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

SPARC:
The Physics Program of the
Stored Particle Atomic Physics Collaboartion

Thomas Stöhlker*

GSI-Darmstadt and University of Frankfurt, Germany

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

SPARC

Stored Particle Atomic Research Collaboration

Presently: 215 participants from 75 institutes and 20 countries

The SPARC-Collaboration:

http://www.gsi.de/sparc

AU
Vie
CA
Uni
Yo
CHINA
China Institute of Atomic Energy, Beijing
Institute of Applied Physics and Computational Mathematics, Beijing
Institute of Modern Physics, Fudan University, Shanghai
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou
Institute of Atomic and Molecular Physics, Jilin University, Jilin
Lanzhou University, Lanzhou
University of
Wuhan Instit
Physics Dep
Department
DENMARK
Department
EGYPT
Physics Department, Beni-Suef Faculty of Science
FRANCE
CIRIL Ganil
Ecole Normale Superieure – Lyon
Institut de Physique Nucléaire de Lyon
GERMANY
Ernst Moritz Arndt Universität Greifswald
Forschungszentrum Jülich
Freiburg University
GSI, Darmstadt
Institut für Kernphysik, Justus-Liebig-Universität Gießen
Institut für Atom- und Molekülphysik, Justus-Liebi
Sektion Physik, LMU Munich
Max-Planck-Institut für Kernphysik, Heidelberg
Institut für Theoretische Physik, TU Dresden
Tübingen University
IKF, J.W.v.Goethe Universität Frankfurt am Main
Institut für Physik, Universität Mainz
Institut für Physik, Universität Kassel
Institut für Theoretische Physik, TU Clausthal
Kirchhoff-Institut für Physik, Universität Heidelberg
TU Darmstadt
Physikalisch-technische Bundesanstalt
Mathematics Institute, University of Munich, 80333 Munich
HUNGARY
Inst. of Nuclear Research (ATOMKI), Debrecen
INDIA
Tata Institute of Fundamental Research

University of Tokyo & Atomic Physics Laboratory RIKEN, Wako
JORDAN
Hashemite University
POLAND
Institute of Physics, Swietokrzyska Academy
Institute of Physics, Jagiellonian University
Institute of Theoretical Physics, Warsaw University
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ineering
Institute of Metrology for Time and Space at VNIIFTRI
Institute of Spectroscopy of the RAS
V.G.Khlopin Radium Institute, St.Petersburg
SERBIA AND MONTENEGRO
Institute of Physics, Belgrade
SWEDEN
Chalmers University of Technology and Goteborg University
Stockholm University
Mid-Sweden University
Lund University
SWITZERLAND
ent of Physics, University Fribourg
ür Physik, Universität Basel
KINGDOM
ent of Physics, The University of Durham
University, Belfast
STATES
Lawrence Berkeley National Laboratory
Georgia State University
University of Missouri Rolla
Oak Ridge National Laboratory
Western Michigan University
Harvard-Smithsonian Center for Astrophysics
Brown University, Physics Department
Univeristy of Texas at Austin
Kansas State University
Columbia Astrophysics Laboratory, Columbia University

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

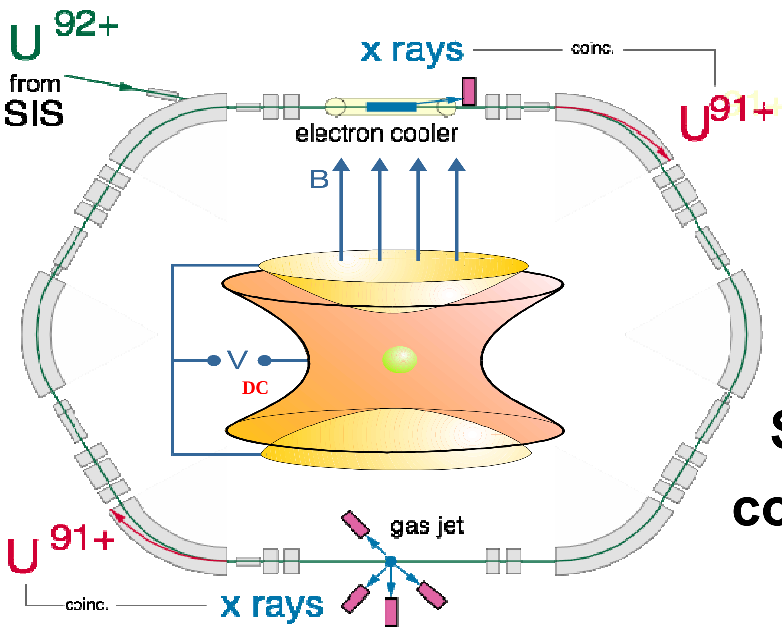
ULTRASHORT Laser Pulses:
ATTOSECOND Pump-Probe

OVERCRITICAL EM Fields:
Pair Production

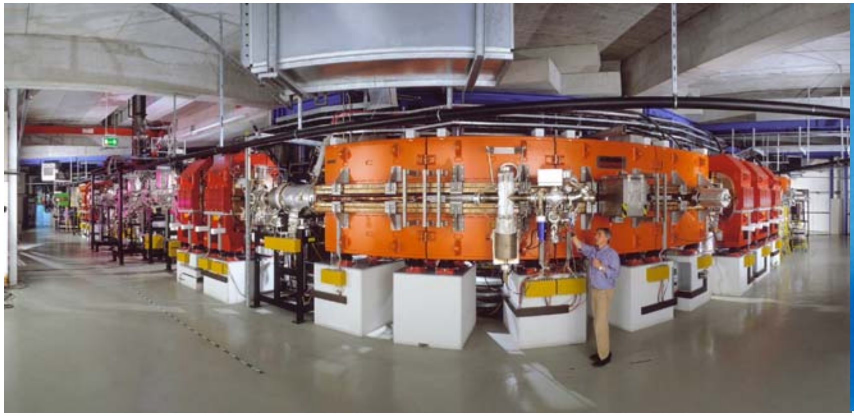
POLARIZED NUCLEI

Weak Interaction in
LOW MOMENTUM TRANSFER

Research Instruments at GSI for Atomic Physics



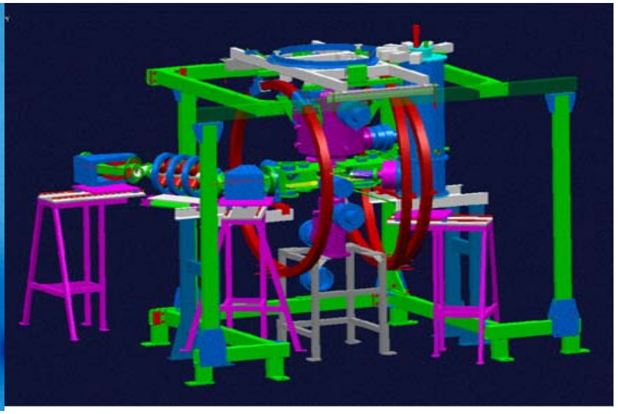
Storage and cooling devices

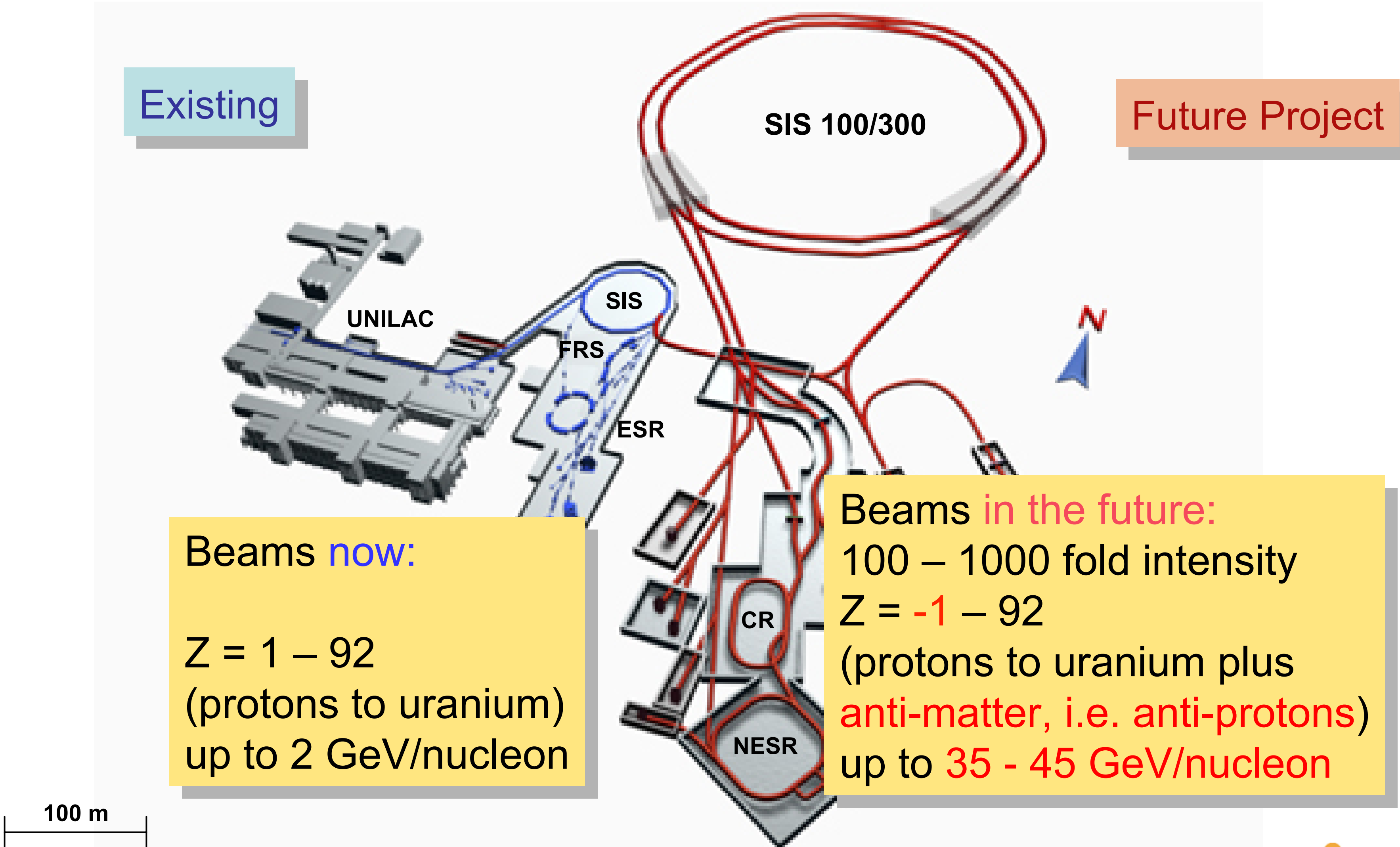


Photon sources

PHELIX

Spectrometers





Beams now:

Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon

Beams in the future:
100 – 1000 fold intensity
Z = -1 – 92
(protons to uranium plus anti-matter, i.e. anti-protons)
up to 35 - 45 GeV/nucleon

Stored Particle Atomic Research Collaboration
SPARC

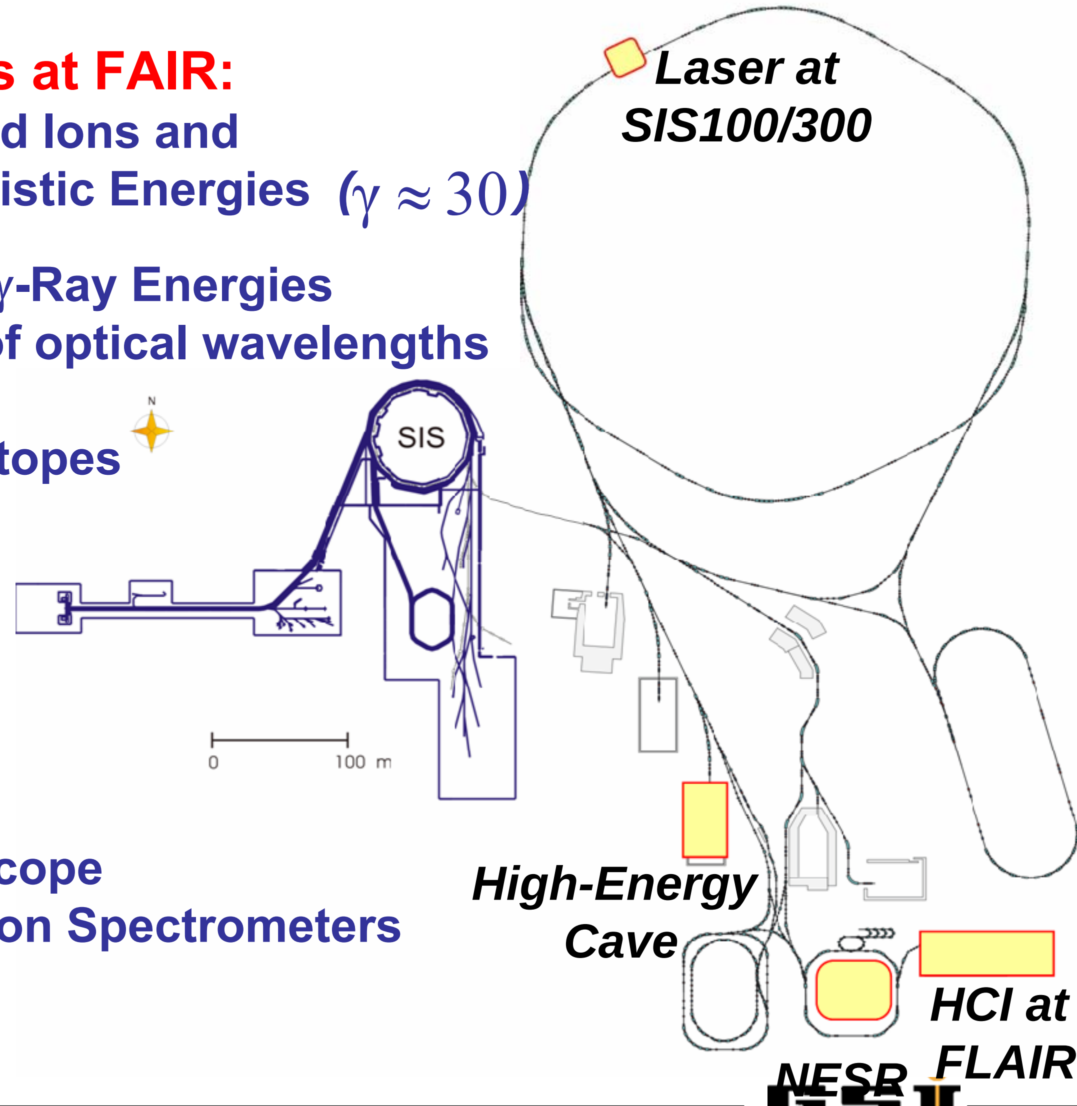
Future Research Opportunities at FAIR:

Stored and Cooled Highly-Charged Ions and Exotic Nuclei from Rest to Relativistic Energies $(\gamma \approx 30)$

Virtual Photon Sources at X- and γ-Ray Energies

XUV Energies via Lorentz Boost of optical wavelengths

Intense Beams of Radioactive Isotopes



.. with Novel Instrumentation:

Ultracold electron-beam target

In-Ring Recoil Momentum Microscope

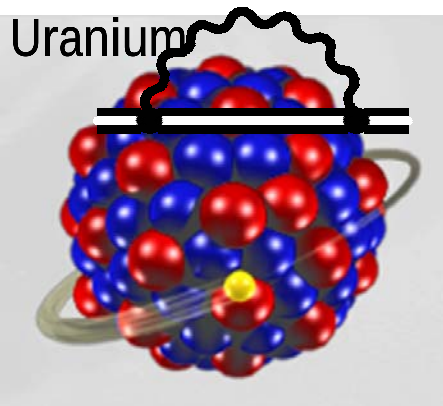
High Resolution X-Ray and Electron Spectrometers

