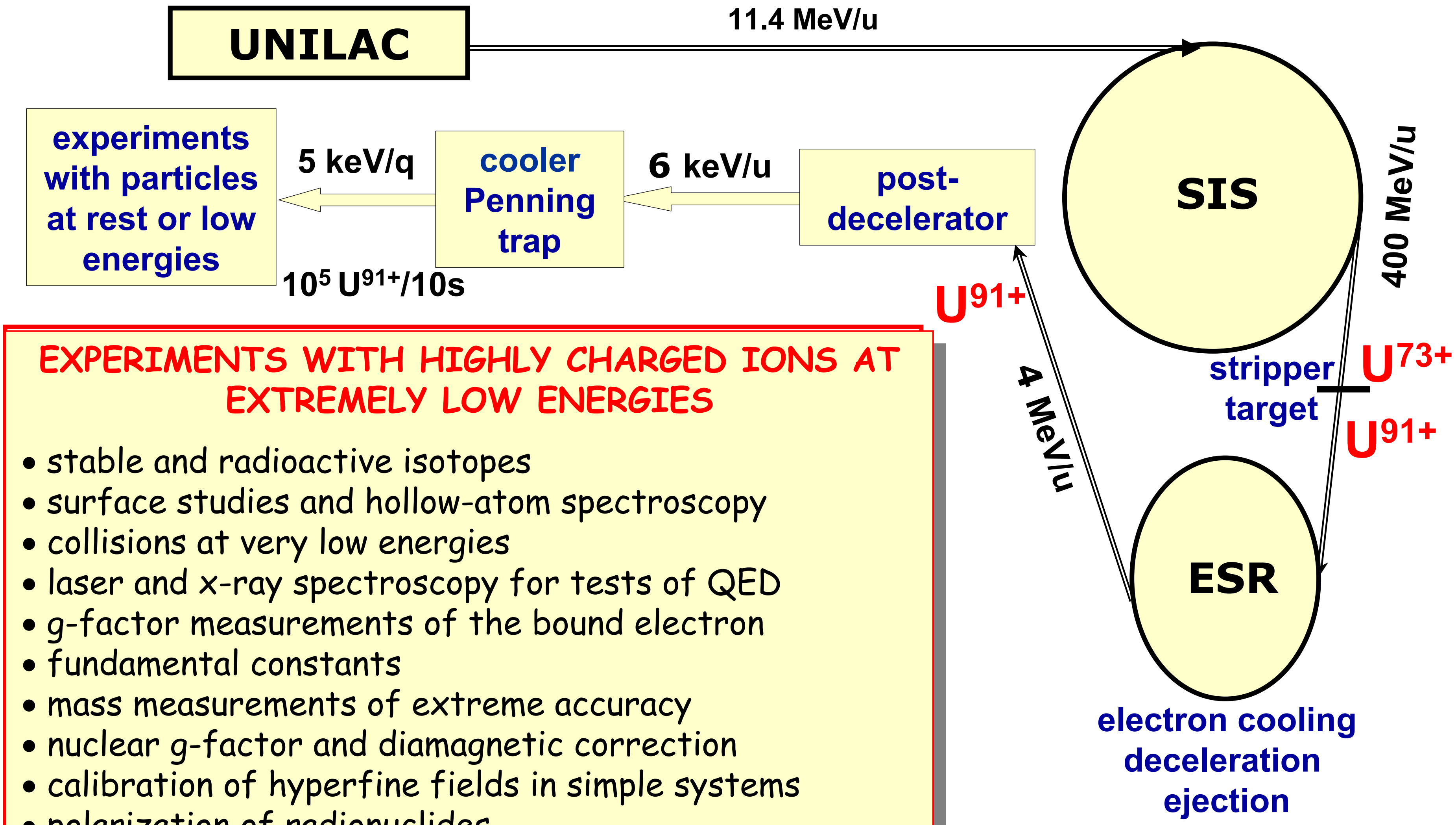
GSI/Darmstadt and University of Heidelberg

International Conference on Precision Physics of Simple Atomic Systems (PSAS 2008)
July 21 – 26, 2008, Windsor, Ontario, Canada

HITRAP: New Opportunities for Studying Highly Charged Ions in Extreme Electromagnetic Fields

1. Layout of the HITRAP facility at GSI
2. Why Highly Charged (Heavy) Ions, why HITRAP?
3. Some experiments with highly charged ions
    - Lamb shift
    - mass spectrometry
    - hyperfine structure of hydrogen-like ions
    - g-factor of bound electron
4. Status of the HITRAP project
5. Outlook and conclusion

1. The HITRAP (Highly charged Ion TRAP) Project at GSI



UNILAC

11.4 MeV/u

SIS

400 MeV/u

stripper target

U^{73+}

U^{91+}

ESR

electron cooling
deceleration
ejection

4 MeV/u

U^{91+}

post-decelerator

6 keV/u

cooler Penning trap

5 keV/q

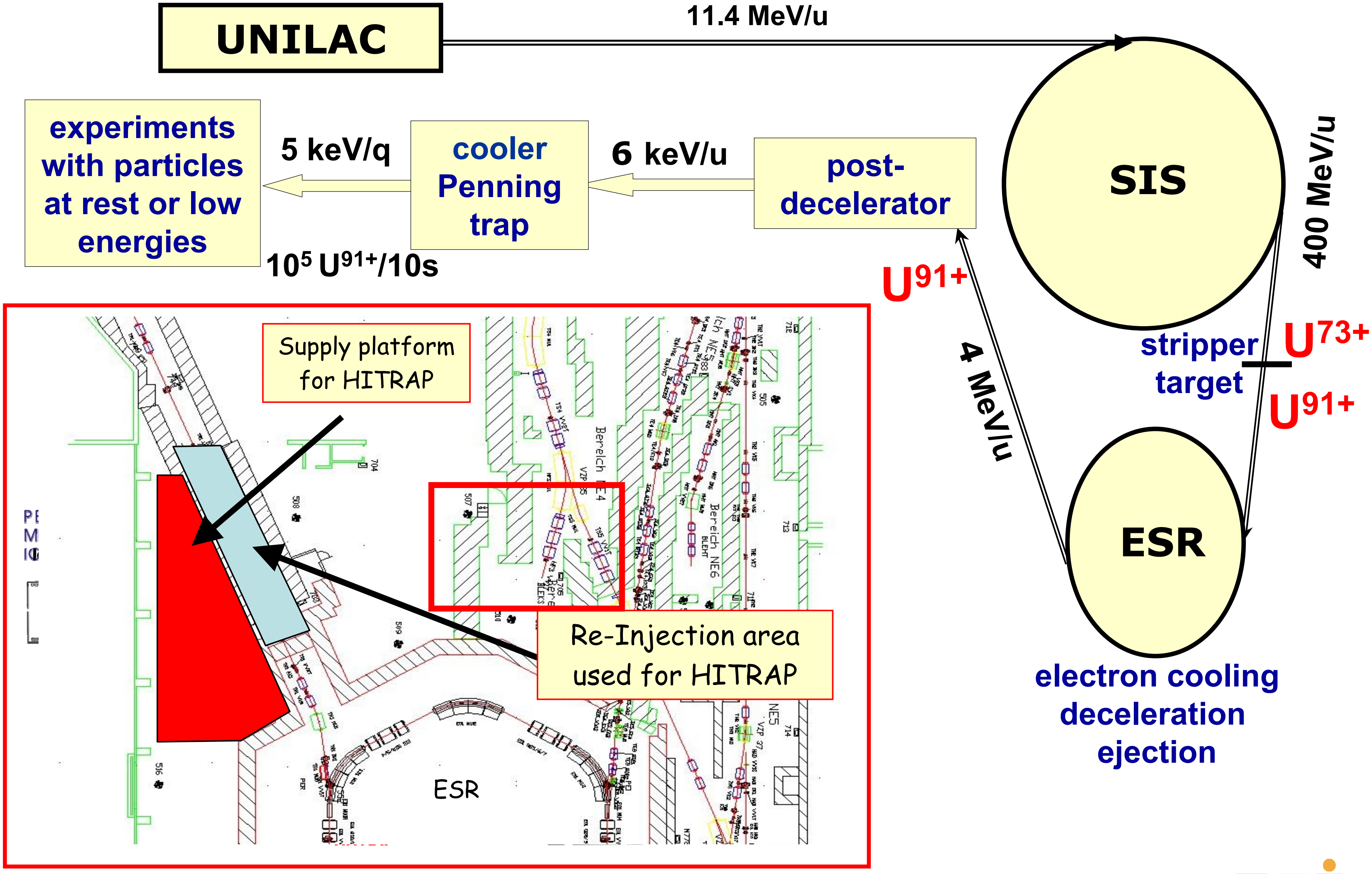
10^5 U^{91+}/10s

experiments with particles at rest or low energies

EXPERIMENTS WITH HIGHLY CHARGED IONS AT EXTREMELY LOW ENERGIES

- stable and radioactive isotopes
- surface studies and hollow-atom spectroscopy
- collisions at very low energies
- laser and x-ray spectroscopy for tests of QED
- g-factor measurements of the bound electron
- fundamental constants
- mass measurements of extreme accuracy
- nuclear g-factor and diamagnetic correction
- calibration of hyperfine fields in simple systems
- polarization of radionuclides
- decay spectroscopy of highly-charged radionuclides

