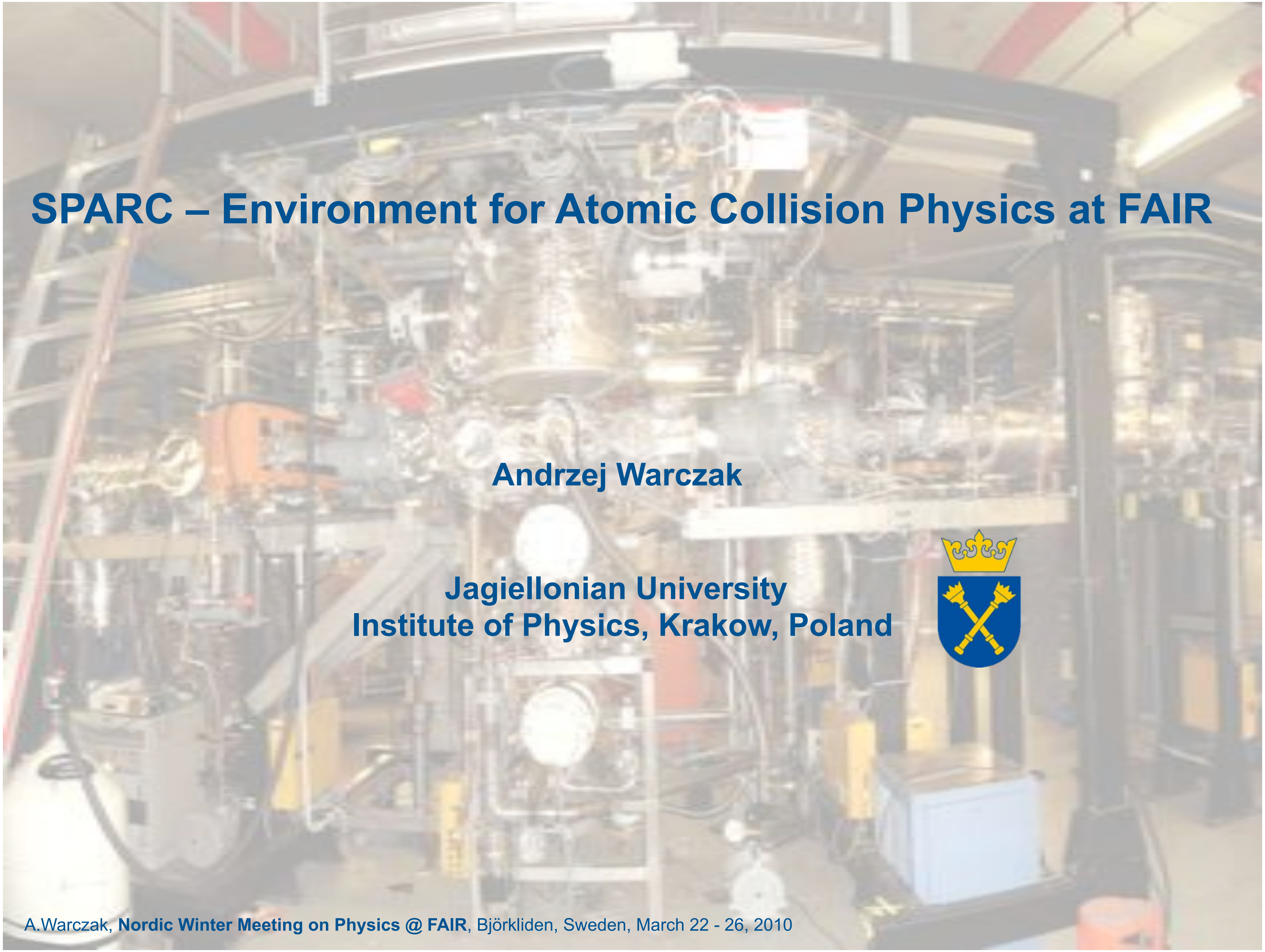

SPARC – Environment for Atomic Collision Physics at FAIR

Andrzej Warczak

Jagiellonian University
Institute of Physics, Krakow, Poland

Contents

Introduction:
  - SPARC within FAIR structure,
  - Collaboration status,
  - General programme.

SPARC physics and experimental infrastructure:
  - Matter in strong static and dynamic e-m fields observed via x-rays emitted in ion-atom collisions (selected topics),
  - Infrastructure development (detectors, targets, HITRAP).

Summary

FAIR research programme includes 14 initial experimental collaborations which form the four scientific pillars

APPA	(Atomic, Plasma Physics and Applications)
CBM/HADES	(Compressed Baryonic Matter)
NUSTAR	(NUclear STructure, Astrophysics and Reactions)
PANDA	(AntiProtons ANnihilation at DArmstadt)

APPA (Atomic, Plasma Physics and Applications)

BIOMAT - BIOlogy and MATerial science

FLAIR - Facility for Low-energy Antiproton and heavy Ion Research

HEDgeHOB / WDM - Plasma physics experimental stations

SPARC - Stored Particles Atomic Physics Research Collaboration

sparc

~ 300 participants from over 20 countries
Collaboration Board: 15 Members from 12 Countries
Spokesperson, Deputies, Local Contact

https://gsi.helmholtz.de/fair/experiments/sparc

AUSTRIA
Vienna University of Technolgy
CANADA
University of Manitoba
York University
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, L
University of Science
Wuhan Institute of Ph
Physics Department,
Department of Physic
DENMARK
Department of Physic
EGYPT
Physics Department, Beni-Suef Faculty of Science
FRANCE
Laboratoire kastler-Brossel, Ecole Normale Sup. Paris
INSP, Univ. Pierre et Marie Curie
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-Liebig-Universität Gießen
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
Vaish College, Rohtak
Nuclear Science Centre, New Delhi
Bhabha Atomic Research Centre
ITALY
Inst. Naz. Fisica Nucleare, Dip. di Fisica, Catania
JAPAN
University of Tokyo & Atomic Physics Laboratory RIKEN, Wako
JORDAN
Hashemite University
POLAND
Institute of Physics, Swietokrzyska Academy
iversity
emy of Sciences
uclear Engineering
Lebedev Physical Institute, Moscow
Institute of Physics, St. Petersburg State University
Institute of Metrology for Time and Space at VNIIFTRI
Institute of Spectroscopy of the RAS
V.G.Khlopin Radium Institute, St.Petersburg
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ersity
Mid Sweden University
Lund University
SWITZERLAND
CERN
Department of Physics, University Fribourg
Institut für Physik, Universität Basel
UNITED KINGDOM
Department of Physics, The University of Durham
Queen's University, Belfast
UNITED 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

Regular SPARC meetings started in 2004 at GSI

SPARC in Lanzhou

24-27th, Aug. 2010

Email: sparc2010@impcas.ac.cn

Http://210.77.72.2/usr/yzwl1/sparc/sparc2010.htm

Campus, Institute of Modern Physics, CAS
Nanchang Rd 509, Lanzhou 730000, China

Organizing Committee: X. Ma, X. L. Zhu, X. Cai, X. M. Chen, C. Z. Dong, D. C. Zhang, G. Q. Xiao, T. Stöhlker, R. Schuch

Program of the SPARC -Collaboration

Scientific Goal:

Precision Studies of the Quantum Dynamics of Exotic Atomic Systems in Extreme Fields

Discovery Potential:

- new concepts for QED in extreme fields
- insight into the correlated many-body dynamics via ultrashort and super intense field pulses (<10^{-18} s)
- precision determination of fundamental constantes (α, m_e)
- proof of fundamental symmetries

Observables:

high-resolution x-ray, electron, positron, projectile and recoil-ion spectroscopy

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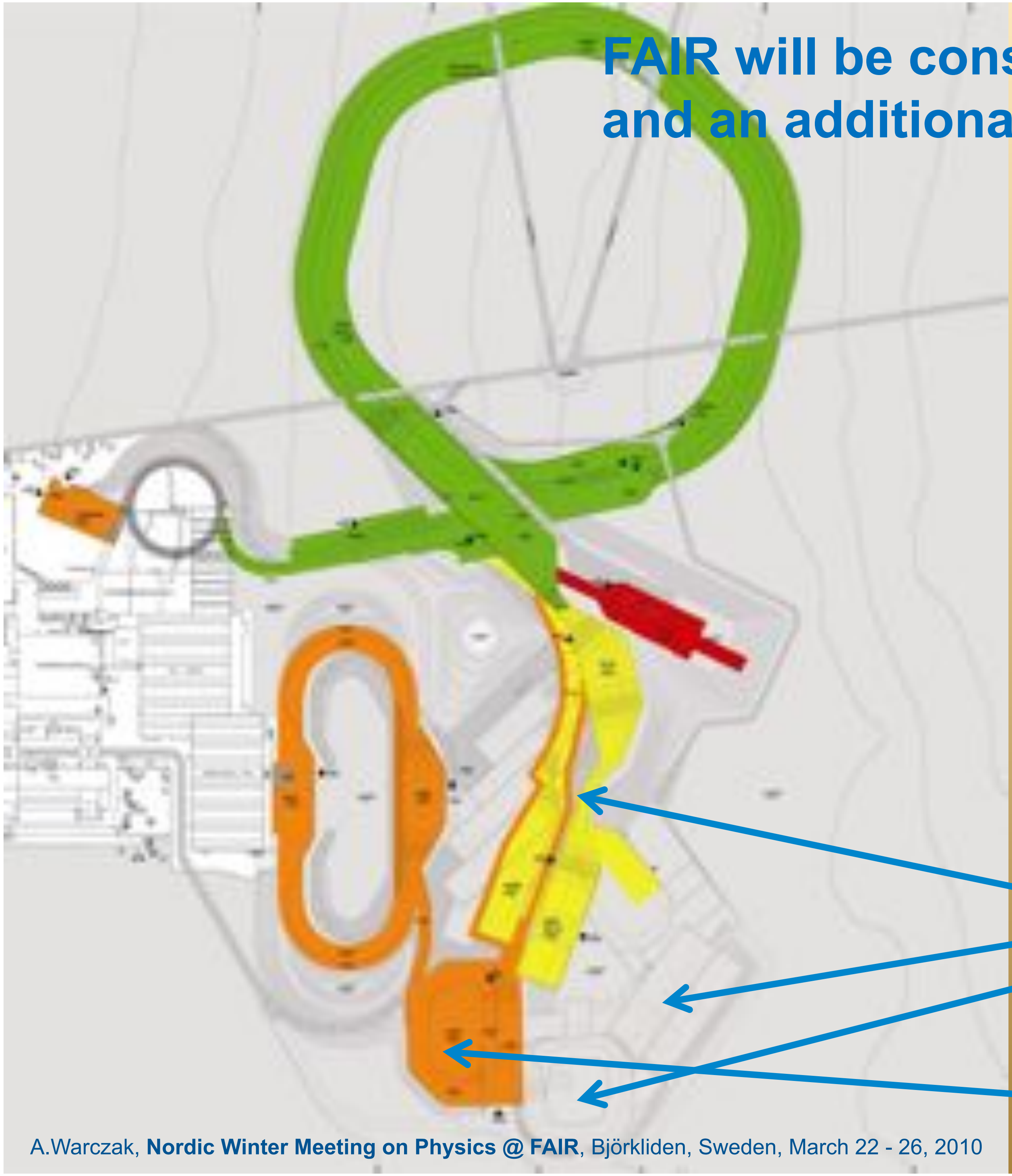
SPARC is Organized within 13 Working Groups

- Charge Separator/Relativistic Collisions
- Reaction Microscope
- Electron and Electron/Positron Spectrometers
- Photon and X-Ray Spectrometers
- Detector Development
- Target Developments (in ring)
- Electron Cooler/Target
- Low Energy Setups
- Traps/HITRAP
- Ion Sources
- Laser Spectroscopy/Laser Cooling
- Intense Laser/Ion Interaction
- Theory