Highly Intense Laser Beams

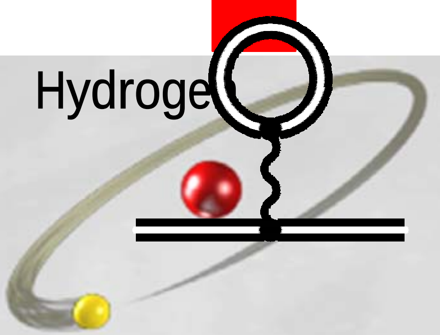
Traps

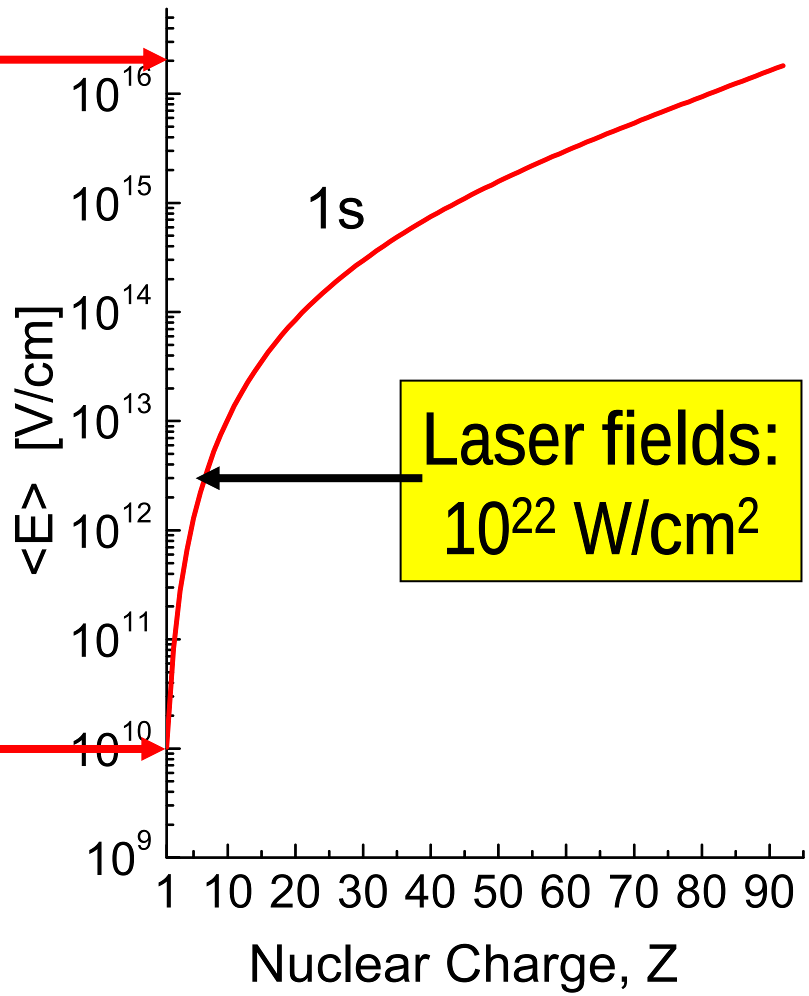
Extreme Static Electromagnetic Fields

Self Energy



Vacuum Polarization



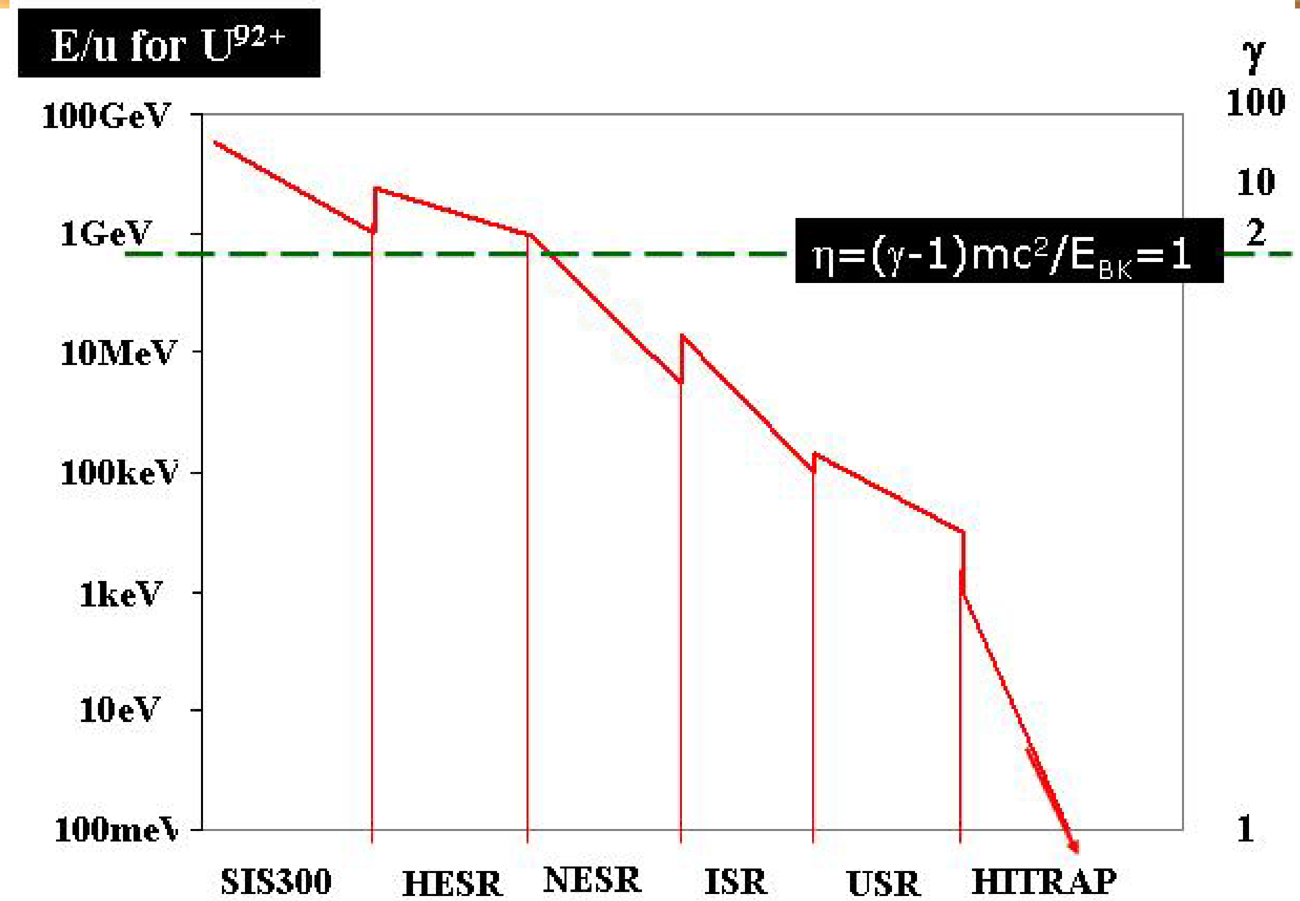


$\Delta E \approx 500$ eV
$Z \cdot \alpha \approx 1$

Quantum
Electro-
Dynamics

$\Delta E \approx 10^{-6}$ eV
$Z \cdot \alpha \approx 10^{-2}$

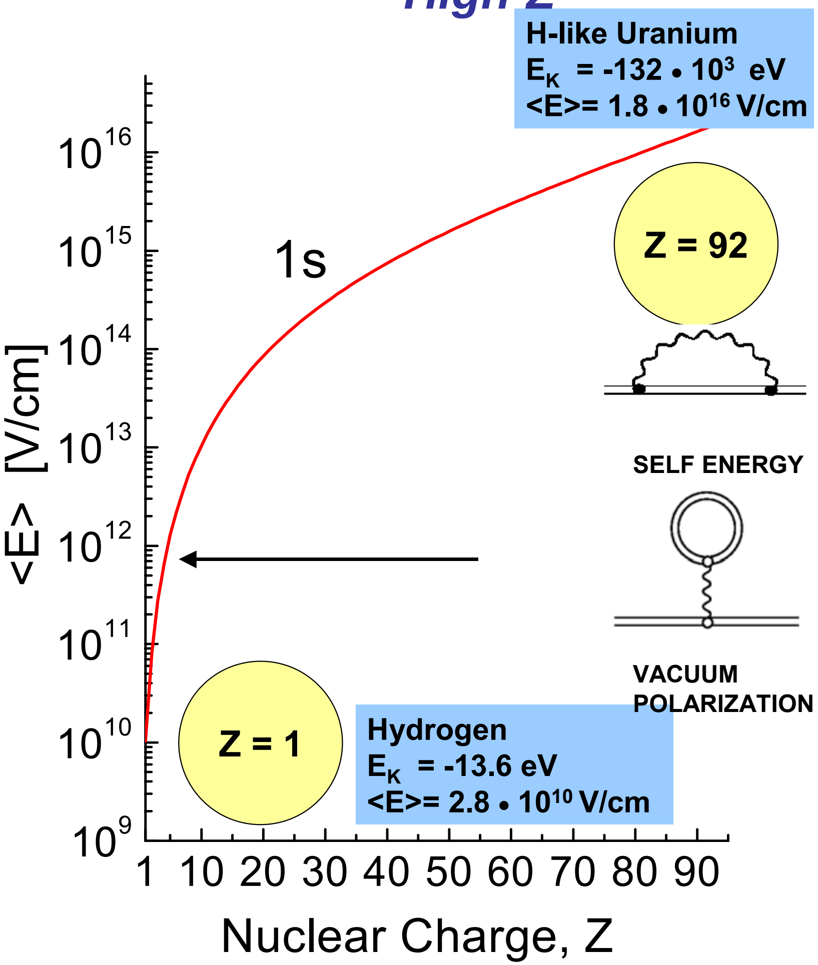
Extreme Velocities –
Extreme Dynamic Fields



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

Electromagnetic Phenomena under Extreme & Unusual Conditions

High-Z

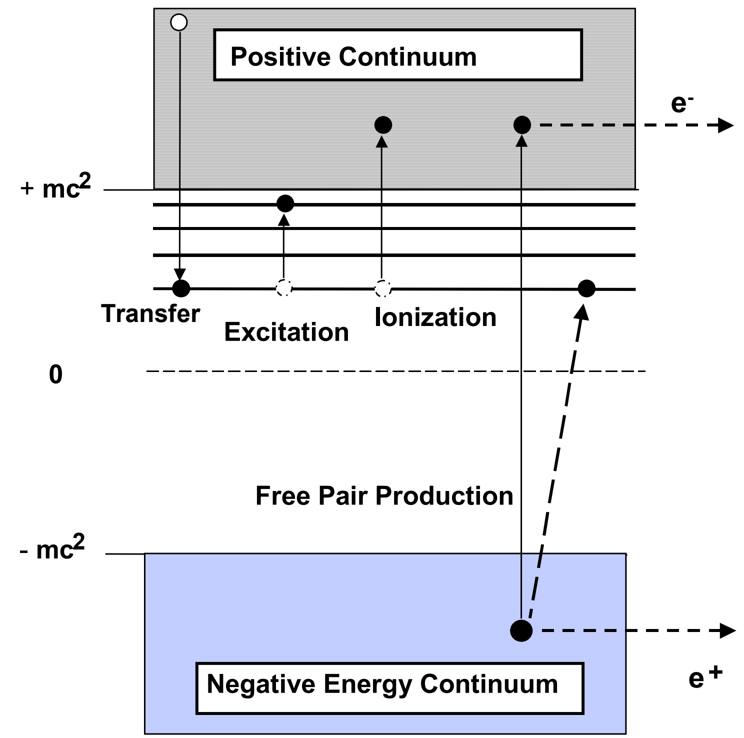


1s-ground state: increase of the electric field strength by six orders of magnitude

High- γ

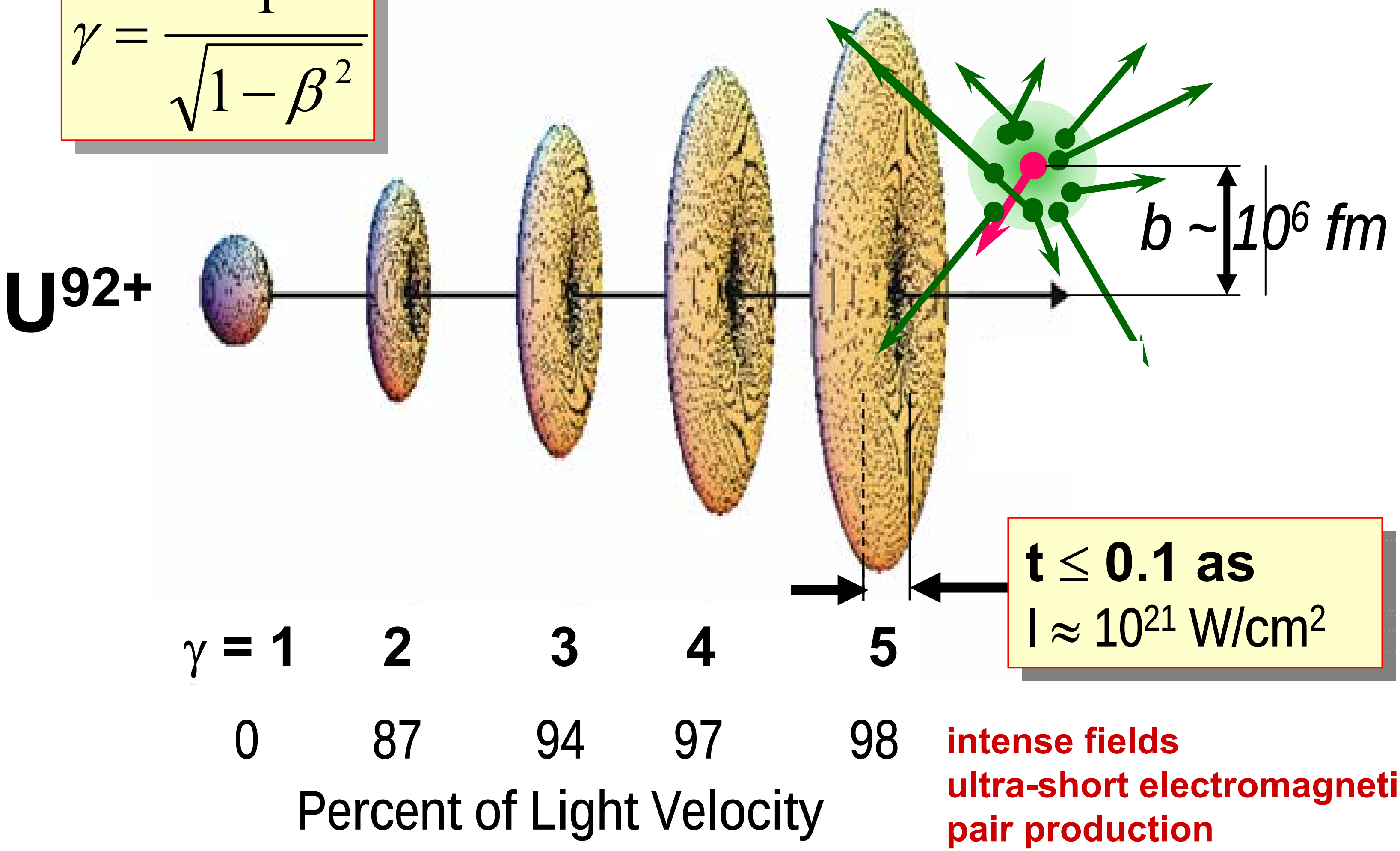
Collision Dynamics of Relativistic Heavy Ions

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



Reactions of Relativistic Projectiles in Extreme Dynamic Fields

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$



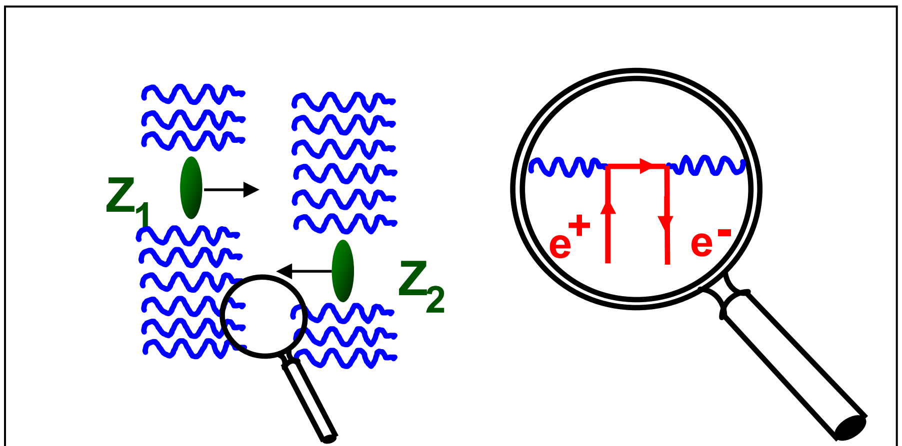
$t \leq 0.1$ as

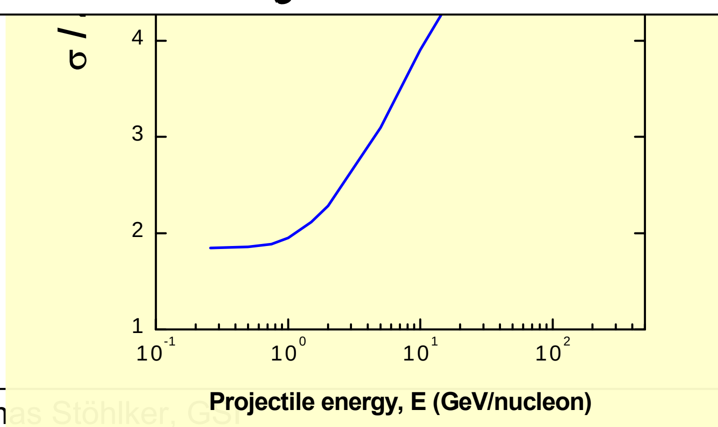
$I \approx 10^{21}$ W/cm^2

intense fields
ultra-short electromagnetic pulses
pair production

Extreme Dynamic Fields

ln(γ) cross-section increase for all excitation like processes such as *ionization or e^{+}-e^{-} pair creation*

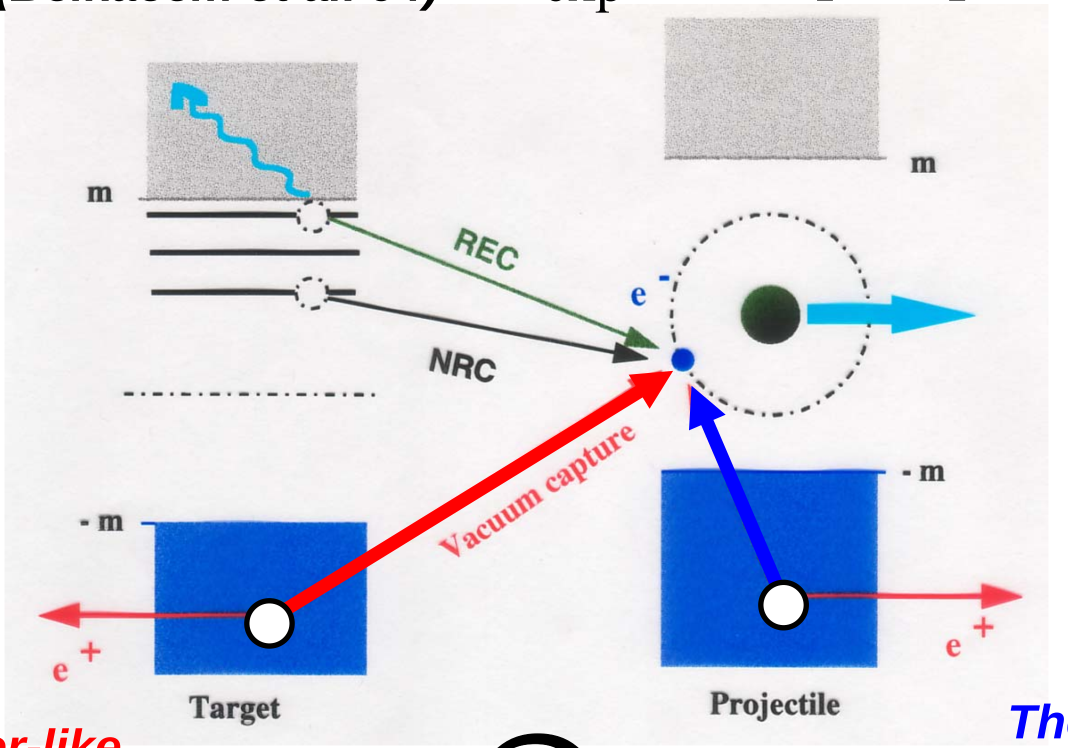




Electron capture by pair production - transfer from the negative energy continuum

Experiment (Belkacem et al. 94)

$$\sigma_{exp} \propto Z_T^{2.9} Z_P^{6.5}$$



Theory: transfer-like (Ionescu & Eichler 96)

$$\sigma_{trans} \propto Z_T Z_P^{6.45}$$

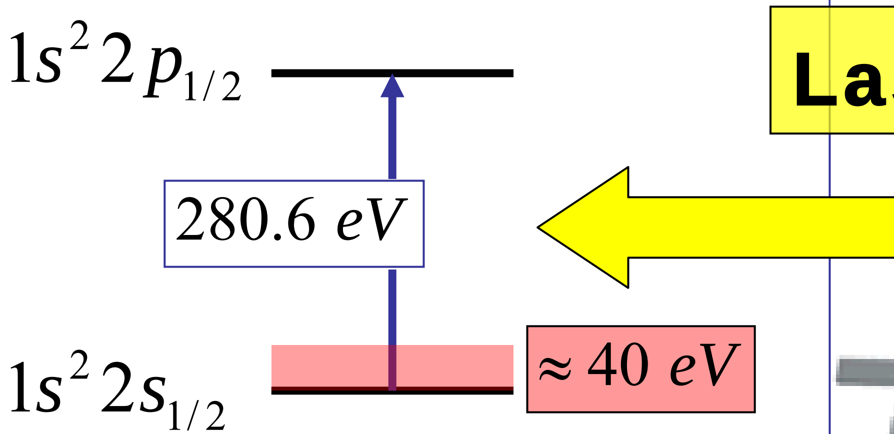
?