The HITRAP (Highly charged Ion TRAP) Project at GSI



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post-decelerator

6 keV/u

cooler Penning trap

5 keV/q

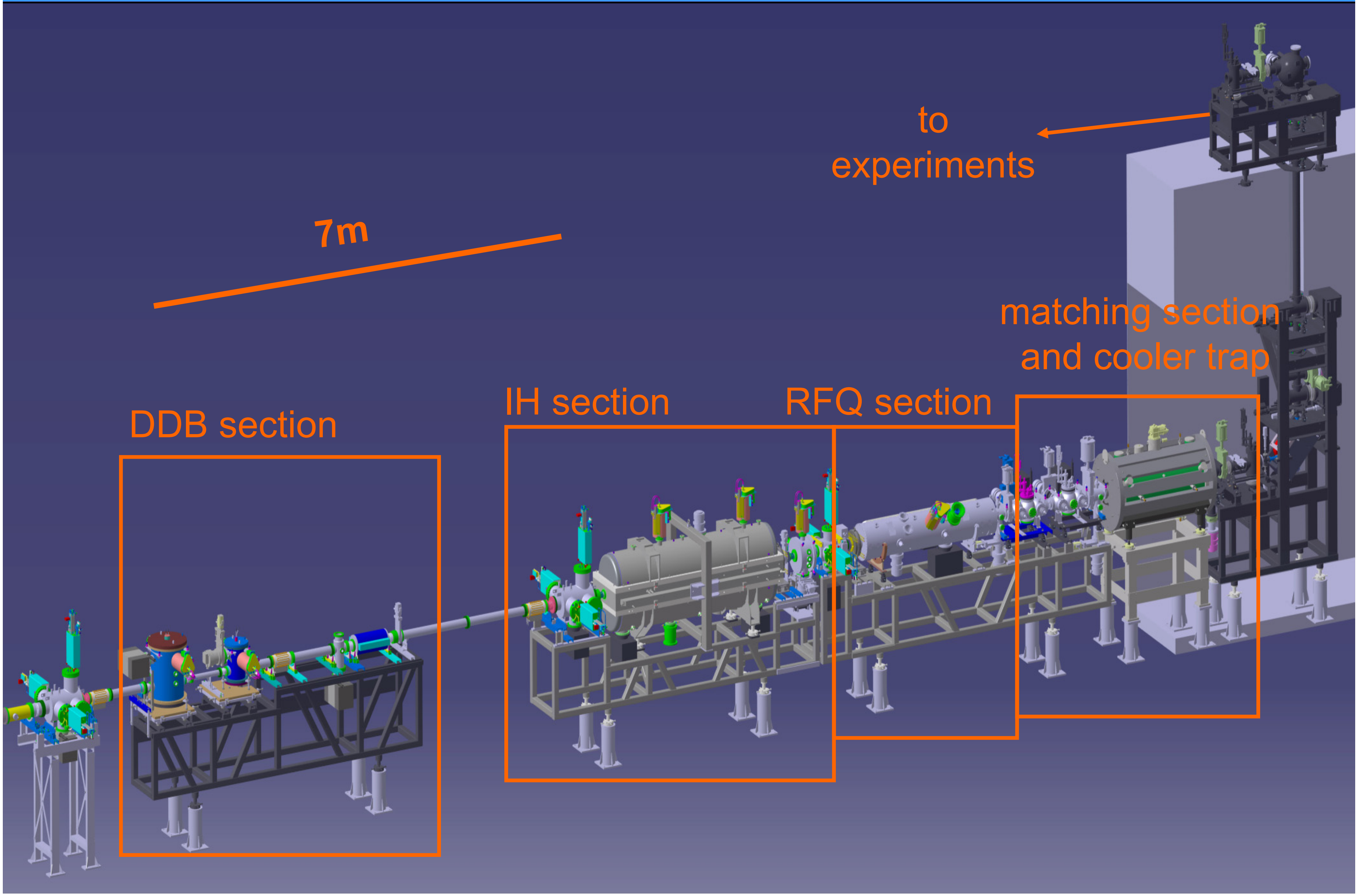
$10^5\ U^{91+}/10s$

experiments with particles at rest or low energies

Supply platform for HITRAP

Re-Injection area used for HITRAP

Artists View of HITRAP



to experiments

7m

matching section and cooler trap

DDB section

IH section

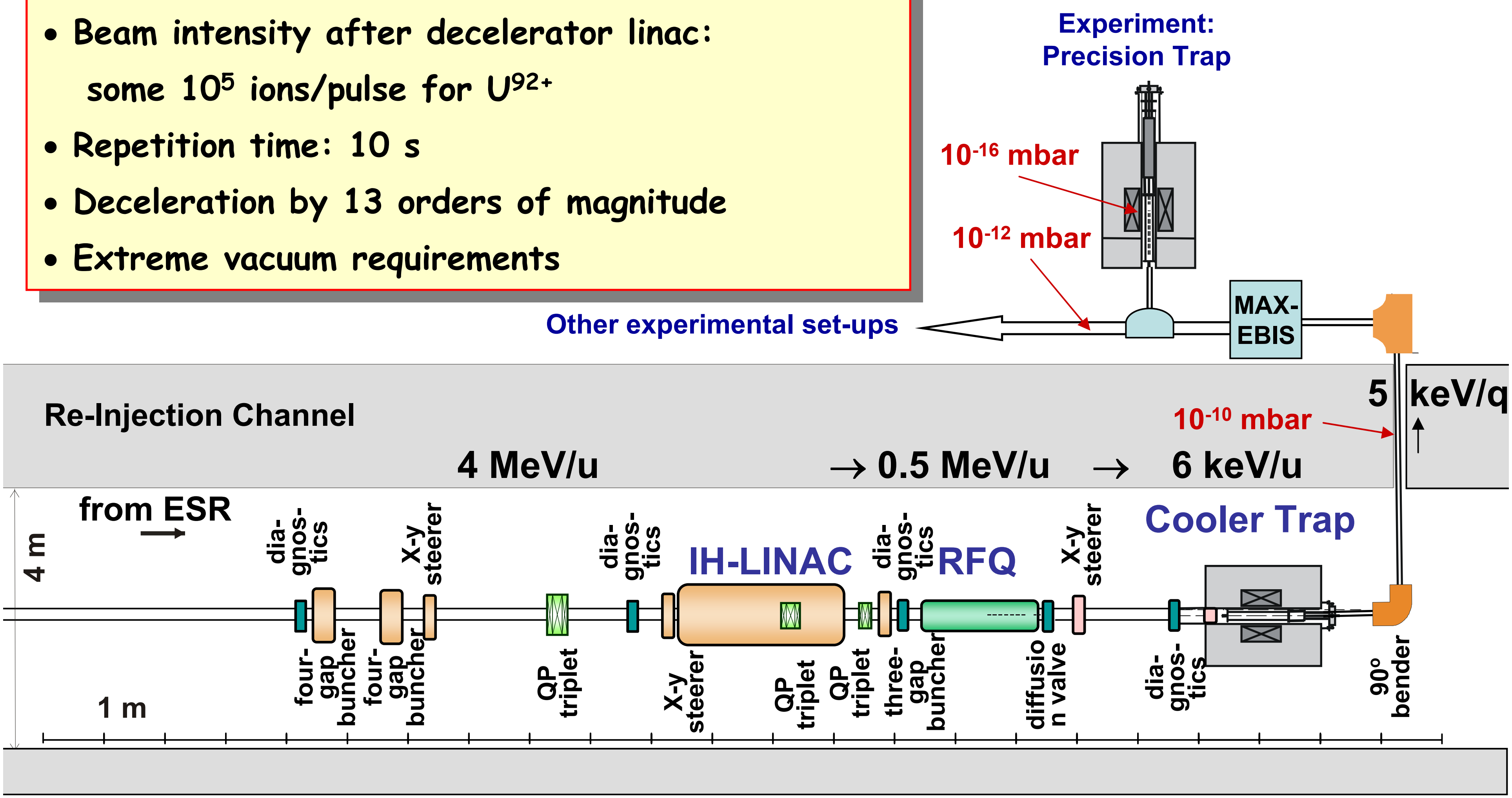
RFQ section

Side View of HITRAP at the ESR in the Re-Injection Channel

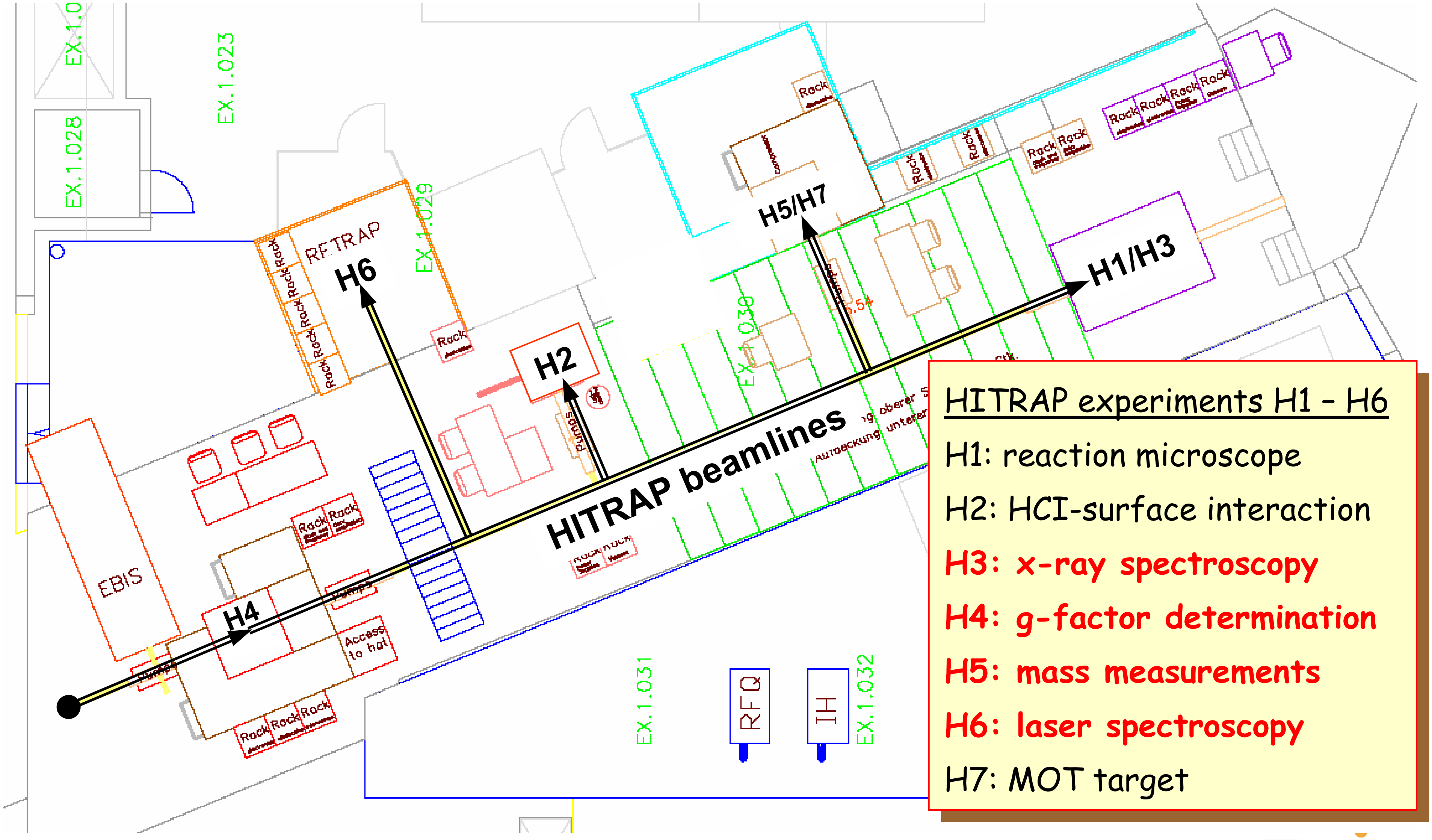
Operational Parameters:

- Clean beams of highly charged ions with $M/q \leq 3$
- Beam intensity after decelerator linac:

  some 10^5 ions/pulse for U^{92+}
- Repetition time: 10 s
- Deceleration by 13 orders of magnitude
- Extreme vacuum requirements



Top View of HITRAP Experimental Area and Planned Experiments



HITRAP experiments H1 – H6

H1: reaction microscope

H2: HCI-surface interaction

H3: x-ray spectroscopy

H4: g-factor determination

H5: mass measurements

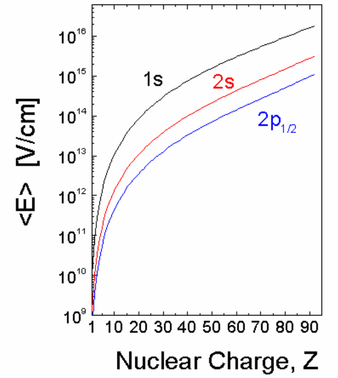
H6: laser spectroscopy

H7: MOT target

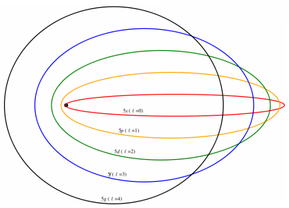
2. Why Highly Charged (Heavy) Ions, why HITRAP?

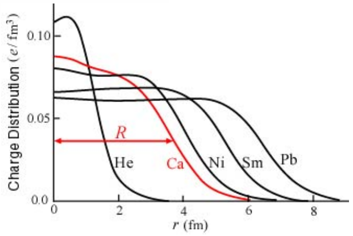
Simple (few-electron) systems:
from hydrogen to hydrogen-like uranium

Test of QED in extreme electromagnetic fields

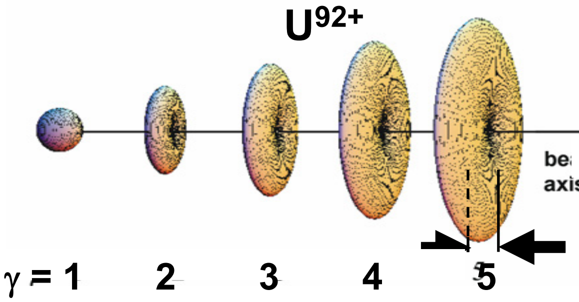


A new access to fundamental constants & to nuclear ground state properties





Extremely short electromagnetic pulses at relativistic energies of highly charged ions



$\Delta t \leq 0.1$ as
$I \approx 10^{21}$ W/cm^2

Why Storing and Cooling of Highly Charged (Radioactive) Ions?

- point-like source & small amplitude of oscillations
- easy manipulation of trapped particles
- extended observation & manipulation time
- reduction of Doppler effect / Doppler broadening

- effective use of rare species
- use as accelerator device:
  - accumulation & bunching
  - q/m-separation
  - charge breeding and post-acceleration
  - increase of luminosity & resolution
- crystalline structures
- backing-free samples for decay studies
- polarization

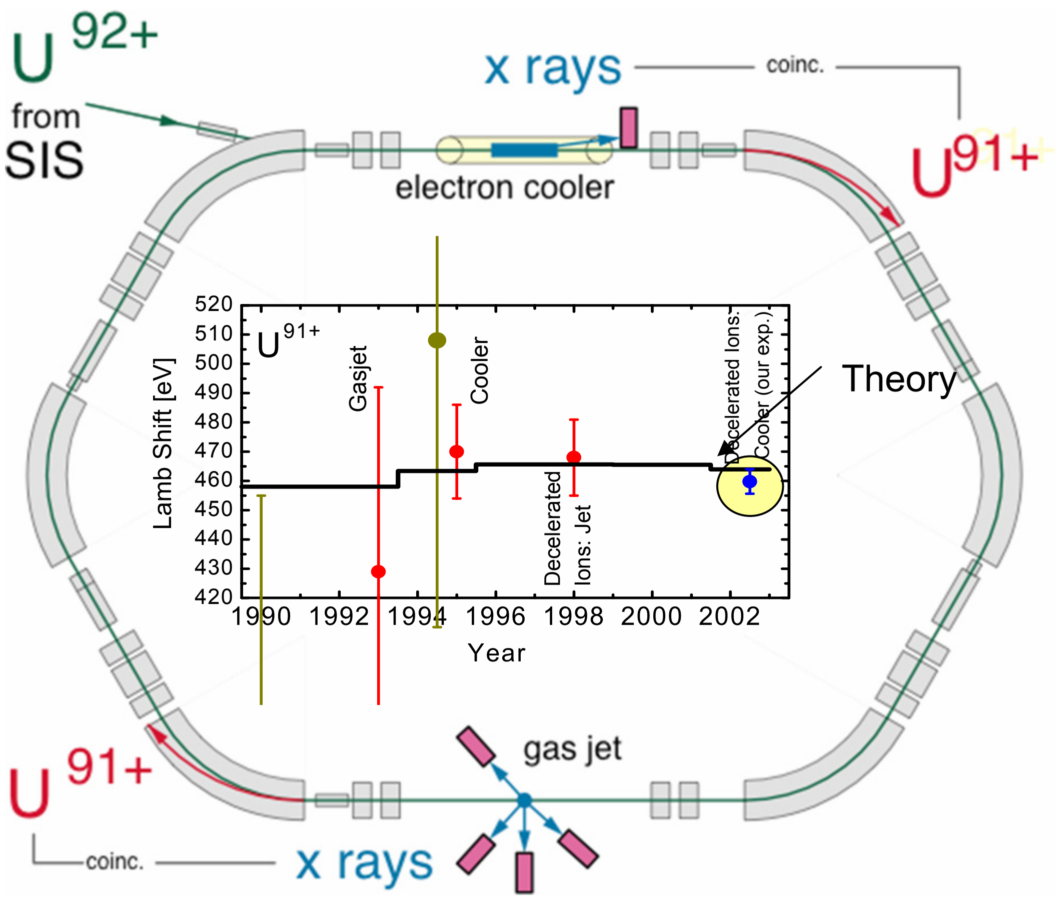
EFFICIENCY

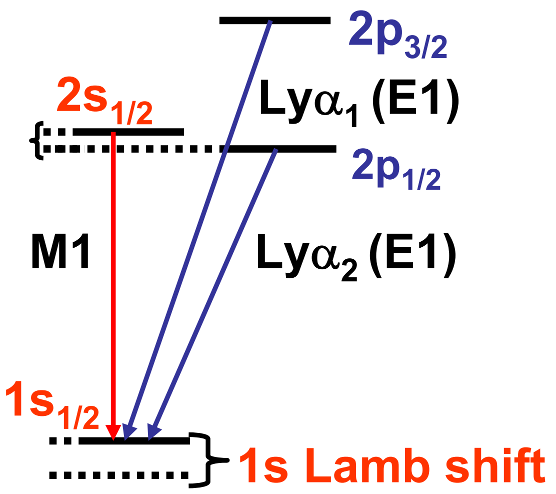
ACCURACY

SENSITIVITY

single-ion
sensitivity
required for
highest
spectroscopic
accuracy

3. Some Experiments with HCI:
1s Lamb Shift in Hydrogen-Like Uranium





1s-Lamb shift of uranium

Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV ± 0.50 eV

future: crystal spectrometer
bolometer
He and Li-like ions
radioactive isotopes
trapped HCI

exp: A. Gumberidze (PhD 2003), T. Stöhlker et al., PRL 94 (2005) 223001

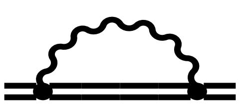
theo: V.A. Yerokhin, V.M. Shabaev et al., PRL. 91, 073001 (2003)
I. Goidenko et al., in Hydrogen Atom: Precision Physics of Simple Atomic System, edited by S. G. Karshenboim et al. (Springer, New York, 2001)

Test of QED: Lamb Shift in Hydrogen-Like Uranium

Heavy ions

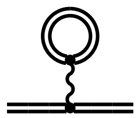
Test of QED to first order in α and
all orders in (Zα)

Self Energy



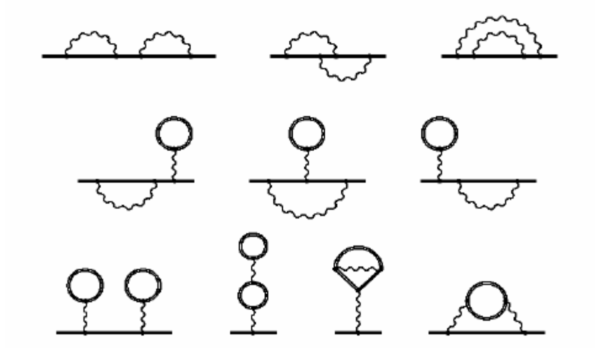
P.J. Mohr,
Ann. Phys., 1974

Vacuum Polarization



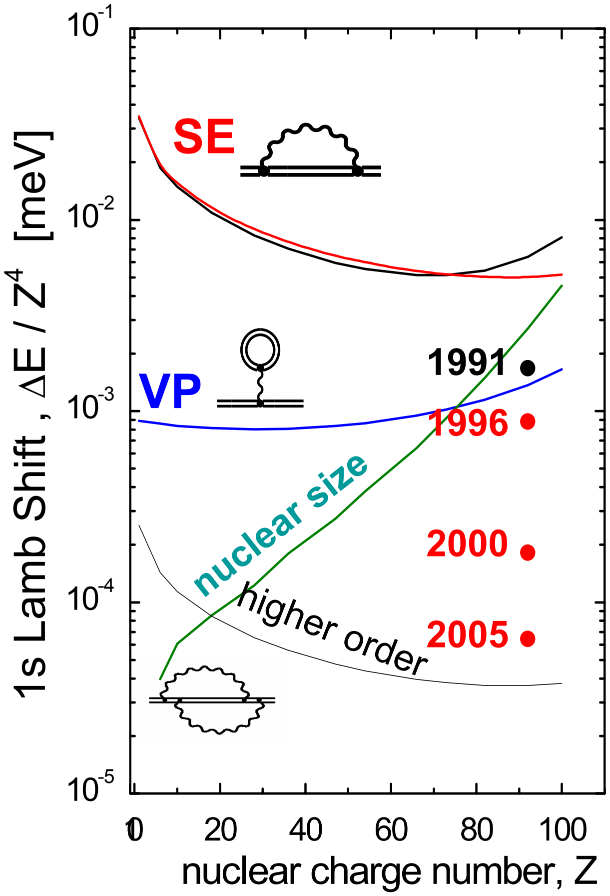
G. Soff, P.J. Mohr, PRA, 1988
N.L. Manakov et al., JETP, 1989