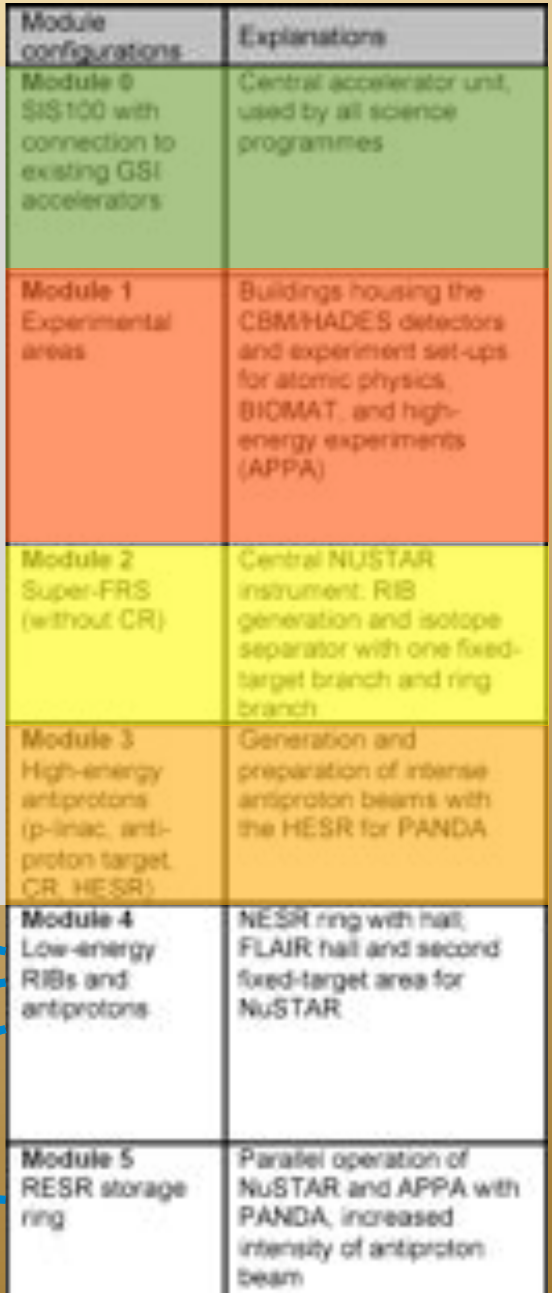
Responsible Working Groups	Work Packages (WP)
High Energetic Ion-Atom Collisions	(WP 2.1) Cave for High-Energy (< 10 GeV/u) Atomic Physics (WP 2.2) Resonant Coherent Excitation (WP 2.3) Pair Production
Reaction Microscope	(WP 3.9) Large Solid Angle Spectrometer for Recoil Ions and Electrons (WP 3.10) Imaging Fast Forward Electron Spectrometer (WP 4.3) Reaction Microscope for Slow-HCI
Electron and	ctrons
Photon and X	
Photon Detect	-rays (WP 4.5) X-ray Studies
Target Developments (in ring)*	(WP 3.2) Dense H_2/He Internal Jet Target (WP 3.12) Infrastructure NESR
Electron Cooler/Target	(WP 3.1) Electron Target (WP 3.12) Infrastructure NESR
Low Energy Setups	(WP 4.1) Low-Energy Cave (WP 4.4) Ion-Surface Interaction Experiments
Traps/HITRAP	(WP 4.2) HITRAP Facility (WP 4.6) g-Factor Measurements (WP 4.7) Mass Measurements (WP4.8) Laser Experiments
Ion Sources	(WP 4.1) Low-Energy Cave (WP 4.2) HITRAP
Laser Spectroscopy/Laser Cooling	(WP 1.1) Laser Cooling

First Technical Design Reports are in preparation and will be submitted in 2010

FAIR will be constructed in 6 modules and an additional phase B (SIS 300)



Start Version



Module configurations	Explanations
Module 0 SIS100 with connection to existing GSI accelerators	Central accelerator unit, used by all science programmes
Module 1 Experimental areas	Buildings housing the CBM/HADES detectors and experiment set-ups for atomic physics, BIOMAT, and high-energy experiments (APPA)
Module 2 Super-FRS (without CR)	Central NUSTAR instrument: RIB generation and isotope separator with one fixed-target branch and ring branch
Module 3 High-energy antiprotons (p-linac, anti-proton target, CR, HESR)	Generation and preparation of intense antiproton beams with the HESR for PANDA
Module 4 Low-energy RIBs and antiprotons	NESR ring with hall, FLAIR hall and second fixed-target area for NuSTAR
Module 5 RESR storage ring	Parallel operation of NuSTAR and APPA with PANDA, increased intensity of antiproton beam

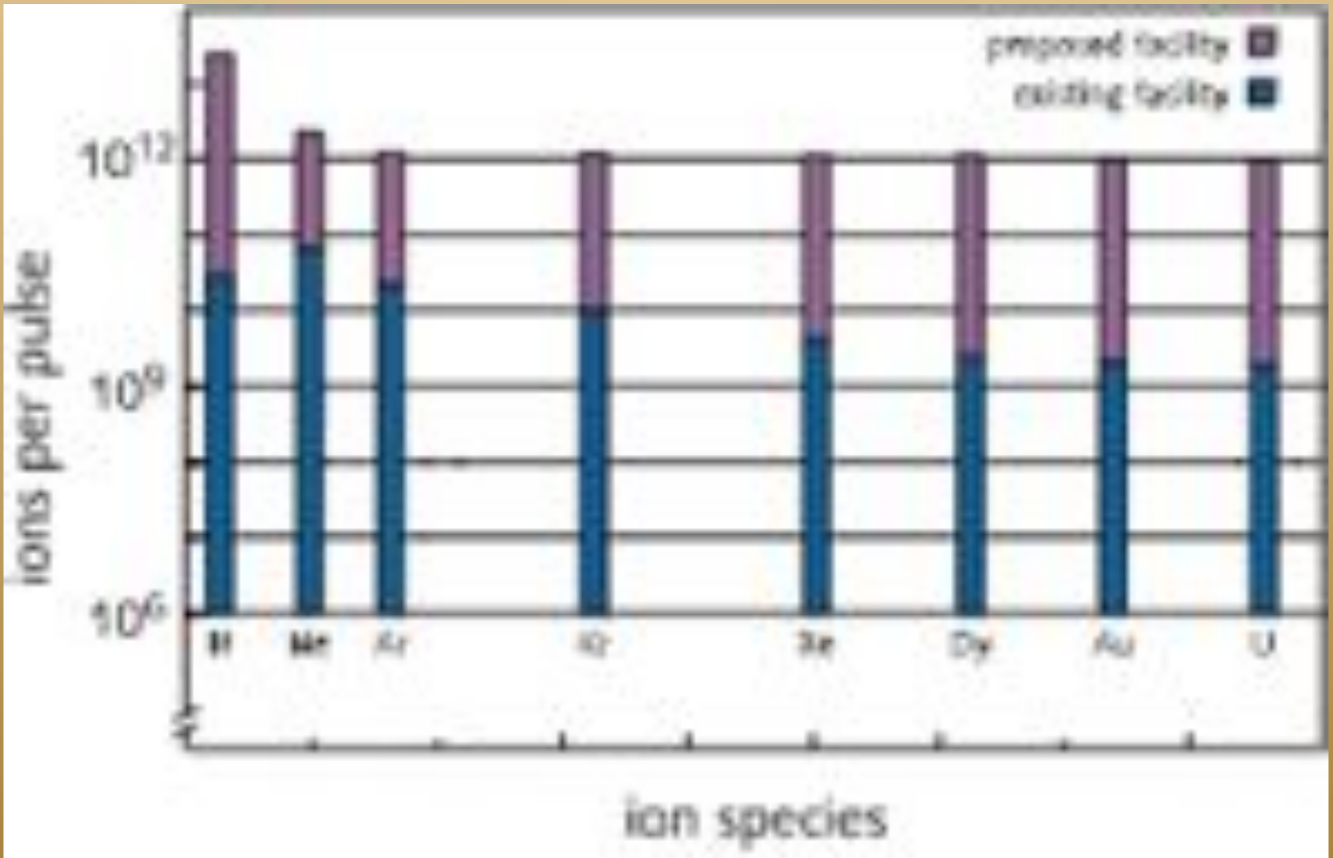
SPARC experimental areas

All the developments within SPARC concentrate on storage rings and traps, and will become fully possible with Module 4.

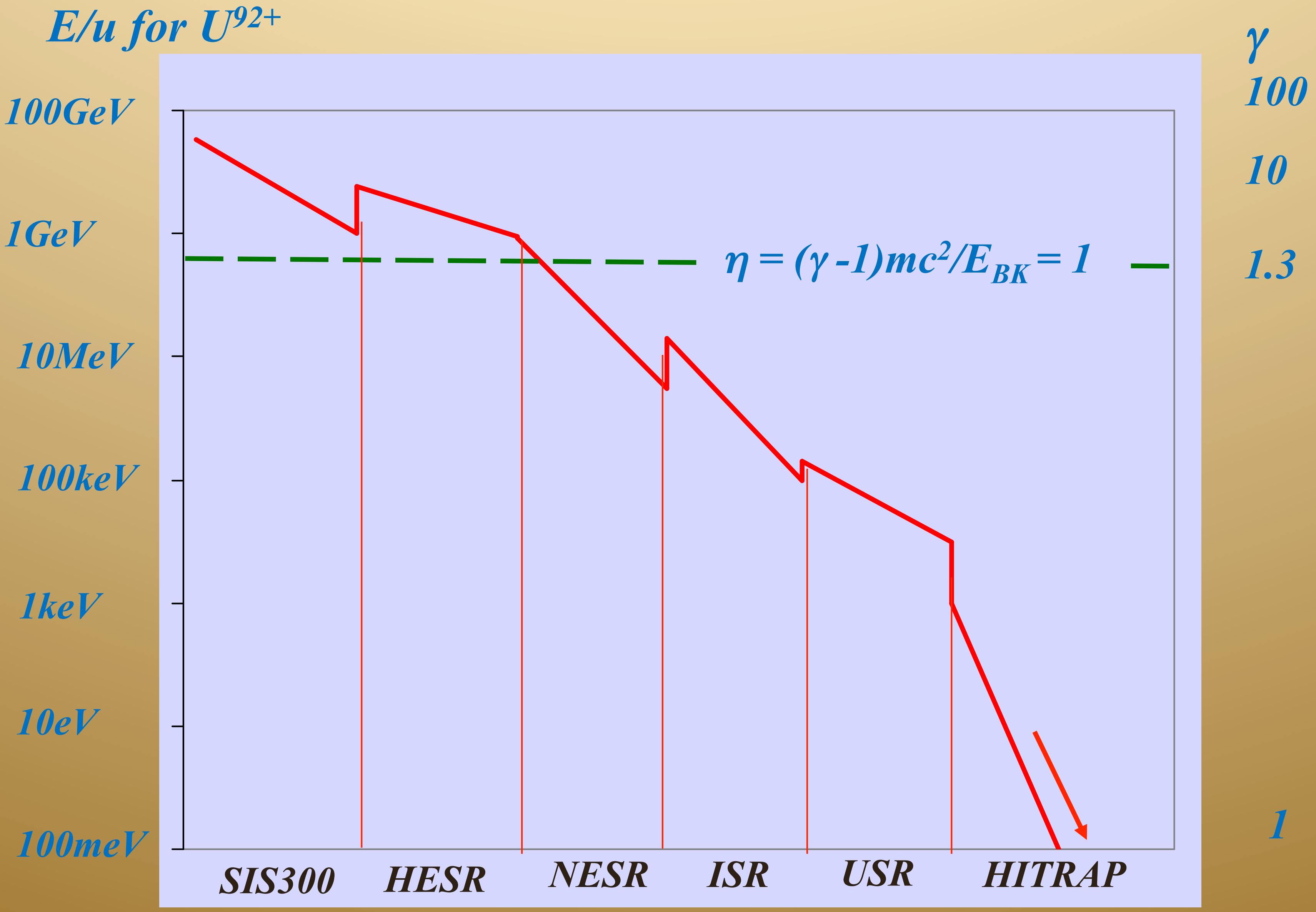
For the realization of this programme the ESR storage ring and the HITRAP need to be maintained in operation at GSI until they shall be surpassed by Module 4.