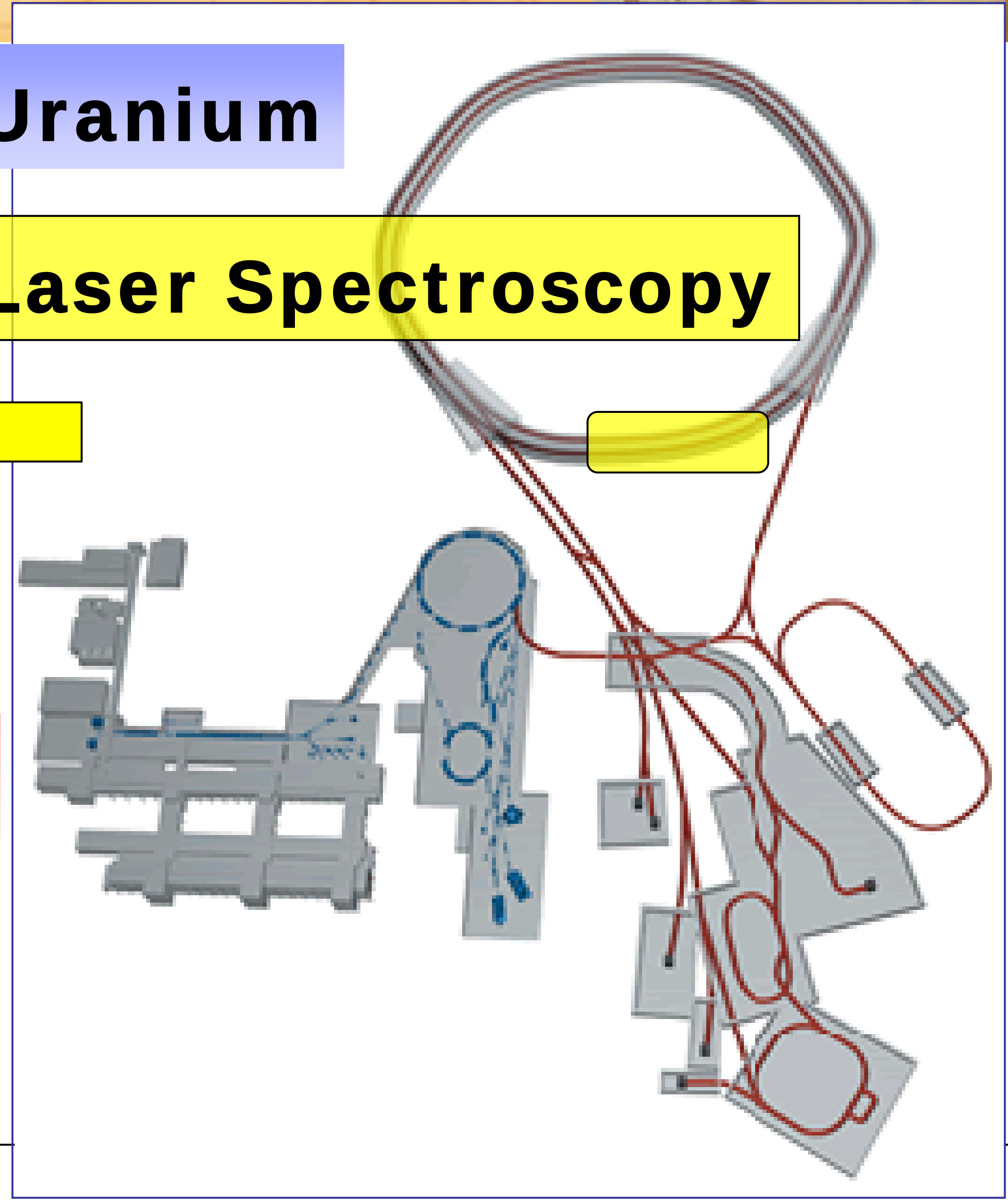
Theory: excitation-like (Becker et al. 87)

$$\sigma_{exc} \propto Z_T^{2} Z_P^{5.3}$$

Quantum Electrodynamics

Three Electrons in Uranium



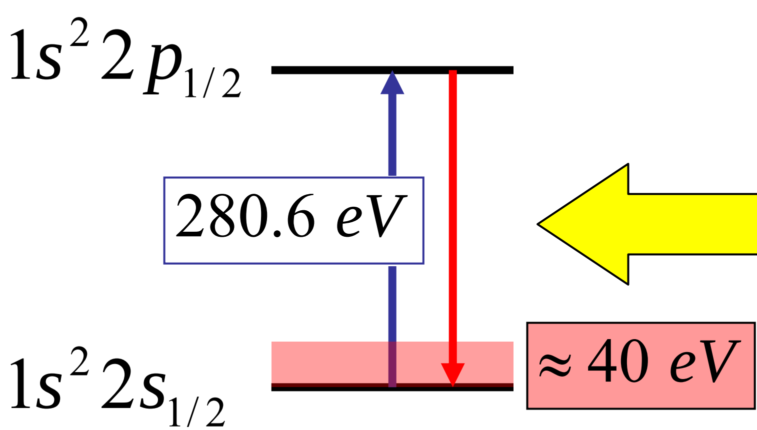


QED in Li-like systems

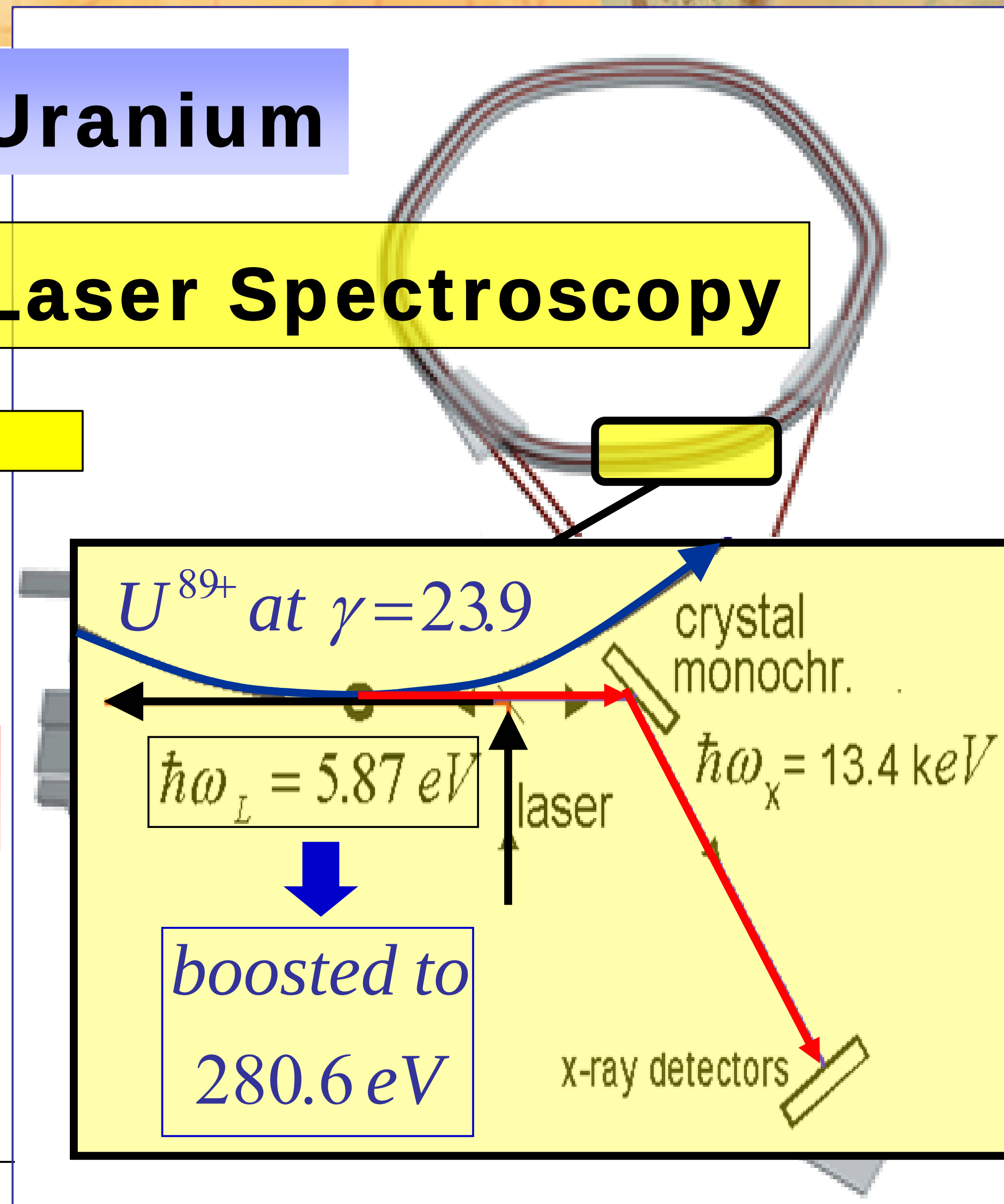
improve resolution factor of 10 to 20

Quantum Electrodynamics

Three Electrons in Uranium



Laser Spectroscopy

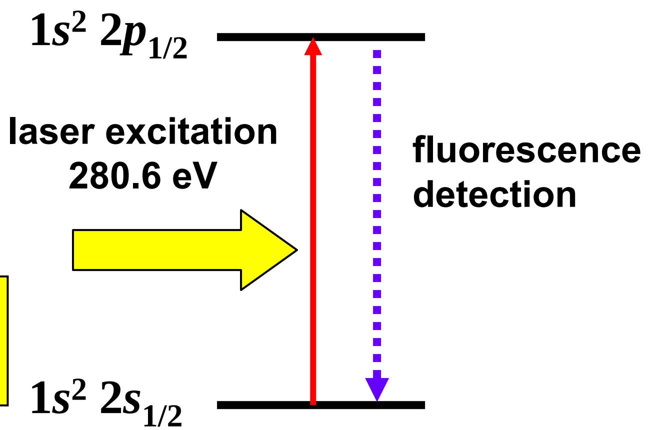


QED in Li-like systems

improve resolution factor of 10 to 20

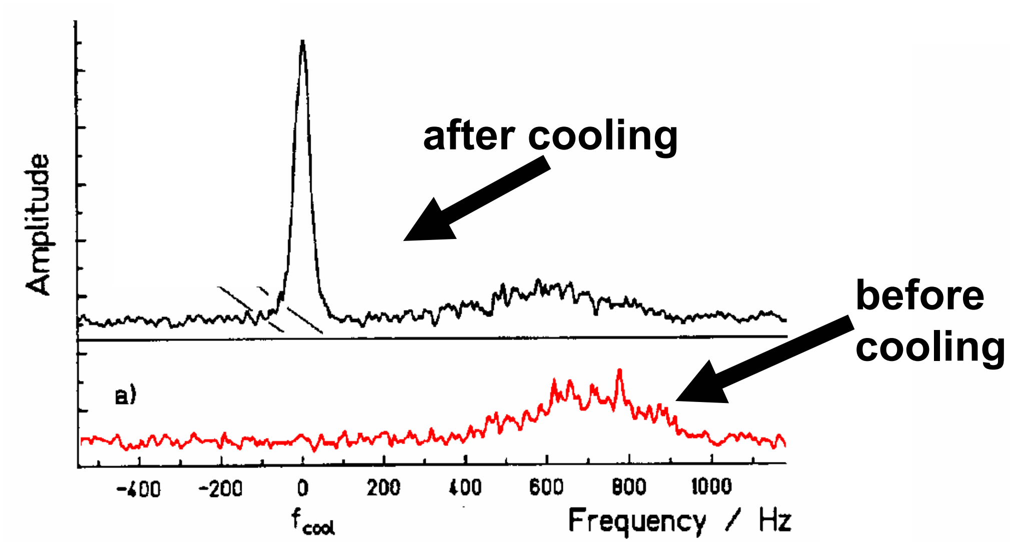
At SIS 300: Laser Cooling and Spectroscopy of Stored Beams

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

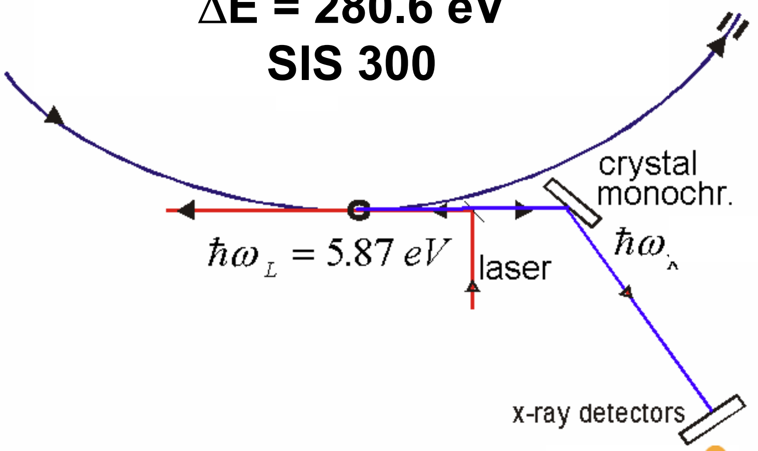
Schottky analysis of laser cooling



Lithium-like uranium

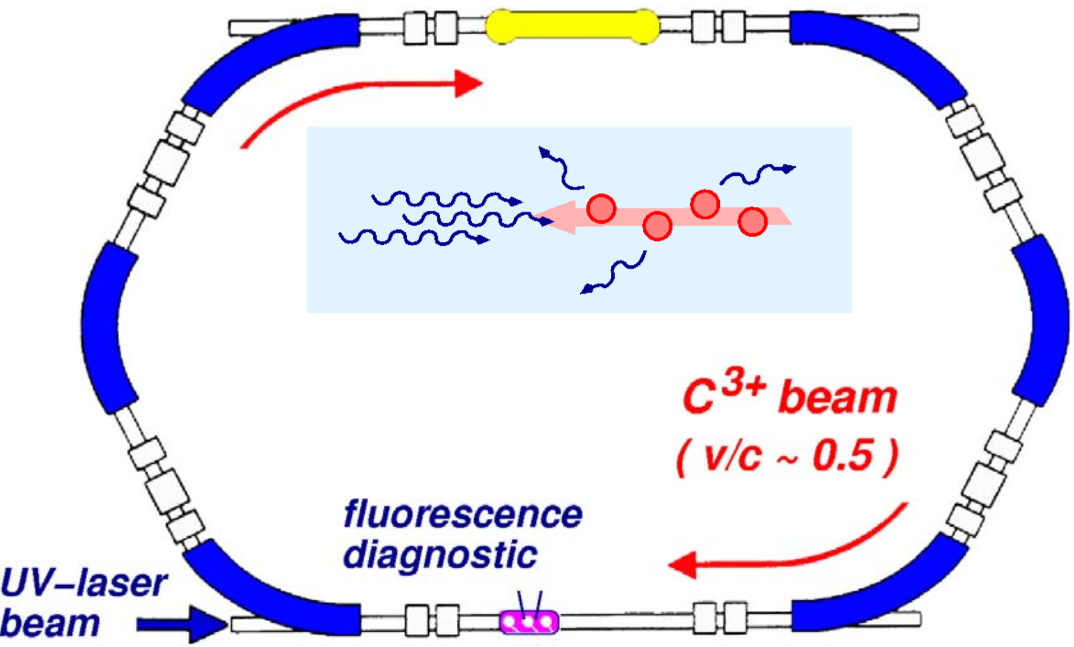
ΔE = 280.6 eV

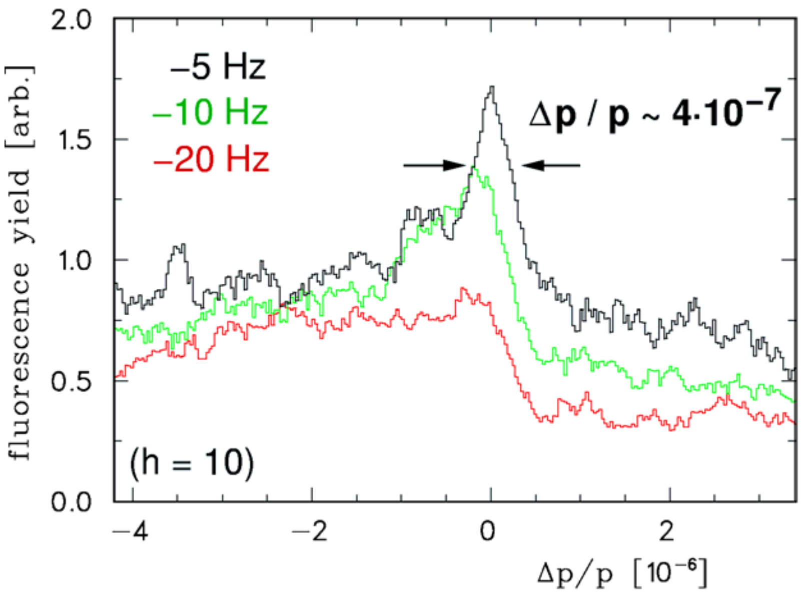
SIS 300



Laser cooling of C^{3+} beams at the ESR

momentum dependent (Doppler tuned)
laser deceleration + bunching
(restoring force) -------> cooling

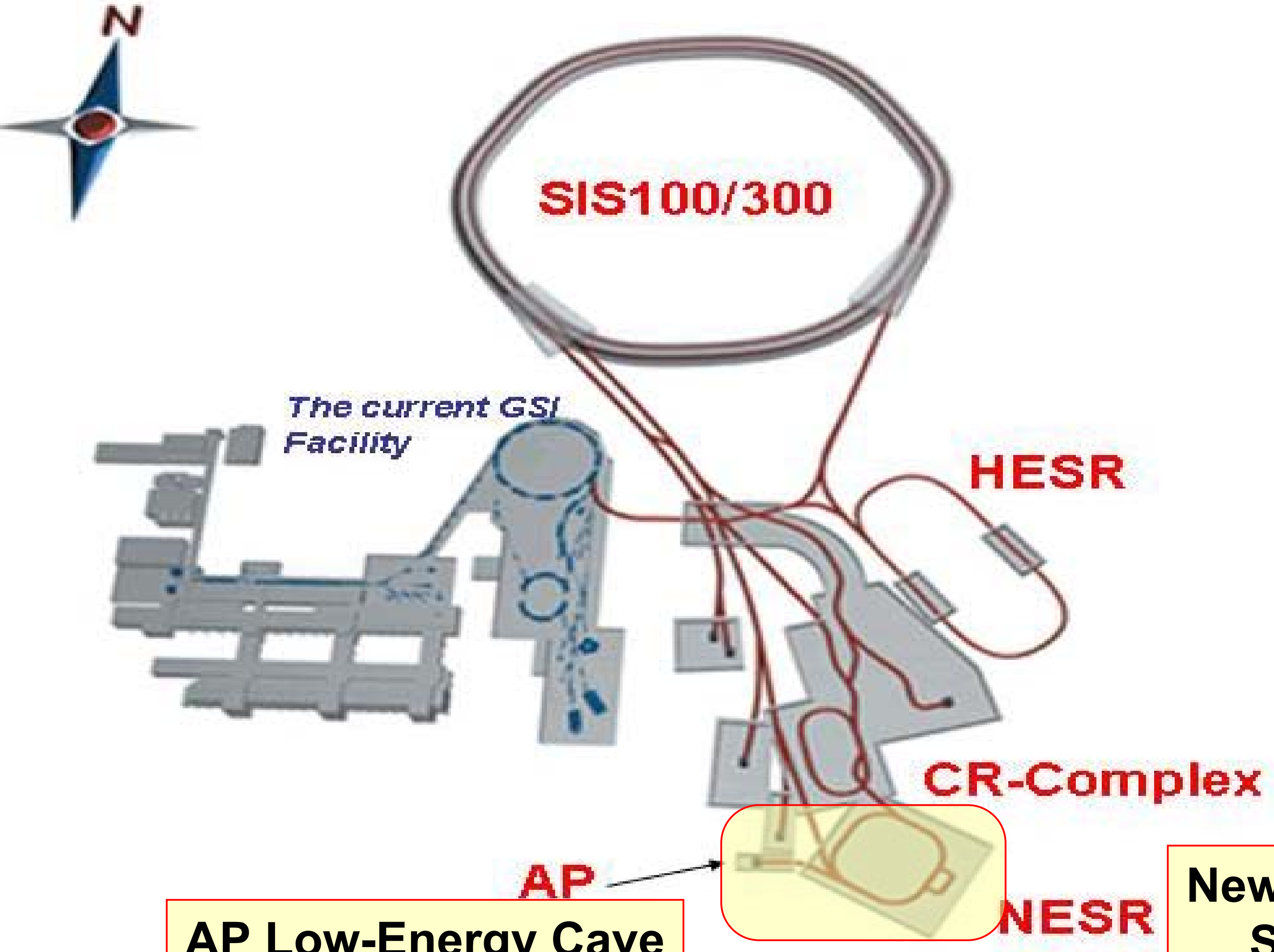




probing of the velocity width by rapid laser scan of the Doppler profile for different revolution frequencies

