Challenges for Atomic Physics with Highly-Charged Ions and Antiprotons at the GSI Future Facility

FAIR: Facility for Antiproton and Ion Research

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Research fields of atomic physics at accelerators

The instruments for atomic physics at GSI

The future GSI heavy-ion and pbar accelerator

Facilities and experiments of the FLAIR/SPARC community

***email: t.stoehlker@gsi.de**

Atomic Physics at Accelerators

ATOMIC SPECTROSCOPY
QED, many body effects

ATOMIC COLLISIONS
in strong perturbative regime

NUCLEAR GROUND STATE PROPERTIES
masses, nuclear moments, charge radii

ATOMIC PHYSICS
with
HIGHLY CHARGED IONS
and
EXOTIC NUCLEI

SLOW Highly Charged Ions: Interactions FAR FROM EQUILIBRIUM

COOLING Techniques and CRYSTALLINE Beams

Lamb Shift and g-Factor in STRONG Fields

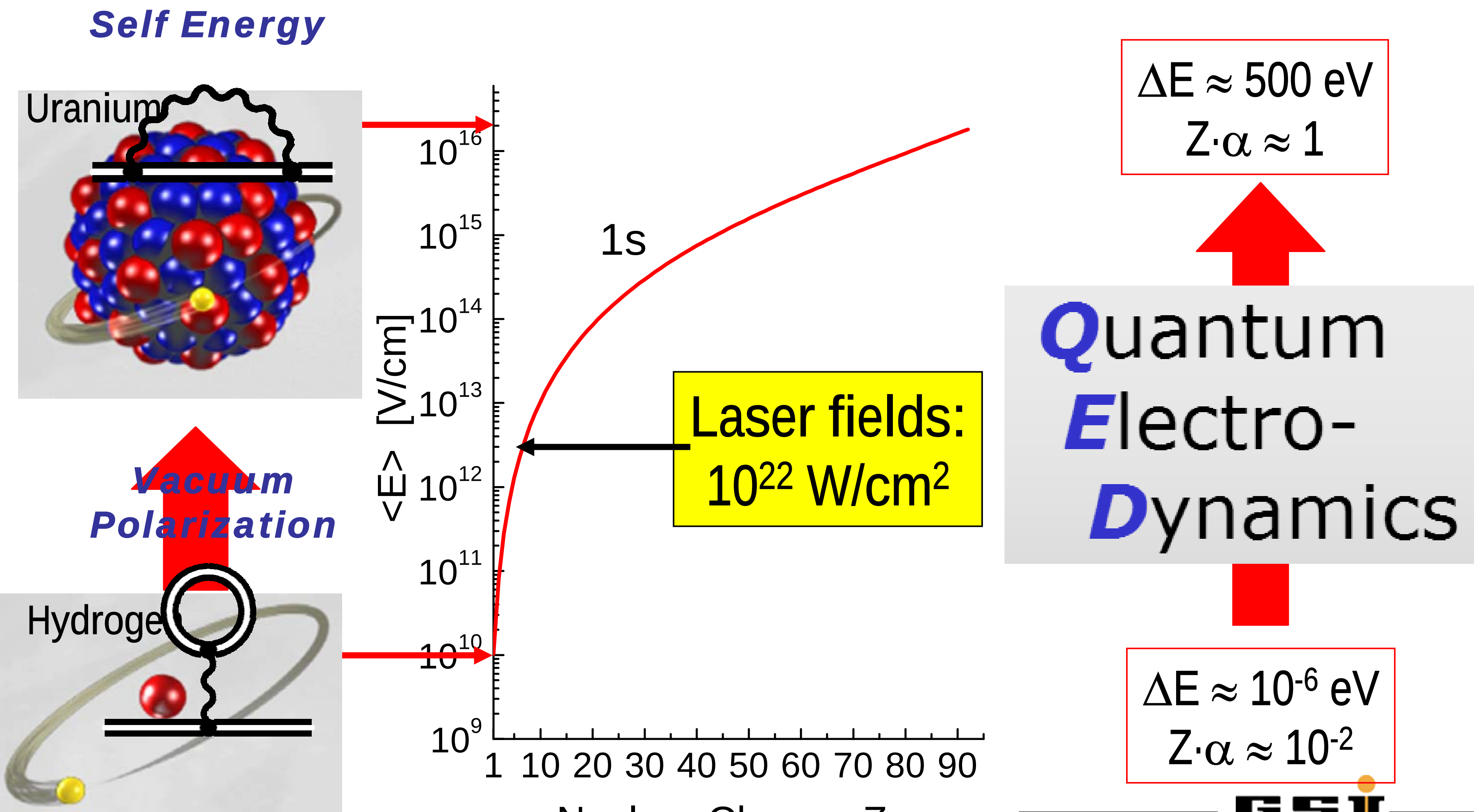
ULTRASHORT Laser Pulses: ATTOSECOND Pump-Probe

OVERCRITICAL EM Fields: Pair Production

POLARIZED NUCLEI

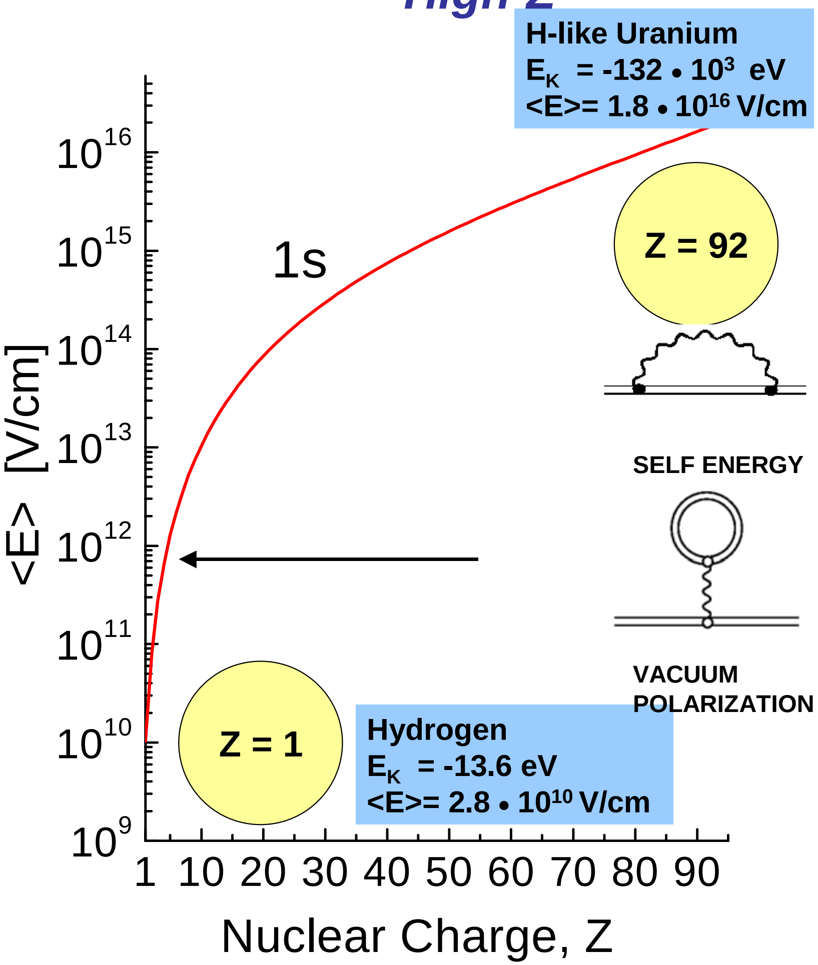
Weak Interaction in LOW MOMENTUM TRANSFER

Extreme Static Electromagnetic Fields



Electromagnetic Phenomena under Extreme & Unusual Conditions

High-Z

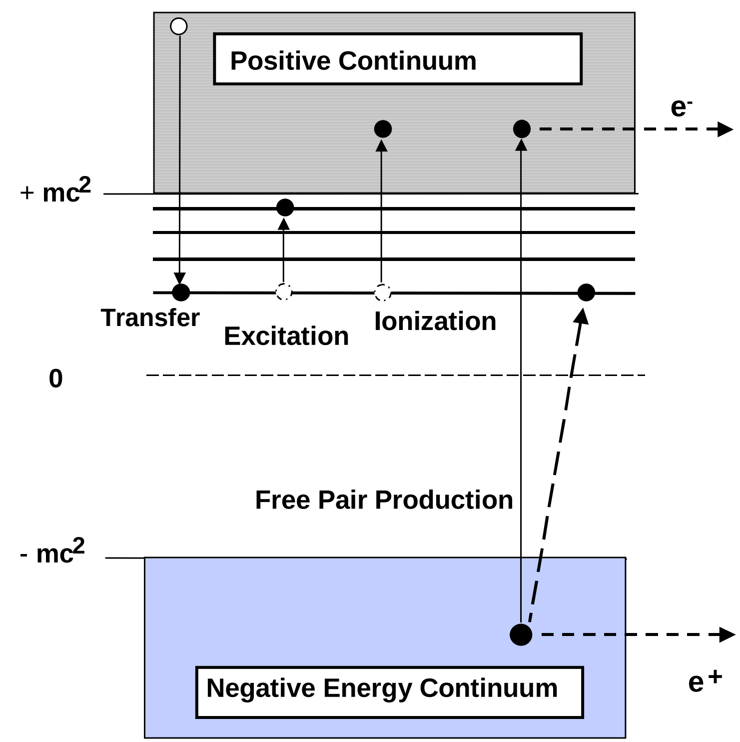


1s-ground state: increase of the electric field strength by six orders of magnitude

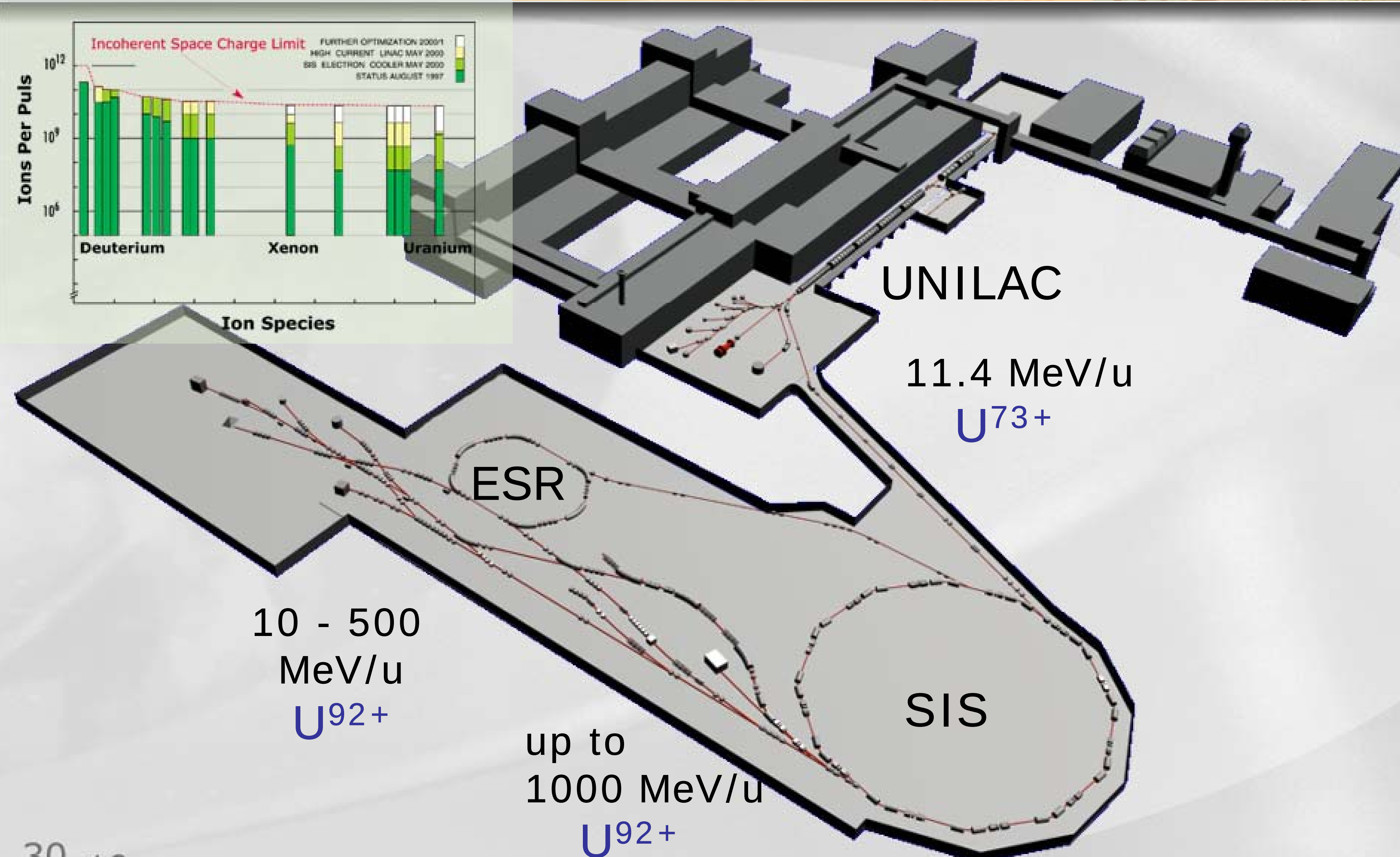
High- γ

Collision Dynamics of Relativistic Heavy Ions

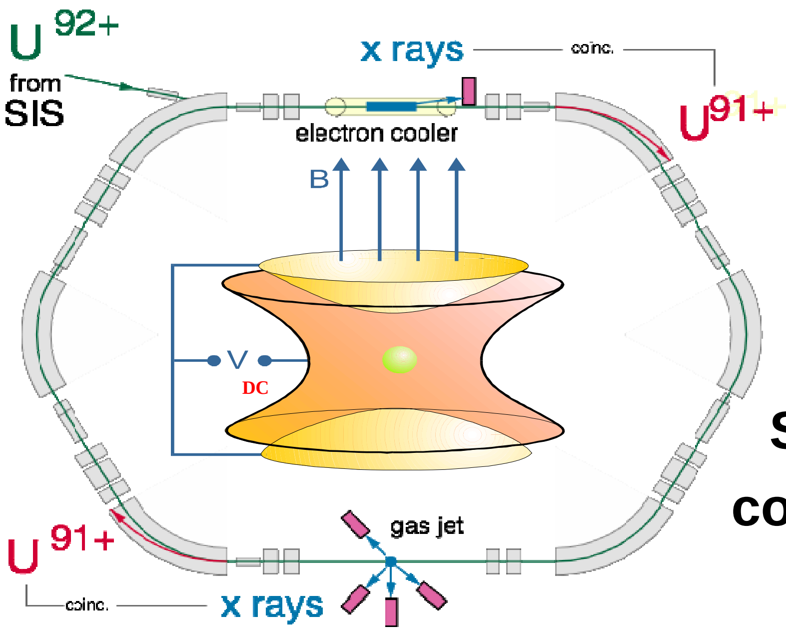
Collision times in the sub-attosecond regime (10^{-22} s < t < 10^{-18}s)