FAIR will offer worldwide unique accelerator and experimental facilities, in particular, characterized by:

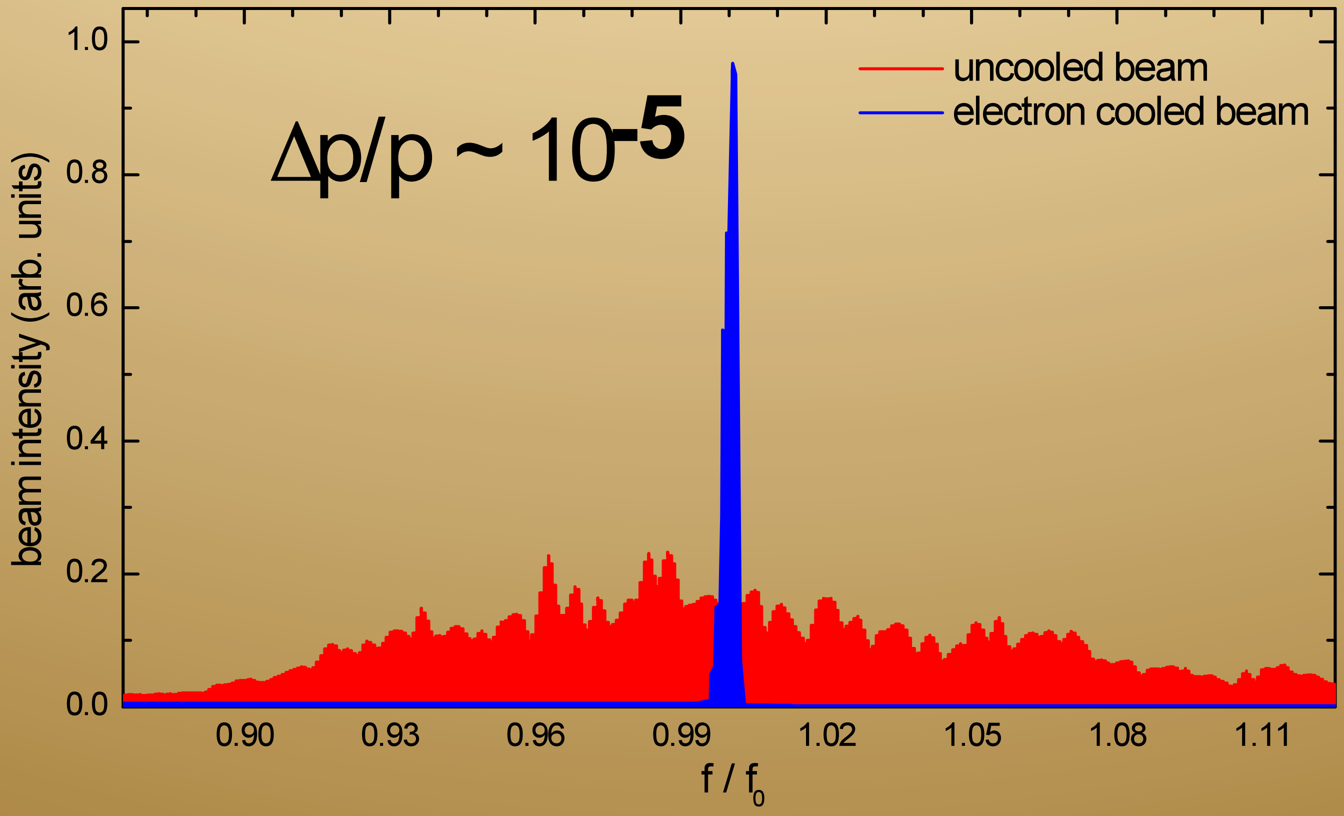
A very broad range of ion species with possibly highest intensities
(up to 10^{14} particles per pulse)



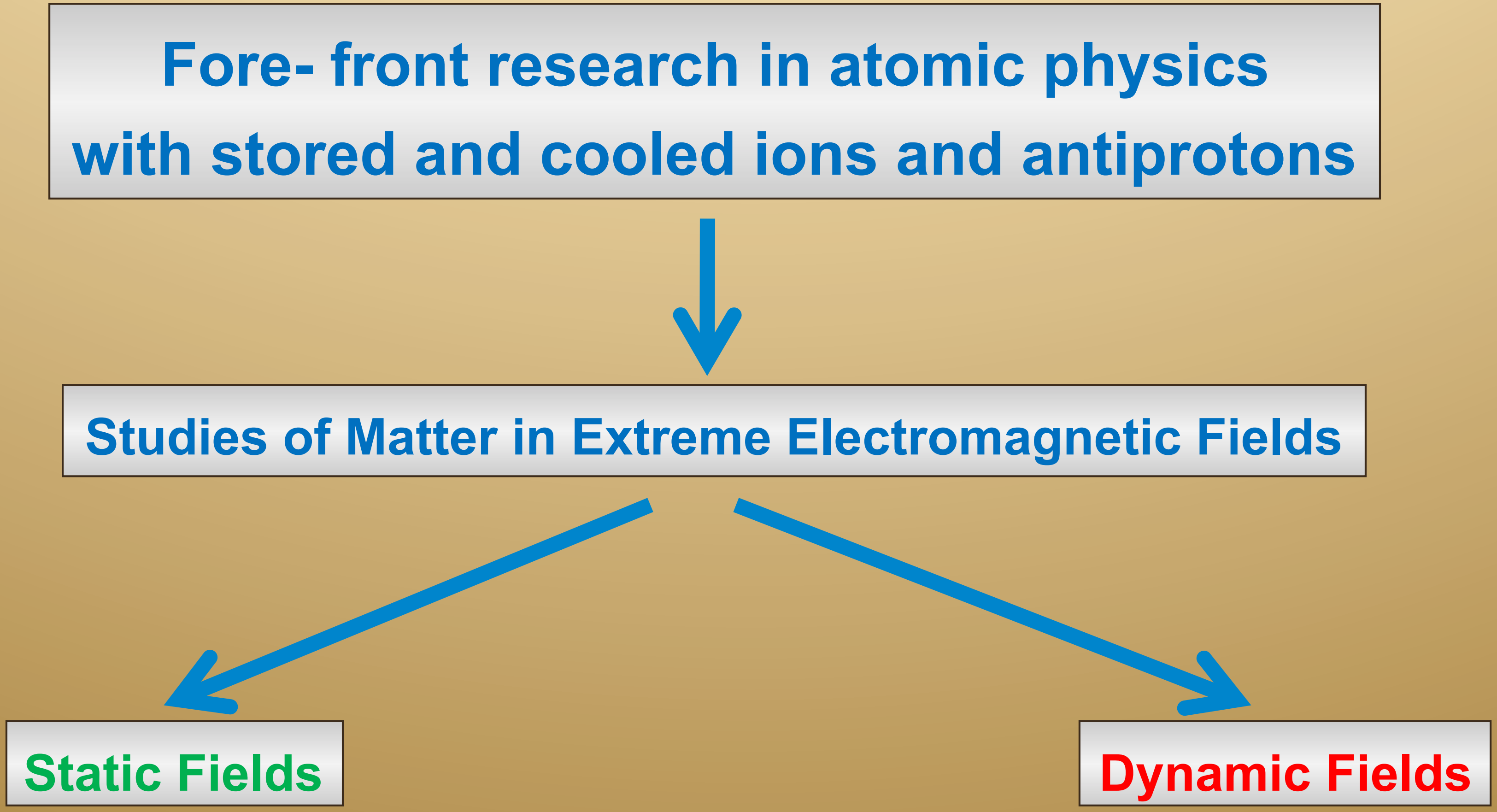
A very broad range of ion energies: 30 GeV/u → rest



Unique beam quality concerning momentum spread (beam cooling)



SPARC will profit from these unique beam properties and proposes:



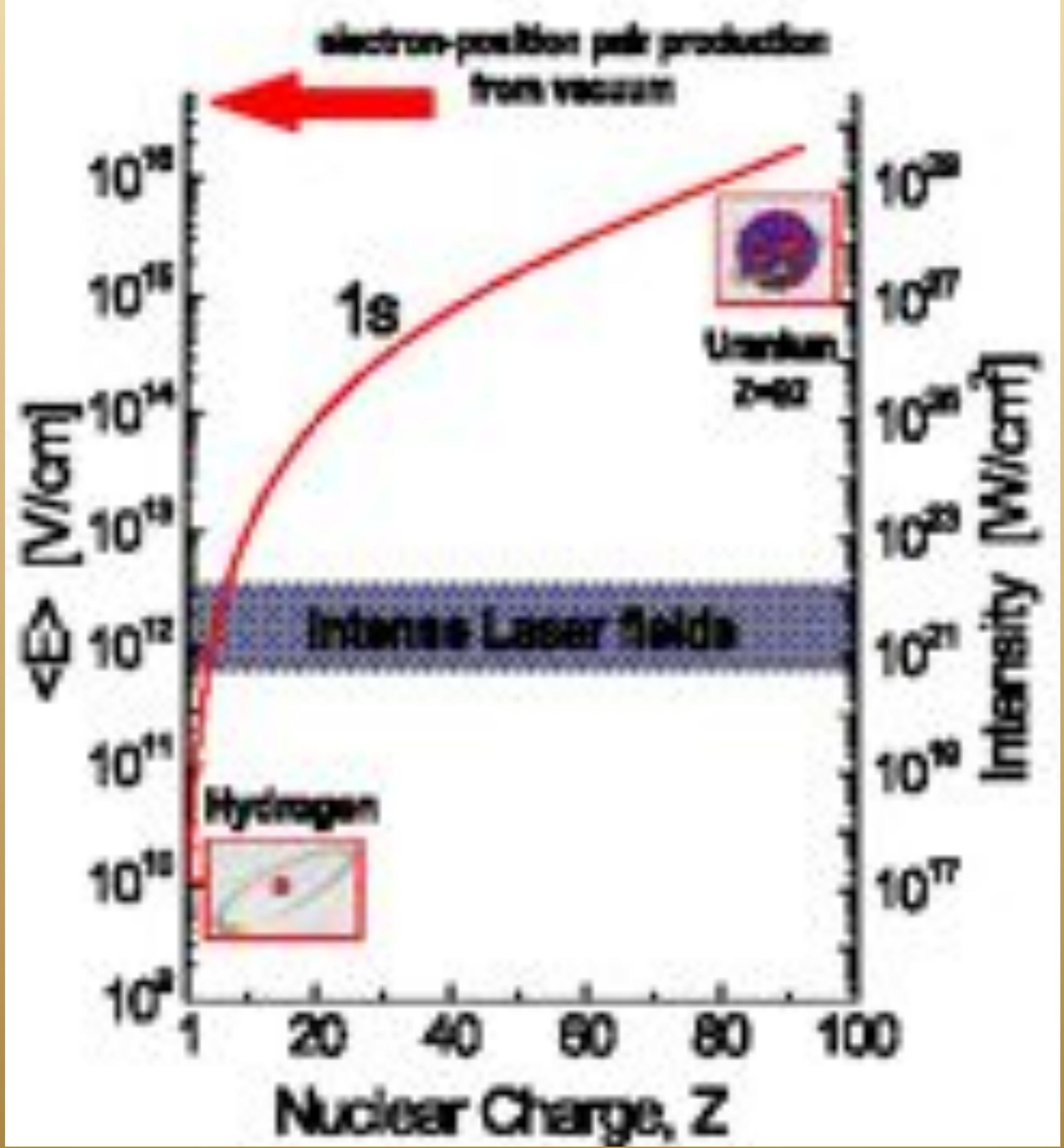
Fore- front research in atomic physics with stored and cooled ions and antiprotons