U. Schramm et al., 2004

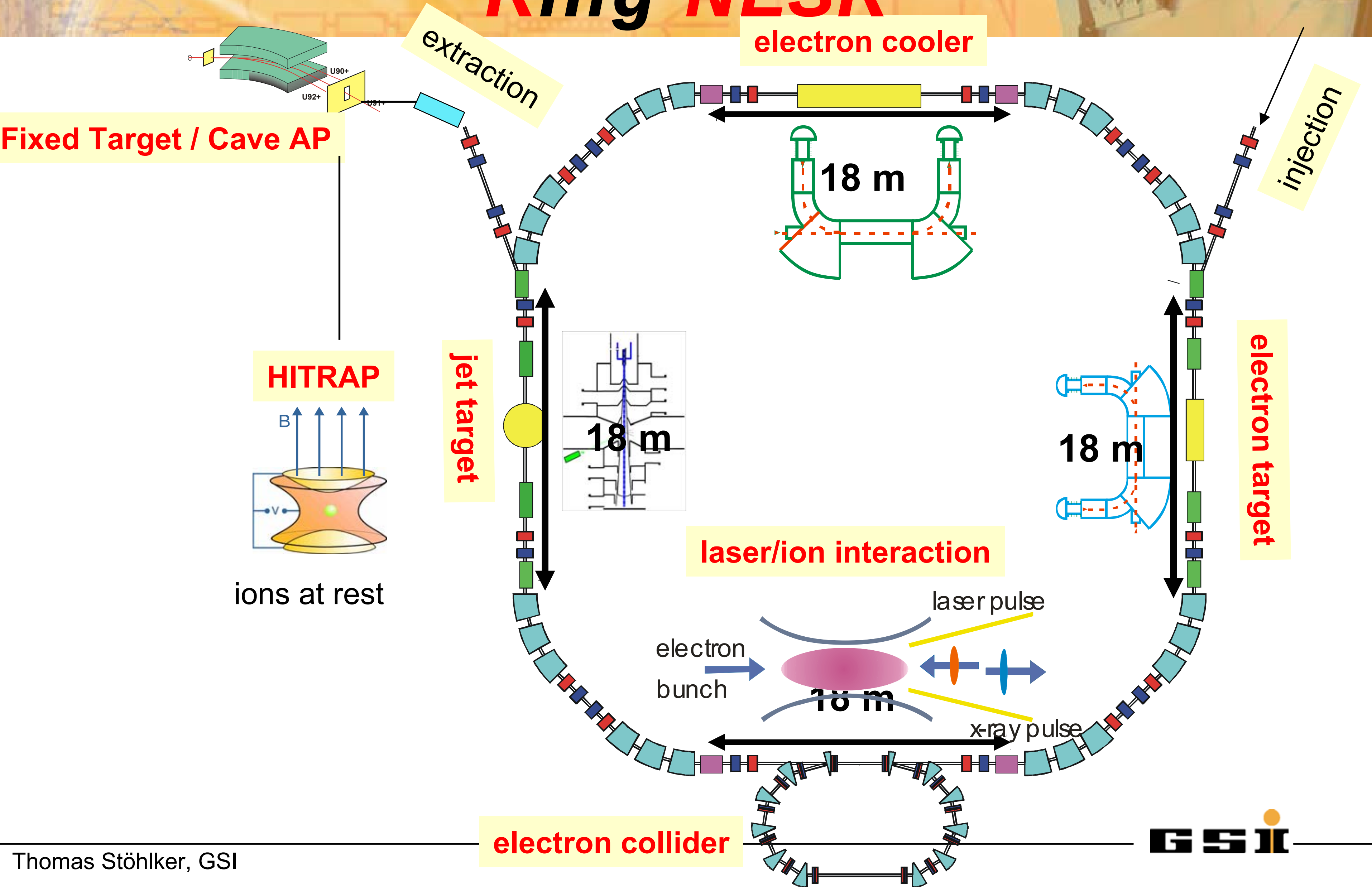
The Future GSI Heavy-Ion and Antiproton Accelerator Facility for Atomic Physics



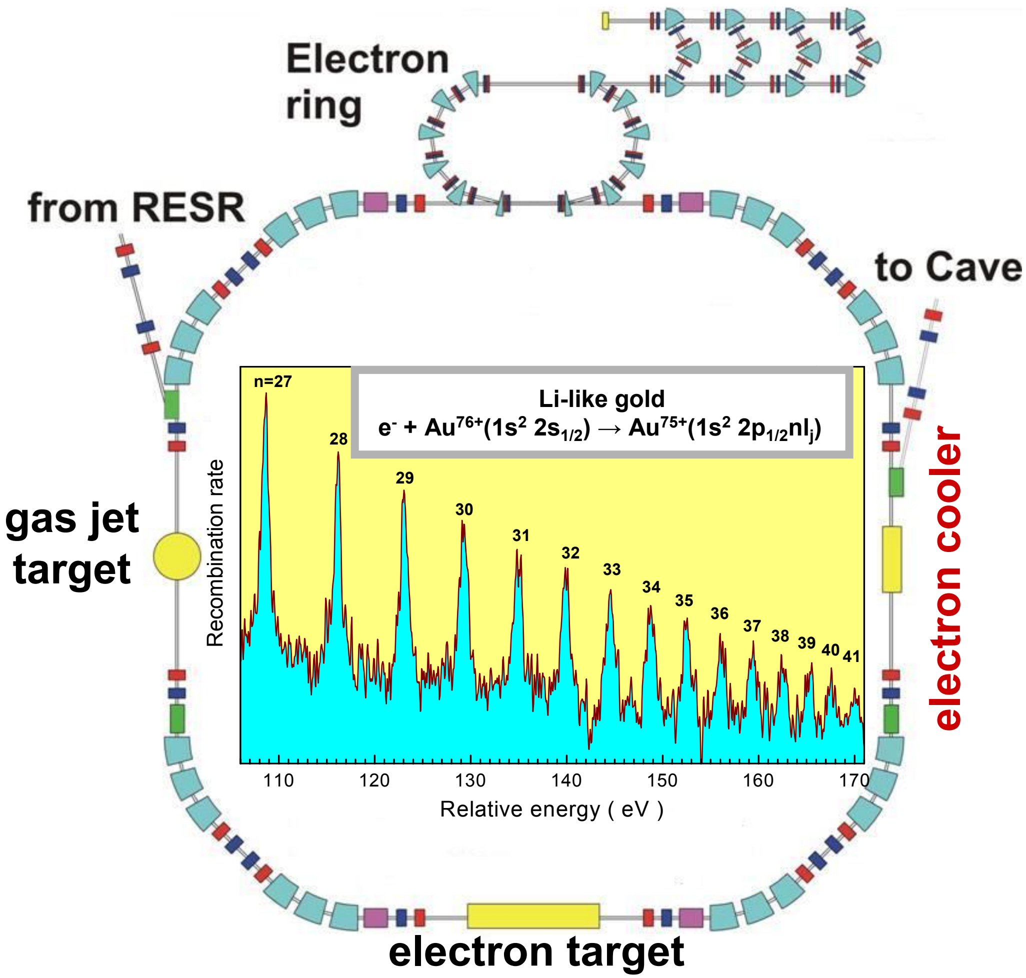
AP Low-Energy Cave

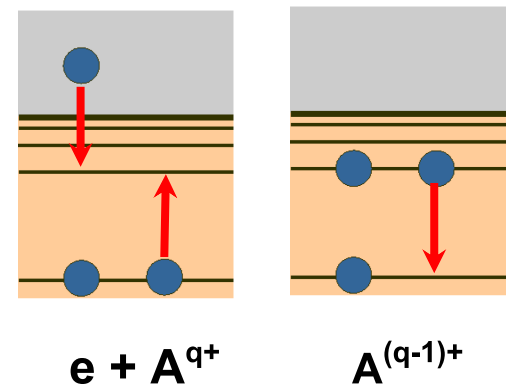
New Experimental Storage Ring

The New Experimental Storage Ring NESR



Experiments – at the Electron Target
Dielectronic Recombination

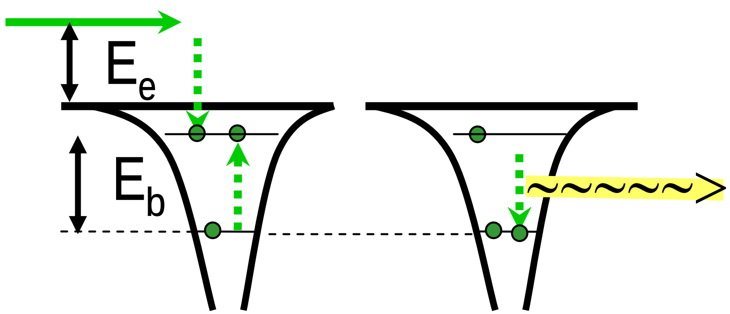


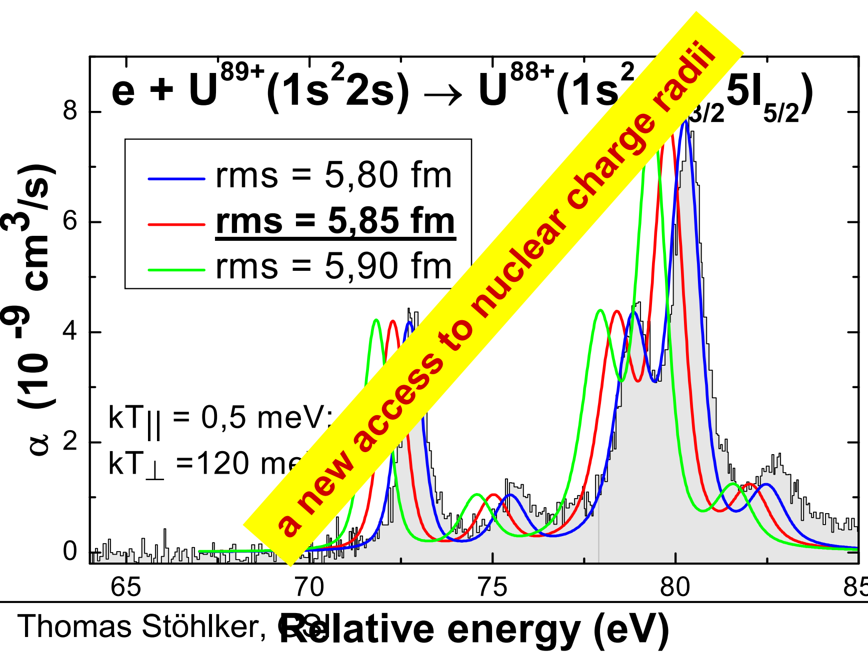


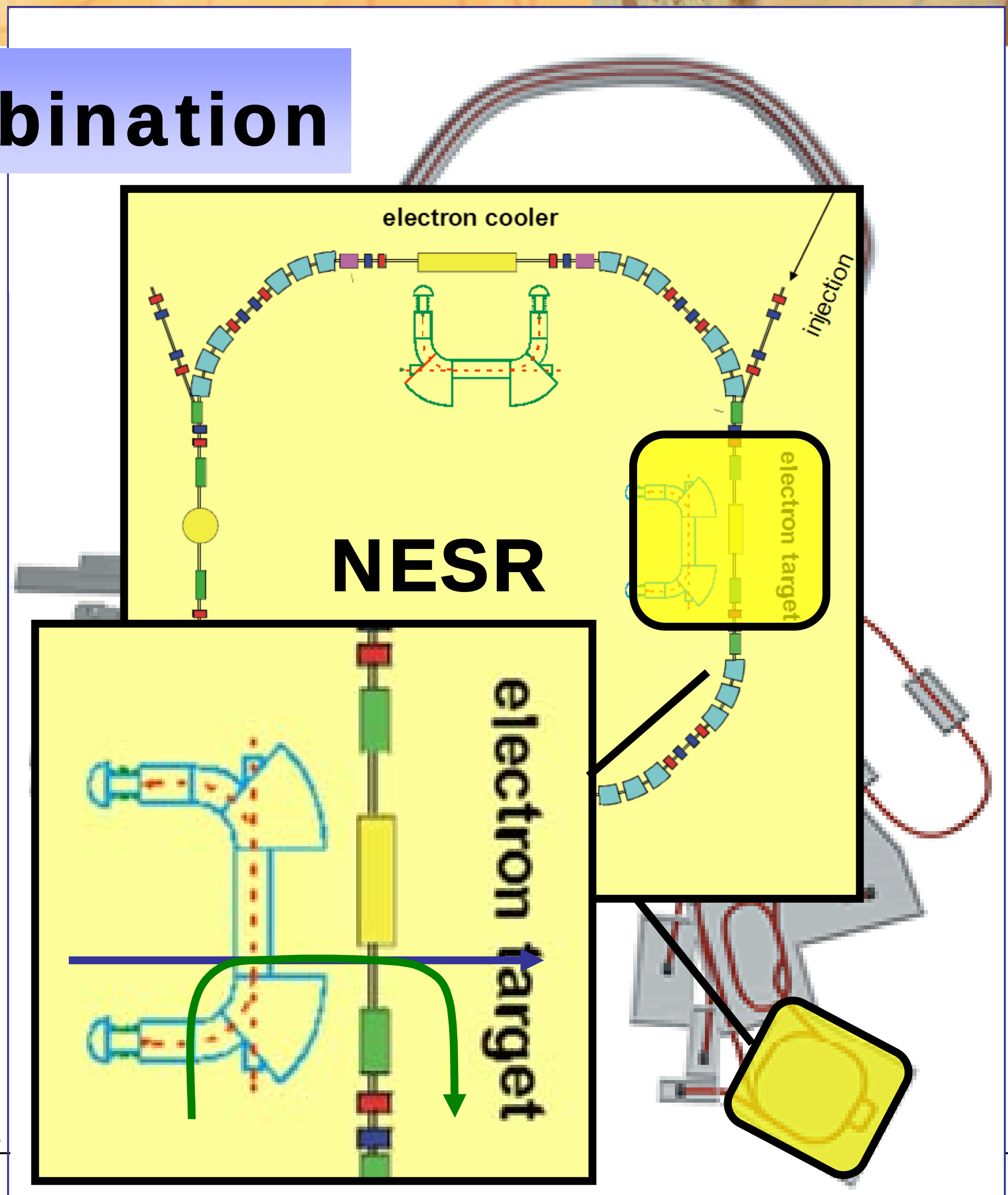
DR experiments for Li-like heavy ions at the ESR: The already achieved accuracy is comparable with the most precise x-ray experiments