GSI-Accelerator Facility



Research Instruments at GSI for Atomic Physics

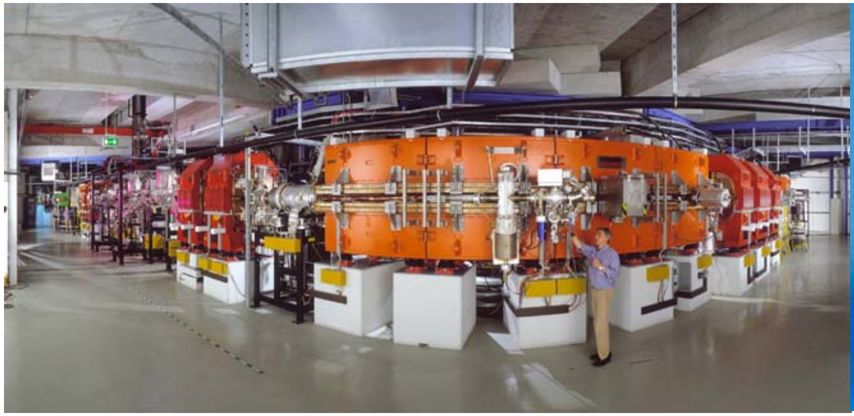


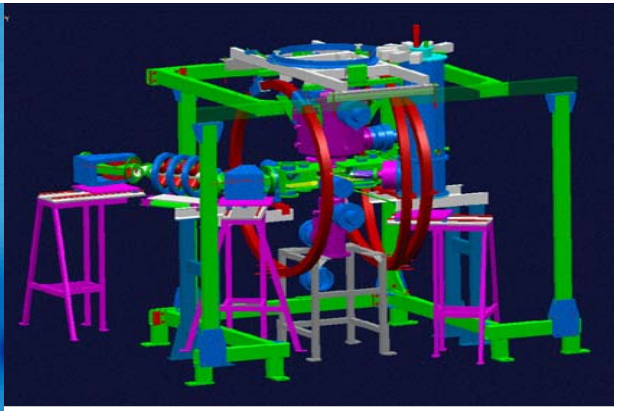
Storage and cooling devices

Photon sources

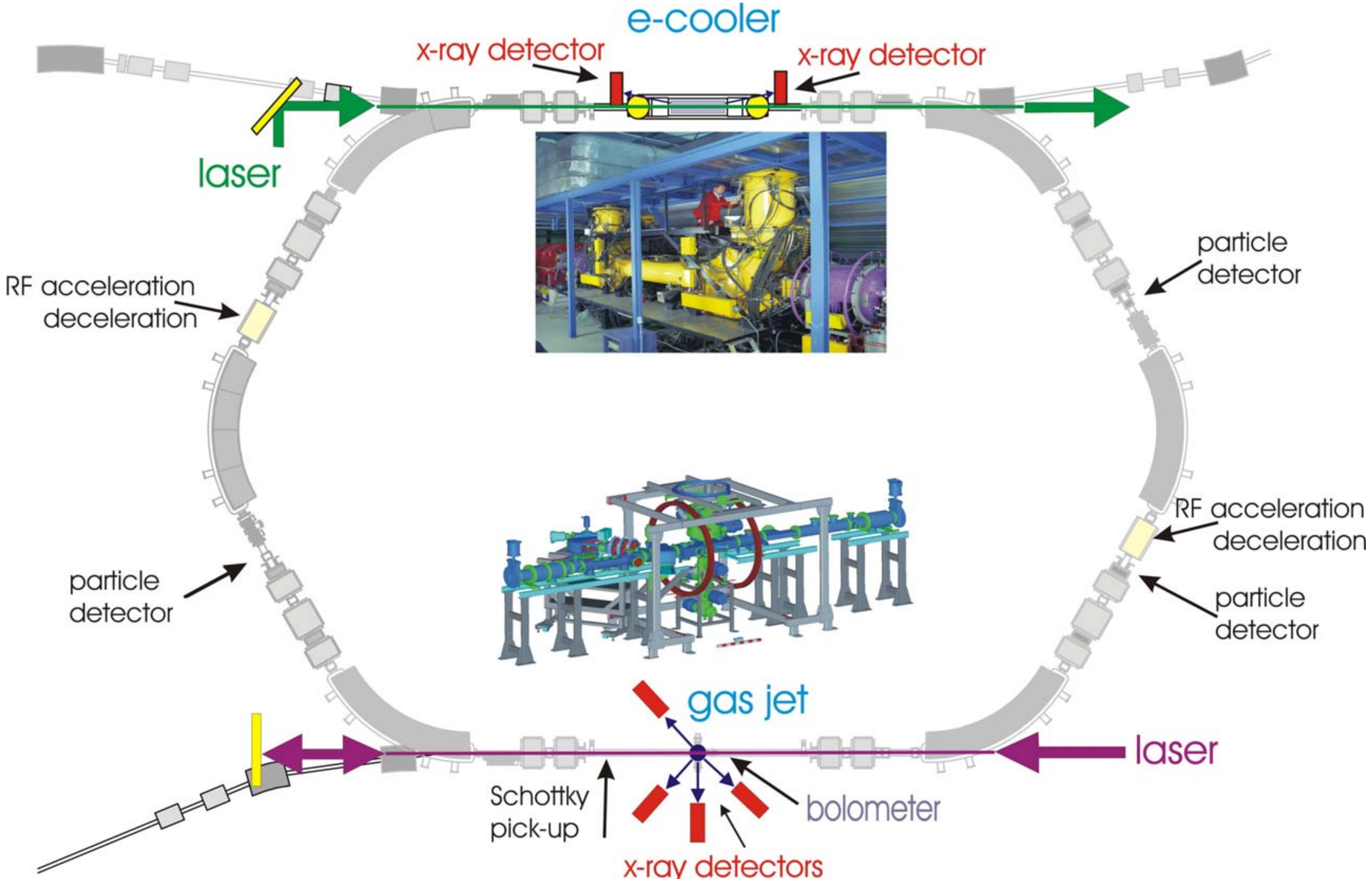
PHELIX

Spectrometers



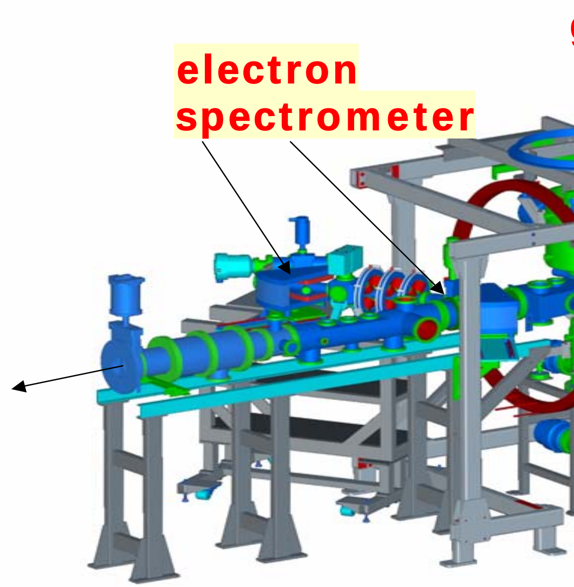


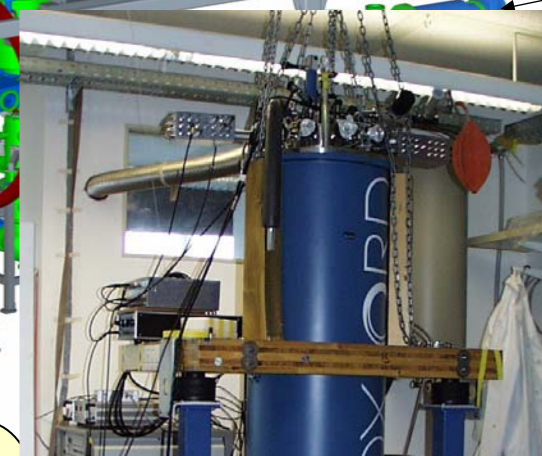
The ESR Storage Ring



Research Instruments at GSI for Atomic Physics

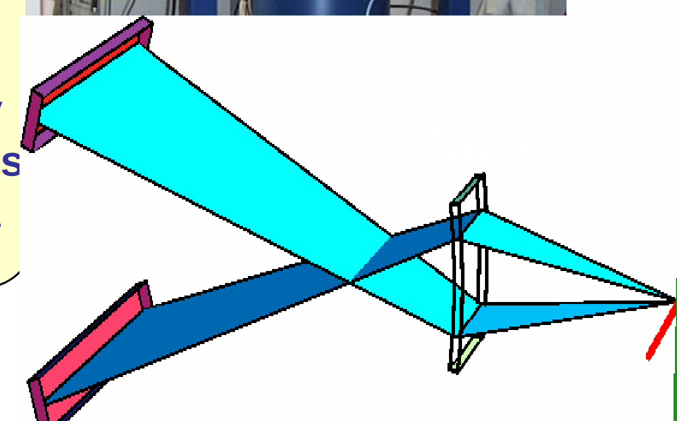
ELECTRON SPECTROSCOPY
high-resolution electron spectroscopy complementray to the x-ray channel





RECOIL ION MOMENTUM SPECTROSCOPY
impact parameter sensitive studies
(e,2e) processes in HCI atom collisions

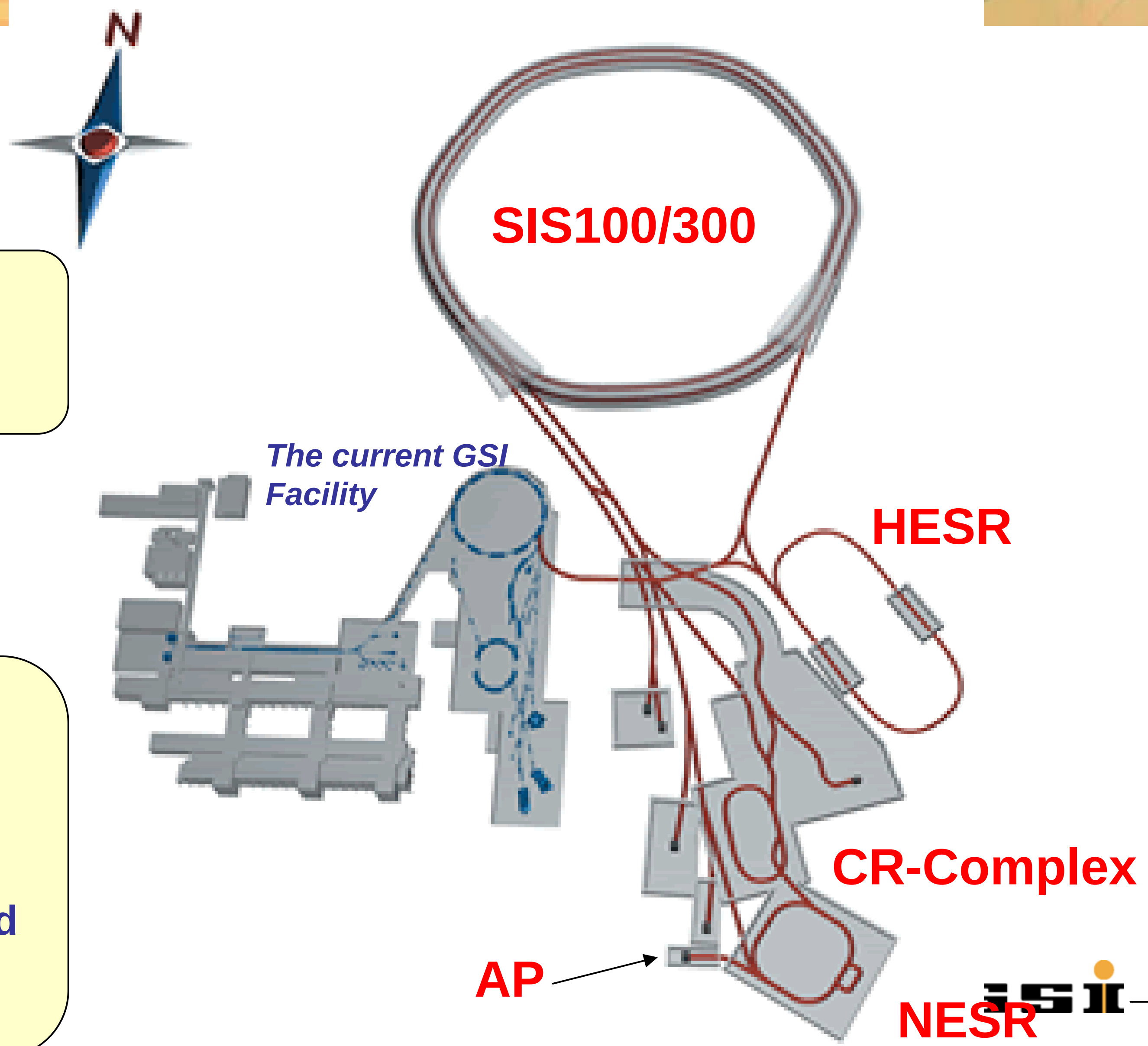
X-RAY SPECTROSCOPY
e.g.
precision spectroscropy
photon correlation studies
polarization phenomena



The FAIR Project

Facility for Anti-Proton and Ion Research

1x10^12 1/s
for U^28+ at
1 GeV/u



Parameter
90 GeV protons
34 GeV/u U^92+

stored and cooled
antiprotons

Challenges for Atomic Physics at the Future GSI Facility

Stored and Cooled

Highly-Charged Ions

Exotic Nuclei

High Energies

Antiprotons

AREAS OF RESEARCH

Fundamental Interactions in

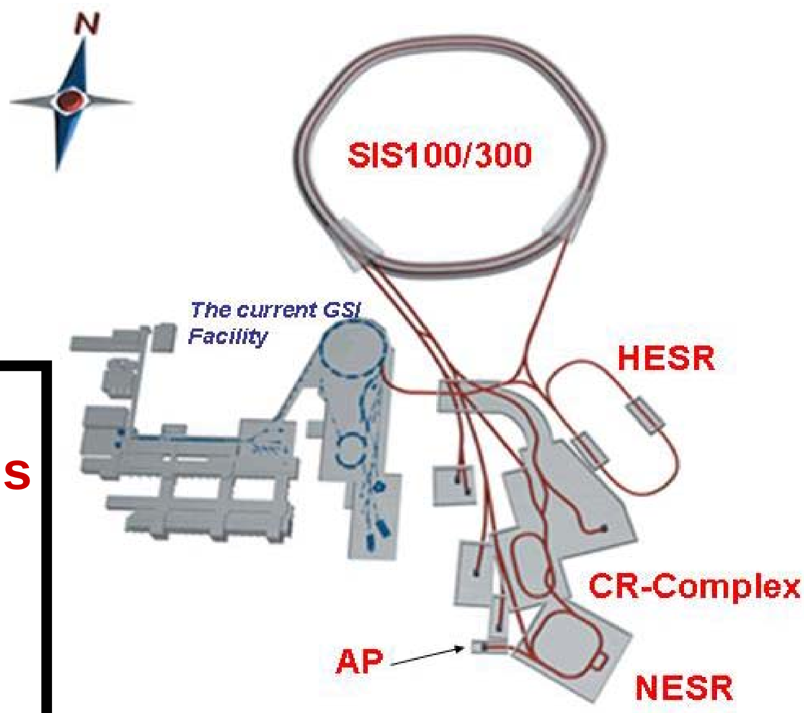
- **extreme Static Electromagnetic Fields**
- **extreme Dynamic Fields**

Fundamental tests: symmetries etc.