Studies of Matter in Extreme Electromagnetic Fields

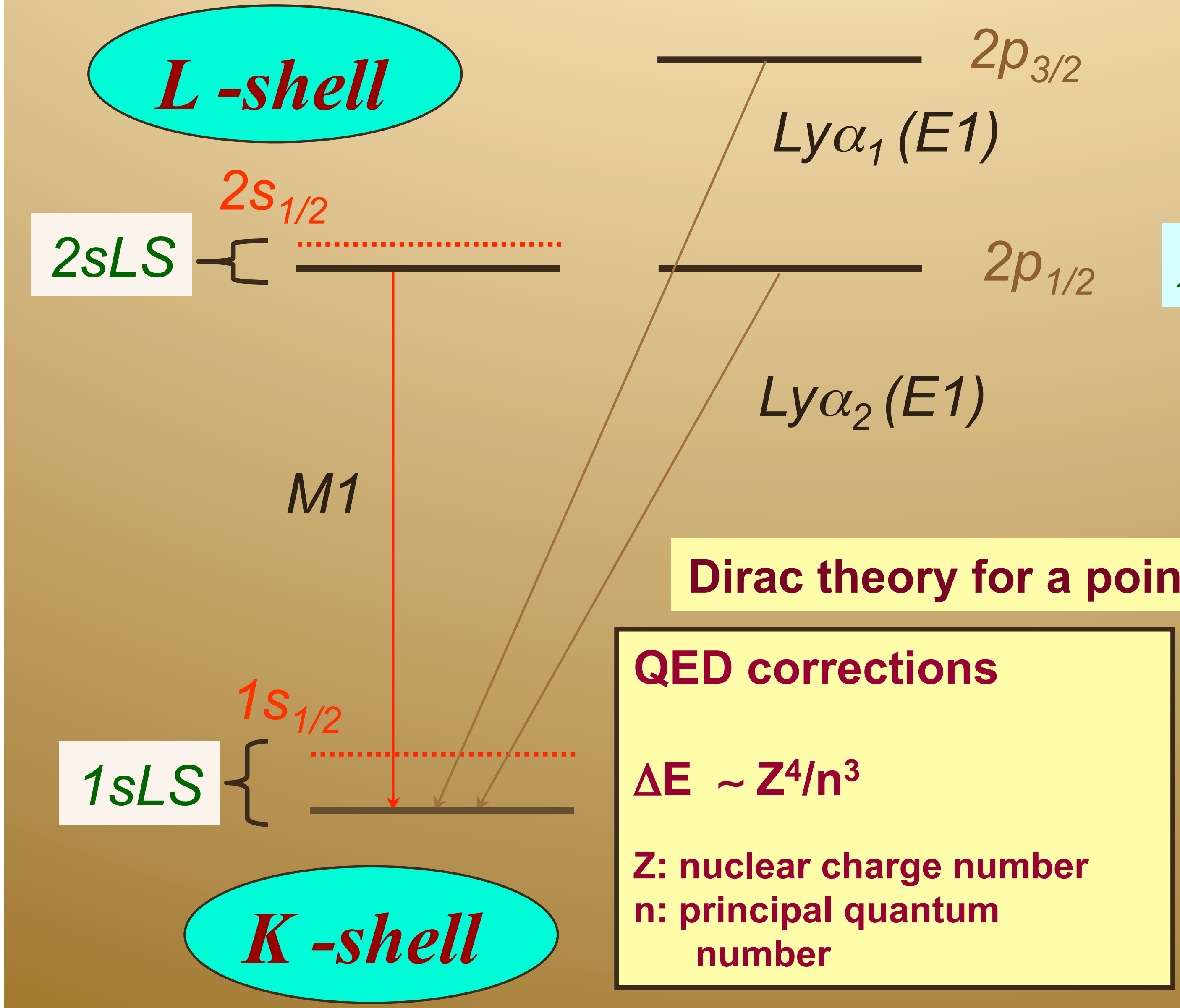
Static Fields

Dynamic Fields

Heavy ions: Huge static fields but of microscopic dimension



Flag- ship experiment: Structure of one-electron systems



$\Delta E_{LS} = 4.3\ \mu eV$

Dirac theory for a point-like nucleus

QED corrections

$\Delta E \sim Z^4/n^3$

Z: nuclear charge number
n: principal quantum number

$\Delta E_{LS} = 34\ \mu eV$

Bound-State QED: 1s Lamb Shift

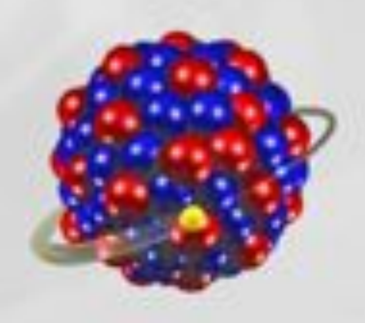
Sum of all corrections, leading to deviations from the Dirac theory for a point like nucleus

U^{92+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

$$\Delta E = \alpha/\pi\ (\alpha Z)^4\ F(\alpha Z)\ m_e c^2$$

Low-Z regime: $\alpha Z \ll 1$

$F(\alpha Z)$: series expansion in αZ

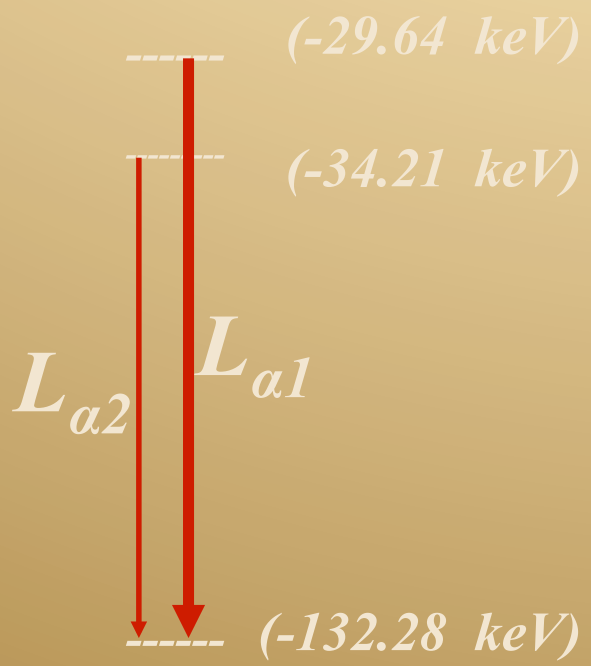


High Z-Regime: $\alpha Z \approx 1$

$F(\alpha Z)$: series expansion in αZ
not appropriate

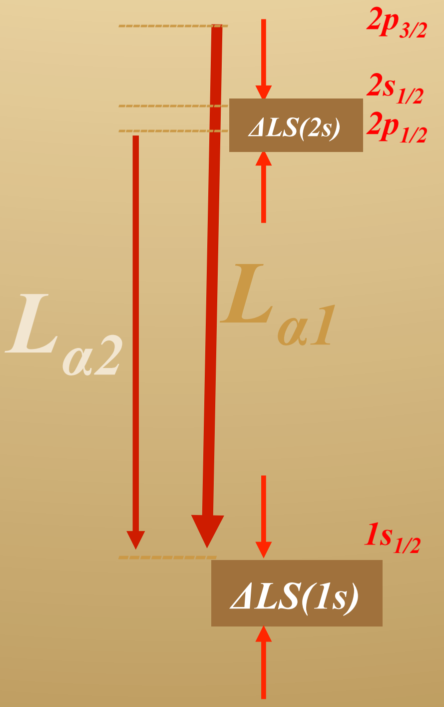
Hydrogen–like Uranium (U^{91+})

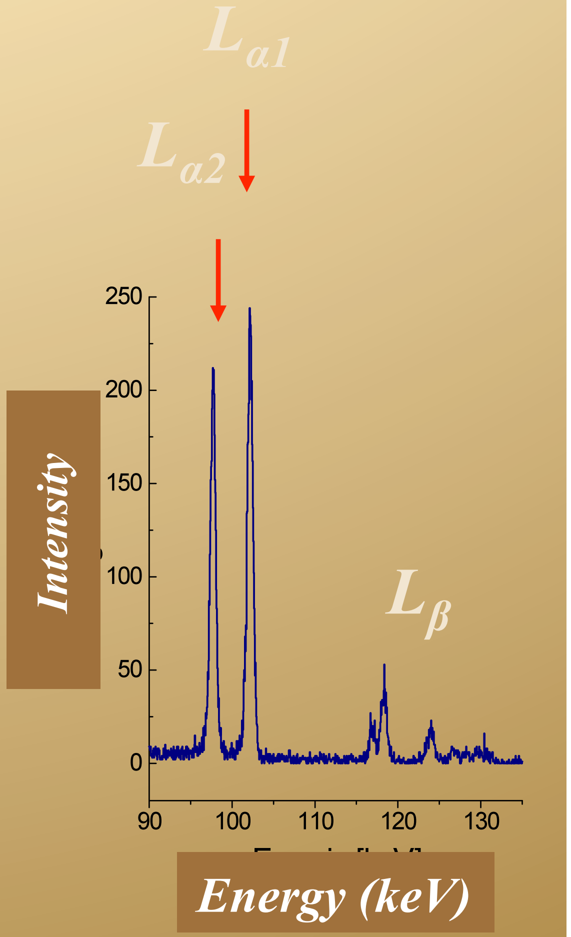
Dirac



QED

ΔLS(2s) = 58 eV

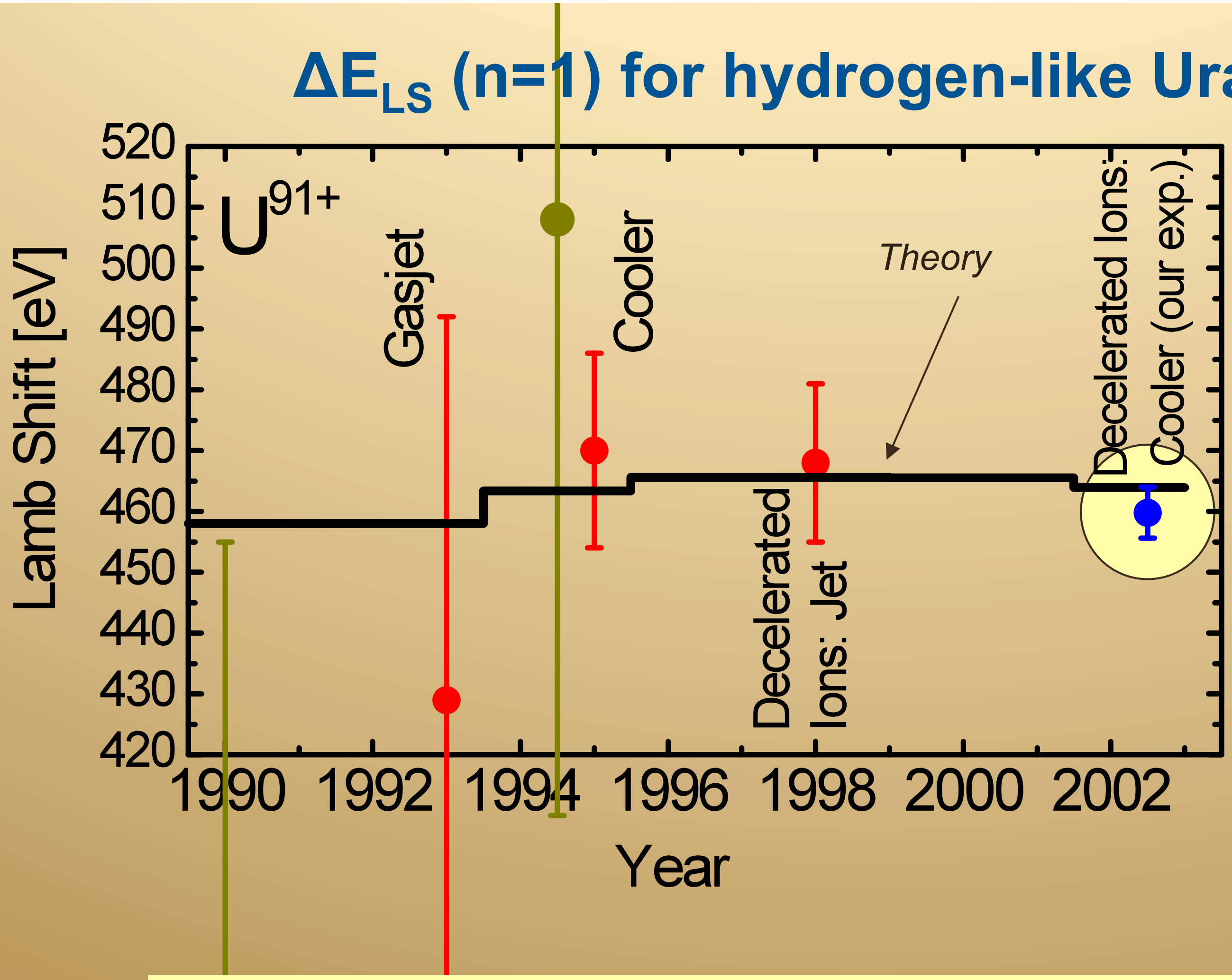




Theory: 463,95 ± 0,50 eV

V. A. Yerokhin and V. M. Shabayev, Phys. Rev. A64, 062507 (2001)

ΔE_{LS} (n=1) for hydrogen-like Uranium



Experiment: 460.2 ± 4.6 eV

A. Gumberidze et al. Phys. Rev. Lett. 94, 223001 (2005)

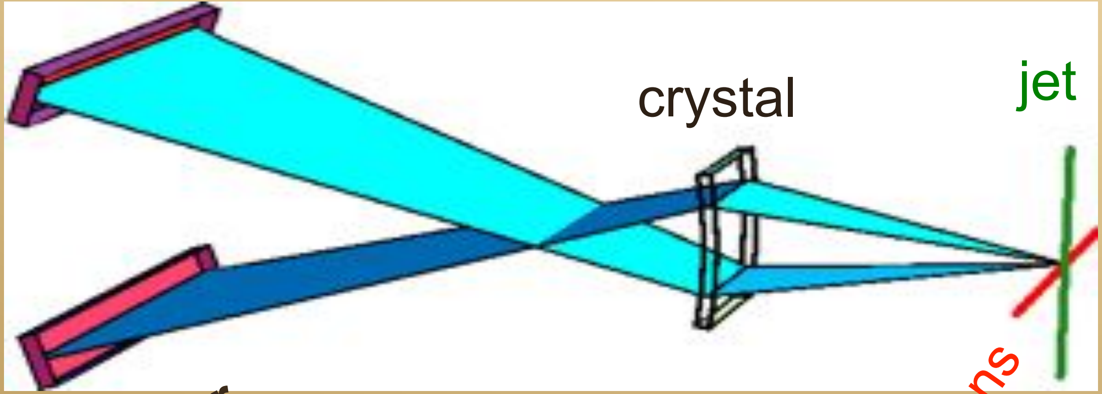
Th. Stöhlker et al.: *Quantum Electrodynamics in Extreme Fields: Precision Spectroscopy of High-Z H-like Systems*, Lect. Notes Phys. **745**, 157–163 (2008)

Solution of the experimental problem

towards an accuracy of 1 eV

Bragg-Laue relation

$$\boxed{n \cdot \lambda = 2 \cdot d \cdot \sin\theta}$$



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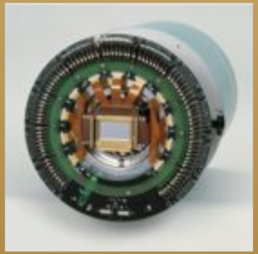
FOCAL

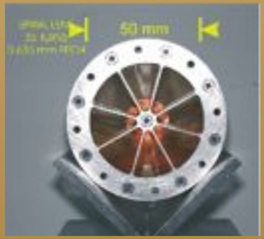
H.F. Beyer et al.