Explore the Nucleus

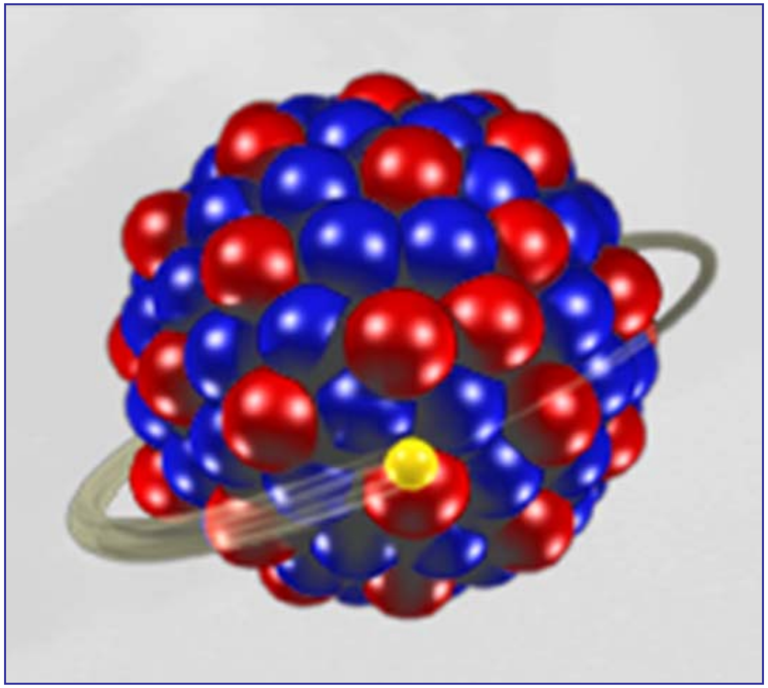
Dielectronic Recombination

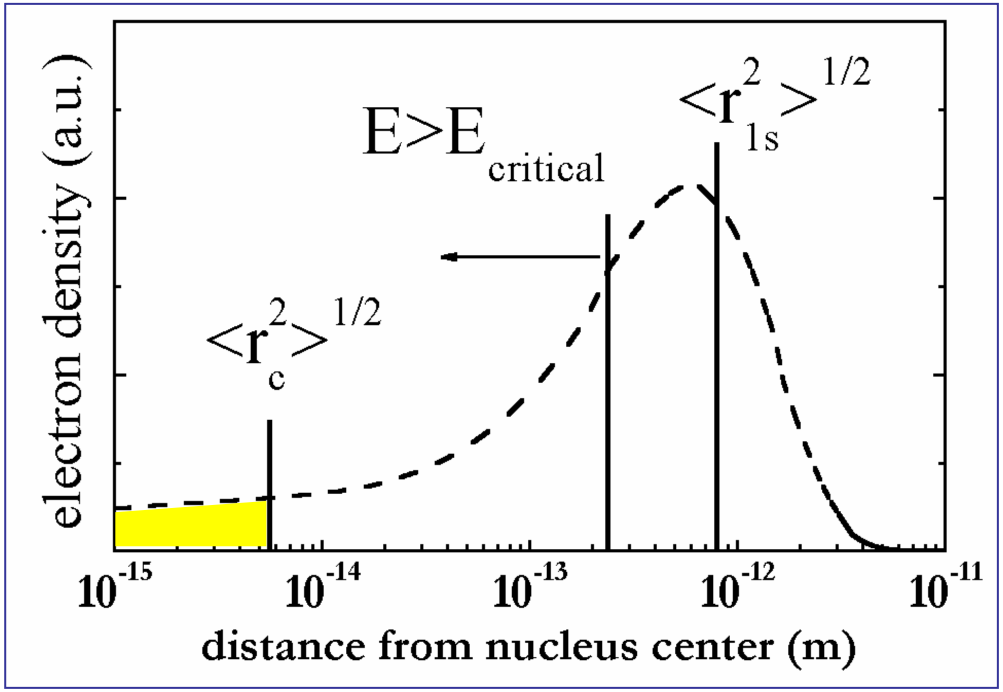






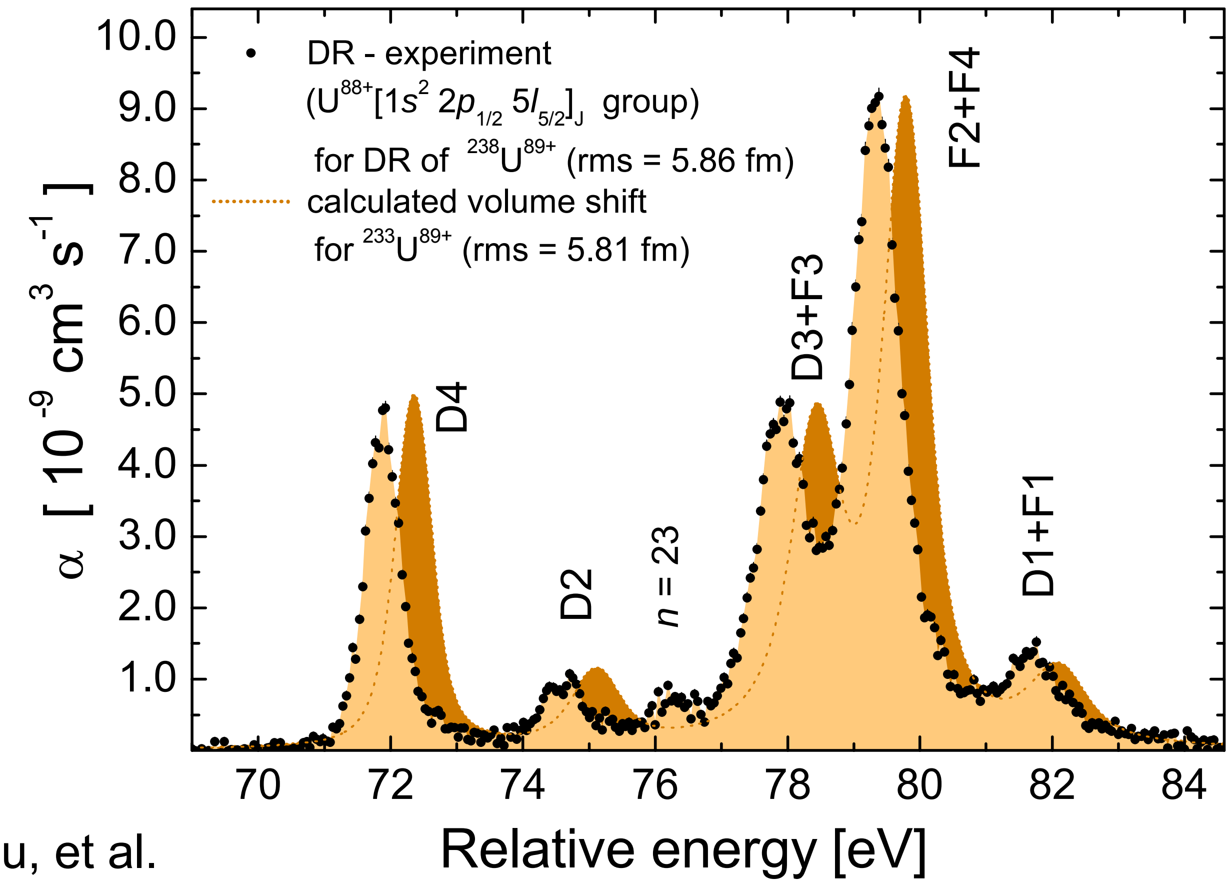
Explore the Nucleus





Explore the Nucleus

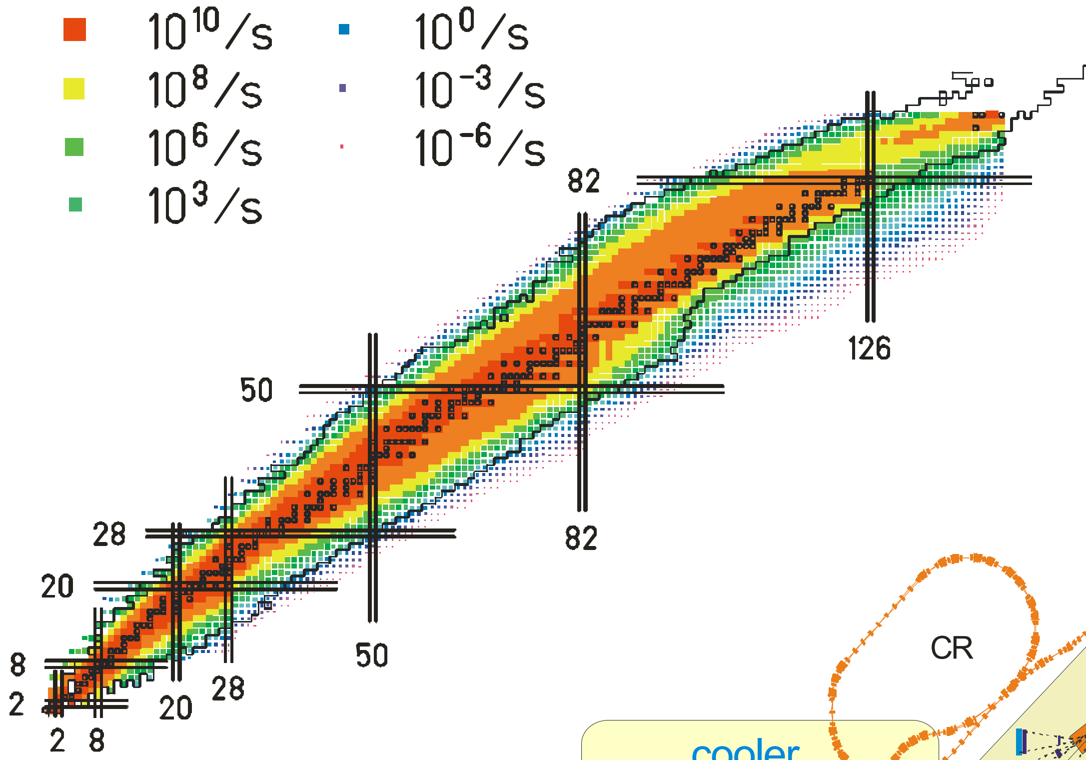
Experimental data for DR of Li-like $^{238}U^{89+}$ and calculated isotopic shift for $^{233}U^{89+}$ (volume shift only).

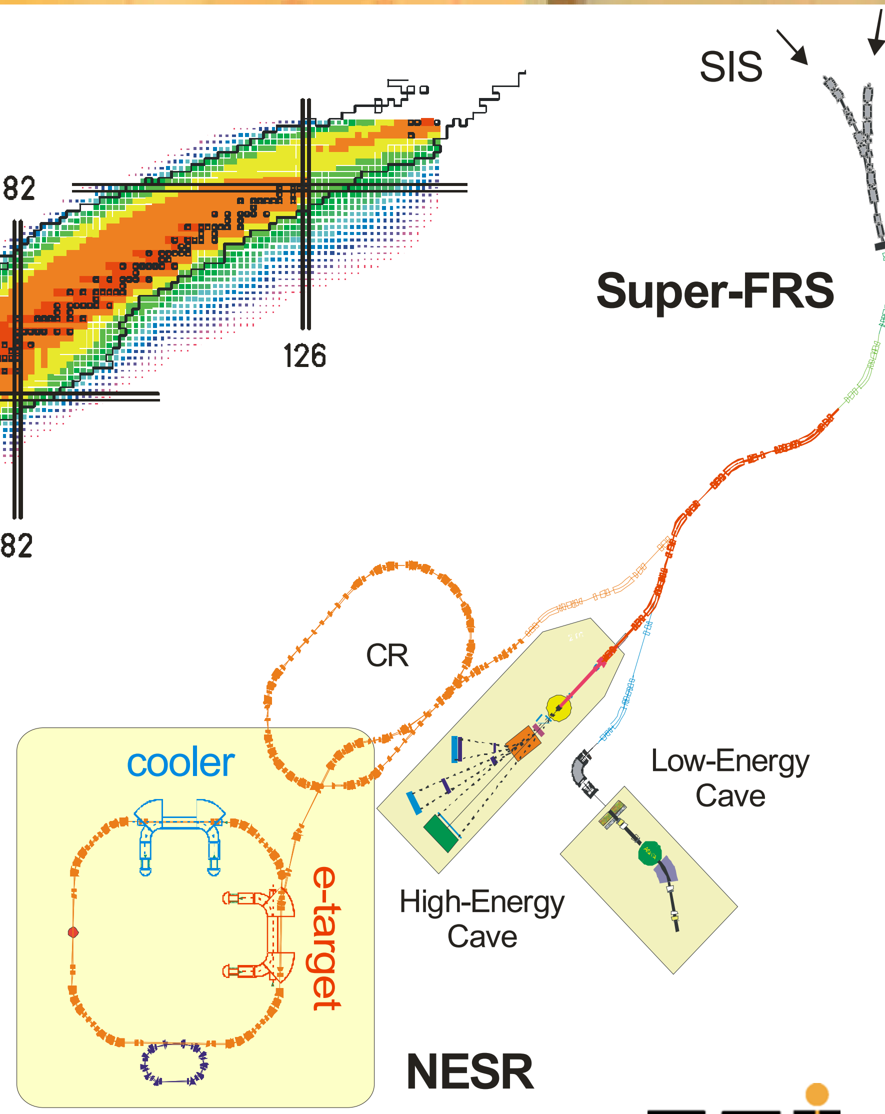


C. Brandau, et al.

New Experimental Possibilities for DR at Super-FRS / NESR

large production rates of radioactive nuclei

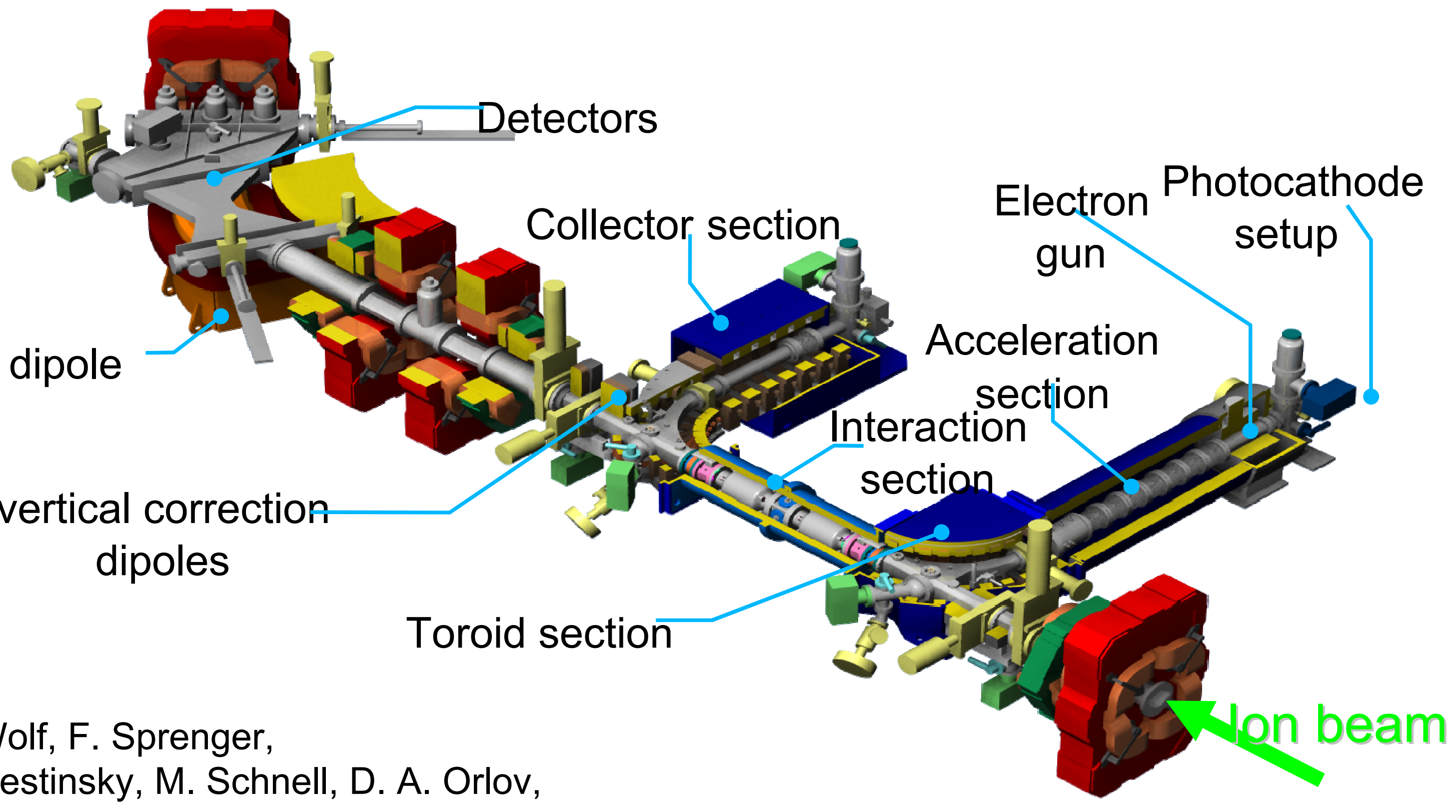




new experimental possibilitites
=> separate cooler and e-target
=> „ultracold" e-target

The Heidelberg (TSR) „Ultracold“ Electron Target

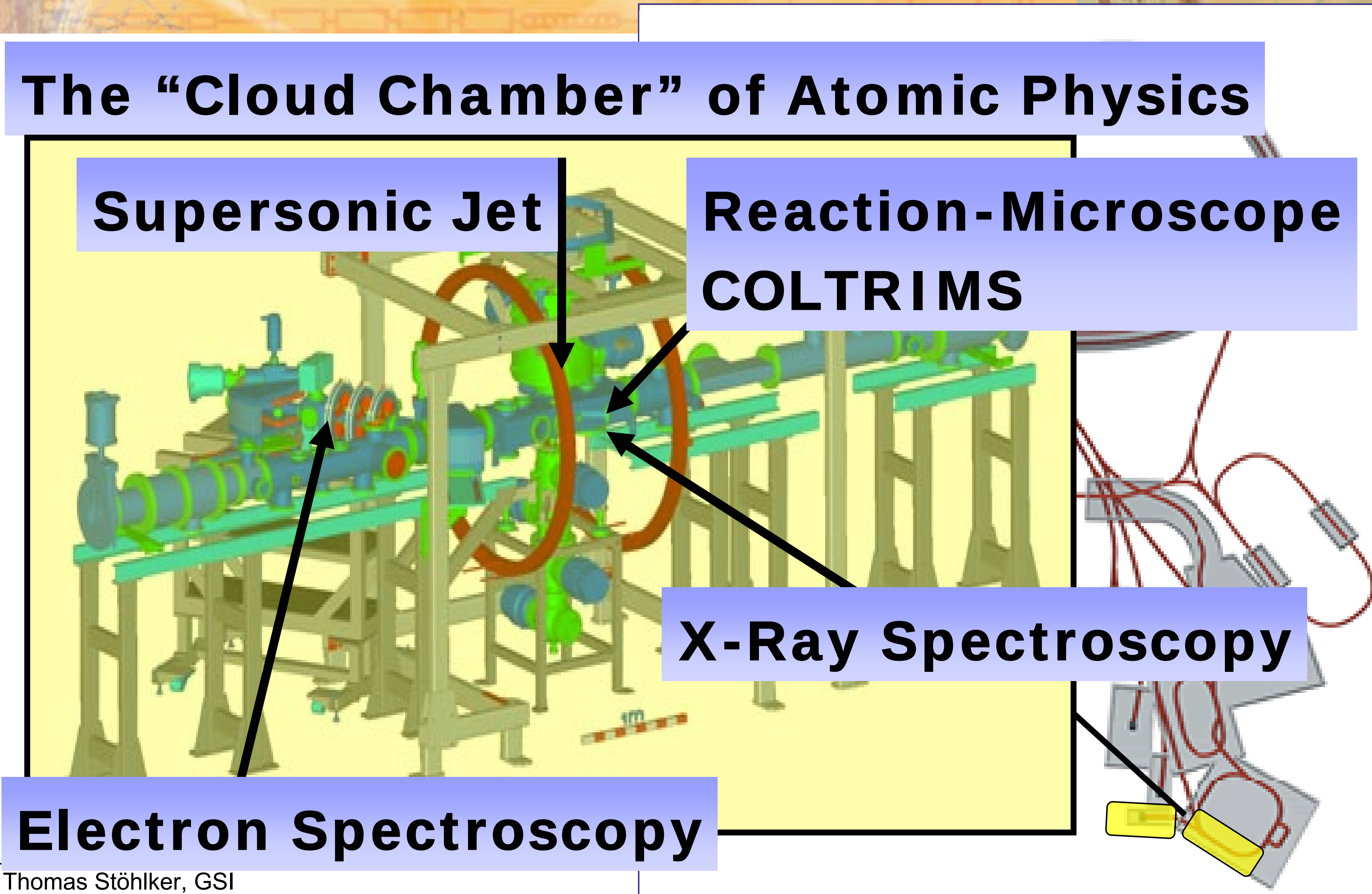
„3rd“ generation electron target (dedicated and optimized with respect to experiments)
Adiabatic expansion / adiabatic acceleration of electrons
Photocathode option for the production of initially cold electrons



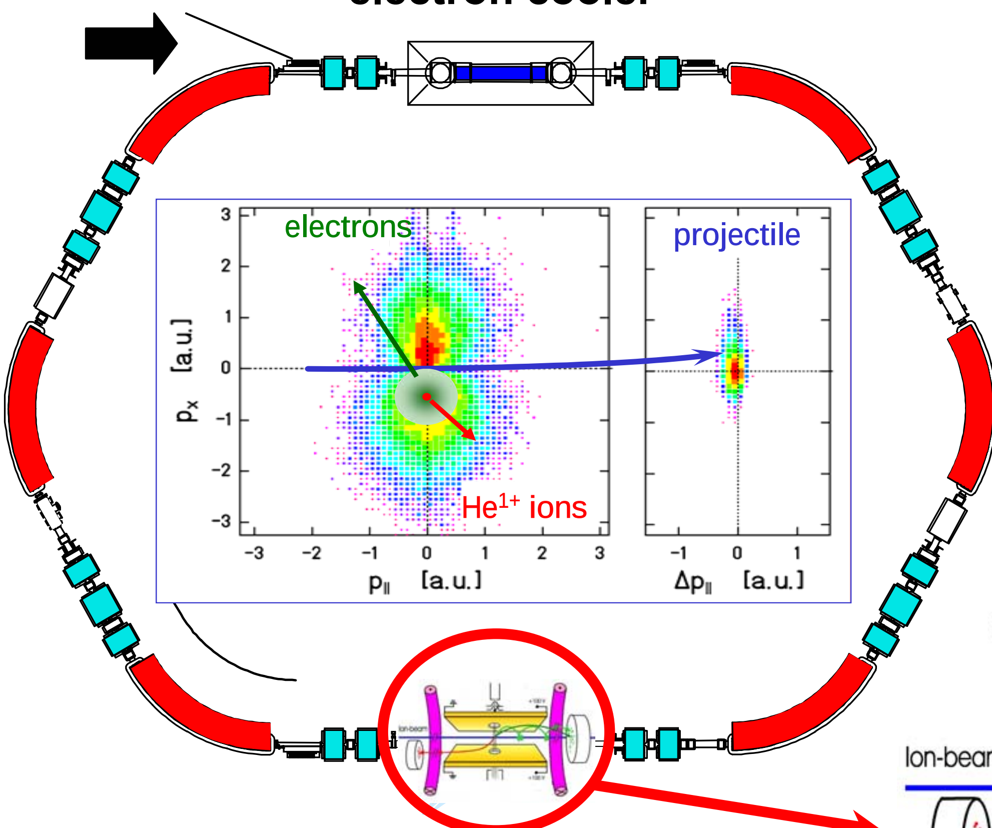
A. Wolf, F. Sprenger,
M. Lestinsky, M. Schnell, D. A. Orlov,
U. Weigel, D. Schwalm, MPI-K HD

In-Ring Spectrometers

The "Cloud Chamber" of Atomic Physics



Recoil Ion Momentum Spectroscopy



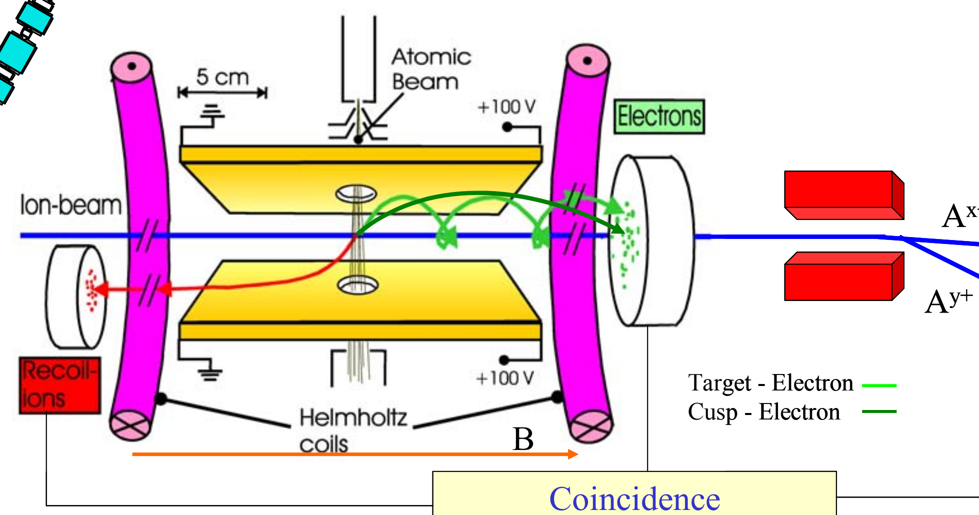
set-up for recoil ion momentum spectroscopy