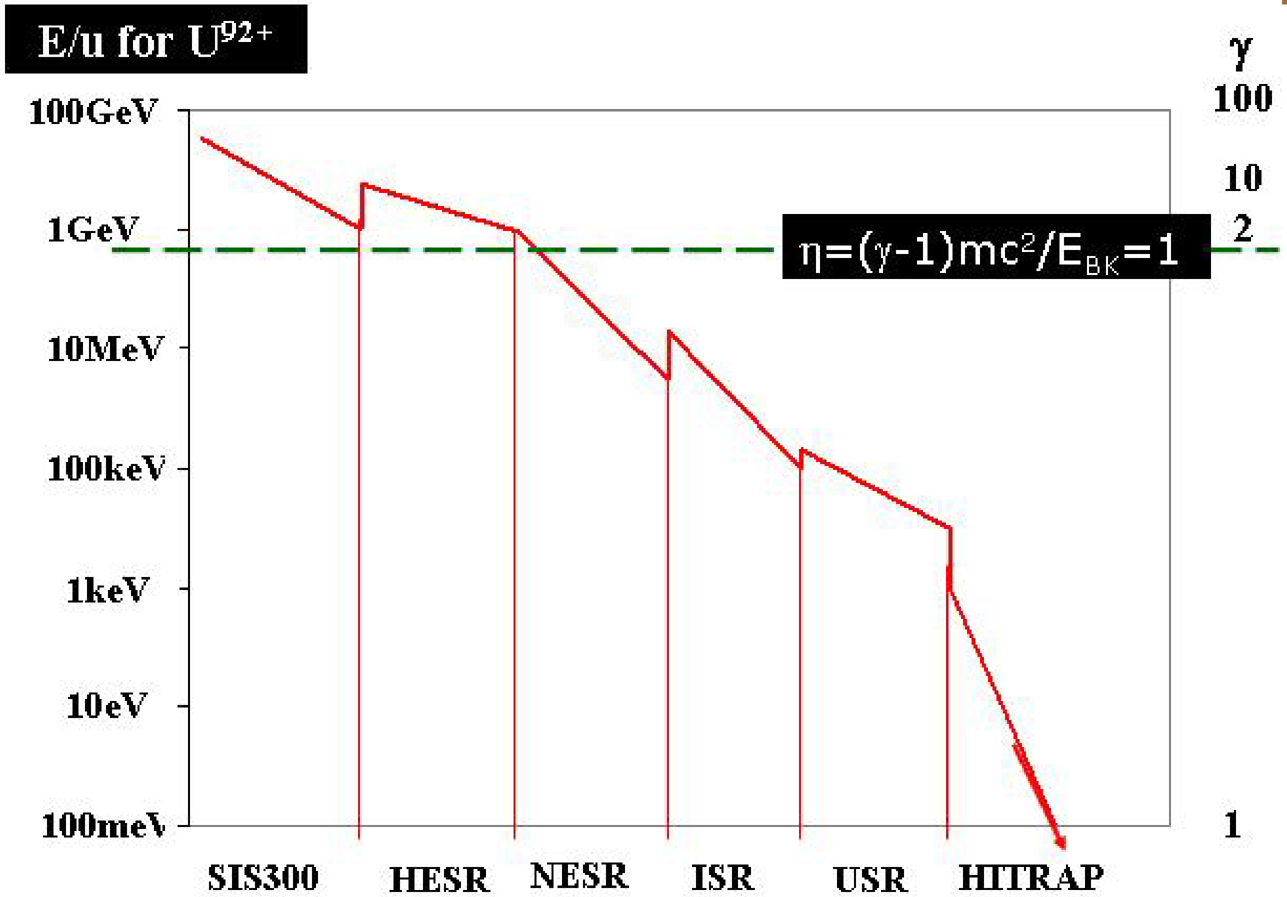
Nuclear Ground-State Properties

Accelerator Issues

- **charge changing collisions**
- **cooling of relativistic ion beams**

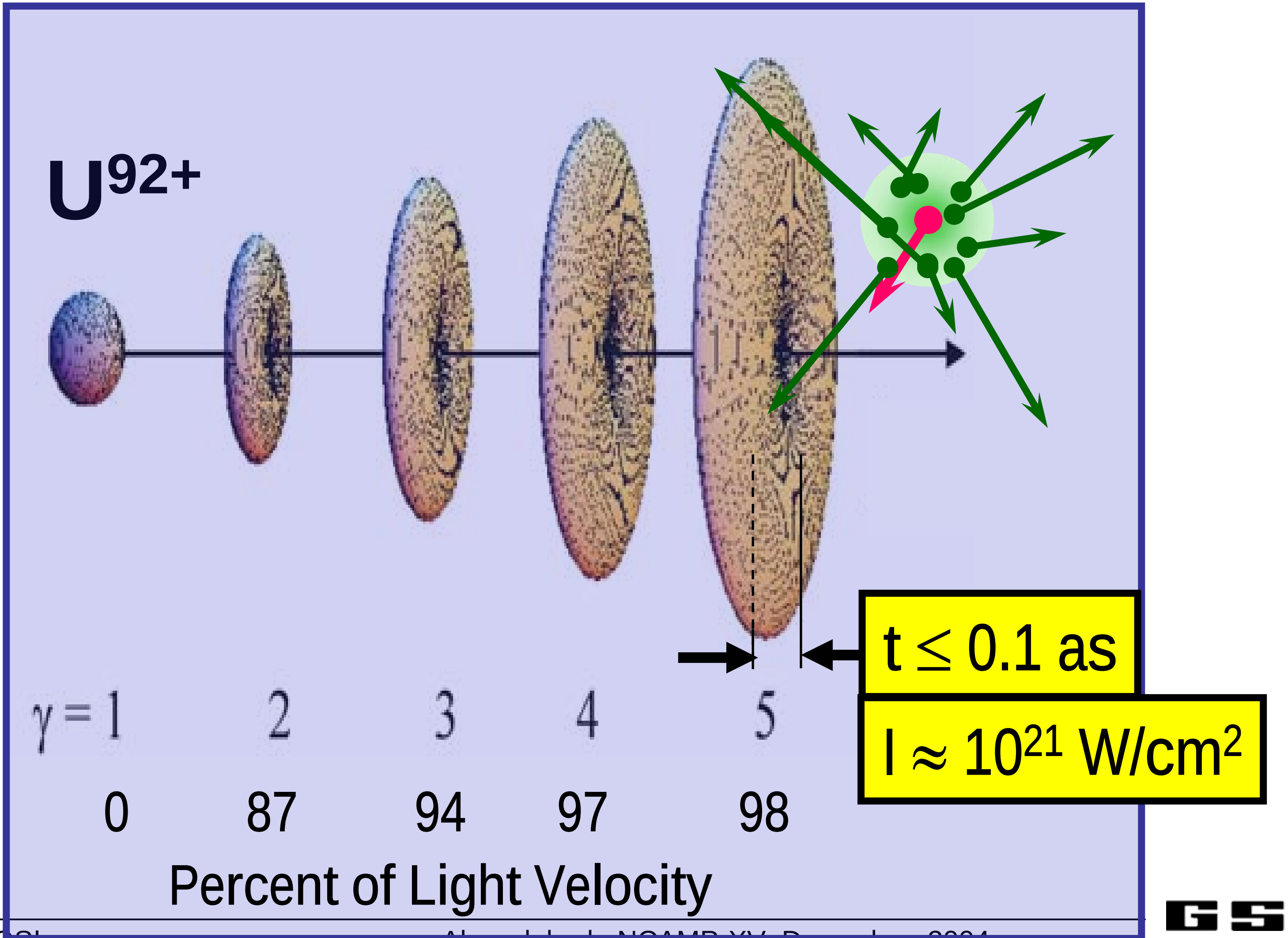


Extreme Velocities – Extreme Dynamic Fields



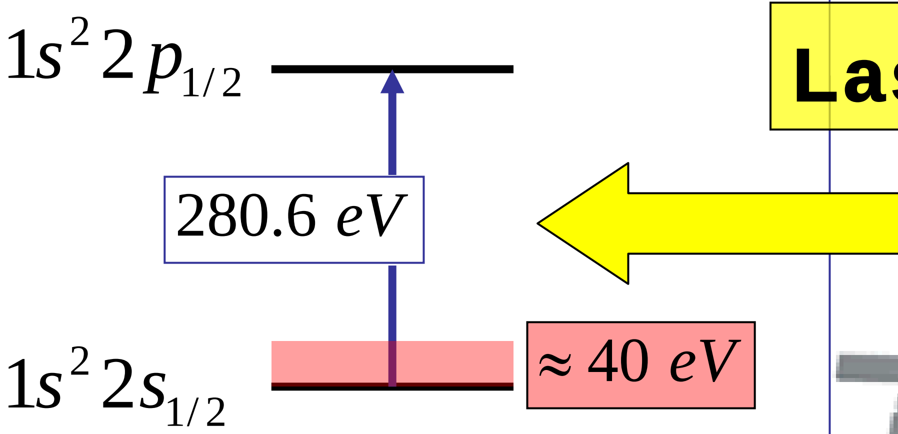
Charge States : $-1 \leq Q \leq +92$

Extreme Dynamic Fields

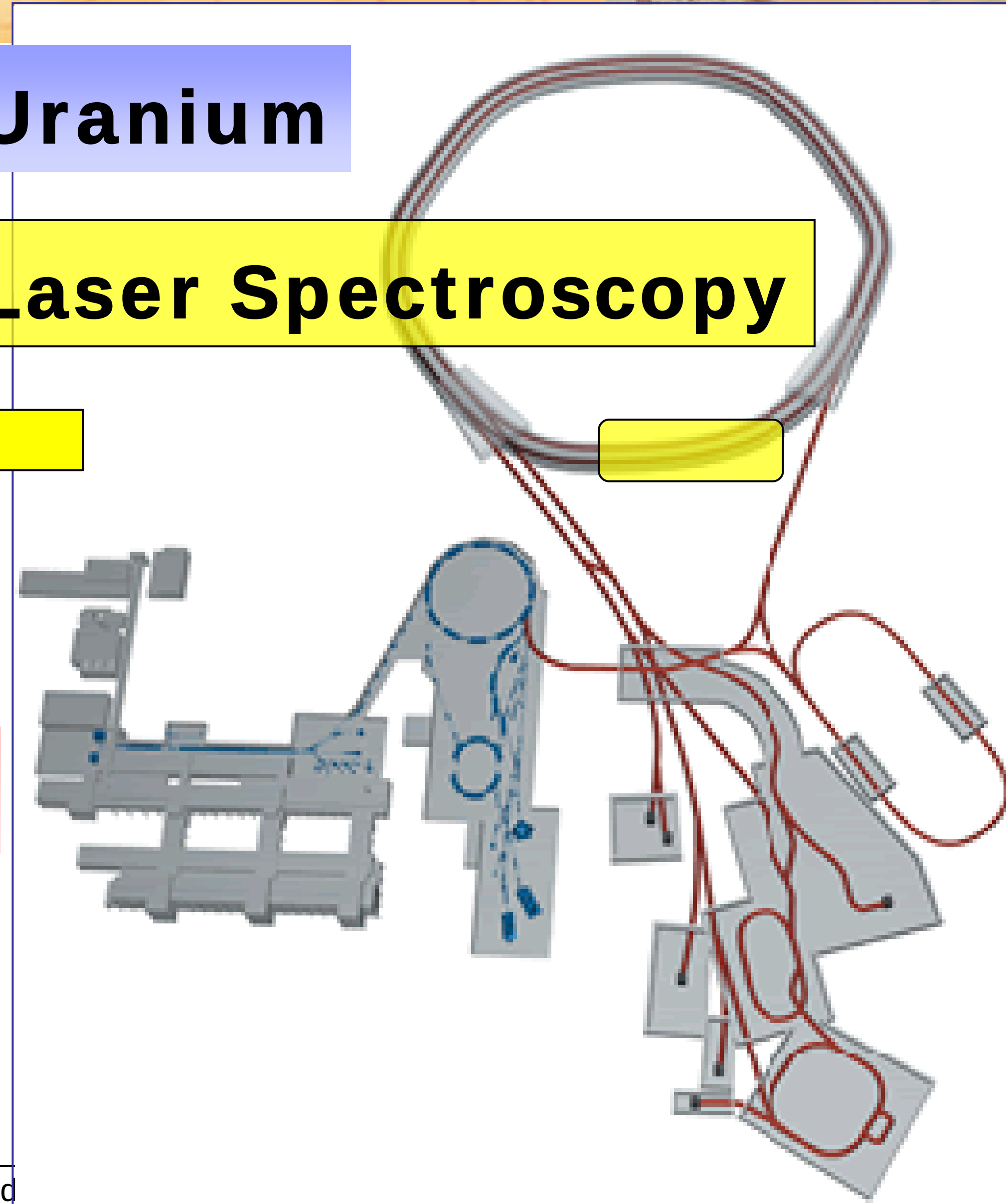


Quantum Electrodynamics

Three Electrons in Uranium



Laser Spectroscopy

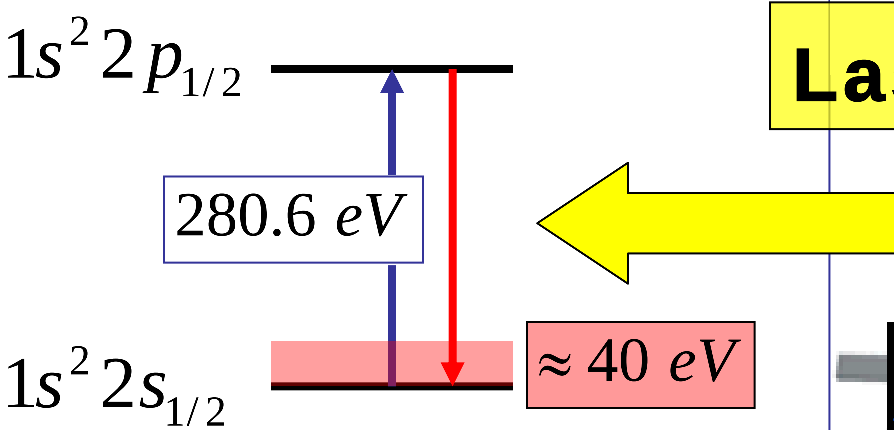


Three-Electron QED

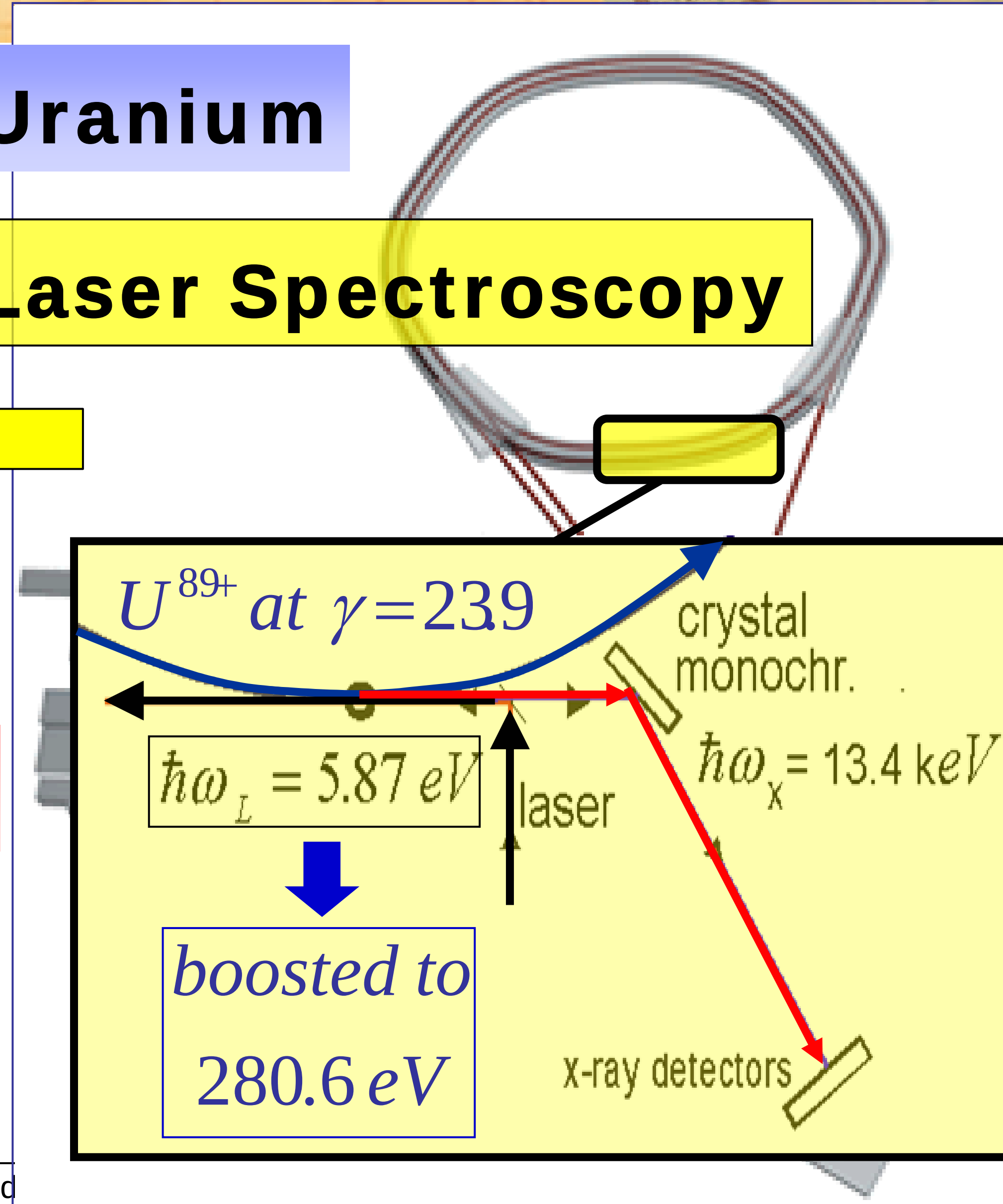
improve resolution factor of 10 to 20

Quantum Electrodynamics

Three Electrons in Uranium



Laser Spectroscopy