Next steps ⟶



Detectors

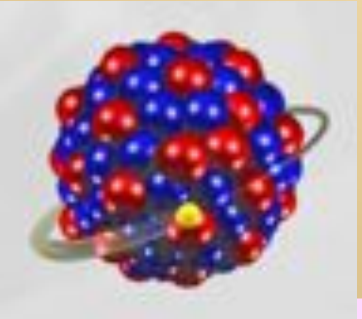
+



Hard X-Ray Optics

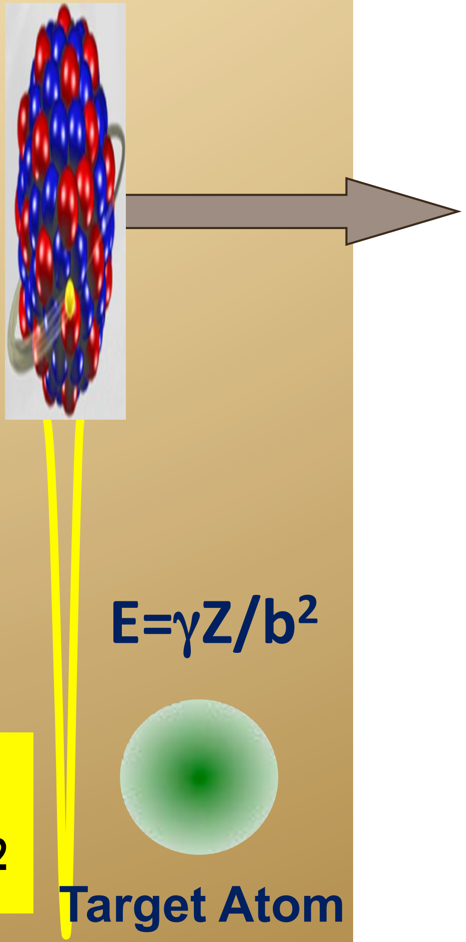
Extreme dynamic fields

Highly charged ion

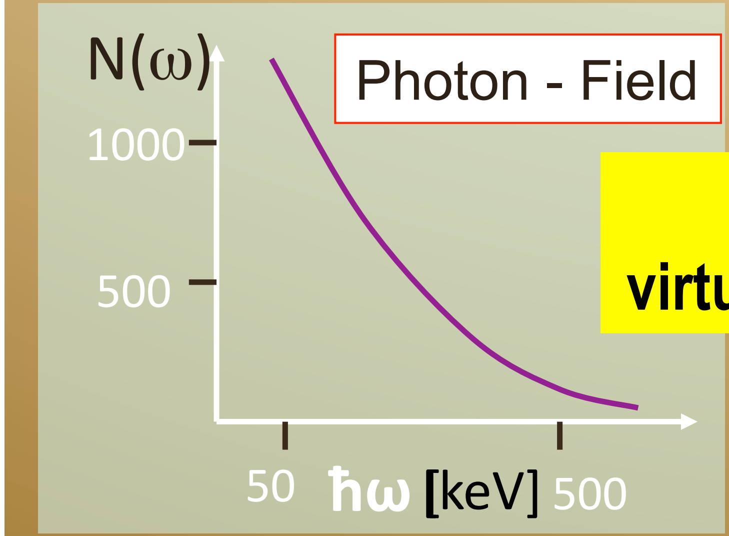


E(t) → Fourier-Transform → Quantization → **N(ω)**

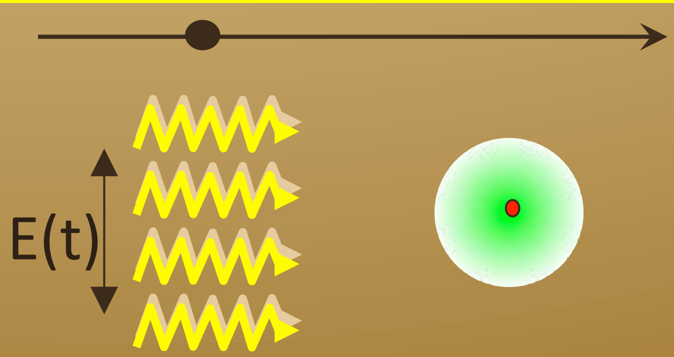
Weizsäcker-Williams (1934)



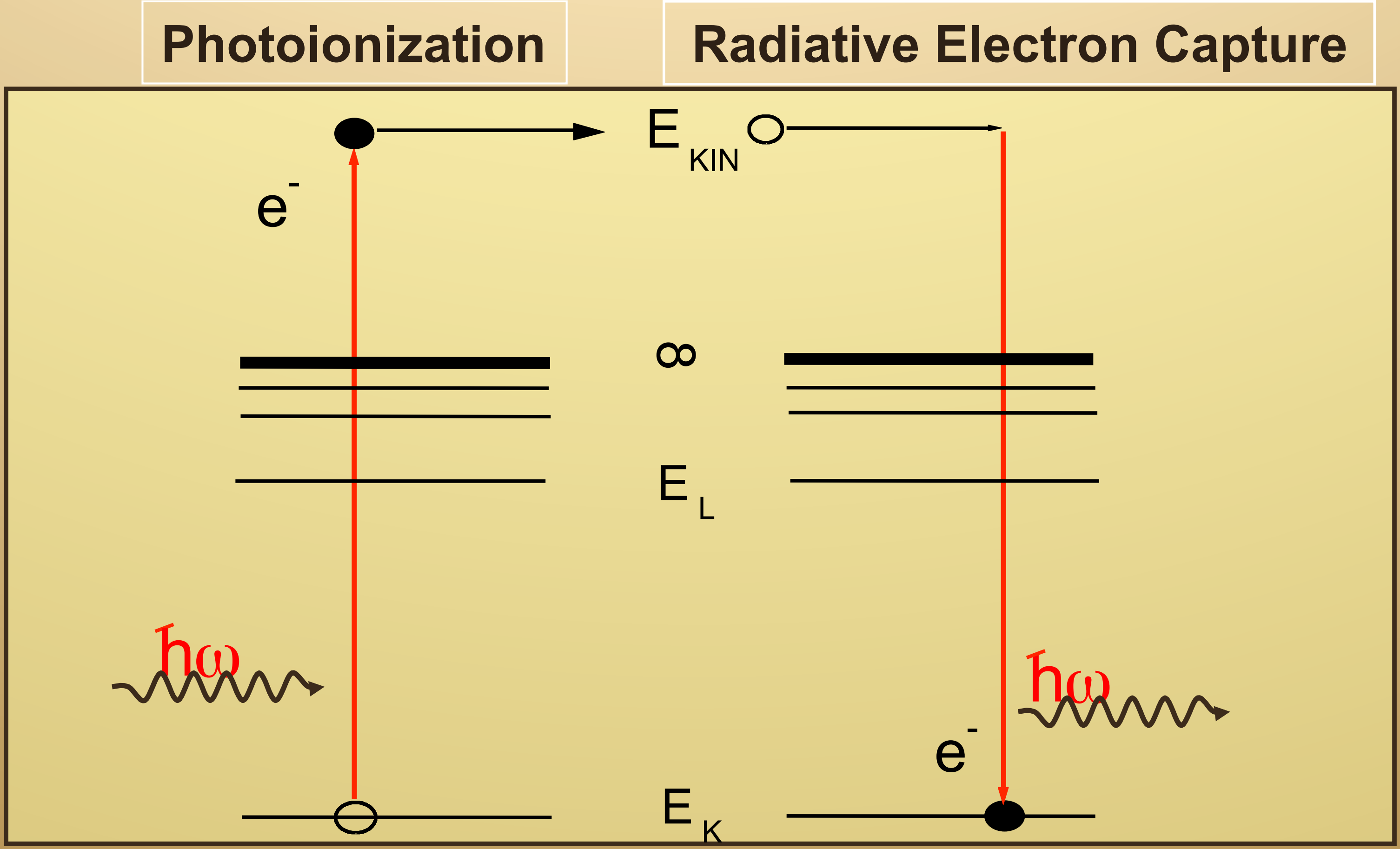
$t \leq 0.1$ as



Atomic processes in strong virtual photon fields with $I \geq 10^{20}$ W/cm^2



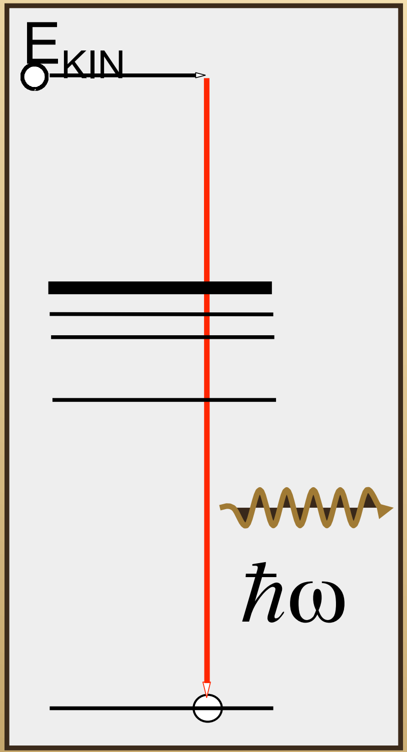
Radiative Electron Capture (REC)

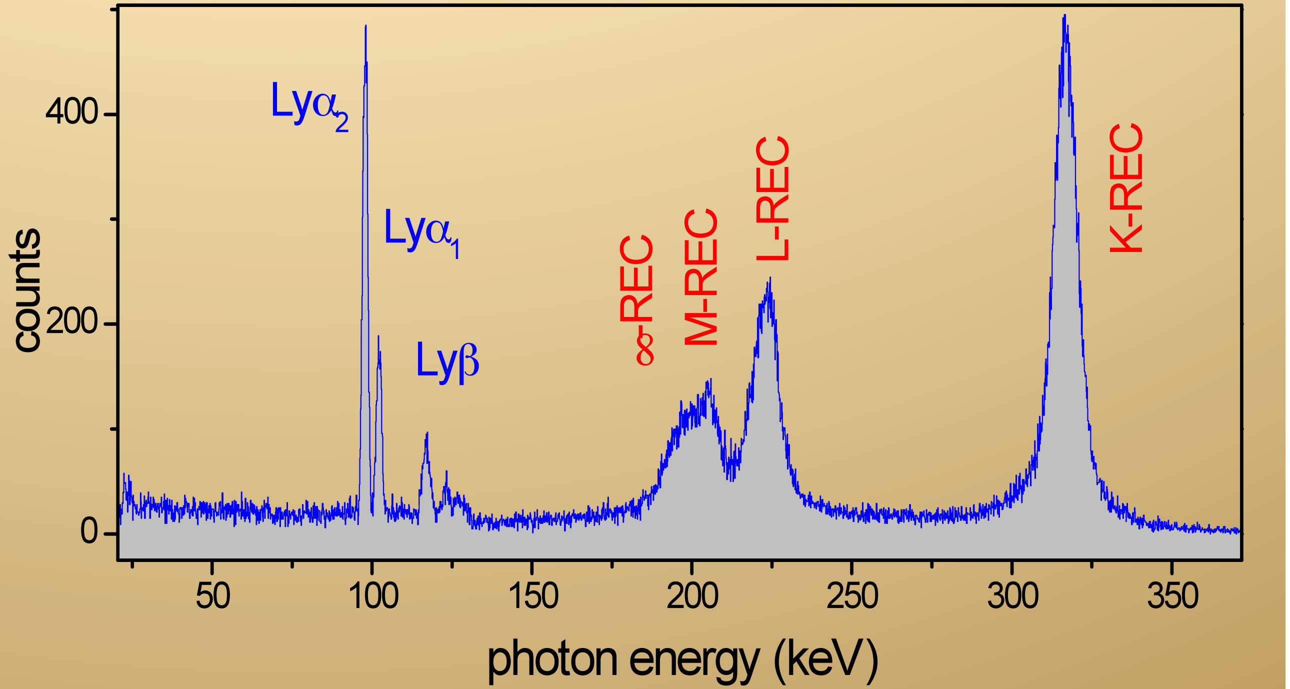


Principle of the detailed balance

$$\sigma_{REC} \cong Z_T \left[\frac{E_{REC}}{\gamma \cdot \beta \cdot mc^2} \right]^2 \sigma_{Ph}$$