Photo ionization by ultra-short 0.1 attosecond (10^{-19} s) pulses

multiple ionization

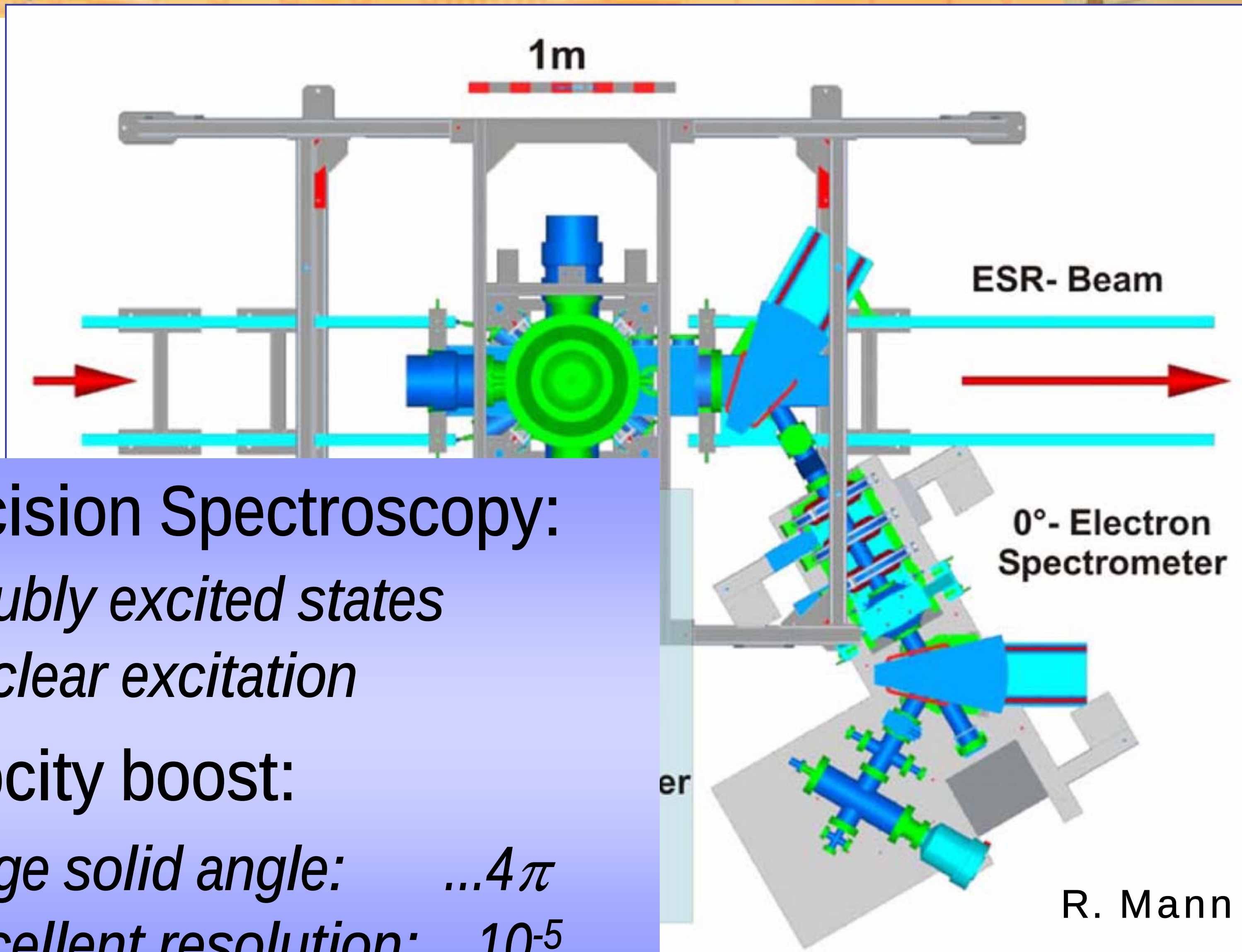
exploration of correlated wave function

no ab-initio theory even for helium



R. Moshammer, J. Ullrich et al.

Forward Emitted Electrons



Precision Spectroscopy:

- *doubly excited states*
- *nuclear excitation*

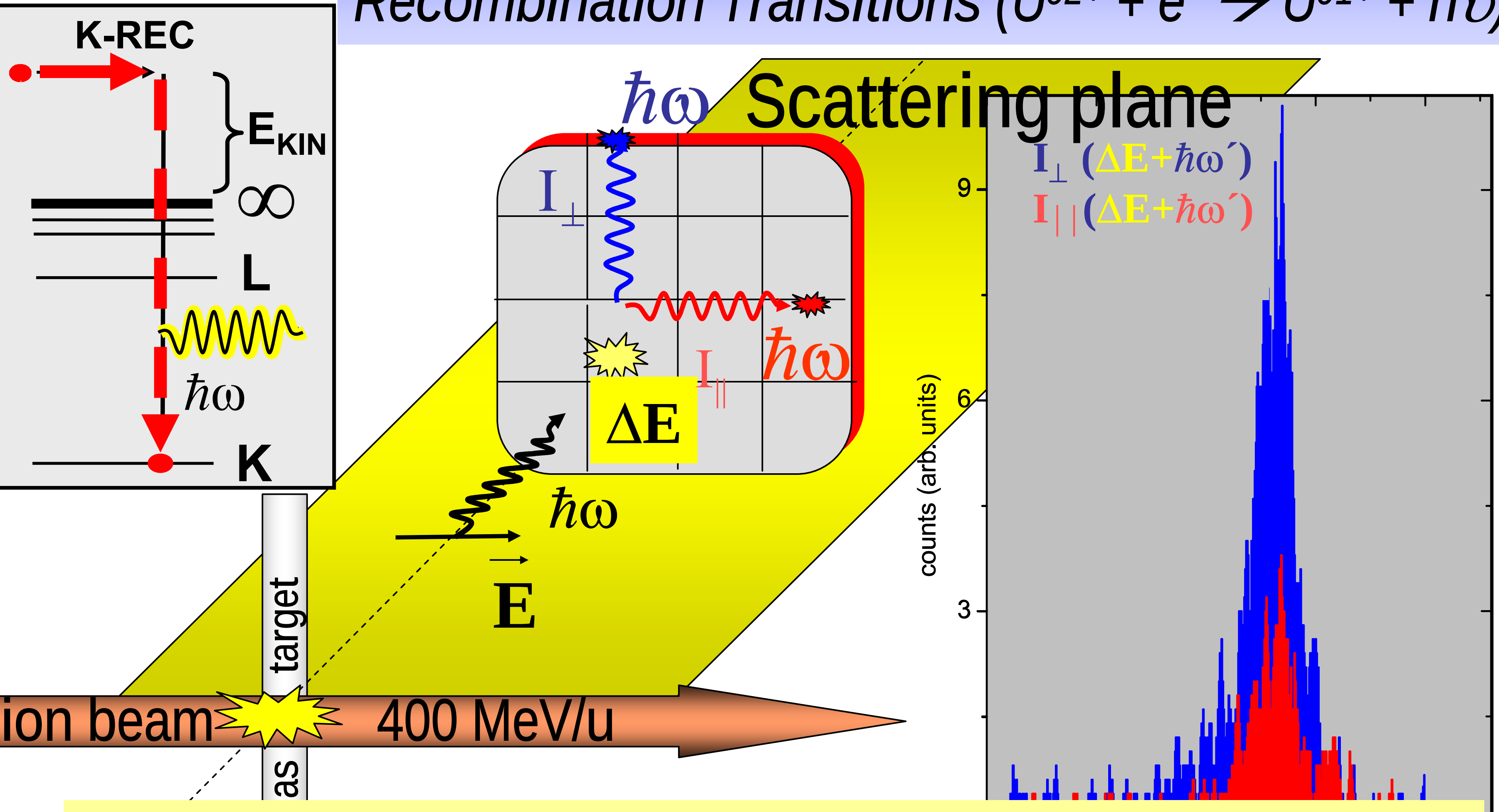
Velocity boost:

- *large solid angle: ...4π*
- *excellent resolution: ...10^{-5}*

R. Mann et al.

X-Rays and Polarization

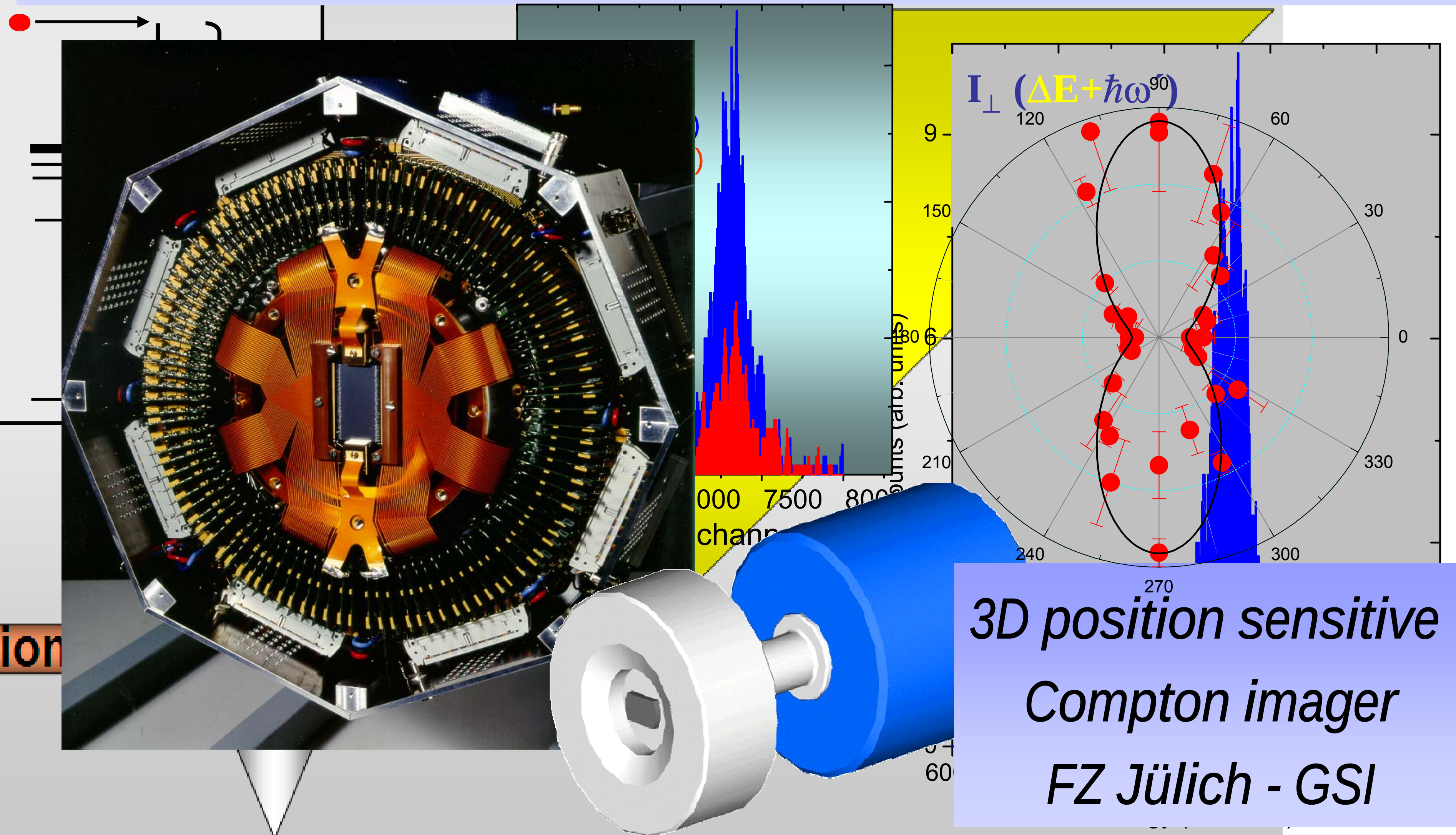
Recombination Transitions ($U^{92+} + e^- \rightarrow U^{91+} + h\upsilon$)



polarization plane depends on the spin-polarization of the projectiles
A. Surzhykov PRL, June 2005

X-Rays and Polarization

Polarization Spectroscopy of Photon-Matter Interaction

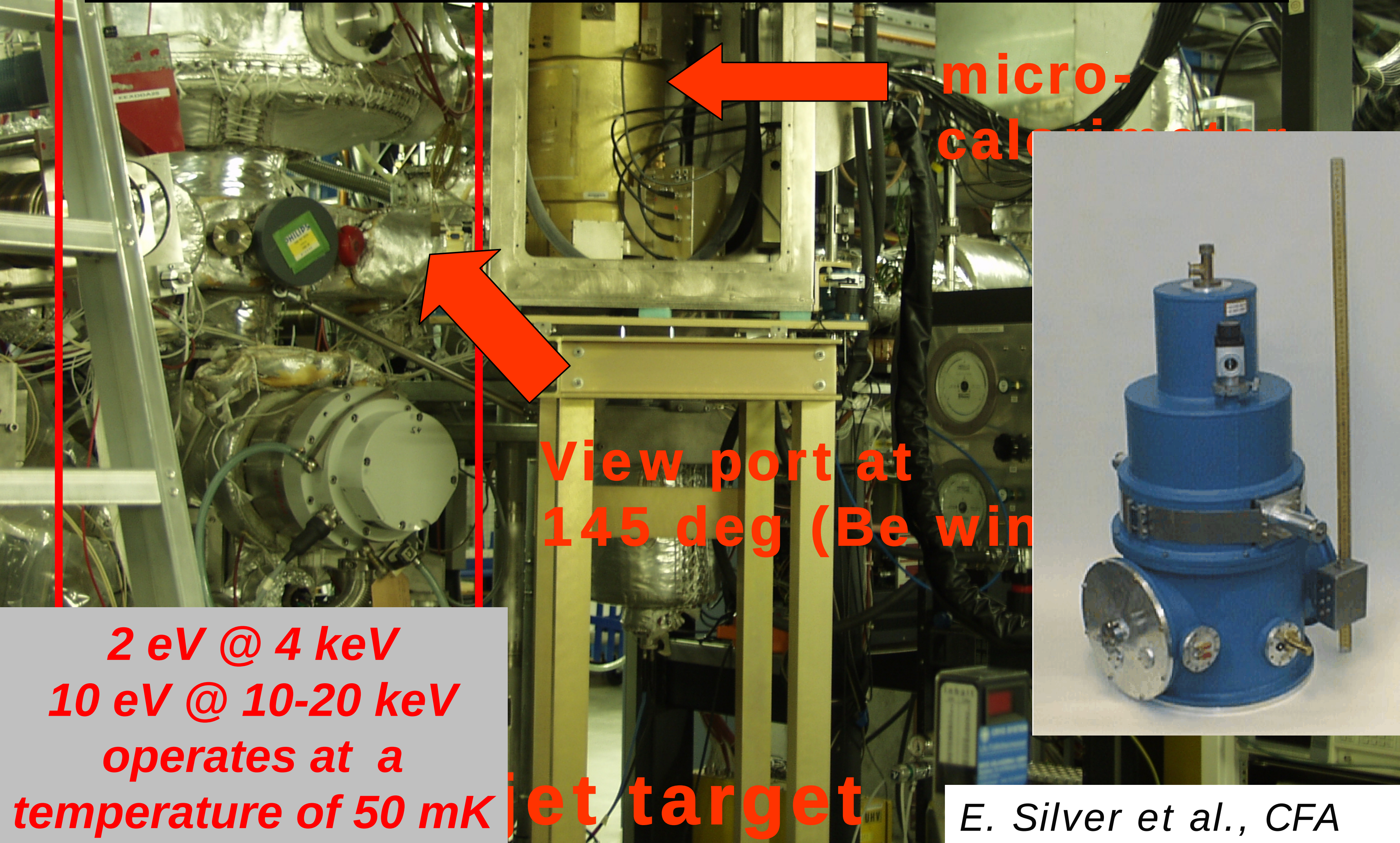


3D position sensitive

Compton imager

FZ Jülich - GSI

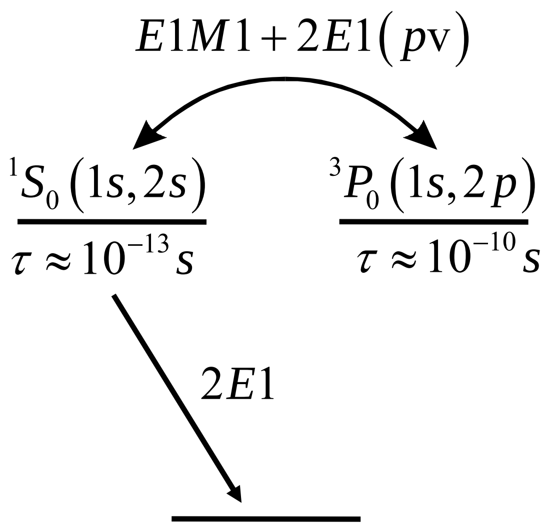
Development of Micro-Calorimeter
Example: Helium-Like Uranium
Accurate Transition Energy Measurements

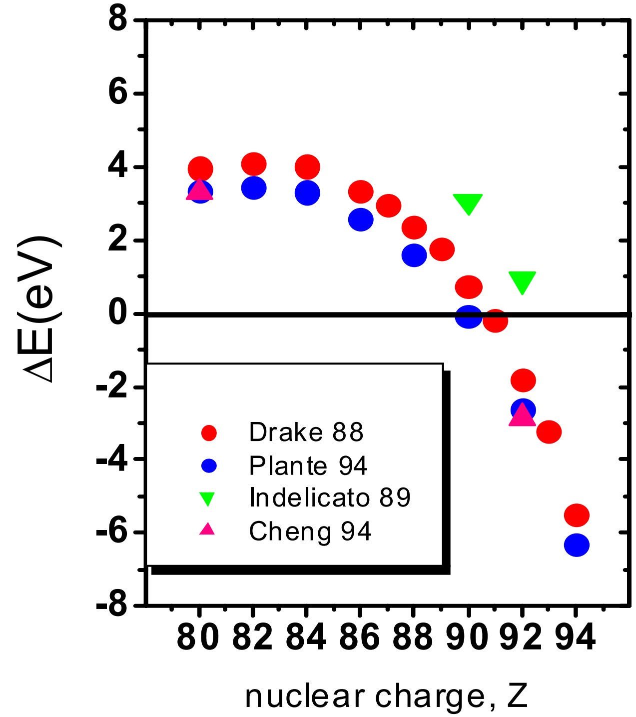


2 eV @ 4 keV
10 eV @ 10-20 keV
operates at a
temperature of 50 mK

E. Silver et al., CFA

Parity Violation in Highly Charged Ions
Helium-like Uranium





Parity admixture

$$\eta = \frac{\left\langle 2\ ^3P_0 \left| \frac{G_F}{2\sqrt{2}} \left(1 - 4\sin^2\Theta_w - \frac{N}{Z}\right) \rho_{\mathrm{el}} \gamma_5 \right| 2\ ^1S_0 \right\rangle}{E\left(2\ ^3P_0\right) - E\left(2\ ^1S_0\right)} \qquad |\eta| = 5 \cdot 10^{-6}$$