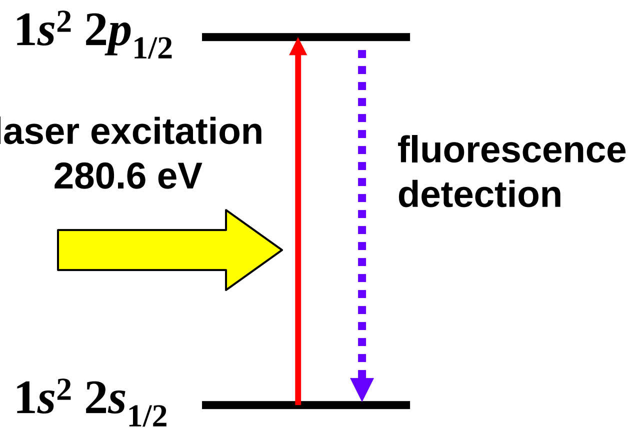
Three-Electron QED

improve resolution

factor of 10 to 20

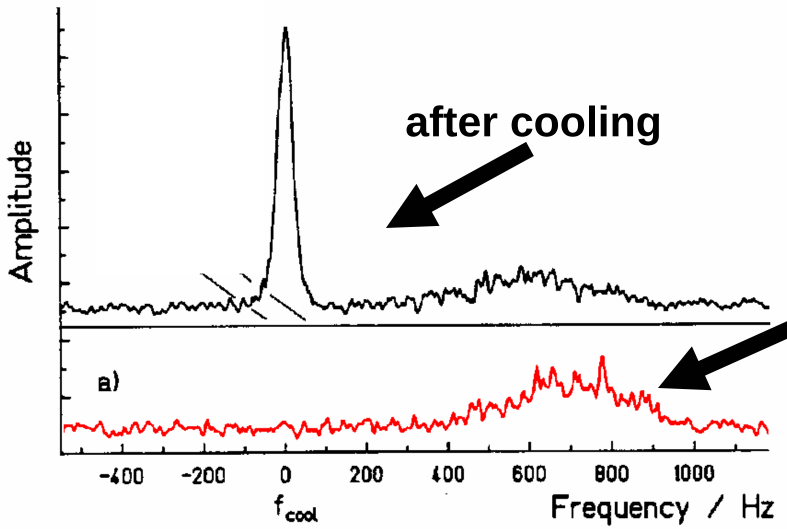
At the SIS 300: Laser Cooling and Spectroscopy of Stored Beams

The large Doppler shift (2γ) allows one to use laser light in the visible spectral range to excite transitions in the energy range up to 280 eV, e.g. 2s-2p transitions in lithium-like heavy ions



Cooling, Crystalline Beams

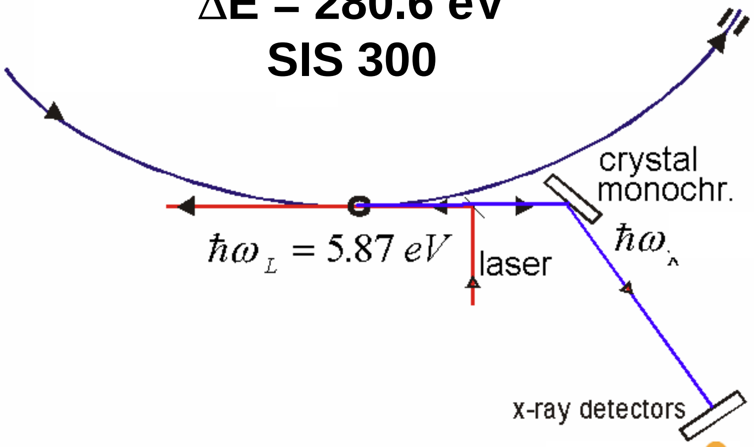
Schottky analysis of laser cooling



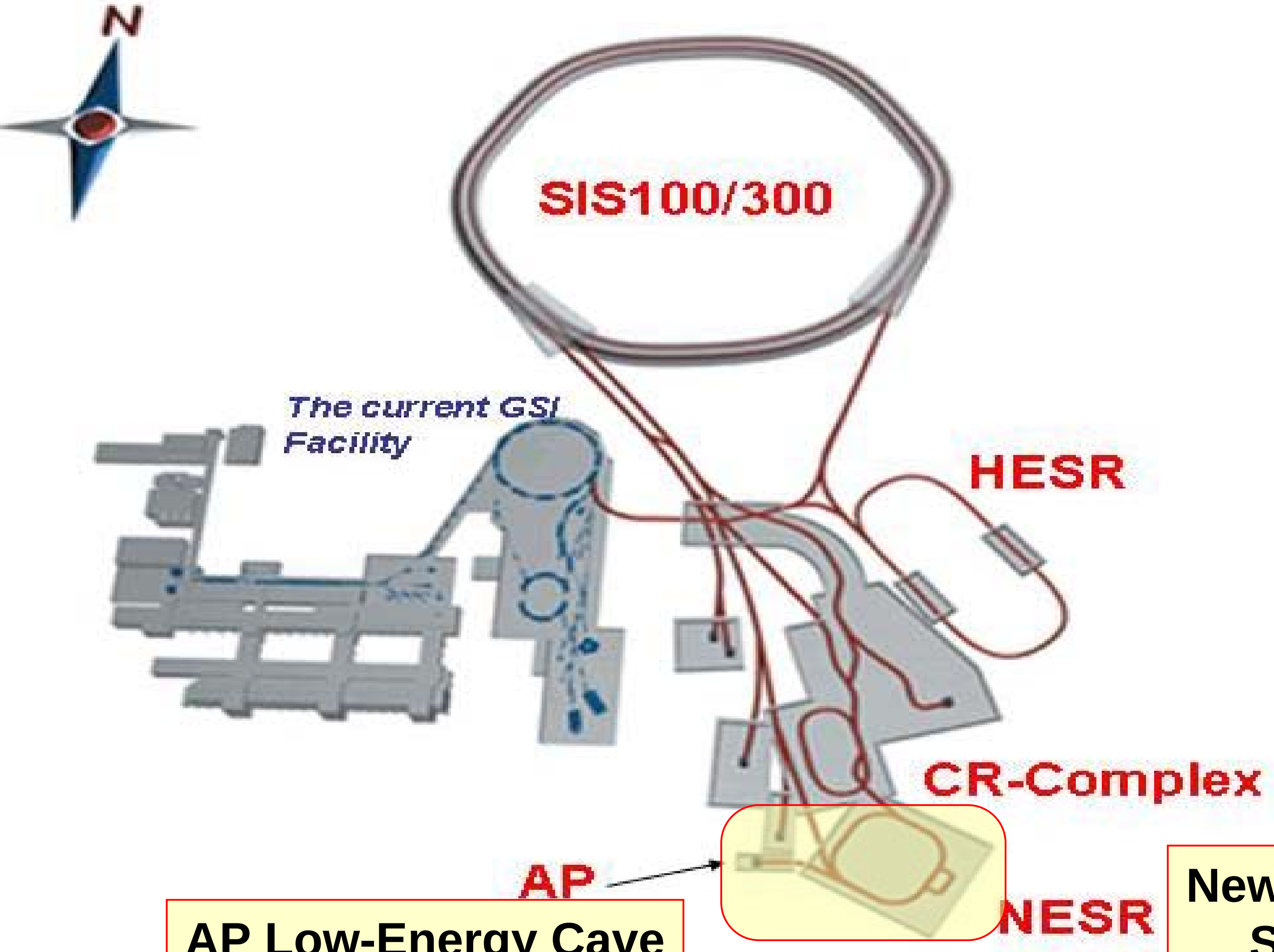
Lithium-like uranium

ΔE = 280.6 eV

SIS 300



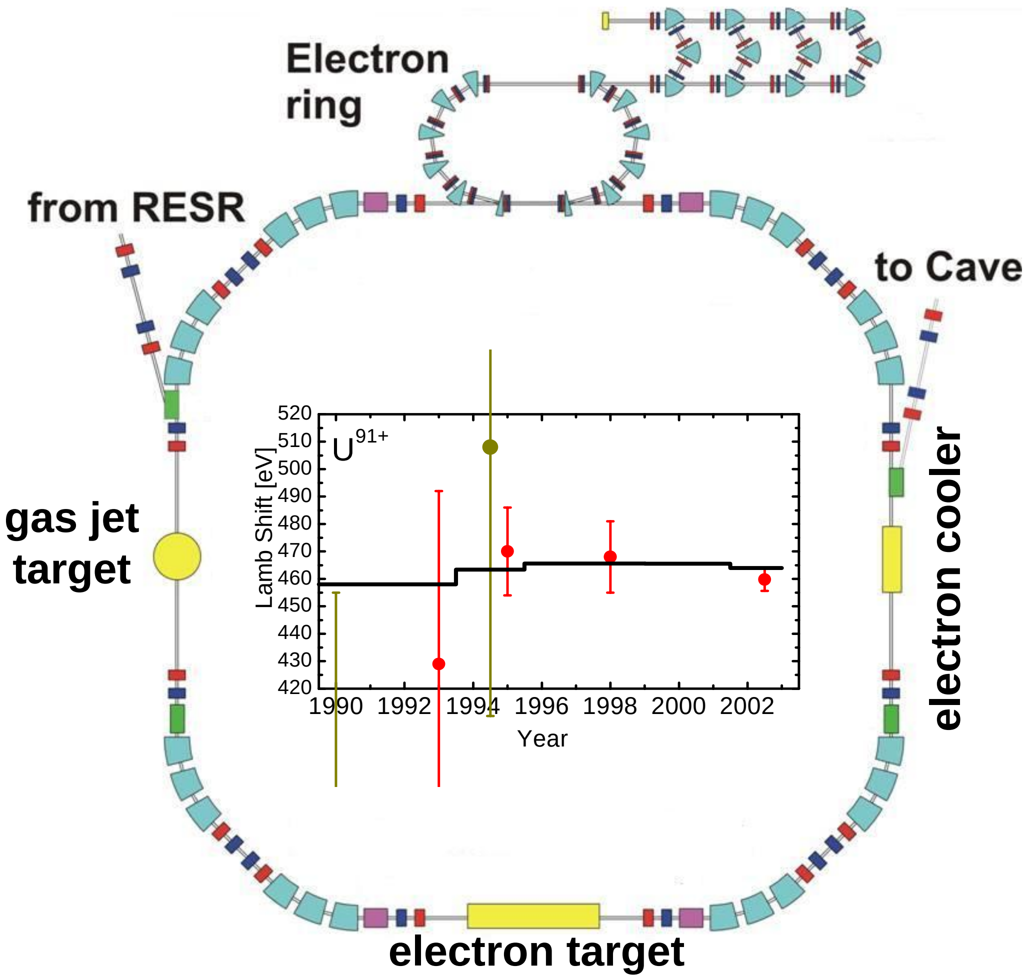
The Future GSI Heavy-Ion and Antiproton Accelerator Facility for Atomic Physics