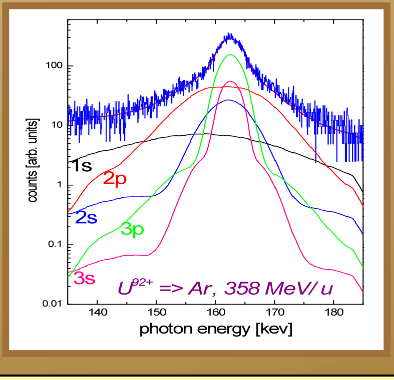
U^{92+} => Ar , 358 MeV/u





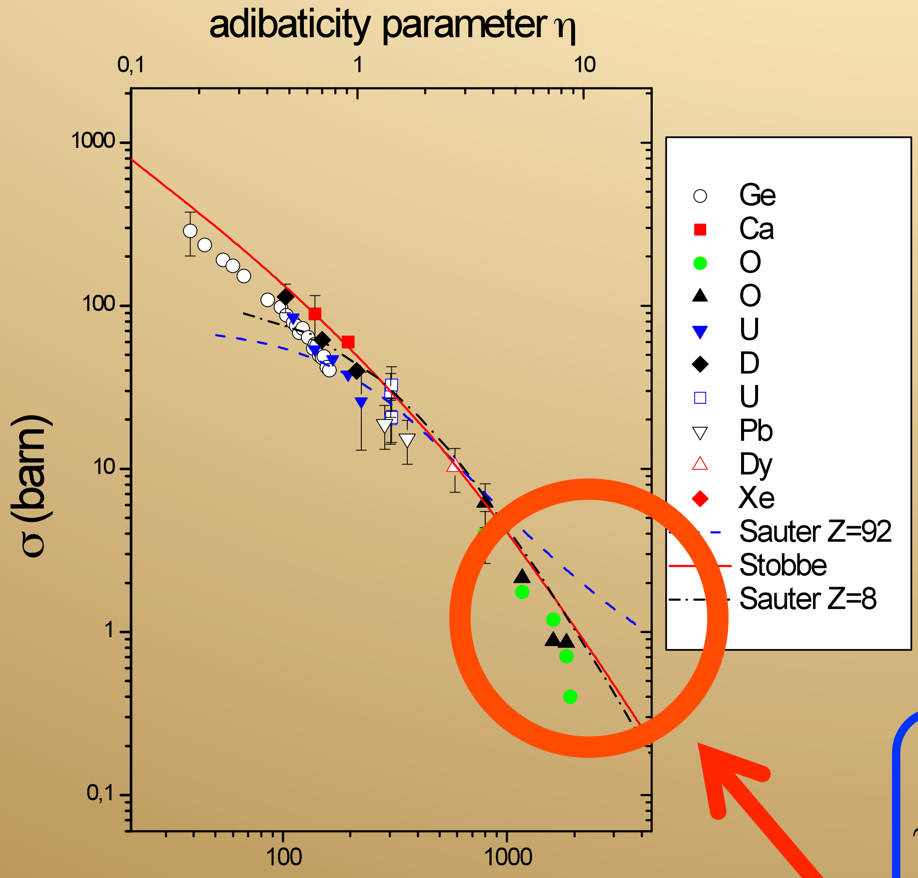
Shape and width of REC lines are determined by the momentum distribution of the target electrons

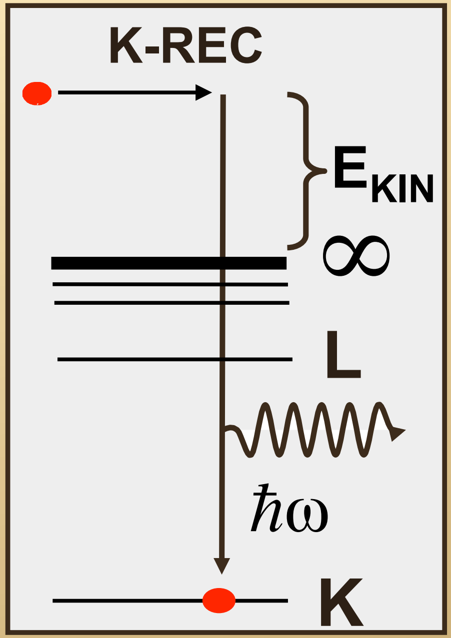
REC photon energy



$$\hbar\omega_{REC} = E_B + m_e c^2 (\gamma - 1) + \gamma (v_i p_z - E_T)$$

$$\sigma_{tot} \approx 1.2 \times \sigma_{K-REC}$$





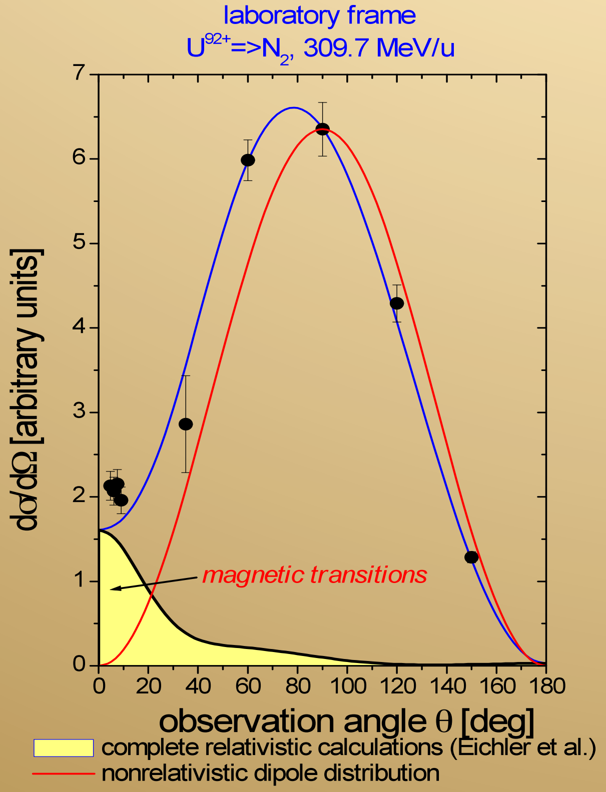
Adiabaticity Parameter

$$\eta = \frac{E_{KIN}}{E_K} \approx 40.32 \times \frac{E_{KIN}^{ION}[\mathrm{MeV/u}]}{Z^2}$$

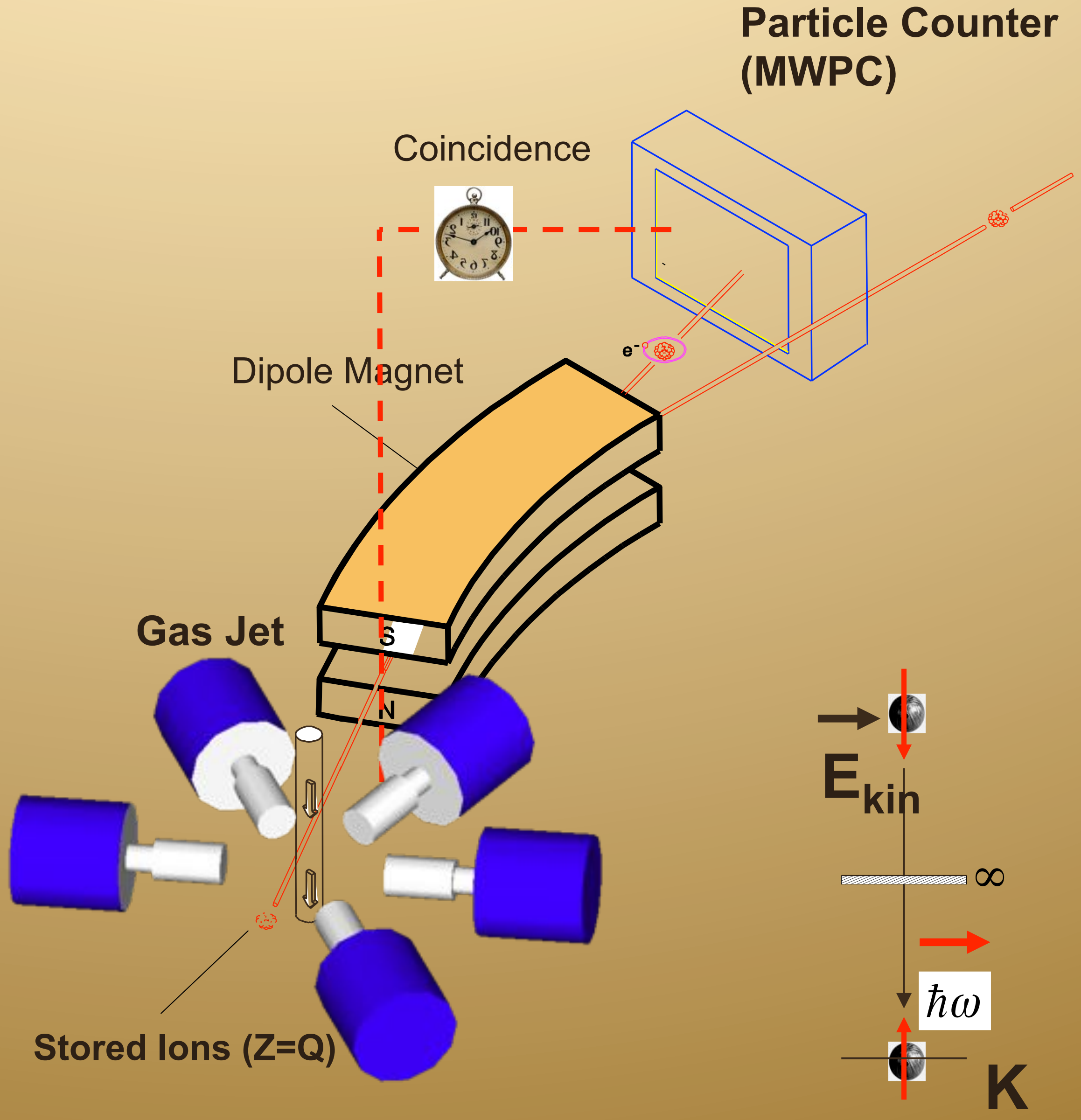
Th. Stöhlker et al., PRA 51 2098 (1995)
J. Eichler and Th. Stöhlker, Phys. Rep. 439, (2007)