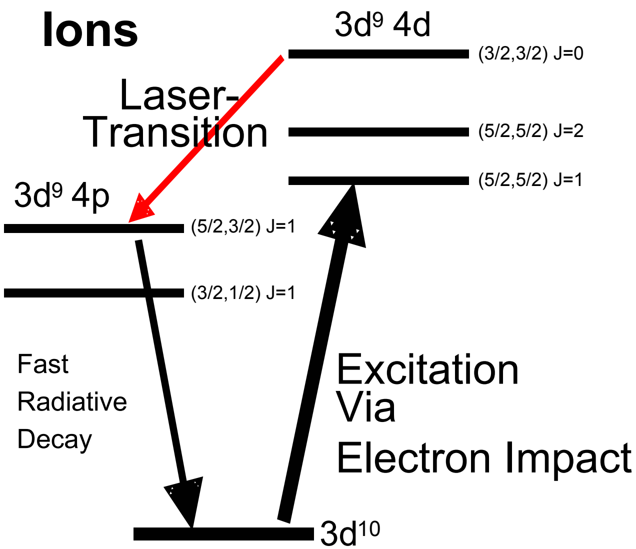
G_F: Fermi constant, Θ_w: Weinberg angle

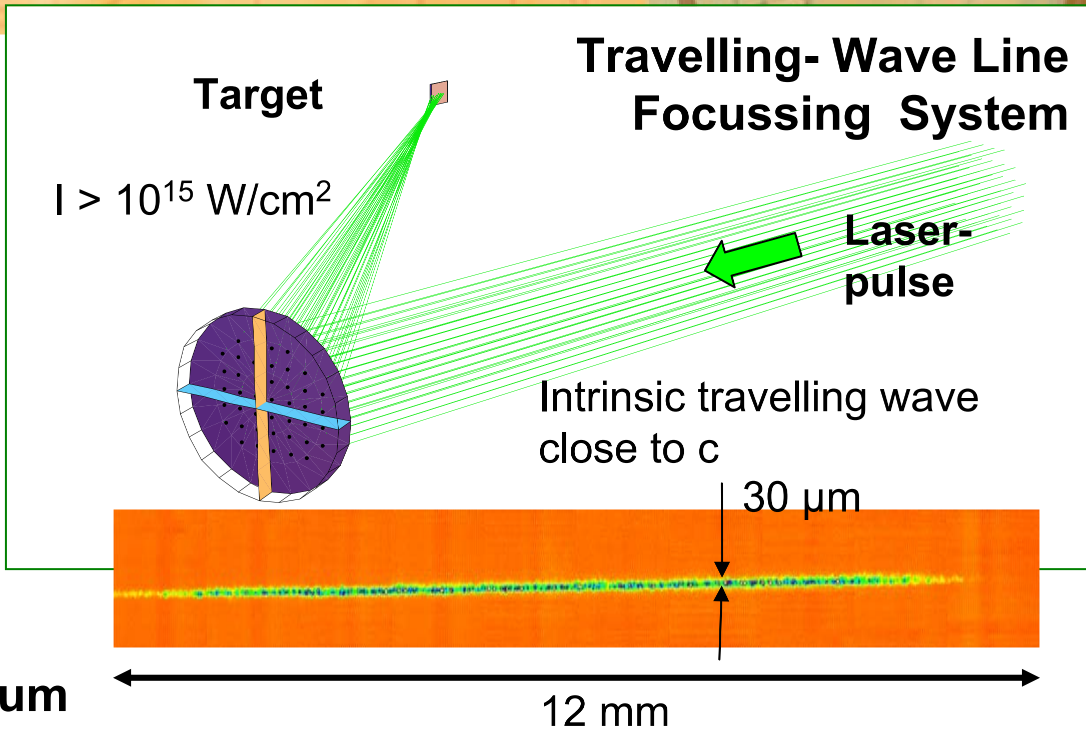
N: neutron number, Z: proton number

ρ_{el}: electric charge density

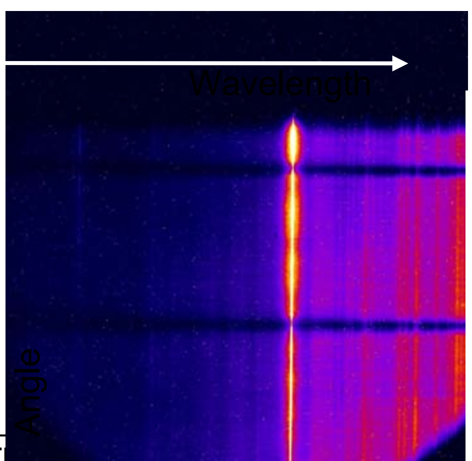
GSI PHELIX: Transient Pumped X-Ray Laser in Nickel-like Ions

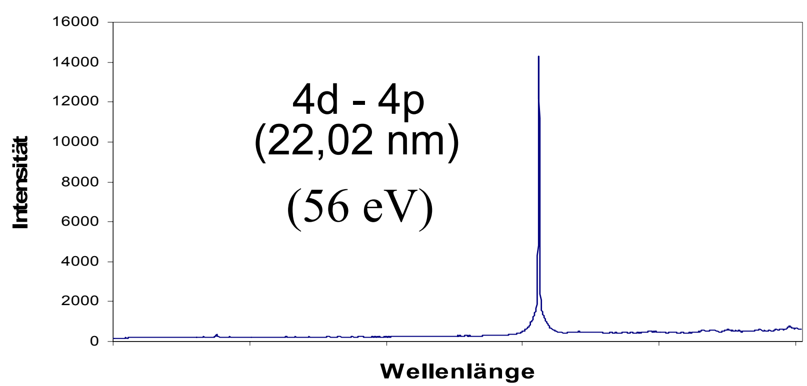
Level Scheme of Ni-like Ions





X-Ray Emission Spectrum

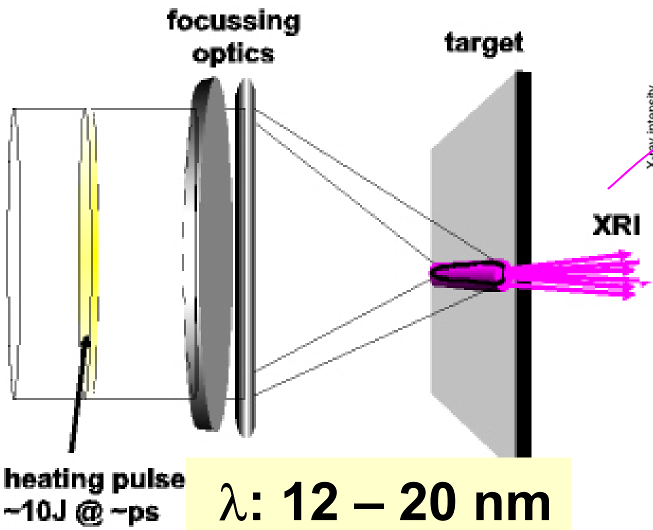


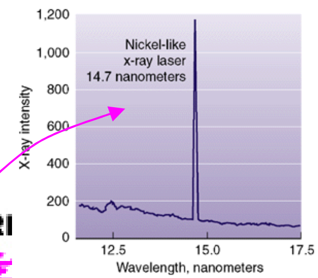


Th. Kühl et al. 2004

X-Ray Laser Spectroscopy on Lithium-like Radioactive Nuclei

Principle of an X-Ray Laser (XRL)

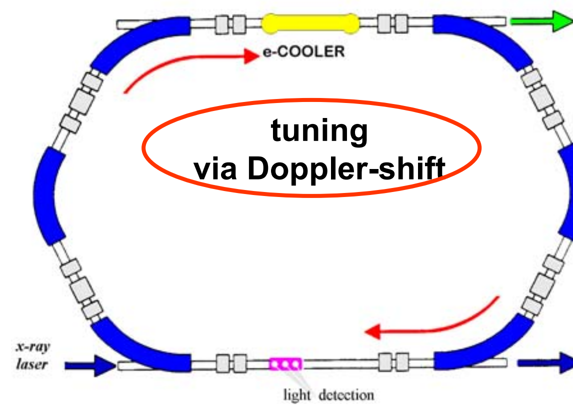


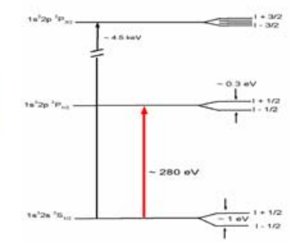


λ: 12 – 20 nm

At NESR:
Wide Range of Accessible Ions

Excitation in the ESR / NESR



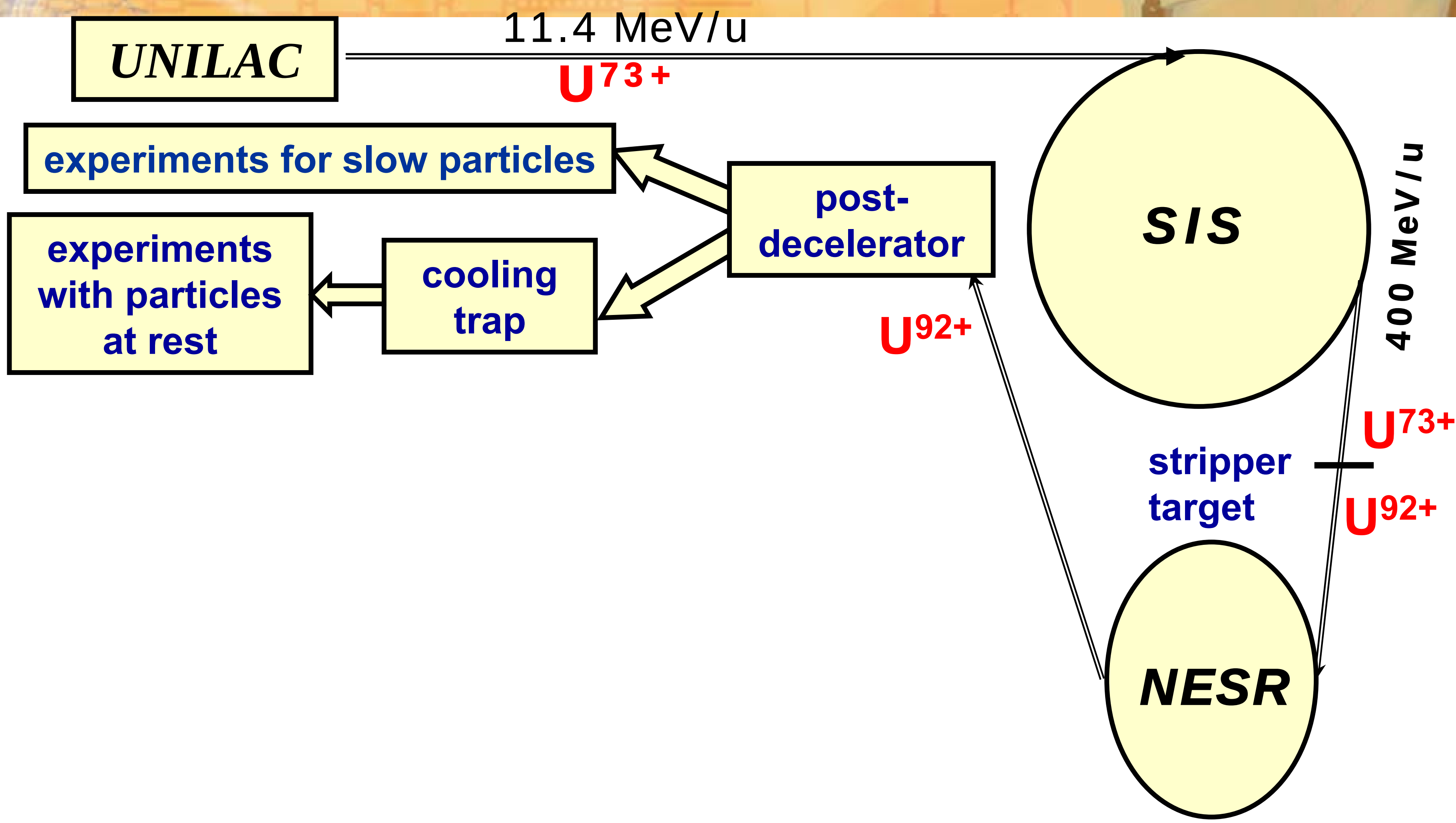


up to Z=92 possible

$\Delta p/p \sim 5x10^{-5}$

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

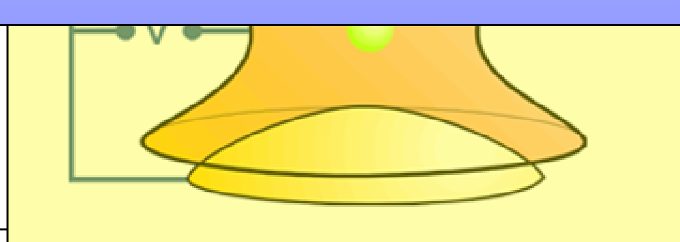
The HITRAP Project at GSI

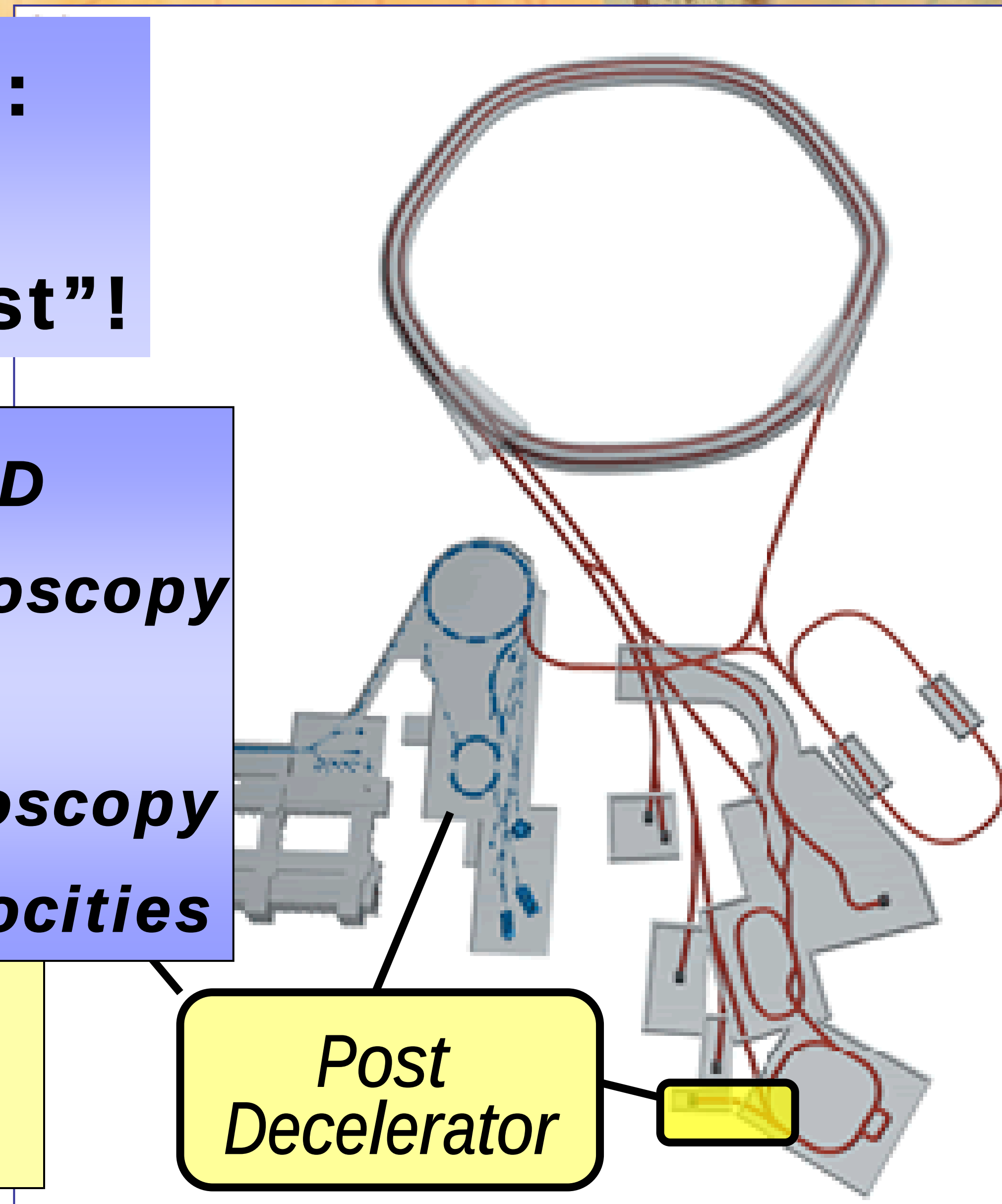


The HITRAP Project at GSI

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***



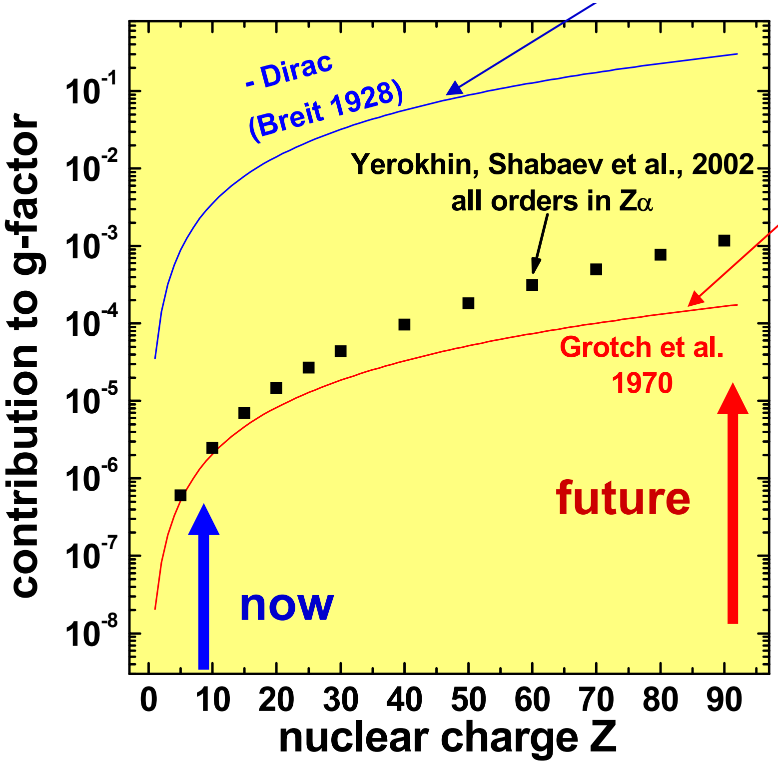


HITRAP – Test of QED: g-Factor of the Bound Electron

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

relativistic effect (Dirac theory)

bound-state QED



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

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

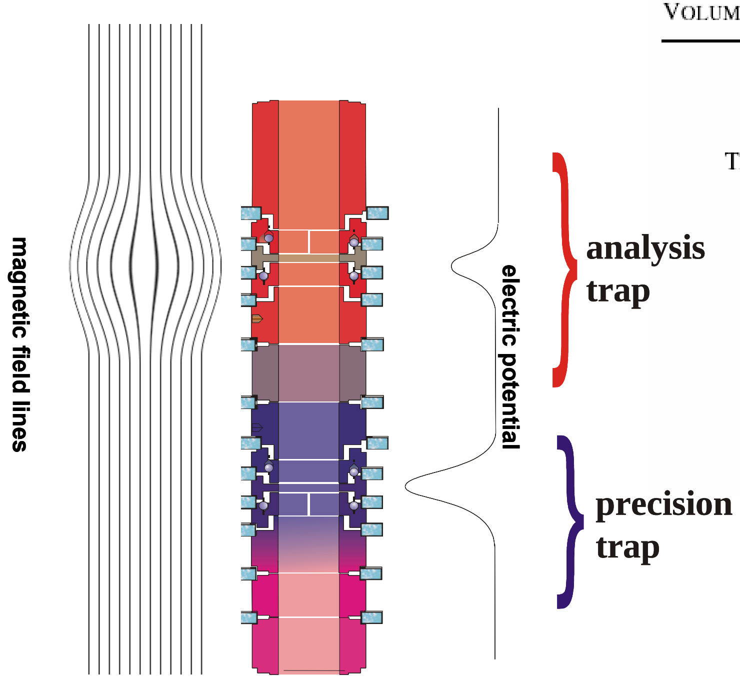
theory: $g(^{12}C^{5+}) = 2.001\ 041\ 589\ 9(9)$

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

total error: $\delta g/g = 2\cdot 10^{-9}$ (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.