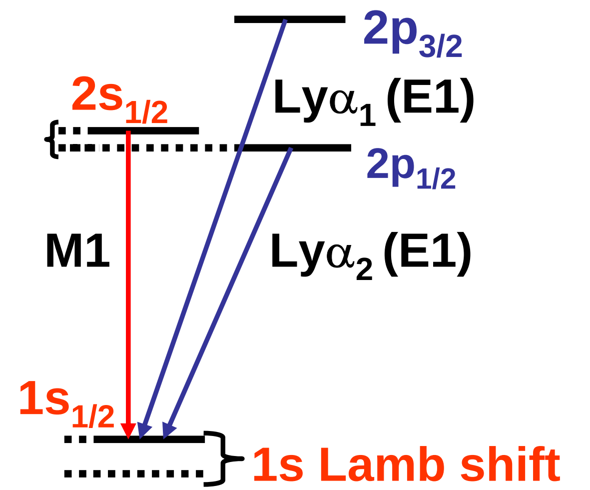


AP Low-Energy Cave

New Experimental Storage Ring

At the NESR:
1s Lamb Shift in Hydrogen-Like Uranium





1s-Lamb shift of uranium

Experiment: 459.8 eV ± 4.2 eV

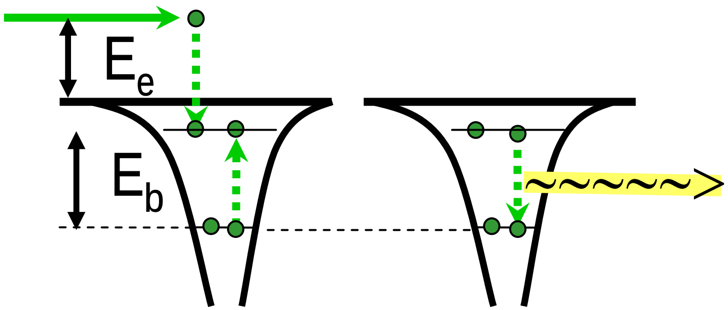
Theory: 463.95 eV ± 0.50 eV

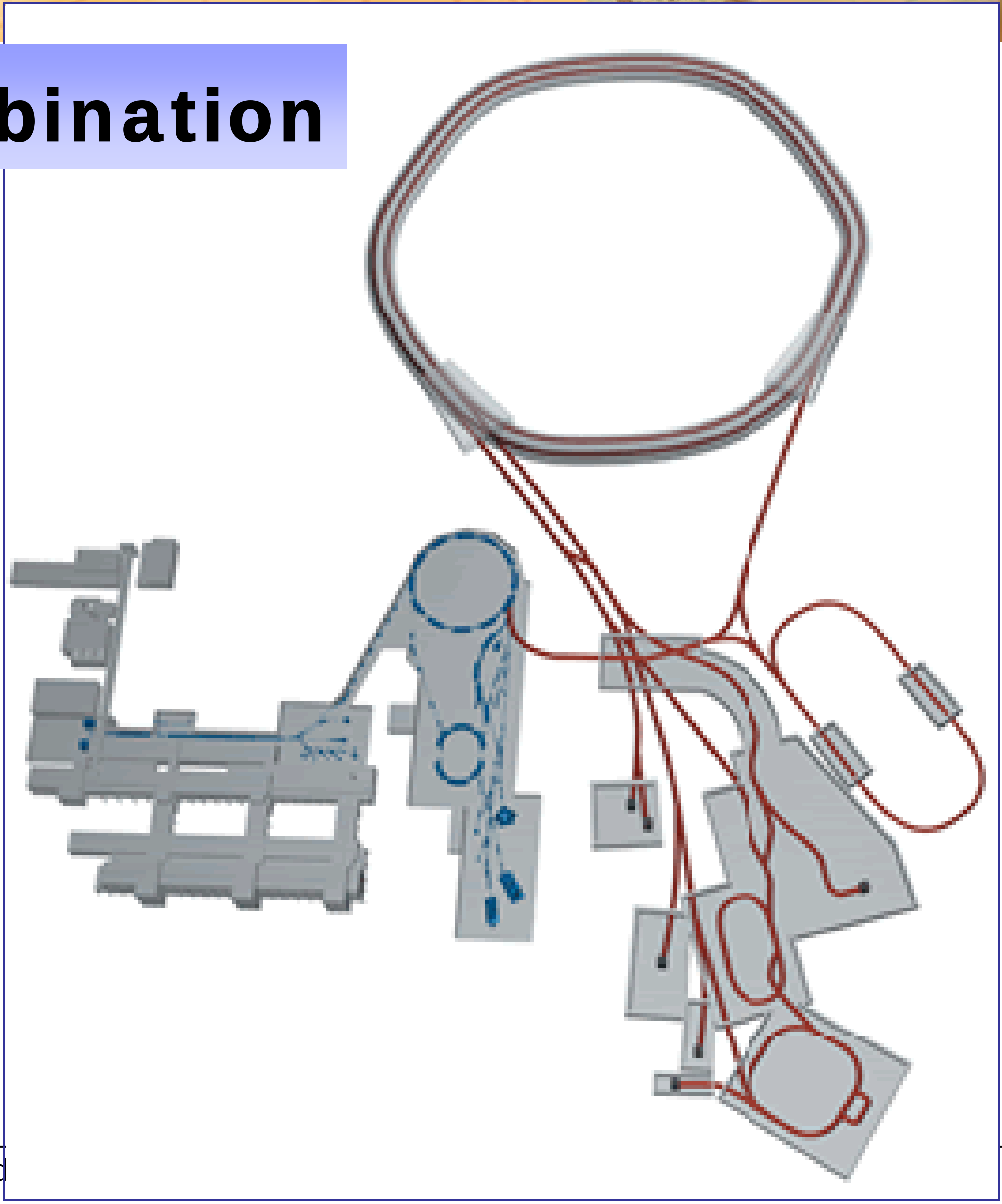
future: radioactive isotopes

exp: T. Stöhlker et al.
theo: V.A. Yerokhin and V.M. Shabaev

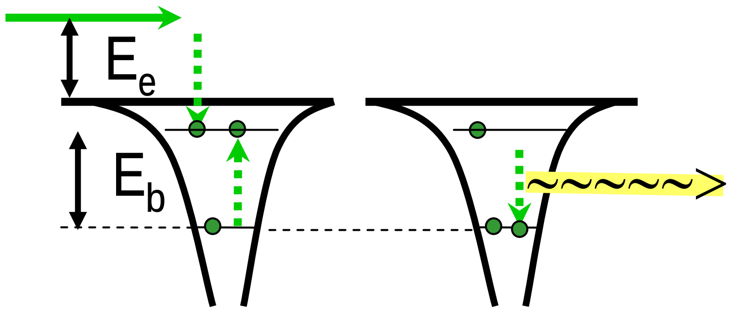
Exploring the Nucleus

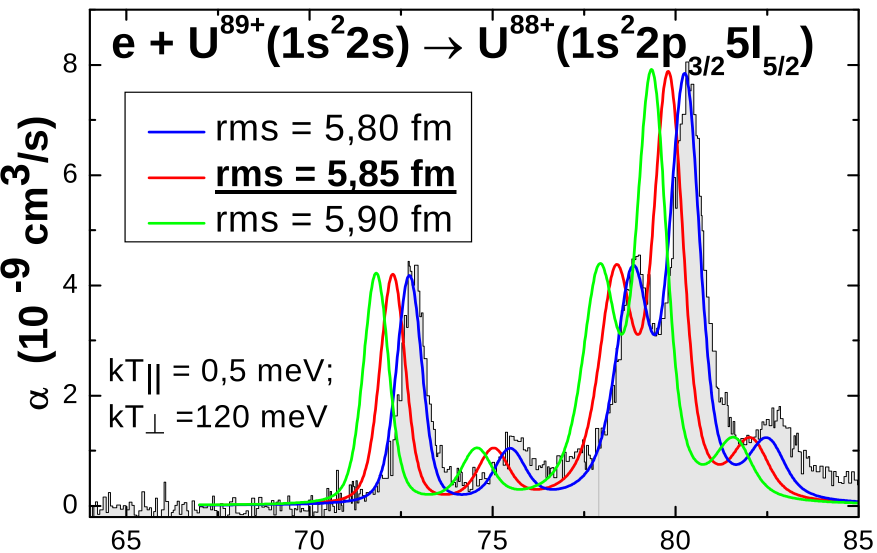
Dielectronic Recombination

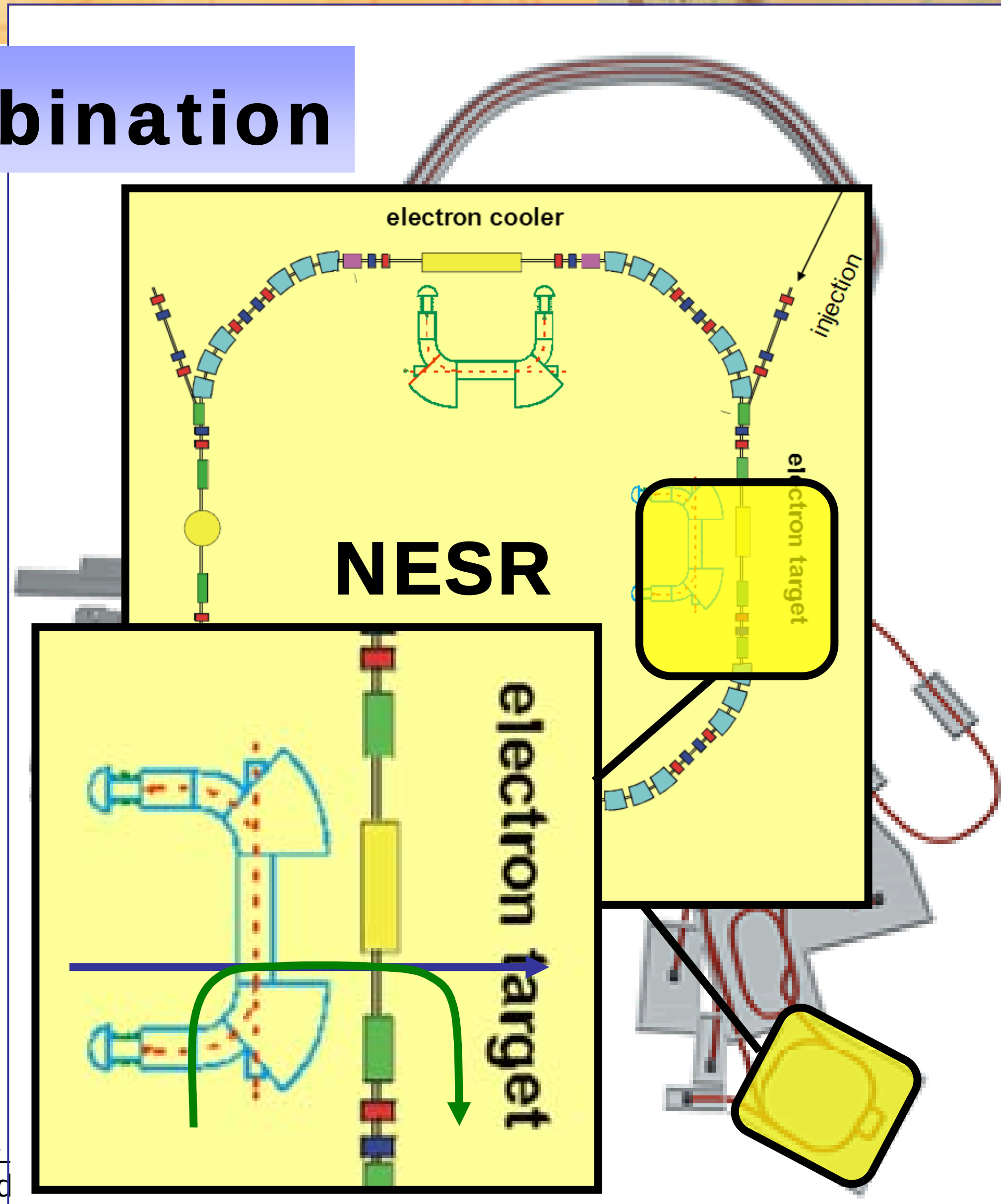




Dielectronic Recombination

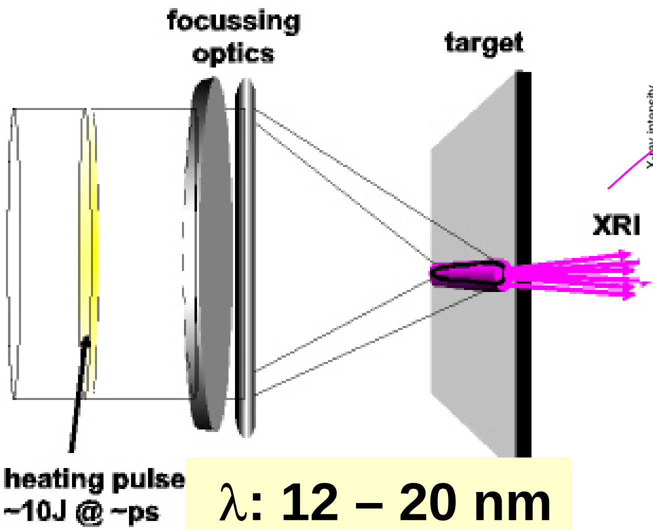




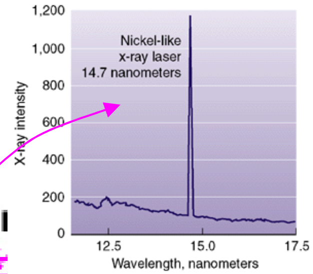


X-Ray Laser Spectroscopy on Lithium-like Radioactive

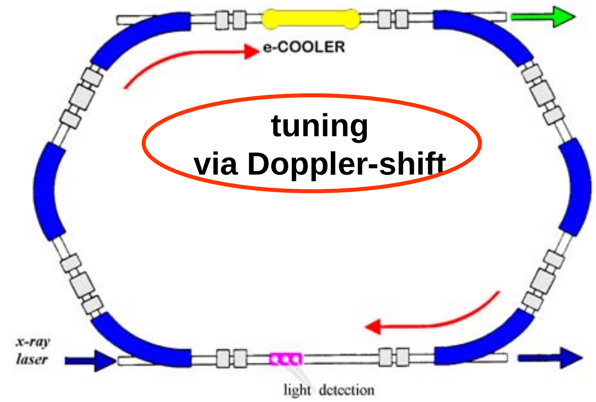
Principle of an X-Ray Laser (XRL)

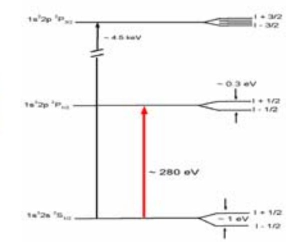


λ: 12 – 20 nm



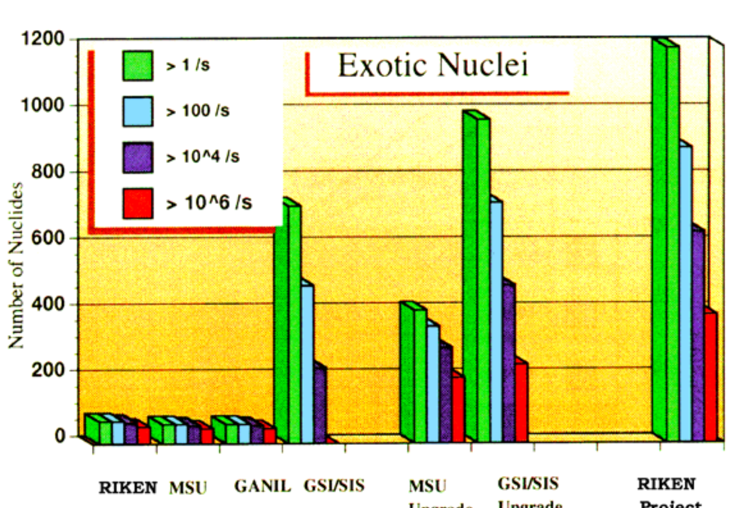
Excitation in the ESR / NESR





up to Z=92 possible