FAIR at high energies

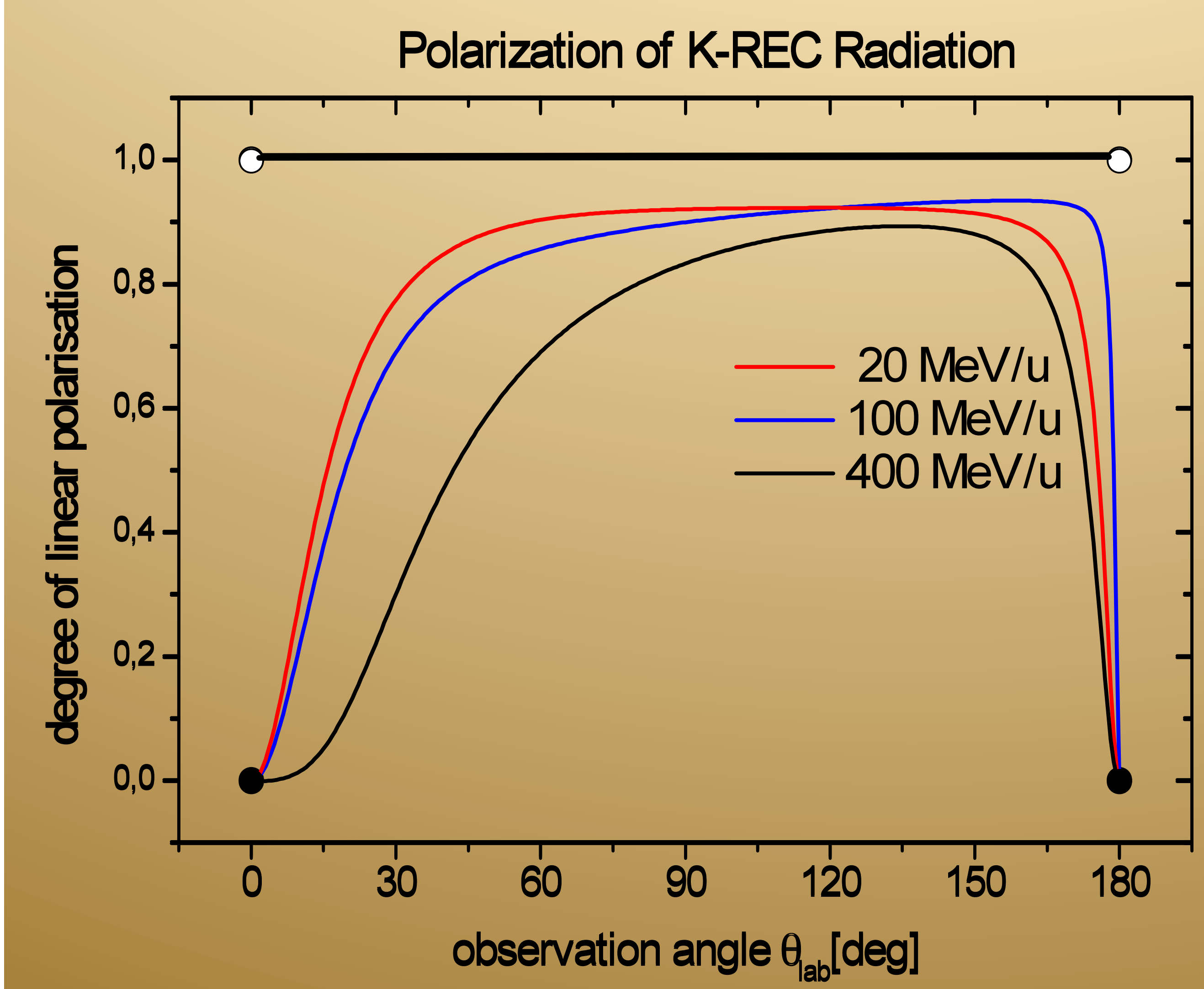
Angular Distributions



Th. Stoehlker et al.



Theoretical predictions for the polarization of K-REC radiation ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)



— non-relativistic dipole approximation

Polarization measurement is a sensitive method to study relativistic contributions to the K-REC process

Theory: S. Fritzsche, A. Surzhykov

Polarization Measurement of REC Photons

v)

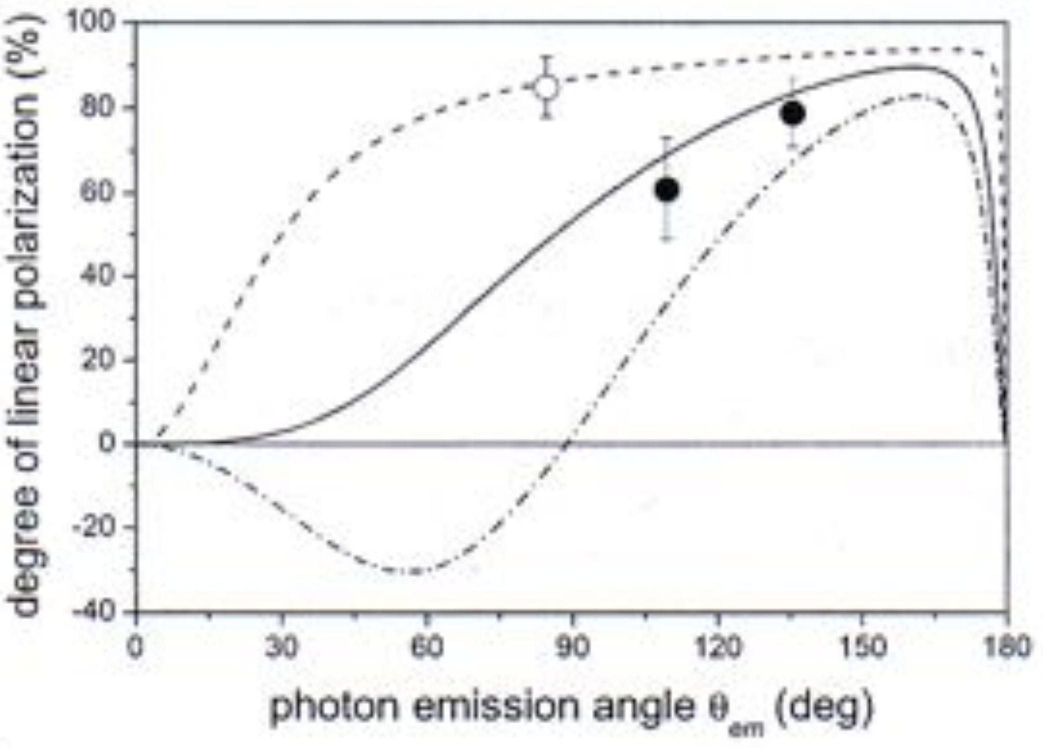
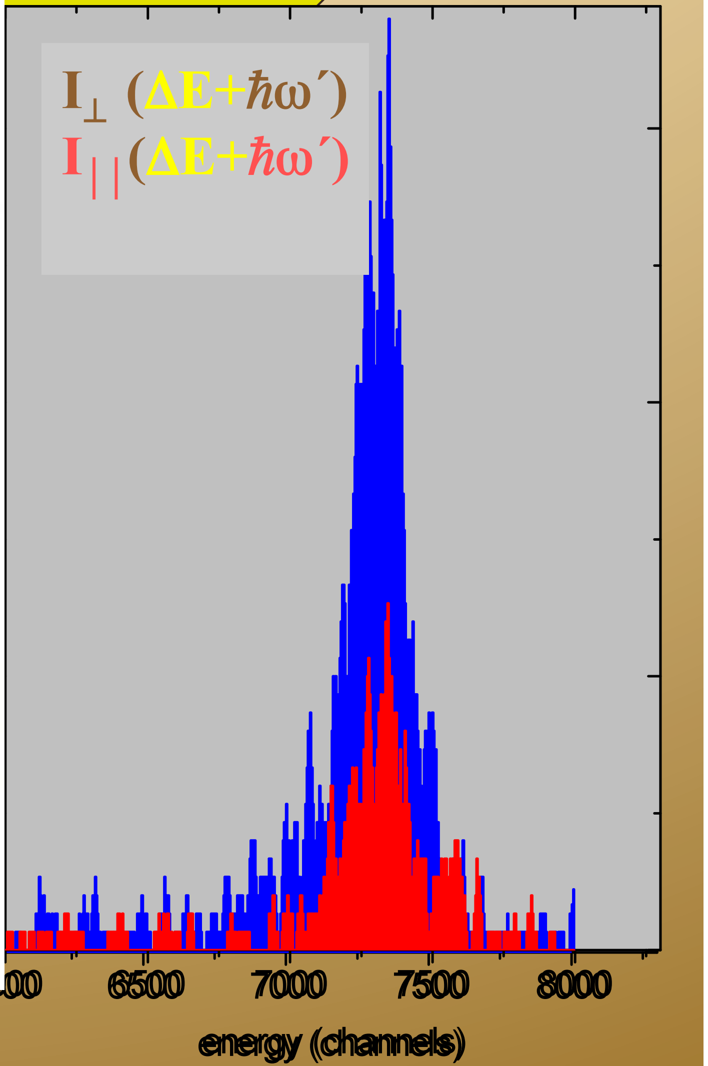
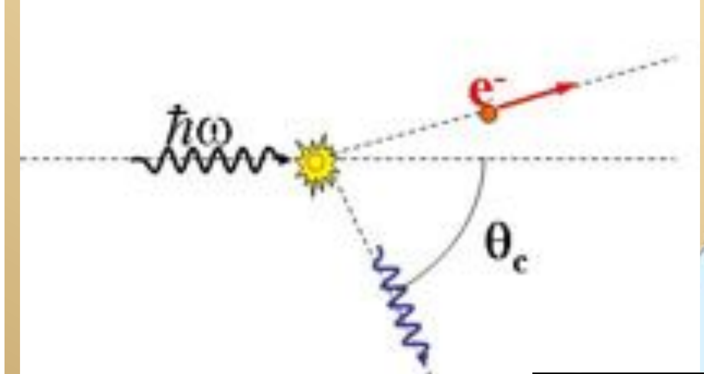


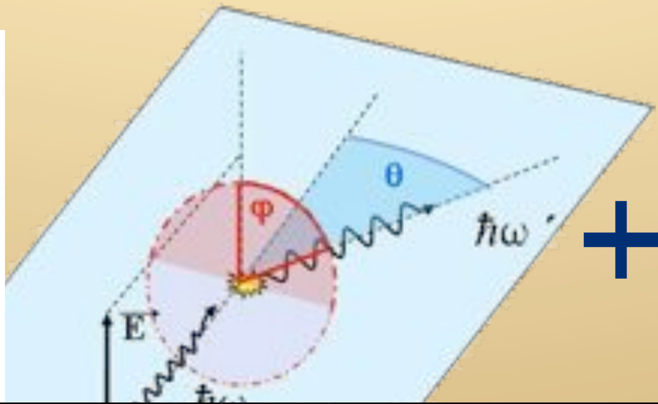
FIG. 4: Linear photon polarization as observed for $U^{92+} \rightarrow N_2$ collisions as function of the photon emission angle (moving system): 400 MeV/u solid circles; 98 MeV/u open circle. For comparison, the results of rigorous relativistic calculations are given: 98 MeV/u dashed line; 400 MeV/u full line; 800 MeV/u dotted line [3–5].



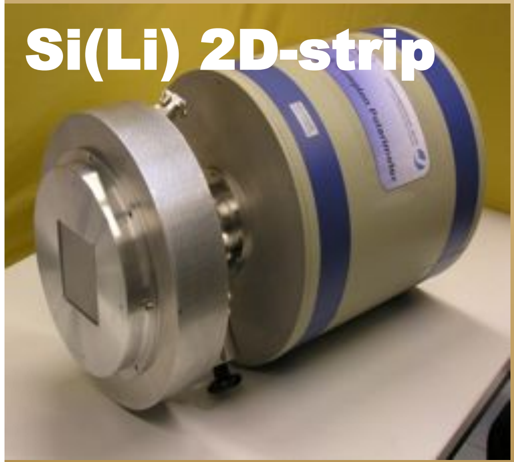
S. Tashenov et al. Phys Rev. Lett. 97, 223202 (2006)

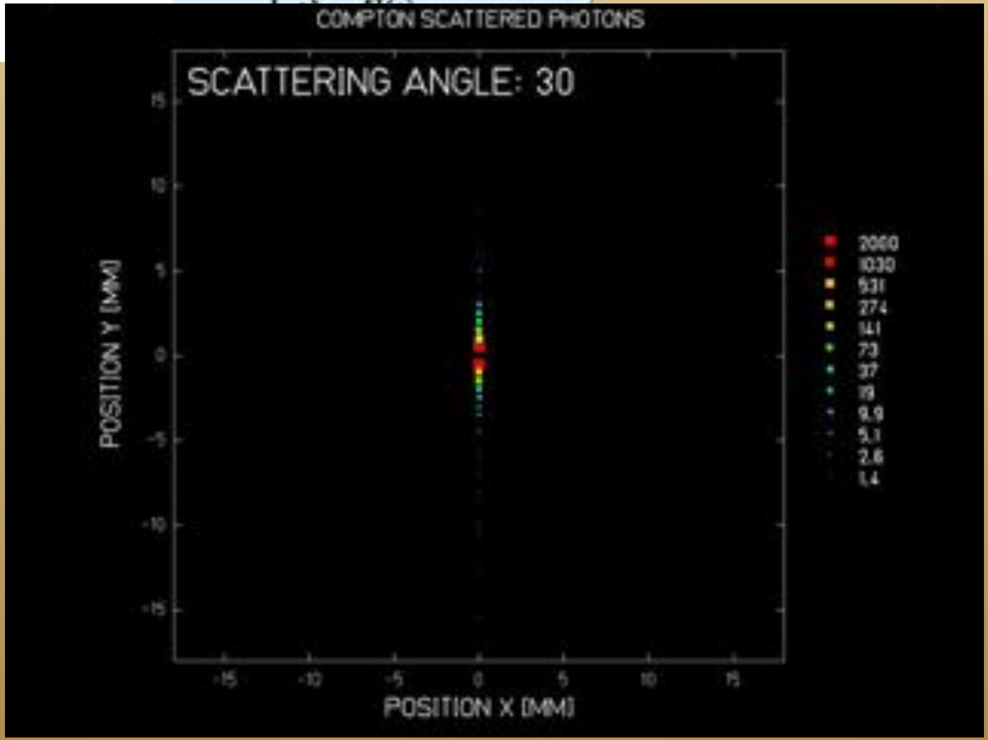
Development of 2D/3D Si(Li) and Ge(i) based Compton polarimeters