1st order contribution:
266.45 eV



2nd order contribution:
-1.26(33) eV

V.A. Yerokhin, P. Indelicato, and V.M. Shabaev, PRL, 2006

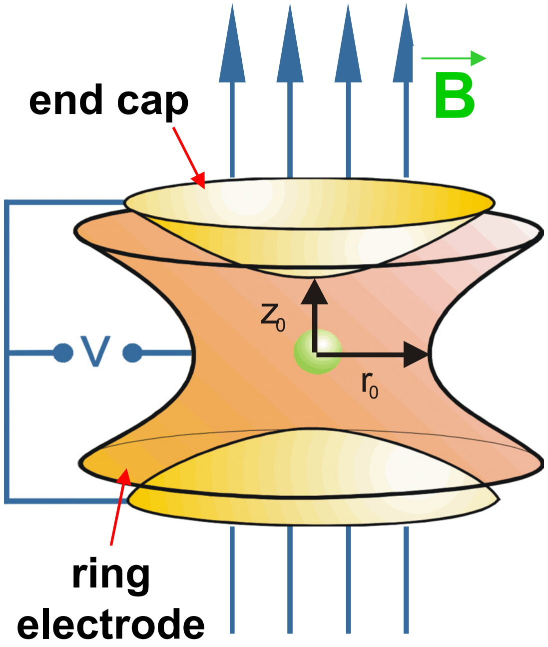


Finite nuclear size:
198.54(19) eV

Nuclear polarization:
-0.20(10) eV

3. Some Experiments with HCI: Mass Measurements in Penning Traps

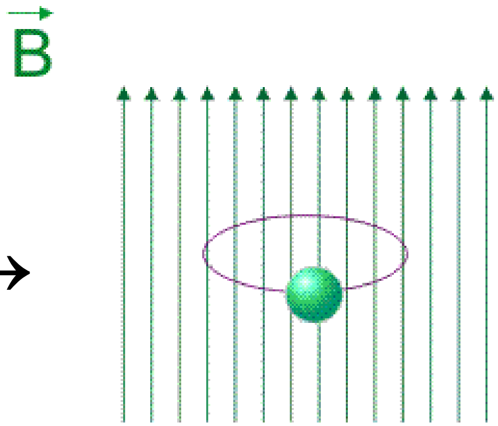
hyperboloidal Penning trap



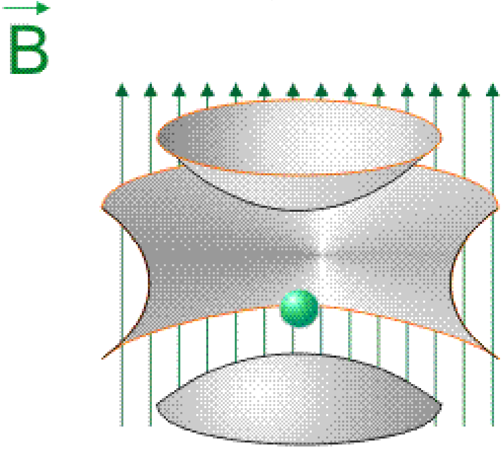
→

superposition of

homogenous magnetic field



electrostatic quadrupole field



cyclotron frequency

$$\boxed{\omega_c = \frac{q}{m} \cdot B}$$

axial frequency

$$\omega_z = \sqrt{\frac{qV}{md^2}}$$

The Advantage of Highly-Charged Ions for Penning Trap Mass Spectrometry

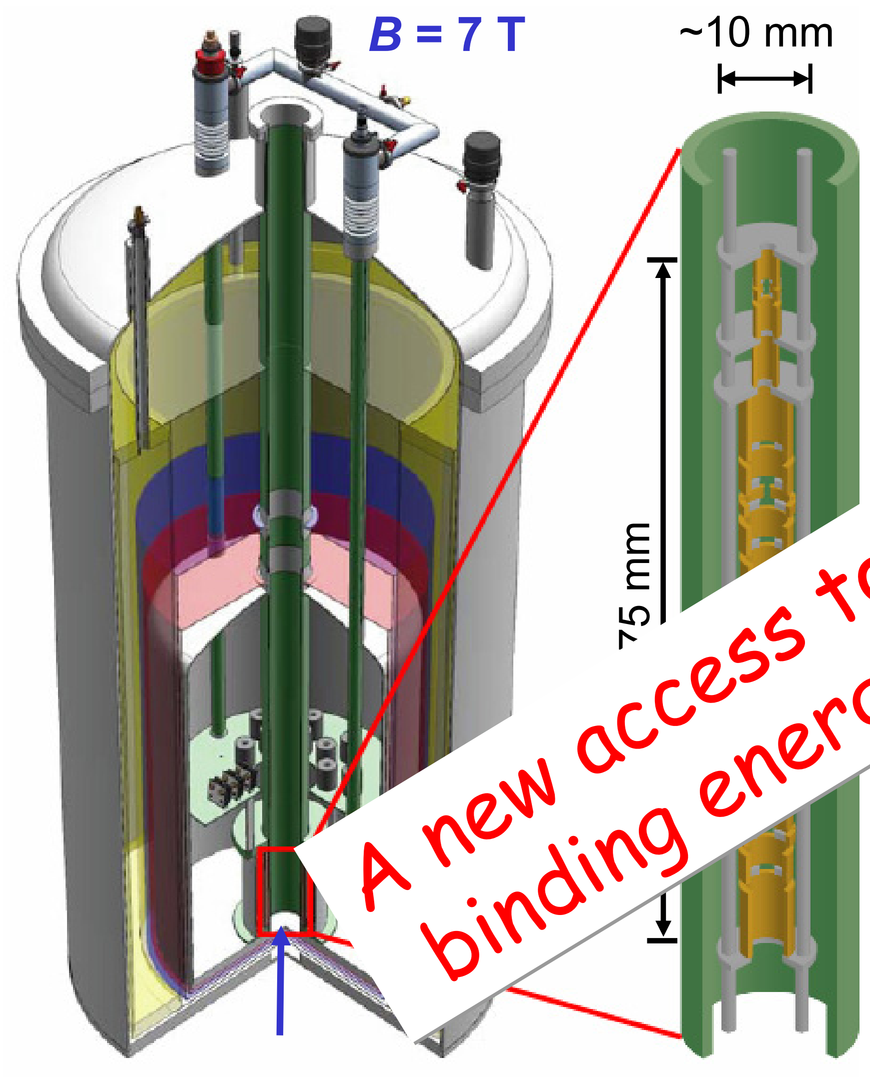
Example: B = 6 T, A = 100

$q = 1$
$\nu_c = 1$ MHz
$T_{obs} = 1$ s → $\Delta\nu_c = 1$ Hz
resolving power $R = 10^6$
accuracy $\delta m/m \approx 10^{-8}$

$q = 50$
$\nu_c = 50$ MHz
$T_{obs} = 1$ s → $\Delta\nu_c = 1$ Hz
resolving power $R = 5 \cdot 10^7$
accuracy $\delta m/m \approx 2 \cdot 10^{-10}$

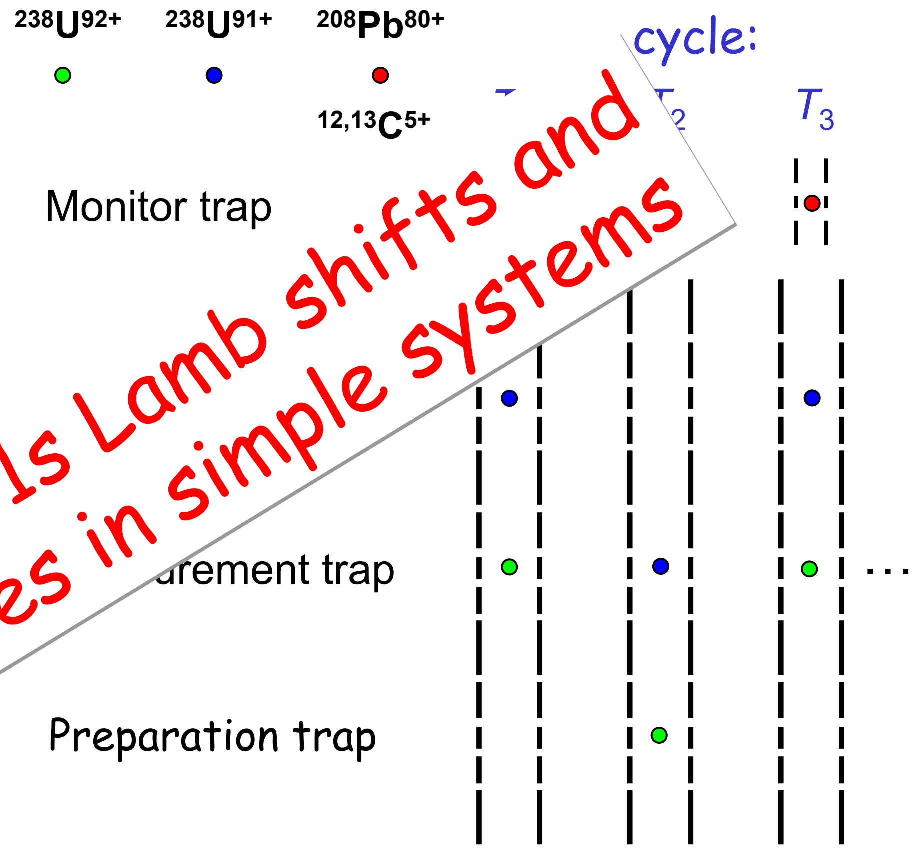
no contamination by molecules
stronger image currents

A New Concept for a High-Accuracy Mass Spectrometer



K. Blaum et al.

Measurement cycle:



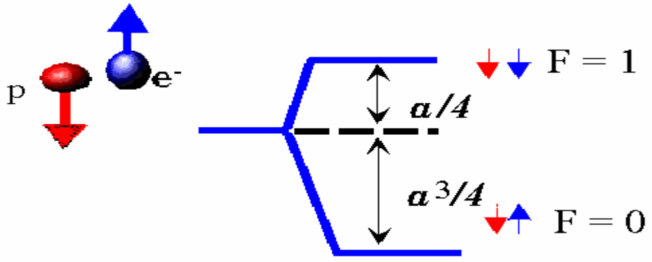
A new access to 1s Lamb shifts and binding energies in simple systems

T = 4 K, $\delta B/B < 10^{-7}/cm^3$, $(dB/dt)\cdot(1/B) < 10^{-10}/h$

simultaneous measurement of three cyclotron frequencies

3. Some Experiments with HCI: Hyperfine Structure in the Ground State of Hydrogen-Like Systems

H:

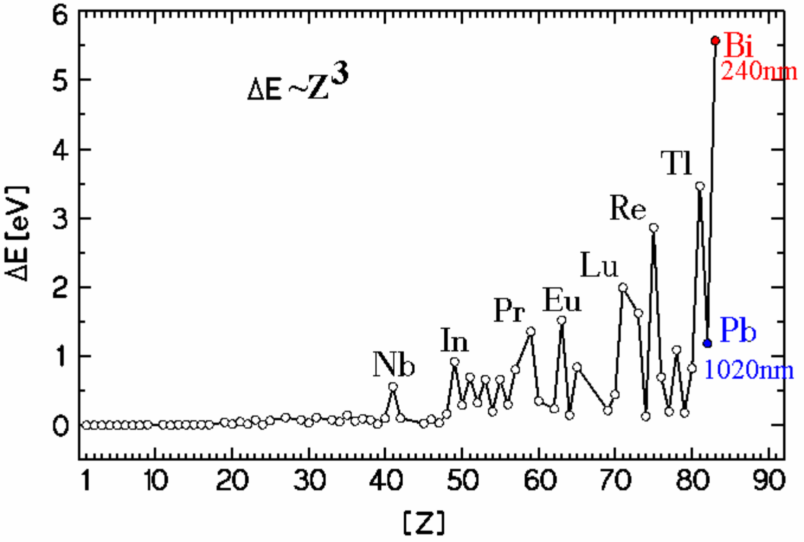


λ = 21.10608180988(2) cm
$\tau = 10^7$ years

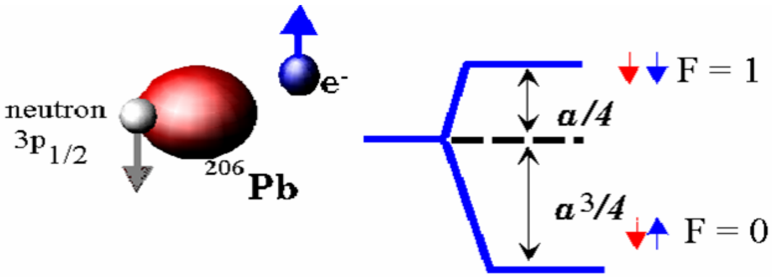
Fermi formula

$$\Delta\nu = \left(I+\frac{1}{2}\right)\cdot\frac{8}{3}\frac{h\cdot c}{n^3}\cdot Z^3\cdot R_\infty\cdot\alpha^2\cdot g_I\cdot\frac{M}{m_e}$$

▪ F(j,Z)	relativistic correction
▪ (1-δ)	Breit-Rosental effect
▪ (1-ε)	Bohr-Weisskopf effect
▪ QED	self energy & vacuum pol.



^{207}Pb:



λ = 1019.7(2) nm
τ = 49.5(6.5) ms

1s Ground State Hyperfine Structure Splitting in $^{209}\mathrm{BI}^{82+}$ and $^{207}\mathrm{Pb}^{81+}$

	$^{209}\mathrm{Bi}^{82+}$	$^{207}\mathrm{Pb}^{81+}$
RMS radius Magnetic moment (corr.)	5.519 fm $\mu = 4.1106\ \mu_b$	5.497 fm $\mu = 0.58219\ \mu_b$
Point nucleus (Dirac)	212.320 nm	880.017 nm
Breit-Schawlow	+ 26.561(50) nm	+ 109.64(1) nm
Bohr-Weisskopf	+ 5.025(330) nm	+ 29.5(2.0) nm
Theory, *no* QED	243.91(38) nm	1019.1(2.1) nm
Vac. polarisation	- 1.64 nm	- 6.83 nm
Self energy	+ 2.86 nm	+ 11.9 nm
Total QED	+ 1.22 nm	+ 5.08 nm
Theory incl. QED	245.13(58) nm	1024.2(2.5)nm
Experiment	**243.87(2) nm**	**1019.5(2) nm**

There is in both cases a 0.5% discrepancy.
A measurement of the 1s HFS in Li-like ions must be performed. Up to now not successful!

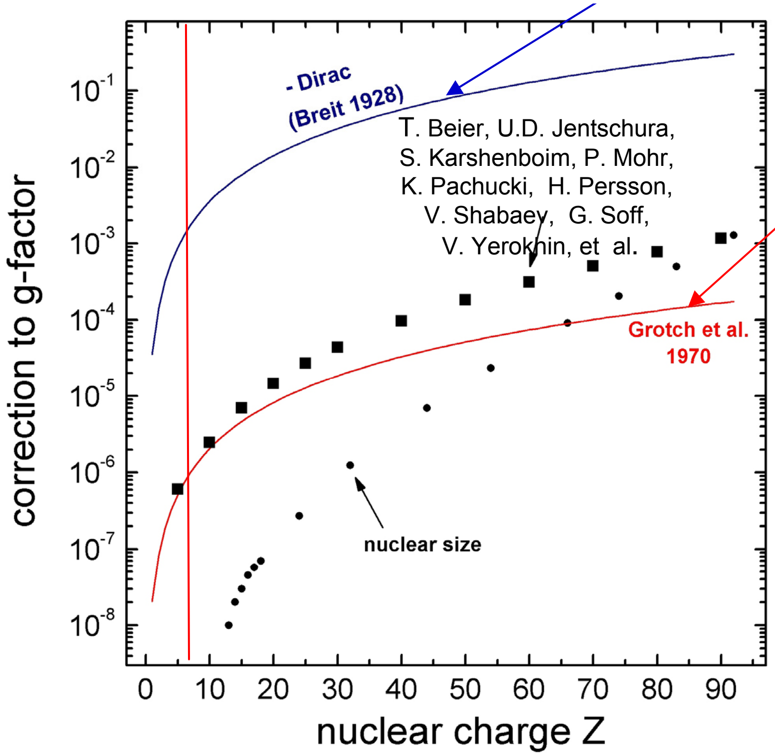
P. Seelig *et al.*, Phys. Rev. Lett. **81**, 4824 (1998)

3. Some Experiments with HCI:
g-Factor of Hydrogen-Like Ions

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

relativistic effect (Dirac theory)

bound-state QED



Dirac value is exact

interaction of the bound electron with the nucleus has to be taken into account when calculating the g-factor of the electron

QED correction can now be calculated with high accuracy to all orders of Z·α

nuclear size effect becomes large for very heavy ions

G. Soff, P. Mohr, Phys. Rev. A38 (1988) 5066
H. Persson, I. Lindgren, S. Salomonson, P. Sunnergren, Phys. Rev. A48 (1993) 2772
V. Shabaev et al., PRL 88 (2002) 091801
V. Yerokhin et al., PRL 89 (2002) 143001
K. Pachucki, Phys. Rev. A 72 (2005) 022108

Principle of the g-Factor Determination of the Bound Electron

cyclotron frequency

is the revolution frequency of a charged particle in an external magnetic field *B*: Lorentz force and centrifugal force are equal.

$$\omega_c = \frac{q_{ion}}{M_{ion}} B$$

Larmor frequency

is the precession frequency of a magnetic moment in an external magnetic field B. It equals the frequency required for flipping the spin.

$$\omega_L = g_S \frac{e}{2m_e} B$$

$$\Rightarrow \quad \omega_c << \omega_L \quad \Rightarrow$$

no gain of 3 orders of magnitude as in the case of the free electron

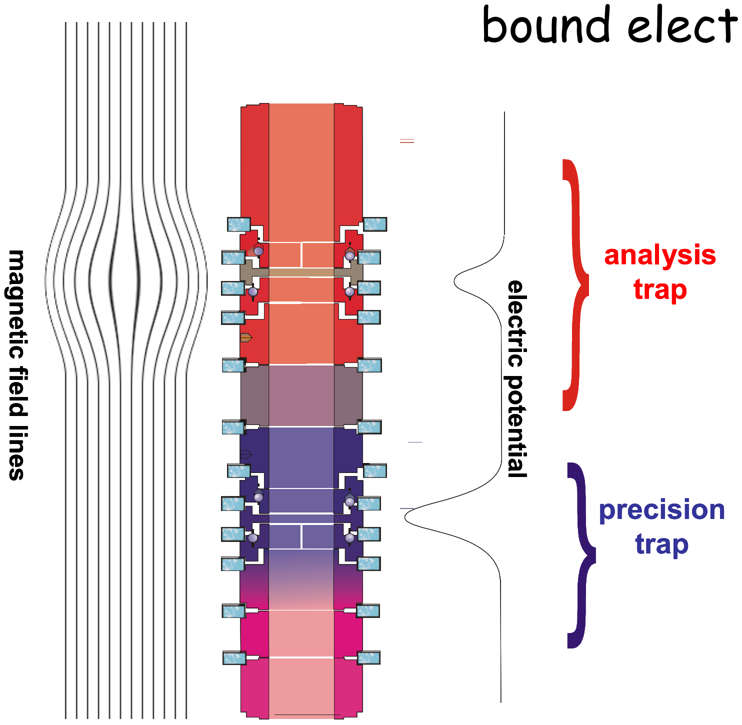
$$g = \left(\frac{\omega_L}{\omega_c} \right) \cdot \frac{\left(\frac{q}{M} \right)_{ion}}{\left(\frac{e}{m} \right)_e}$$