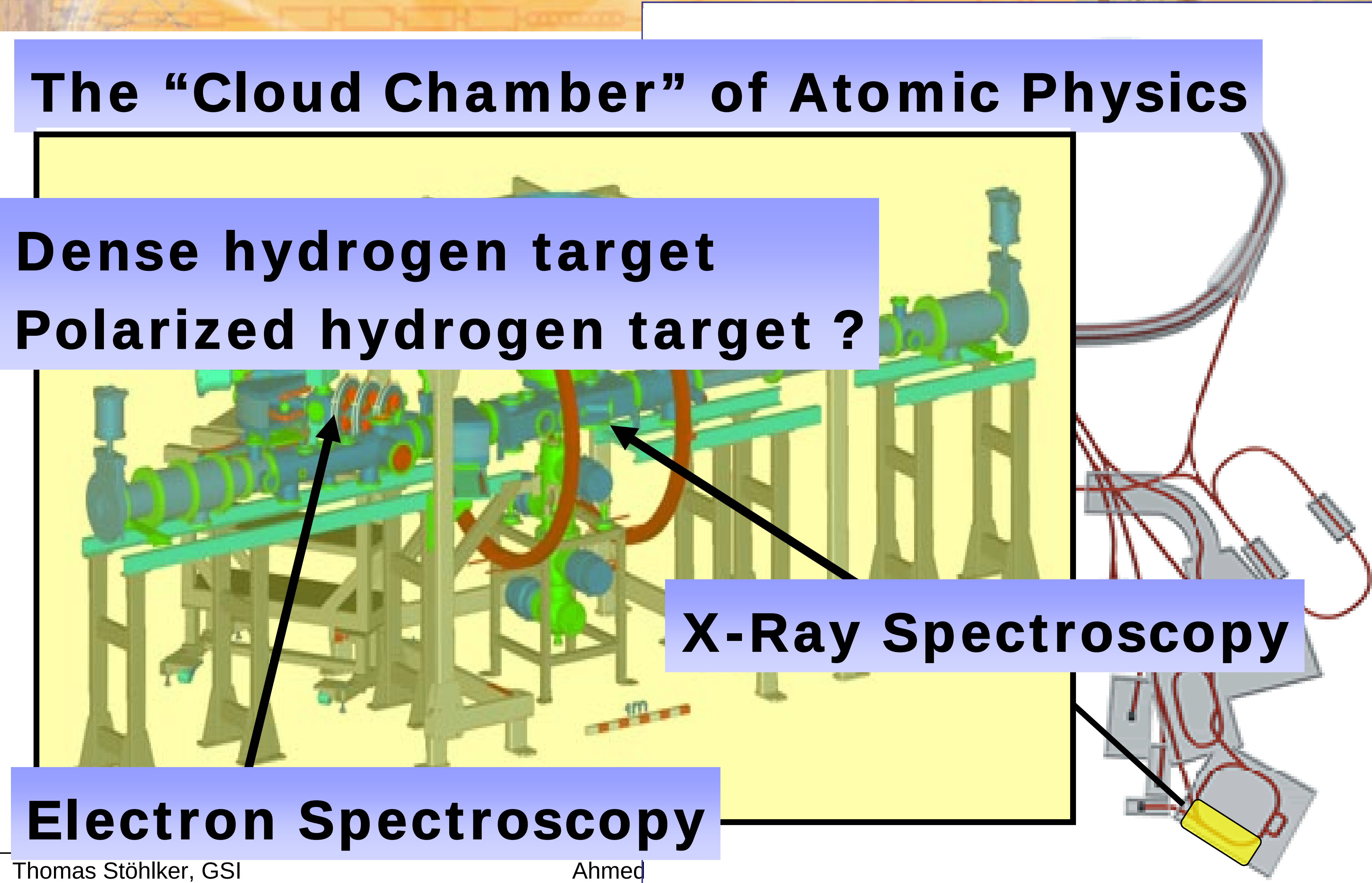
At NESR: Wide Range of Accessible Ions



$\Delta p/p \sim 5 \times 10^{-5}$

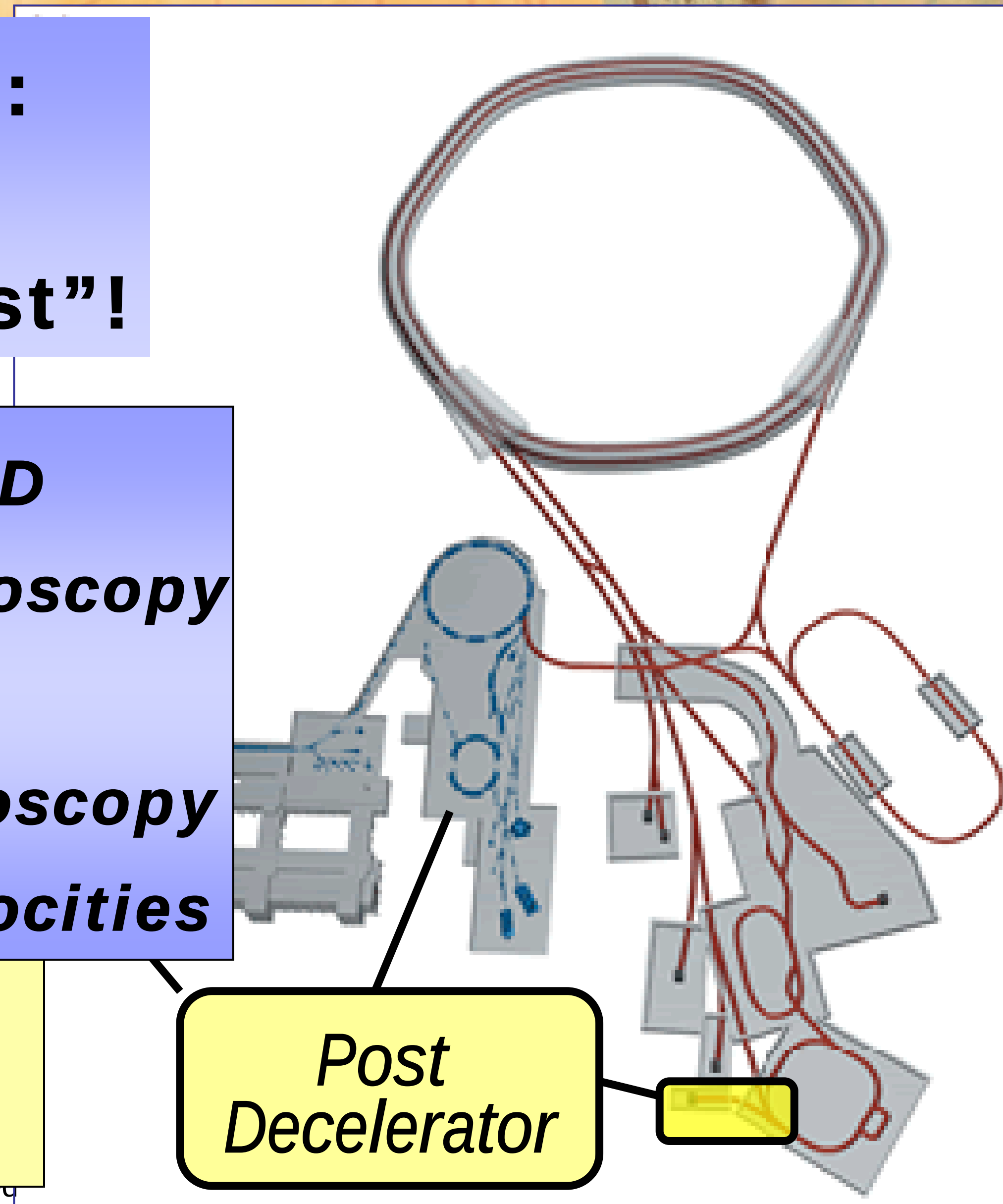
$\Delta E_{Dopp.}/E \sim 10^{-4} \ldots 10^{-5}$

Research Instruments at GSI for Atomic Physics



The HITRAP facility: highly charged single ions “at rest”!

- ***g-factor: tests of QED***
- ***laser & x-ray spectroscopy***
- ***surface interactions***
- ***hollow-atom spectroscopy***
- ***collisions at low velocities***

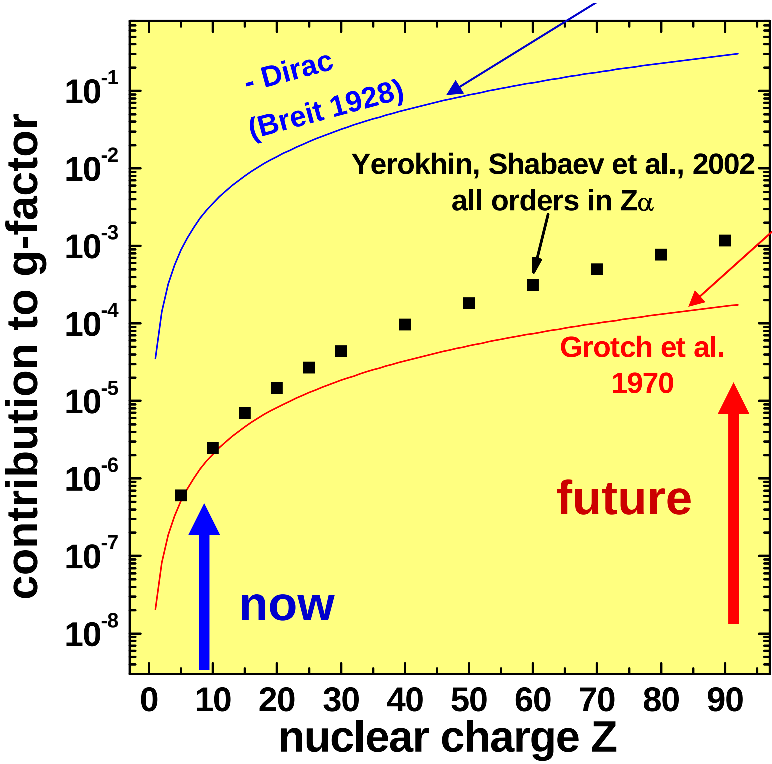


HITRAP – Test of QED: g-Factor of the Bound Electron

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

relativistic effect (Dirac theory)

bound-state QED



experiment: $g(^{12}C^{5+}) = 2.001\,041\,596\,4(14)(44)$

$[\ g(^{16}O^{7+}) = 2.000\,047\,025\,4(15)(44)\ ]$

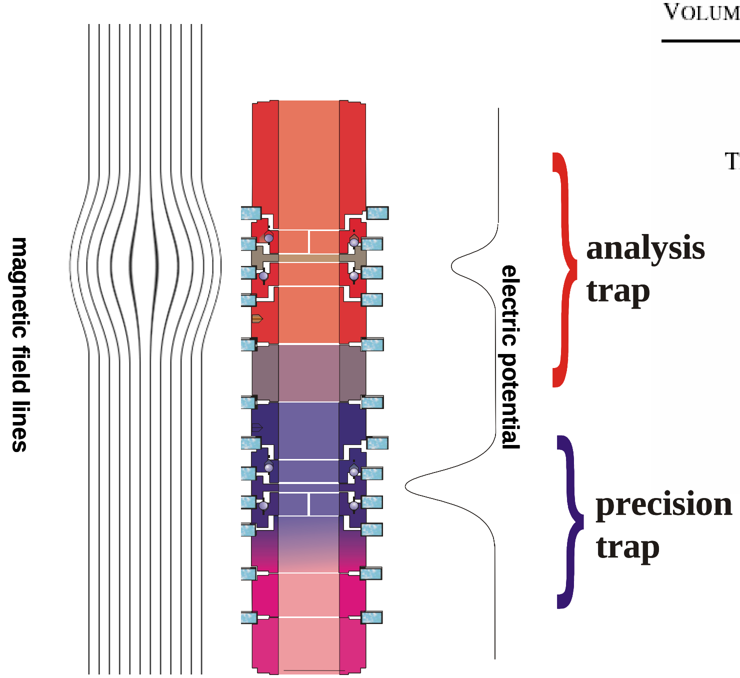
theory: $g(^{12}C^{5+}) = 2.001\,041\,589\,9(9)$

statistical error: $\delta g/g = 5\cdot10^{-10}$

total error: $\delta g/g = 2\cdot10^{-9}$ (limited by the knowledge of m_e)