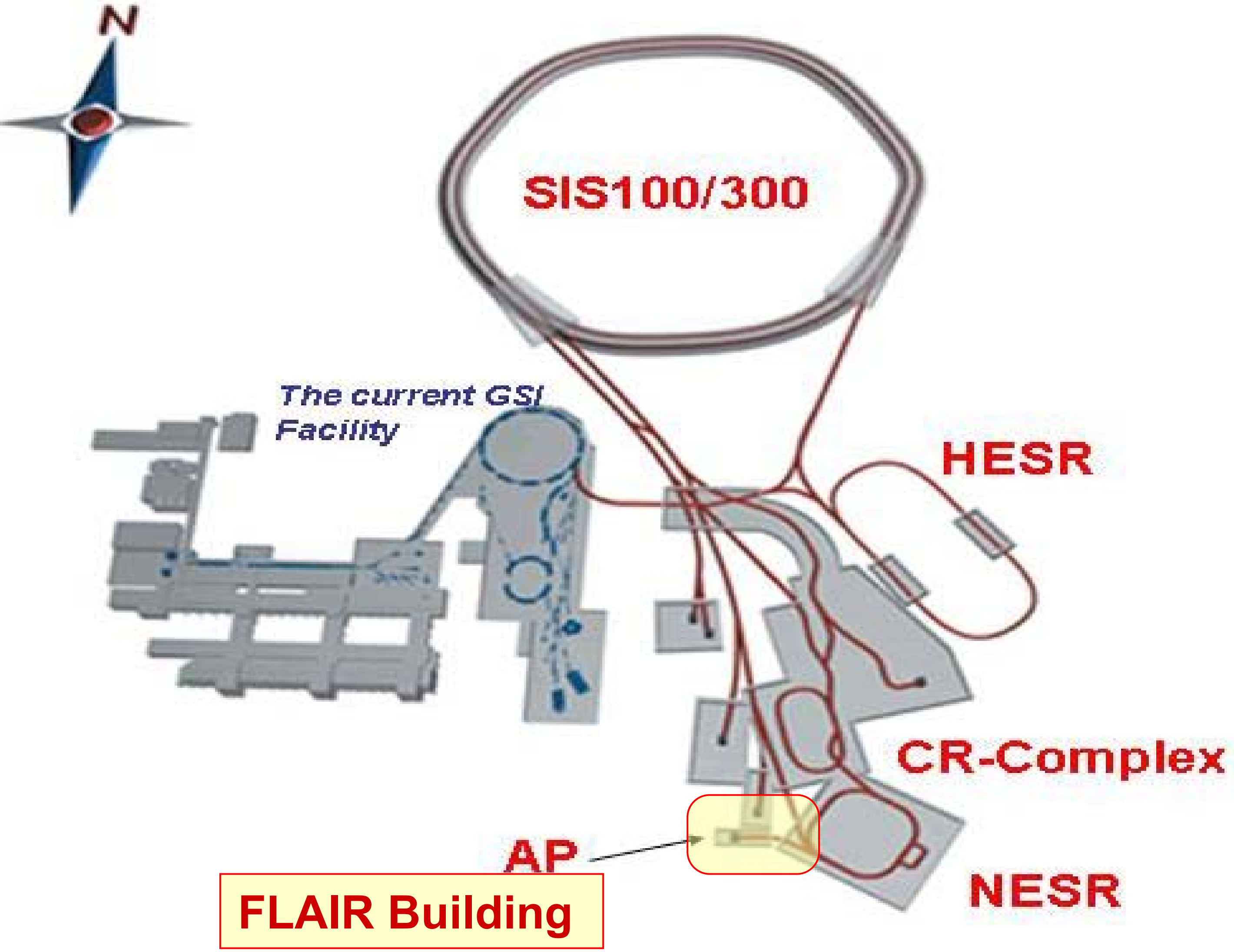
theoretical value:	**2.001 041 589 9(9)**
experimental value:	**2.001 041 596 4(10) {44}**
QED correct ⇒	**m_e = 0.000548 579 909 2(4) u**
van Dyck (1995)	**m_e = 0.000548 579 911 1(12) u**
CODATA (1998)	**m_e = 0.000548 579 911 0(12) u**

⇒ improvement by a factor of 4*

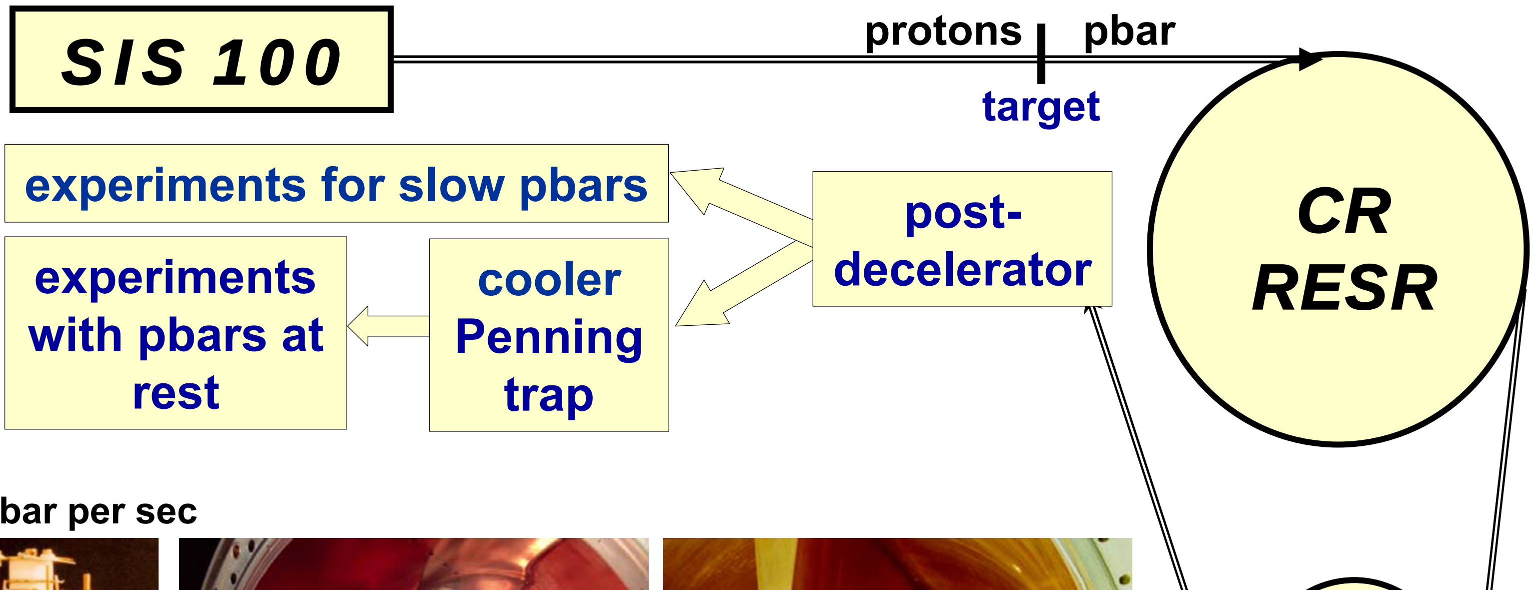
future: fine-structure constant α

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

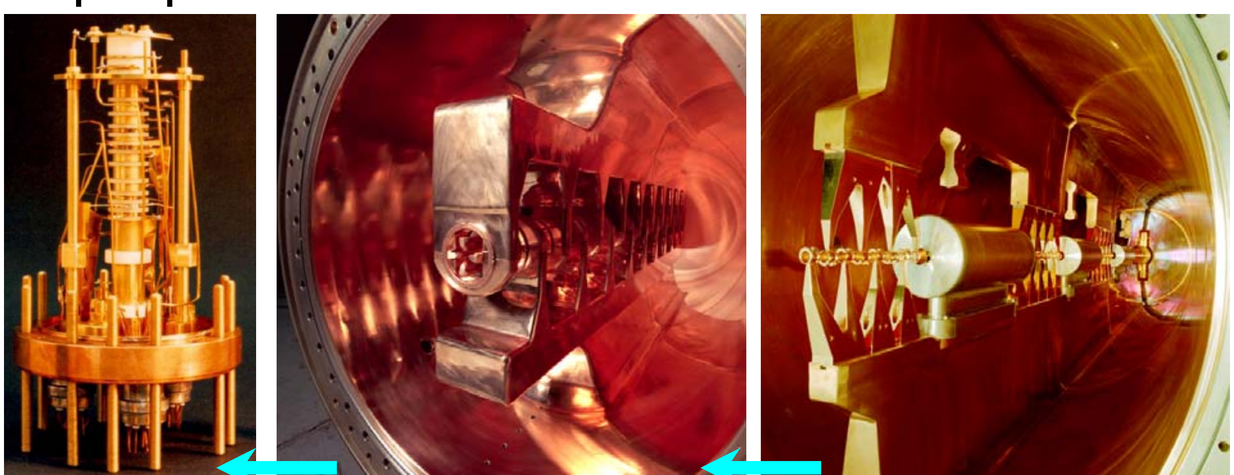
The Future GSI Heavy-Ion and Antiproton Accelerator Facility for Atomic Physics



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



10^6 pbar per sec



HITRAP works for antiprotons and HCI !

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)

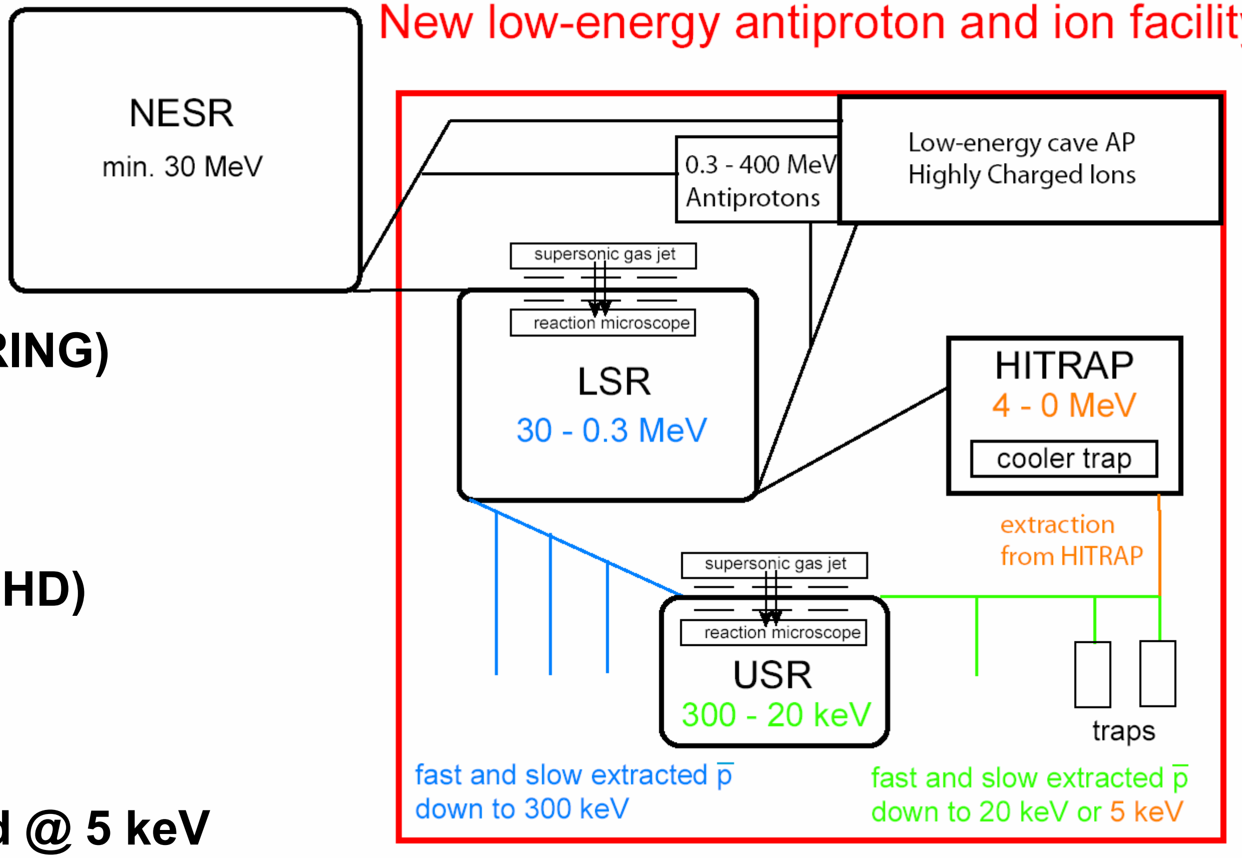
HITRAP

Pbar and ions

Stopped & extracted @ 5 keV

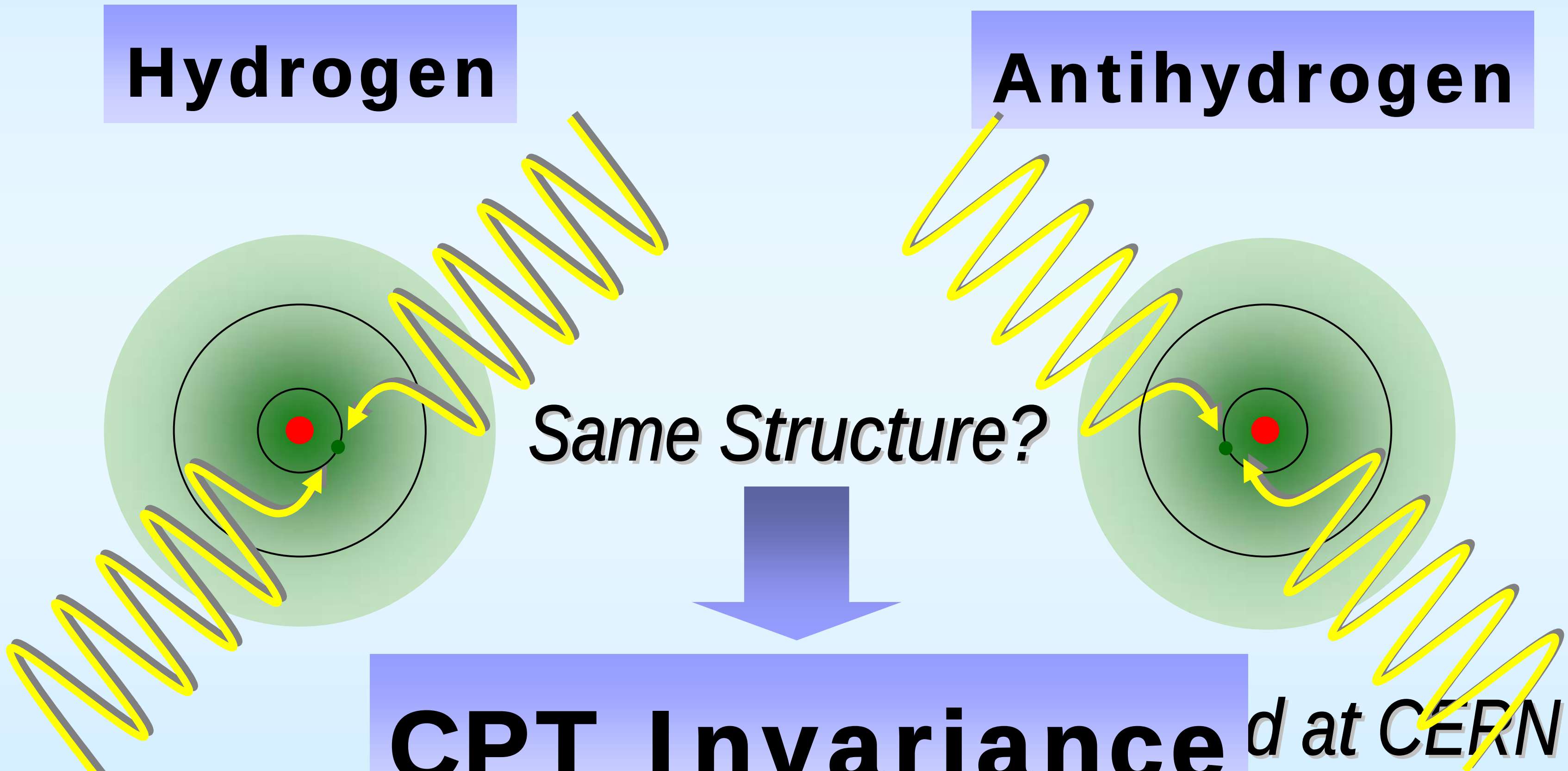
(under construction for ESR)

New low-energy antiproton and ion facility



energy range: 400 MeV – 1 meV

Ultracold & Trapped $\bar{p}$



CPT Invariance

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

d at CERN

t: 1996

s: 2002

Expected production rate:

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

~ 100 x Antiproton Decelerator (AD)

(2-4 · 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:

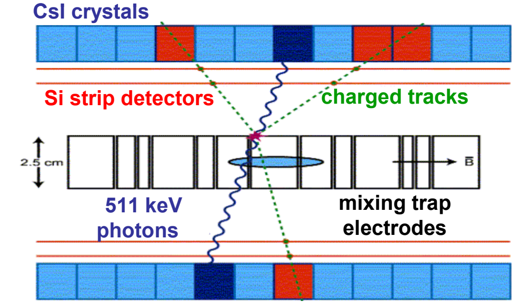
ATHENA: CPT
ATRAP: CPT
ASACUSA: structure and dynamics

GSI will provide the most intense source of antiprotons

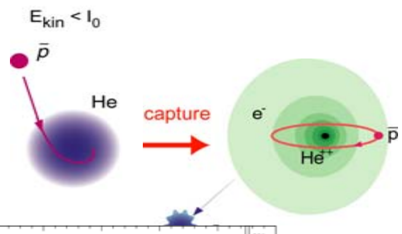
Research Topics with Low-Energy Antiprotons

EXPERIMENTS WITH ANTIPROTONS AT EXTREMELY LOW ENERGIES

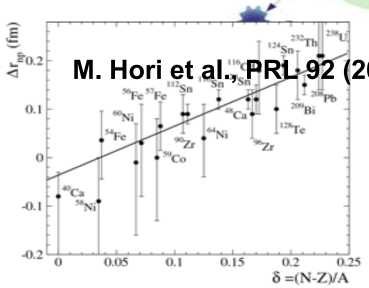
- **fundamental interactions**
  - CPT (antihydrogen, HFS, magnetic moment)
  - gravitation of antimatter
- **atomic collision studies**
  - ionization
  - energy loss
  - matter-antimatter collisions
- **antiprotonic atoms**
  - formation
  - strong interaction and surface effects



ATHENA Nature 419 (2002) 456



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



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

Summary

Atomic physics at accelerators is a rich field of research

There are unique opportunities and challenges for collision and structure studies in the realm of heavy ions

Storing and cooling is the key to precision

Have in mind:

plenty of new ideas will emerge !

experiments will be done, not even envisioned today !