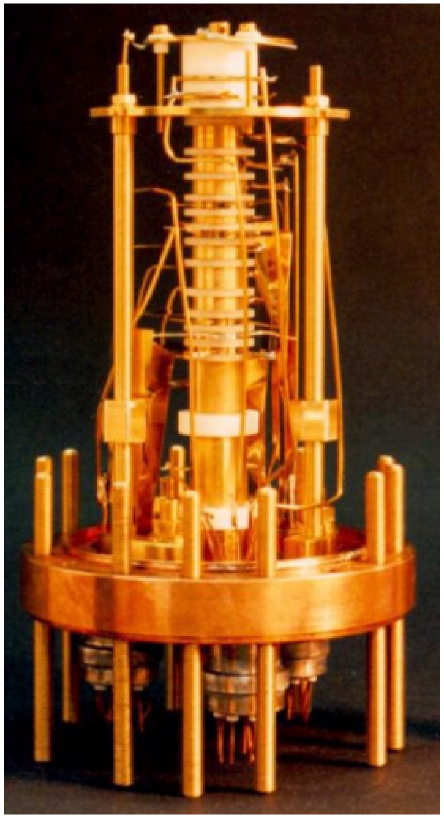
Set-Up for g-Factor Determination of the Bound Electron in a Single H-Like Ion

- two Penning traps:

  precision trap: homogeneous magnetic field for measurement of B via determination of the cyclotron frequency of a single ion and induction of spin flips

  analysis trap: inhomogeneous field for detection of spin direction of the bound electron



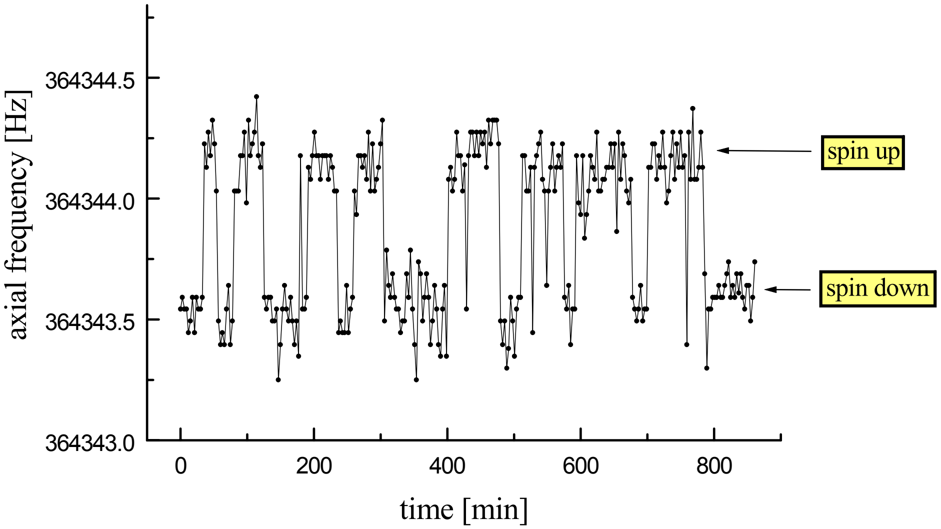


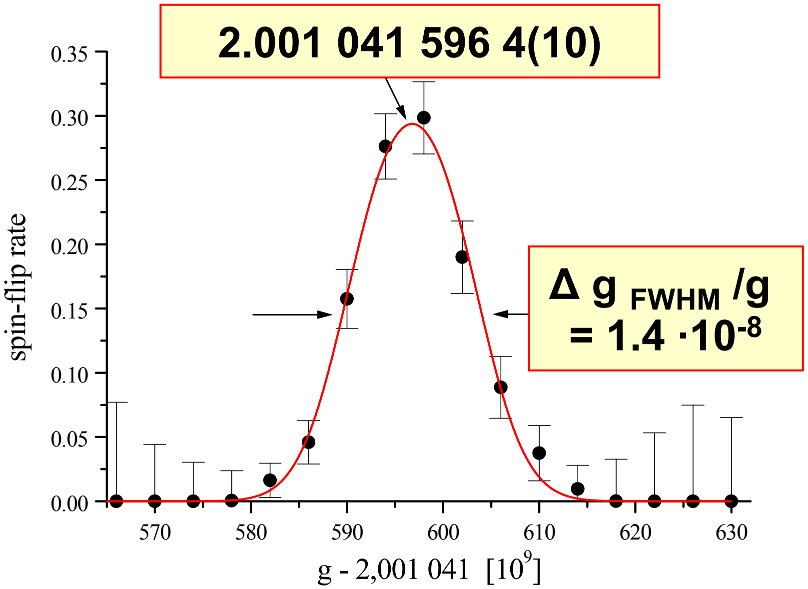
- LHe temperature:
  - single-ion detection
  - small amplitudes
  - extreme ultra-high vaccum
  - long storage time

- superconducting magnet:
  - high frequencies
  - high stability
  - high accuracy

GSI – University of Mainz collaboration

g-Factor of the Bound Electron





2.001 041 596 4(10)

$\Delta g_{FWHM}/g = 1.4 \cdot 10^{-8}$

	g(^{12}C^{5+})	g(^{16}O^{7+})
experiment	**2.001 041 596 4(10) (44)**	**2.000 047 025 4(15)(44)**
theory	**2.001 041 590 18(3)**	**2.000 047 020 32(11)**

statistical error: $\delta g/g = 5\cdot 10^{-10}$

total error: $\delta g/g = 2\cdot 10^{-9}$ **(limited by the knowledge of m_e)**

Experiment agrees with theory at medium charge for ^{12}C^{5+} and ^{16}O^{7+}
limited only by the knowledge of the mass of the electron
→ stringent test of medium-Z QED and the fundamental constant m_e can be determined

Fundamental Constants from g-Factor Measurements: Mass of the Electron

$$g = \left(\frac{\omega_L}{\omega_c}\right)\cdot\frac{\left(\frac{q}{M}\right)_{ion}}{\left(\frac{e}{\underset{\uparrow}{m}}\right)_e}$$

QED correct ⇒ $m_e = 0.000548\,579\,909\,3(3)$ u [§]
$m_e = 0.000548\,579\,909\,43(23)$ u [$]

van Dyck (1995) $m_e = 0.000548\,579\,911\,1(12)$ u
CODATA (1998) $m_e = 0.000548\,579\,911\,0(12)$ u

⇒ improvement by a factor of 5 $\delta m_e/m_e = 4.2\cdot 10^{-10}$

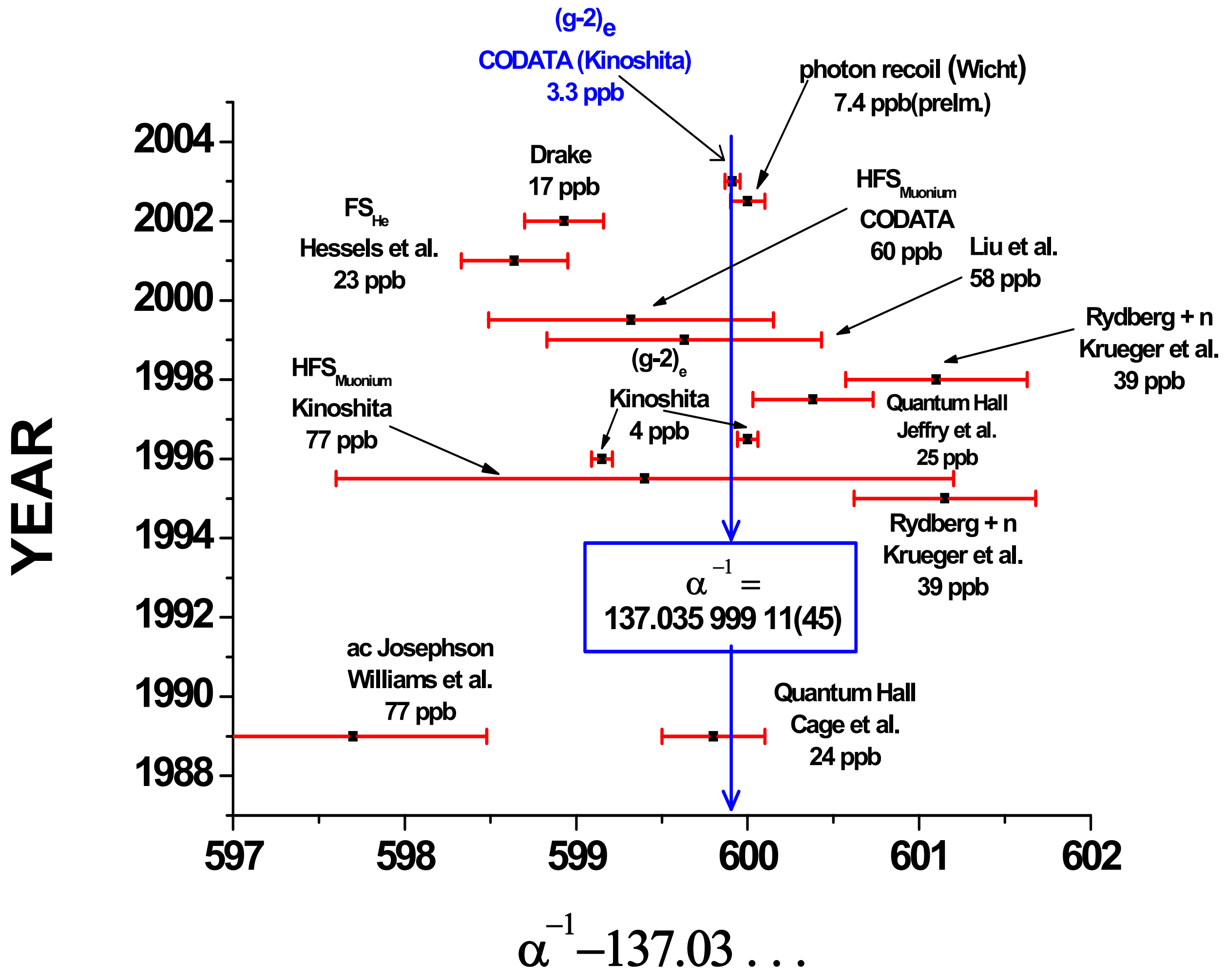
[§] T. Beier et al., NIM B205 (2003) 15
[$] P.J. Mohr et al. Rev. Mod. Phys. 80 (2008) 633

exp: H. Häffner et al., PRL 85 (2000) 5308, updated with new value of fine structure constant
J. Verdú et al., PRL 92 (2004) 093002
G. Werth et al., Int. J. Mass Spectrometry 251 (2006) 152

theo: 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)

Fundamental Constants from g-Factor Measurements: Fine Structure Constant

$$g_{Dirac} = {}^{2}\!/_{3}\left(1+2\sqrt{1-(Z\alpha)^2}\right) \qquad \frac{\delta\alpha}{\alpha} \propto \frac{1}{(Z\alpha)^2}\,\frac{\delta g}{g}$$