T. Beier et al., PRL 88, 011603 (2002), V. Yerokhin et al., PRL 89, 143001 (2002)
J. Verdú et al., PRL 92, 093002 (2004)

HITRAP - Fundamental Constants: Mass of the Electron



single hydrogen-like ion in a Penning trap: measurement of the cyclotron and Lamor frequency

VOLUME 88, NUMBER 1 PHYSICAL REVIEW LETTERS 7 JANUARY 2002

New Determination of the Electron's Mass

Thomas Beier,[1] Hartmut Häffner,[1,2] Nikolaus Hermanspahn,[2] Savely G. Karshenboim,[3,4] H.-Jürgen Kluge,[1]
Wolfgang Quint,[1] Stefan Stahl,[2] José Verdú,[1,2] and Günther Werth[2]
[1]*Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany*
[2]*Institut für Physik, Universität Mainz, 55099 Mainz, Germany*
[3]*D.I. Mendeleev Institute for Metrology (VNIIM), 198005 St. Petersburg, Russia*
[4]*Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
(Received 29 August 2001; published 19 December 2001)

A new independent value for the electron's mass in units of the atomic mass unit is presented, m_e = 0.000 548 579 909 2(4) u. The value is obtained from our recent measurement of the g factor of the electron in $^{12}C^{5+}$ in combination with the most recent quantum electrodynamical (QED) predictions. In the QED corrections, terms of order α^2 were included by a perturbation expansion in $Z\alpha$. Our total precision is three times better than that of the accepted value for the electron's mass.

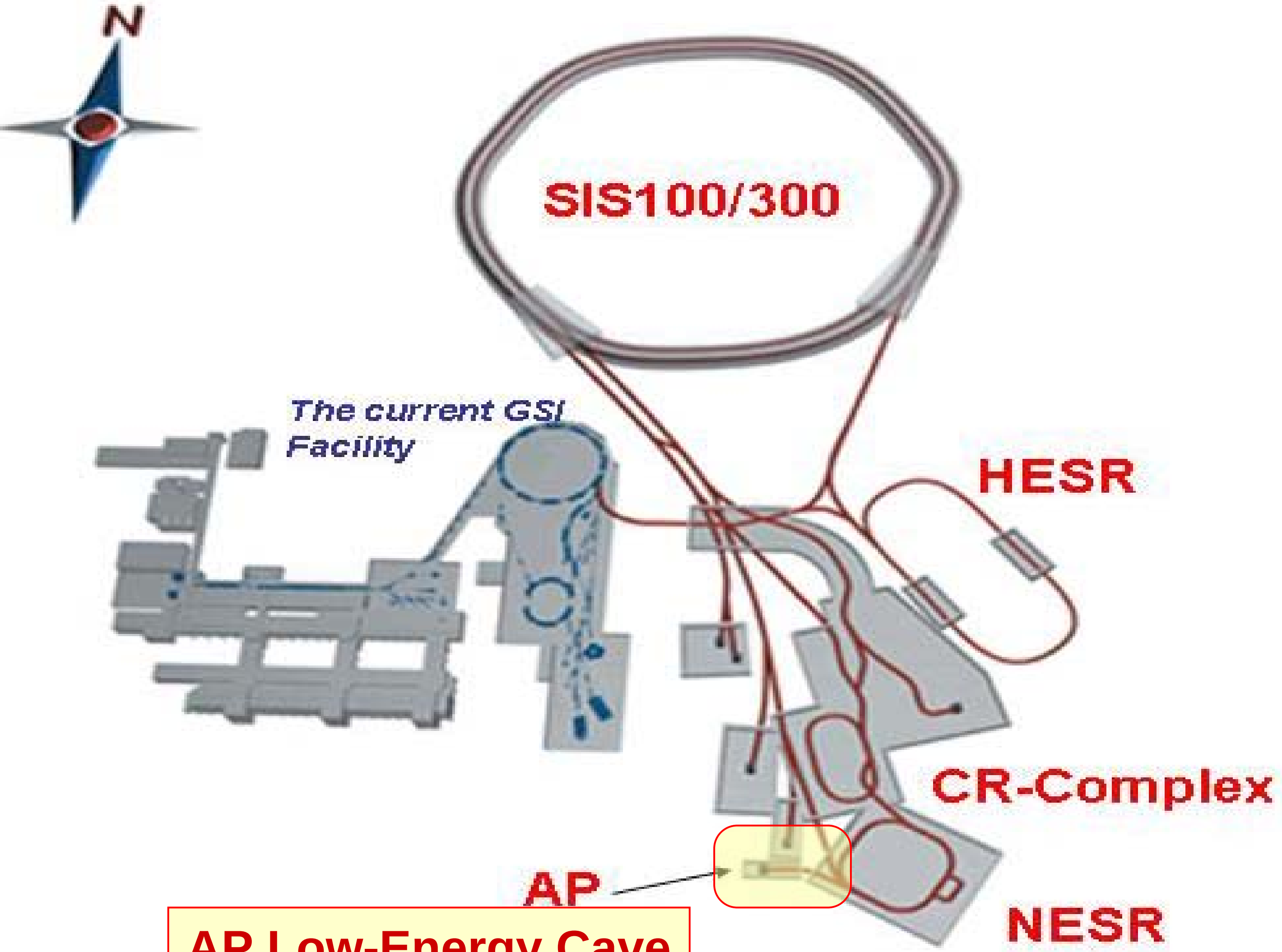
theoretical value:	**2.001 041 589 9(9)**
experimental value:	**2.001 041 596 4(10) {44}**
QED correct ⇒	**m_e = 0.000548 579 909 2(4) u**
van Dyck (1995)	**m_e = 0.000548 579 911 1(12) u**
CODATA (1998)	**m_e = 0.000548 579 911 0(12) u**

⇒ improvement by a factor of 4*

future: fine-structure constant α

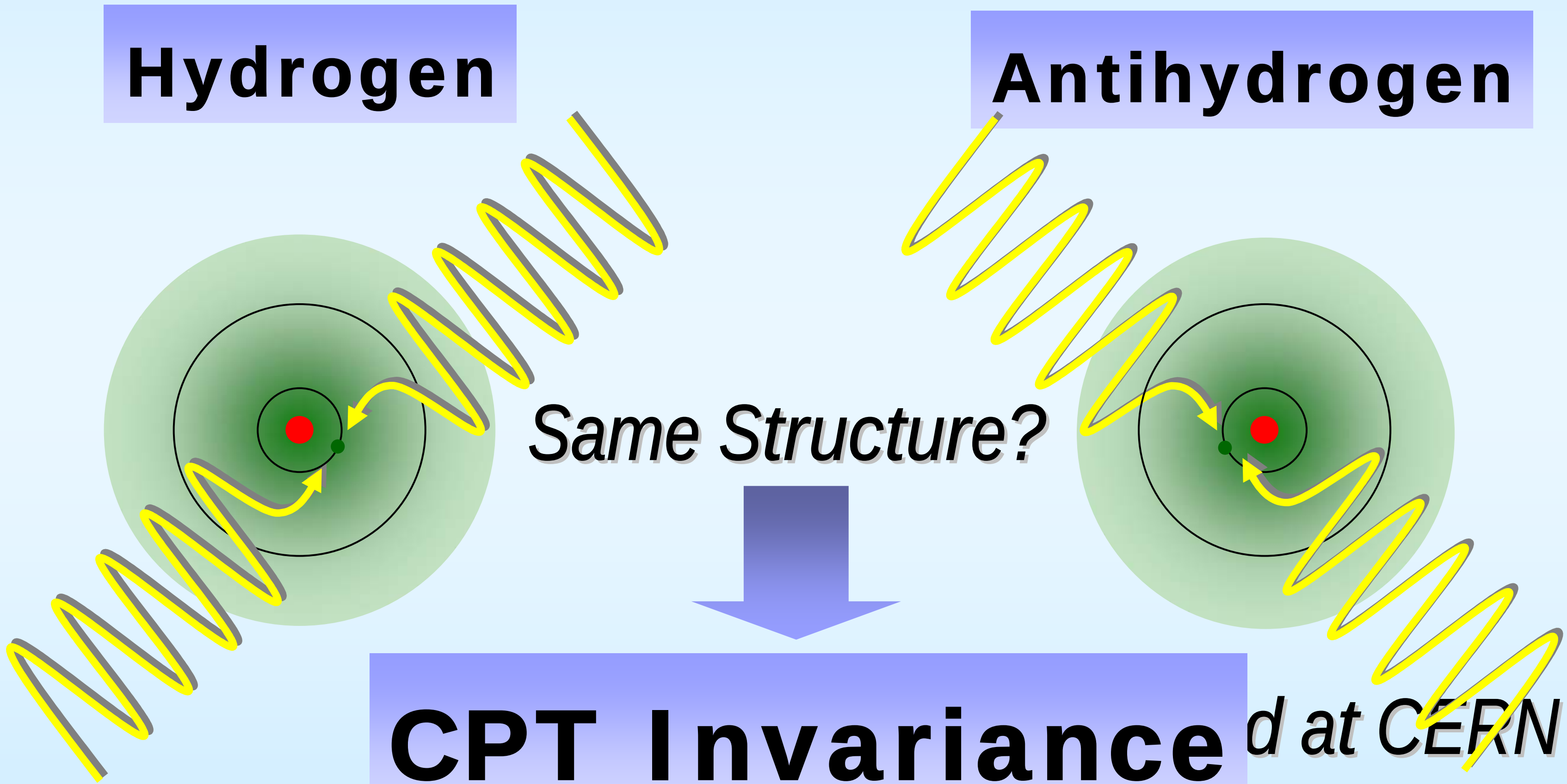
* from $^{12}C^{5+}$ and $^{16}O^{7+}$ g-factor measurement ,J. Verdú et al., PRL 92, 093002 (2004)

The Future GSI Heavy-Ion and Antiproton Accelerator Facility for Atomic Physics



AP Low-Energy Cave

Ultracold & Trapped $\bar{p}$



CPT Invariance

$$\Delta E / E \approx 10^{-14}$$

d at CERN

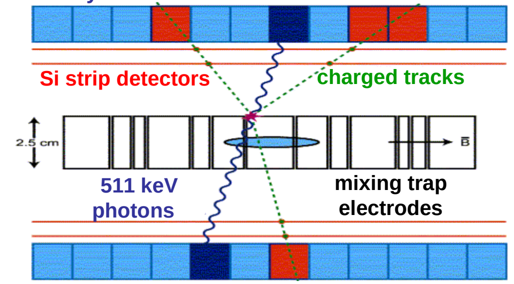
t: 1996

s: 2002

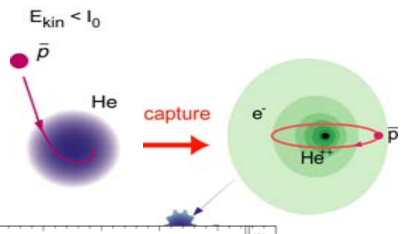
Research Topics with Low-Energy Antiprotons

EXPERIMENTS WITH ANTIPROTONS AT EXTREMELY LOW ENERGIES

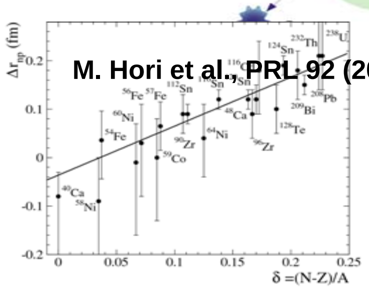
- **fundamental interactions**
  - CPT (antihydrogen, HFS, magnetic moment)
  - gravitation of antimatter
- **atomic collision studies**
  - ionization
  - energy loss
  - matter-antimatter collisions
- **antiprotonic atoms**
  - formation
  - strong interaction and surface effects



ATHENA Nature 419 (2002) 456



M. Hori et al., PRL 92 (2003) 123401



A. Trzcinska, J. Jastrzebski et al.PRL 87 (2001) 082501

Antiproton Production and Research at the AD and the Future GSI Facility

Expected production rate:

10^8 $\bar{p}$ every 4 sec

~ 100 x Antiproton Decelerator (AD)

($2\text{-}4 \cdot 10^7$ $\bar{p}$ every 85 sec)

- develop "next generation" technology
- improve performance of most present experiments
- enable experiments that are not feasible at the AD

Present $\bar{p}$ collaborations at the AD/CERN:

ATHENA: CPT
ATRAP: CPT
ASACUSA: structure and dynamics

GSI will provide the most intense source of antiprotons

Facility for Research with Antiprotons and Ions

NESR

Pbar & ions

30 – 400 MeV

LSR:

Standard ring

Min. 300 keV (CRYRING)