T. Beier et al.
Eur. Phys. J. A15 (2002) 41
g(^{40}Ca^{19+}): δg/g = 0.7 ppb
→ δα/α ≈ 10 ppb

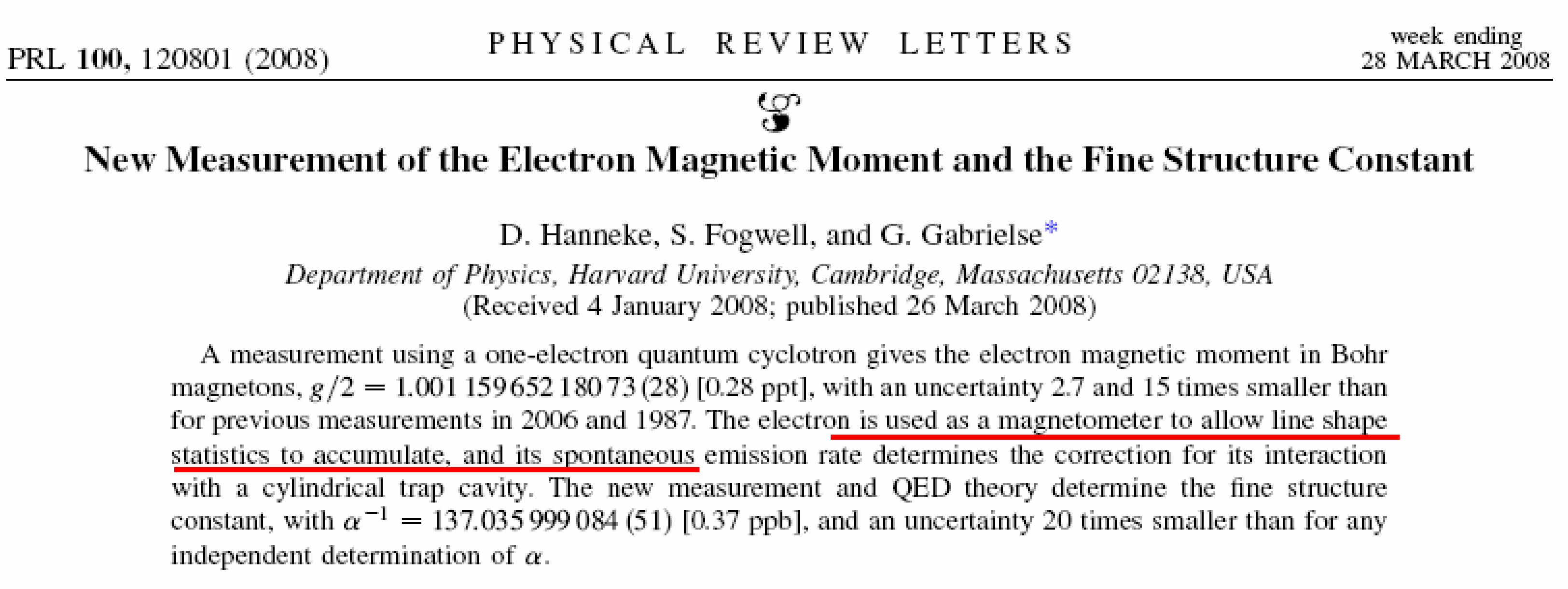
^{40}Ca mass measured
by SMILETRAP at Stockholm
S. Nagy et al.,
Eur. Phys. J. D39 (2006) 1

U.D. Jentschura et al., Intern. J. Mass spectrometry, 251 (2006) 102
improved two-loop calculation
g(^{40}Ca^{19+}): δg/g = 0.7 ppb
→ δα/α ≈ 3 ppb
exp. work in progess at Mainz:
B. Schabinger, K. Blaum et al.

V.M. Shabaev et al.,
PRL 96 (2006) 253002
g-factor determination in H-like and
B-like Pb: δg/g = 0.7 ppb
→ δα/α < 3 ppb

D. Hanneke, S. Fogwell, G. Gabrielse
PRL 100 (2008) 120801
new determination of the
g-factor of the free electron
δα/α = 0.37 ppb

A Tough Competition



PRL 100, 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

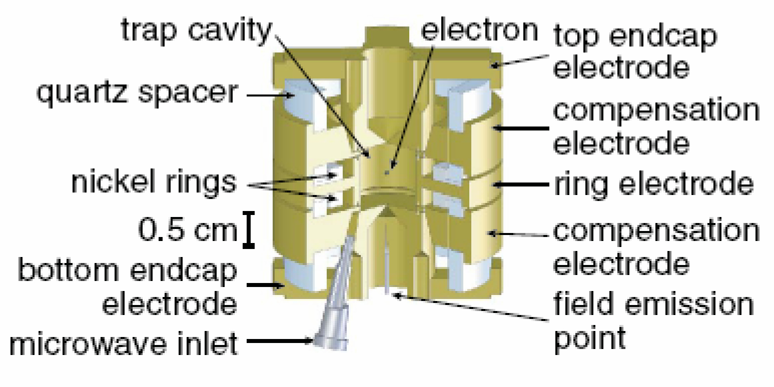
New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

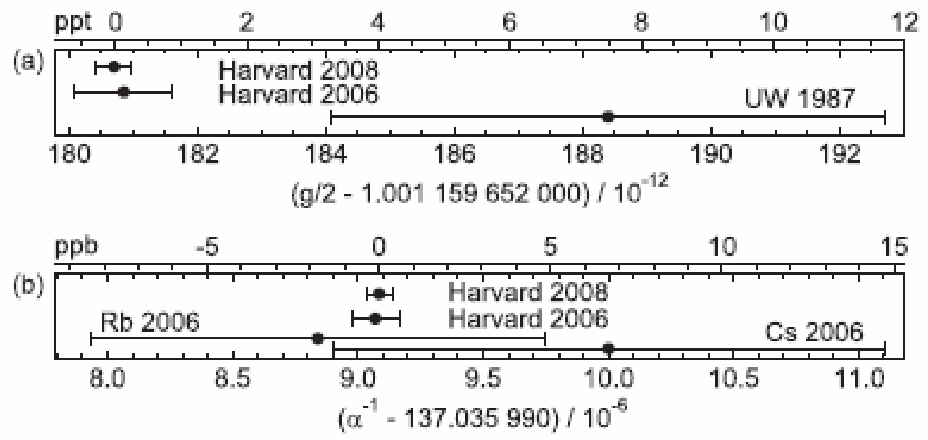
D. Hanneke, S. Fogwell, and G. Gabrielse*

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.





Nuclear Moments and Charge Radii from g-Factor Experiments

NUCLEAR MAGNETIC MOMENT

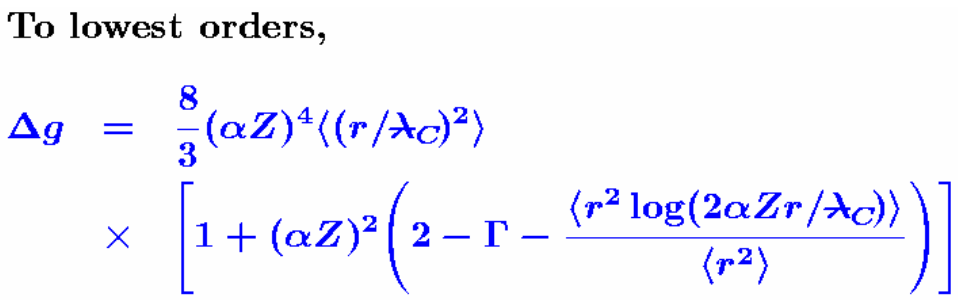
NUCLEAR CHARGE RADII

$$g_F = g_J \frac{F(F+1)+J(J+1)-I(I+1)}{2F(F+1)} - g_I \frac{F(F+1)+I(I+1)-J(J+1)}{2F(F+1)} \quad \Rightarrow \quad \Delta g_{AA'} \cong A(Z\alpha)\delta\left\langle r^2 \right\rangle^{1/2}_{AA'}$$

theory 10^{-9}

experiment 10^{-9}

$\Rightarrow$ **10^{-6}**



To lowest orders,

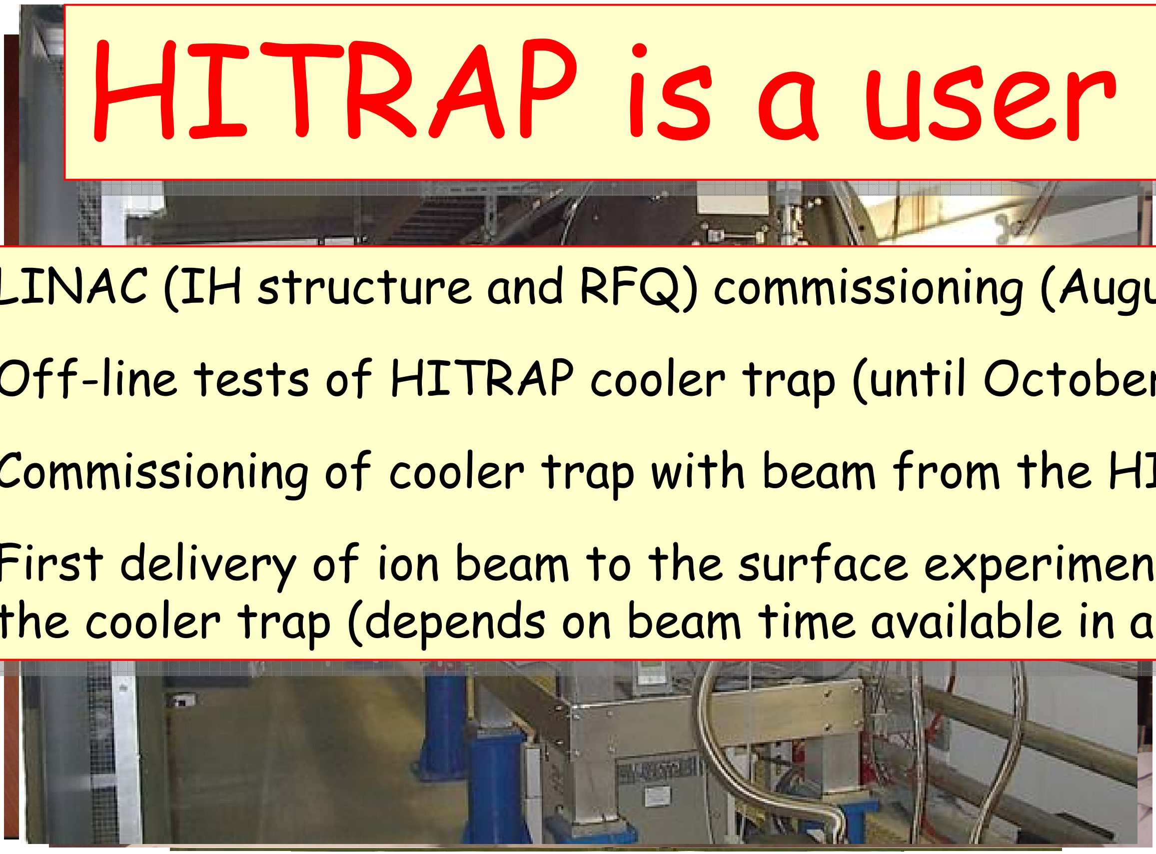
$$\begin{aligned}\Delta g &= \frac{8}{3}(\alpha Z)^4 \langle (r/\bar{\lambda}_C)^2 \rangle \\ &\times \left[1 + (\alpha Z)^2 \left(2 - \Gamma - \frac{\langle r^2 \log(2\alpha Z r/\bar{\lambda}_C) \rangle}{\langle r^2 \rangle} \right) \right]\end{aligned}$$

Glazov and Shabaev, PL A297 (2002) 408

For the first time:
check of diamagnetic correction

exact calculations are possible!