USR

Electrostatic

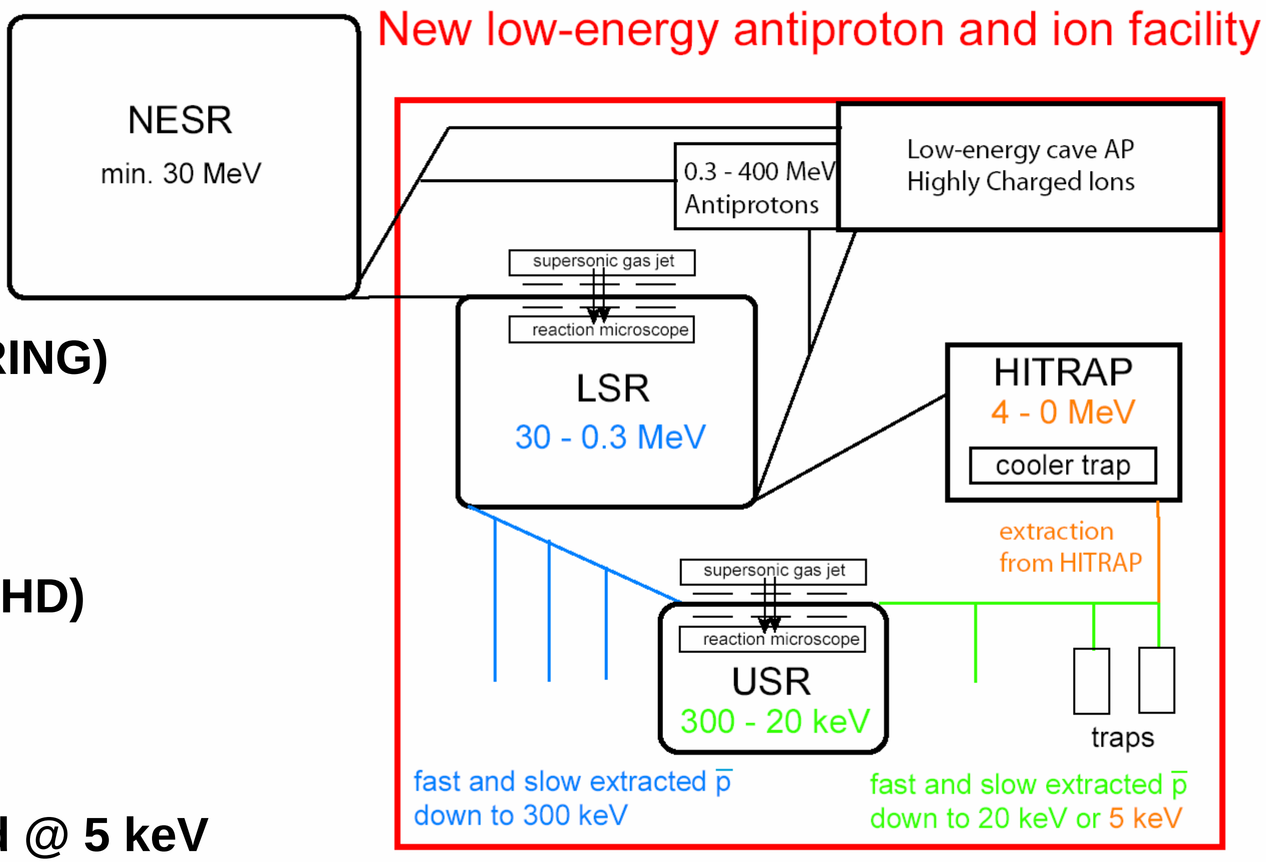
Min 20 keV (MPI KP HD)

HITRAP

Pbar and ions

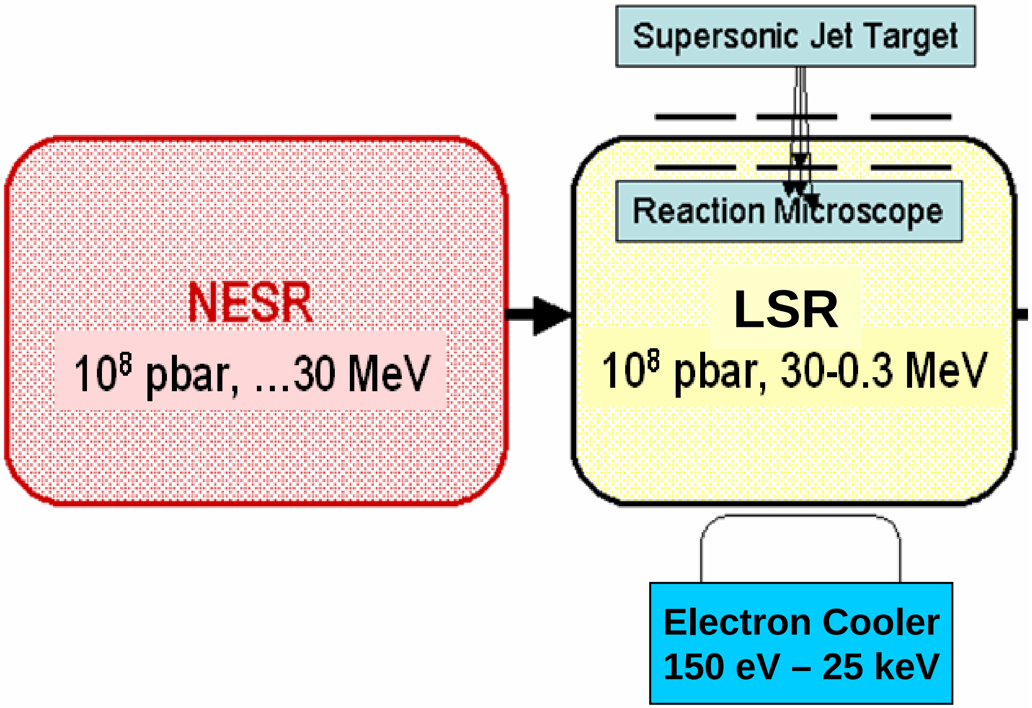
Stopped & extracted @ 5 keV

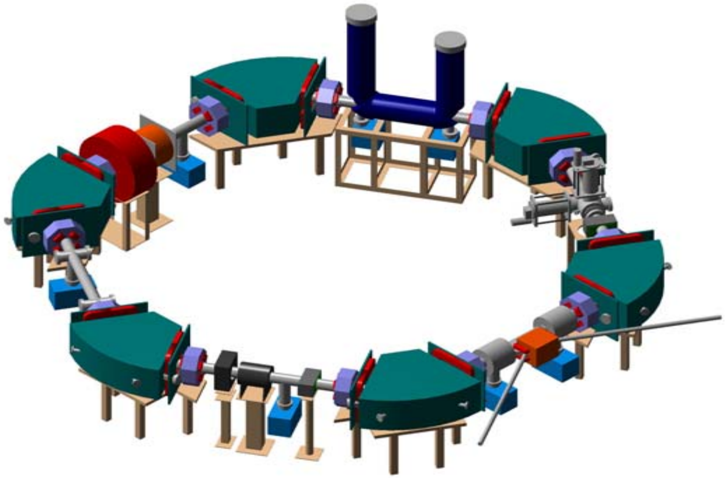
(under construction for ESR)



energy range: 400 MeV – 1 meV

The Low-Energy Storage Ring LSR





LSR: A cooler storage ring like CRYRING or TSR
- **medium to low energies**
- **in-ring experiments: gas target, “reaction microscope”**
- **ns beam pulses for ionization experiments**

The FLAIR/HITRAP Project at the NESR for Antiprotons and Ions

SIS 100

protons | pbar

target

CR RESR

experiments for slow pbars

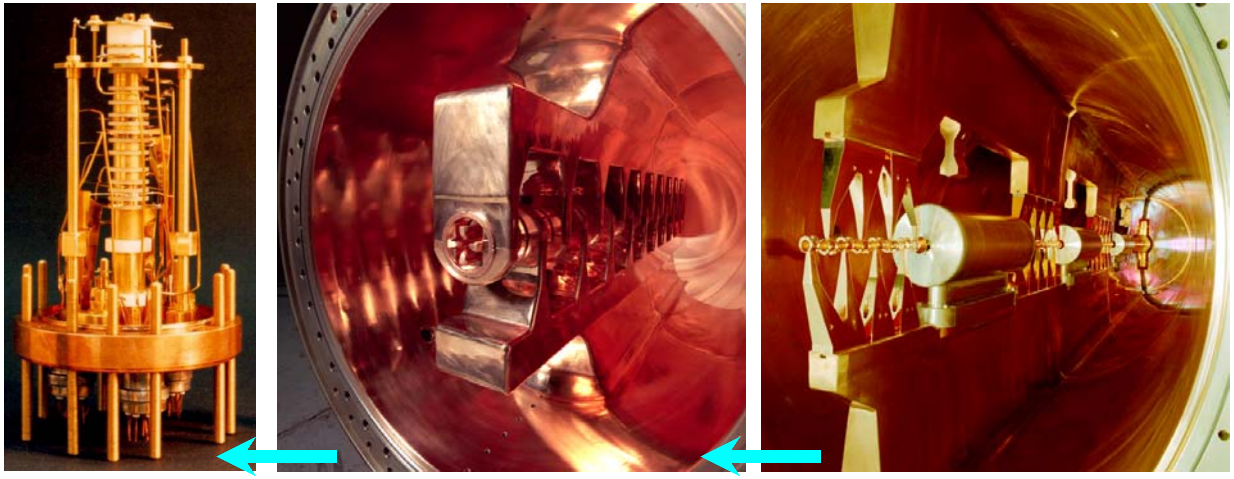
post-decelerator

experiments with pbars at rest

cooler Penning trap

NESR LSR

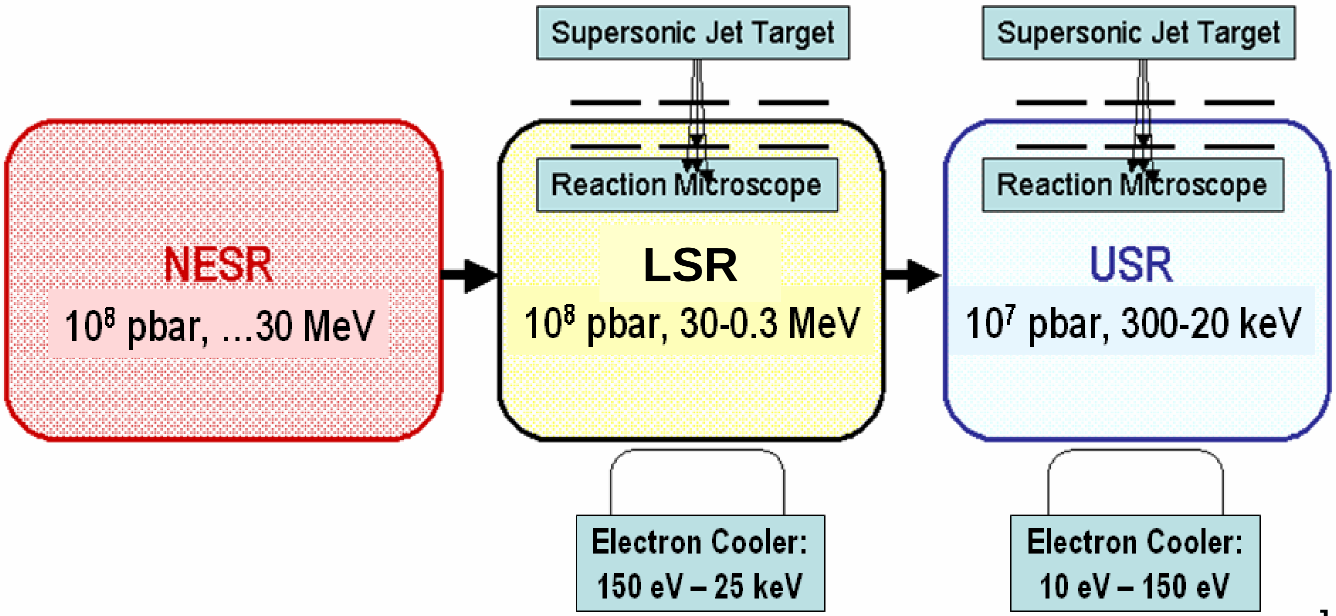
10^6 pbar per sec

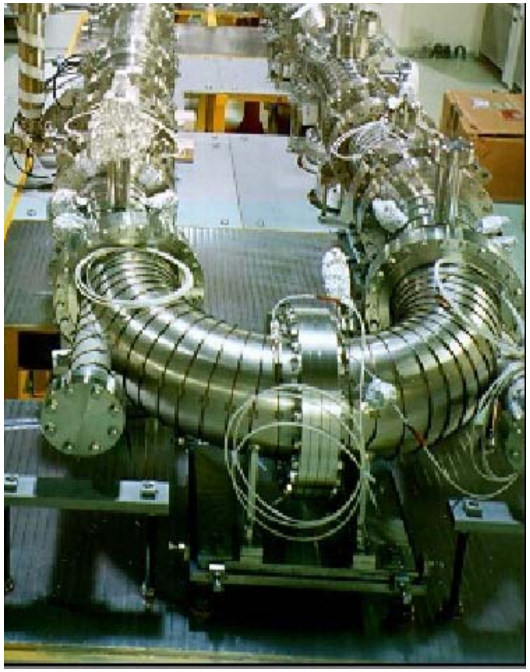


electron cooling and deceleration down to few MeV/u

HITRAP works for antiprotons and HCI !

The Electrostatic Storage Ring USR for Antiprotons and Ions at Ultra-Low Energy





J. Ullrich et al.

USR: **A novel electrostatic cooler storage ring:**

- **low to ultra-low energies**
- **excellent beam quality and large number of stored $\bar{p}$**
- **high luminosity for in-ring experiments**

Summary

Atomic physics at accelerators is a rich field of research

There are unique opportunities and challenges

Storing and cooling is the key to precision

Effects of extreme electromagnetic fields can be investigated

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

Highly-charged (stable & radioactive) ions and antiprotons are test grounds for symmetries and fundamental interactions

Atomic physics techniques offer model-independent information on nuclear ground state properties

The SPARC-Collaboration: Atomic Physics with Heavy Stable and Radioactive Ions

http://www-linux.gsi.de/~sparc

The FLAIR-Collaboration: Atomic Physics with Slow Antiprotons

http://www-linux.gsi.de/~flair