4. Status of HITRAP



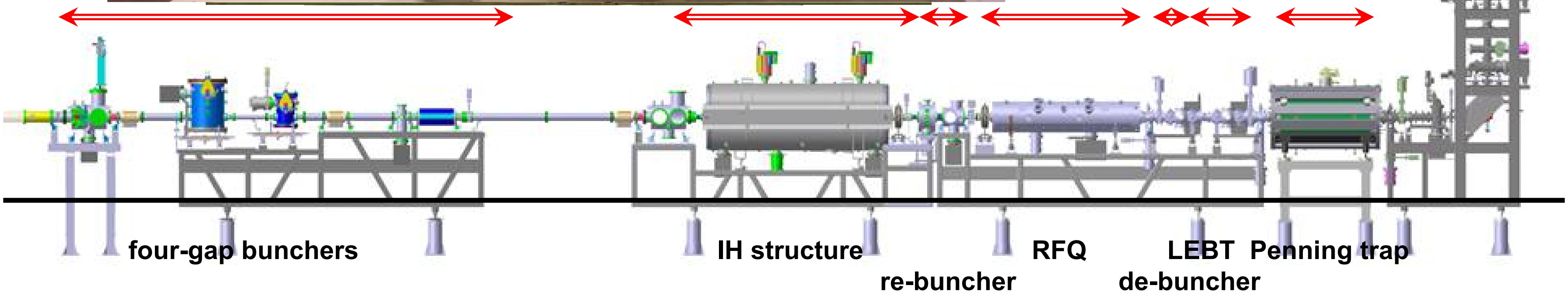
HITRAP is a user facility !

LINAC (IH structure and RFQ) commissioning (August 08)

Off-line tests of HITRAP cooler trap (until October 08)

Commissioning of cooler trap with beam from the HITRAP linac (October 2008)

First delivery of ion beam to the surface experiment installed down stream the cooler trap (depends on beam time available in autumn/winter 2008)



The Collaboration

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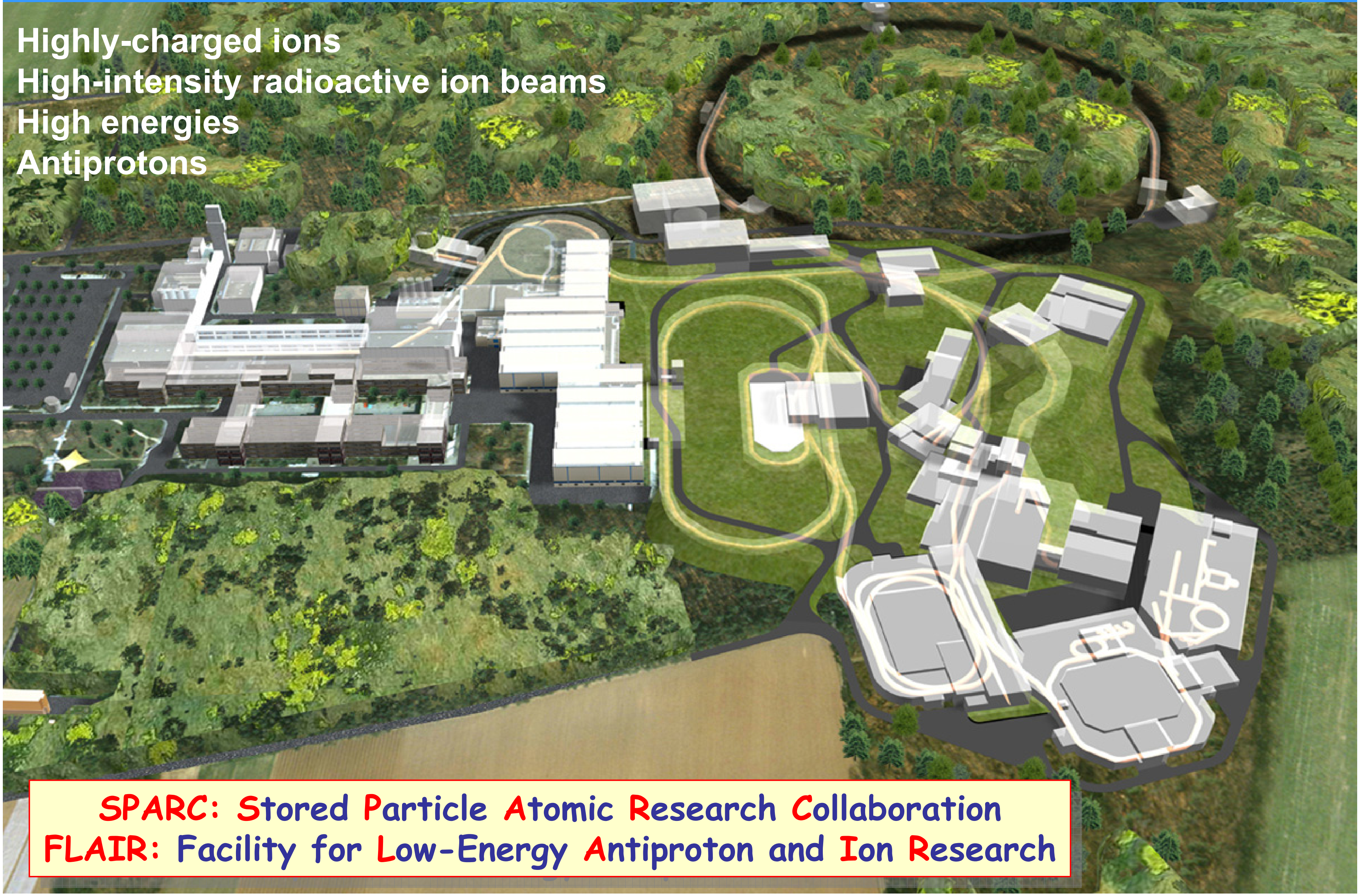
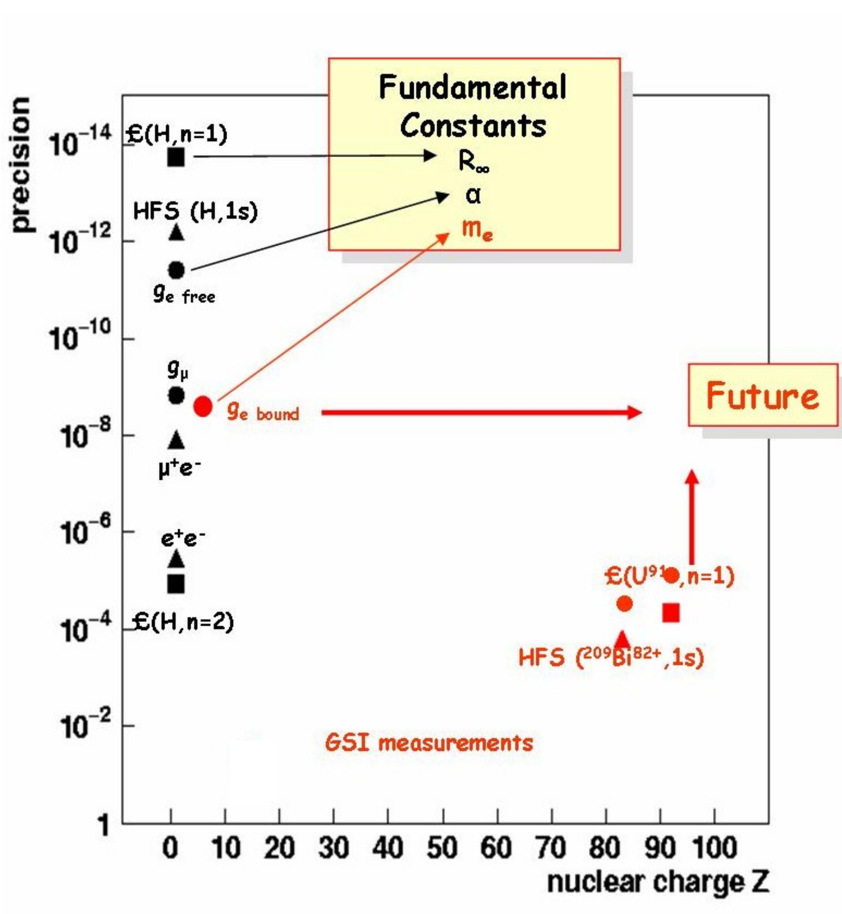
Outlook: The Future International Facility "FAIR" for Antiproton and Heavy-Ion Research at Darmstadt



Highly-charged ions
High-intensity radioactive ion beams
High energies
Antiprotons

SPARC: **S**tored **P**article **A**tomic **R**esearch **C**ollaboration
FLAIR: Facility for **L**ow-Energy **A**ntiproton and **I**on **R**esearch

Summary & Conclusion



HITRAP at the present GSI and at the future FAIR facility will provide excellent conditions for a large variety of high-accuracy atomic-physics experiments with highly charged ions and antiprotons.

Storing and cooling are key ingredients at HITRAP.

Starting 2009:

Effects of extreme electromagnetic fields can be investigated with very high accuracy.

Highly-charged ions offer a new access to the determination of fundamental constants.

Atomic physics techniques offer model-independent information on nuclear ground state properties. Hyperfine fields of highly-charged ions can be calculated very accurately.

And much more ....