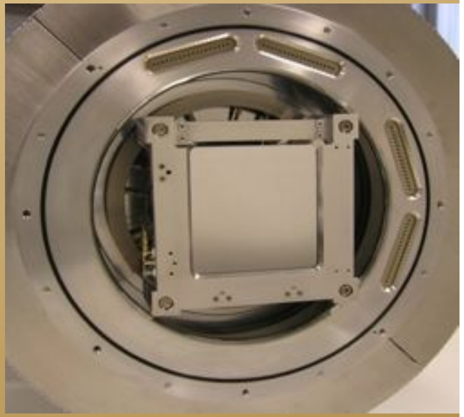


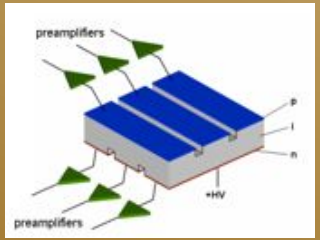


+ **Klein – Nishina formula**









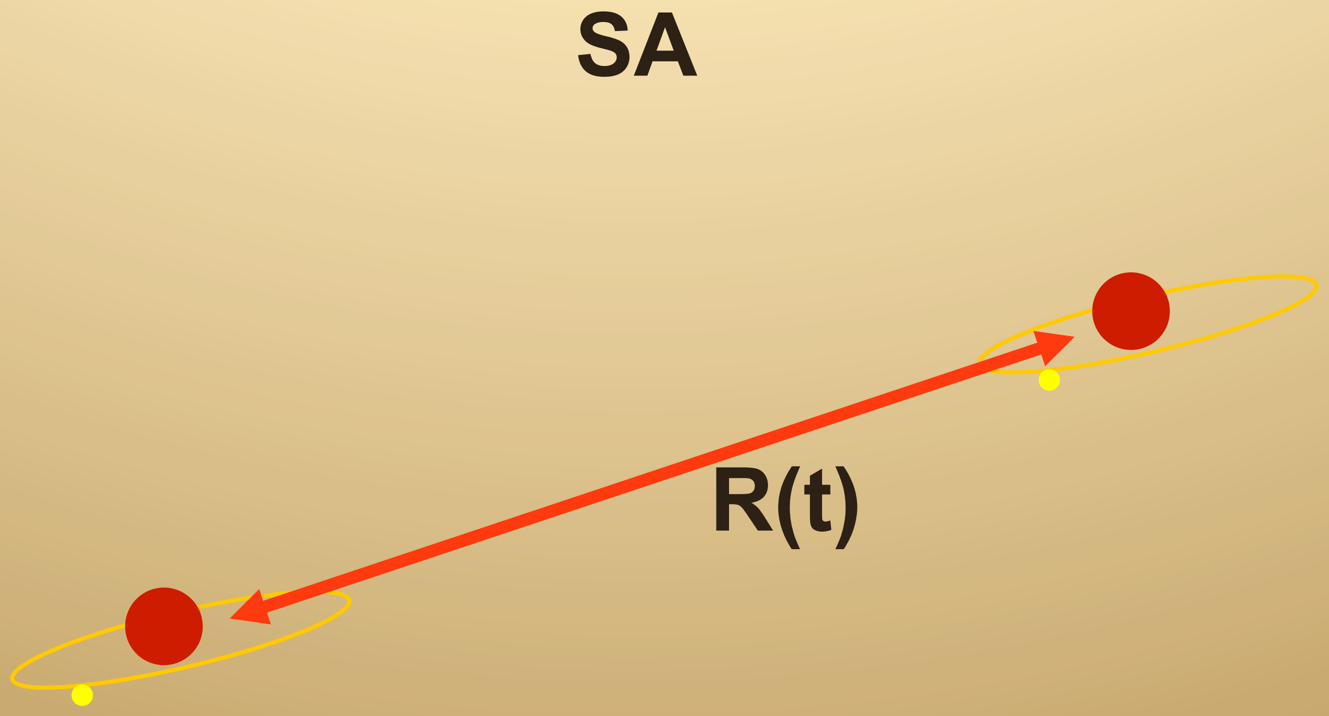
U. Spillmann et al., Rev. Sci. Instr. 79, 083101 (2008)

Slow heavy-ion atom collisions

In slow ion-atom collisions selected electrons are fast enough to adjust their motion to the presence of the other nucleus.
The appropriate basis wave functions could approximate a diatomic **Molecular Orbital** around the projectile and target nucleus

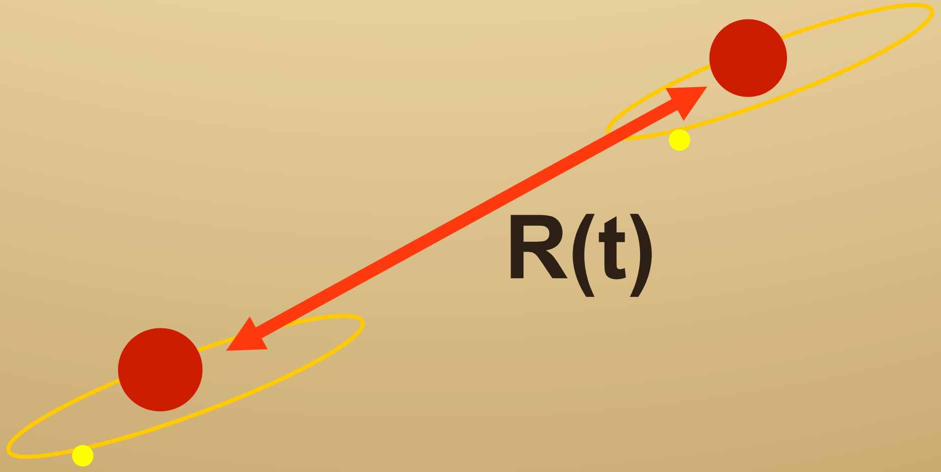
Slow heavy-ion atom collisions

Slow heavy-ion atom collisions

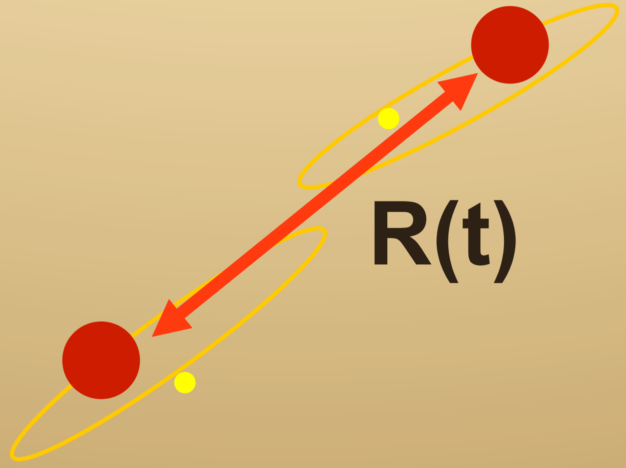


Slow heavy-ion atom collisions

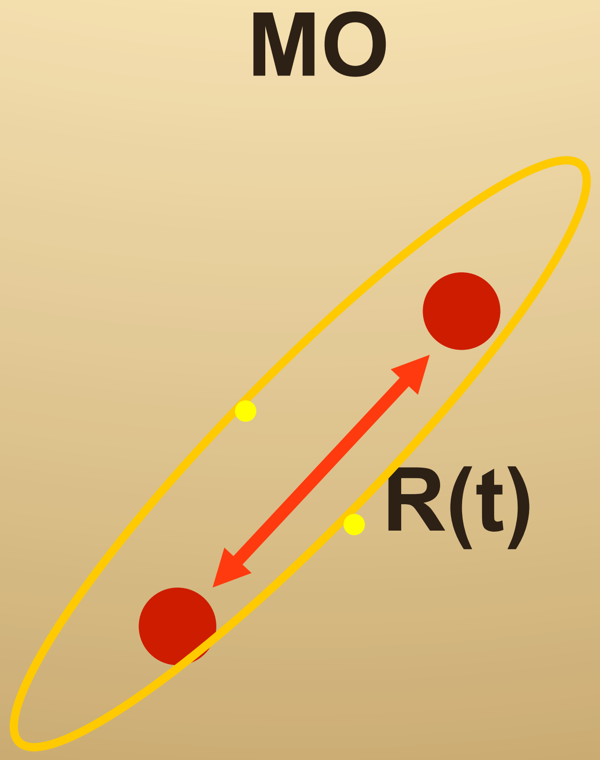
SA



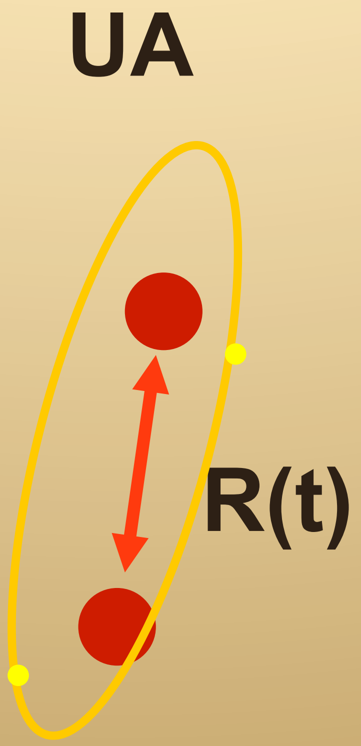
Slow heavy-ion atom collisions



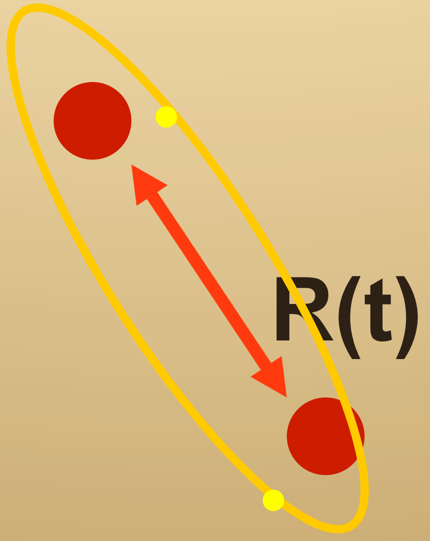
Slow heavy-ion atom collisions



Slow heavy-ion atom collisions

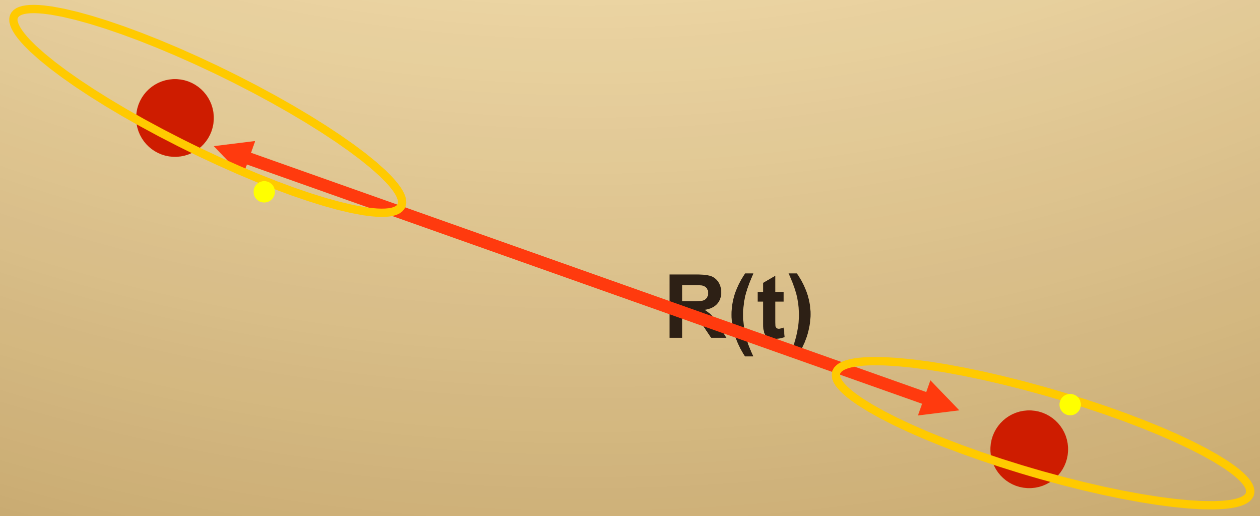


Slow heavy-ion atom collisions



Slow heavy-ion atom collisions

SA



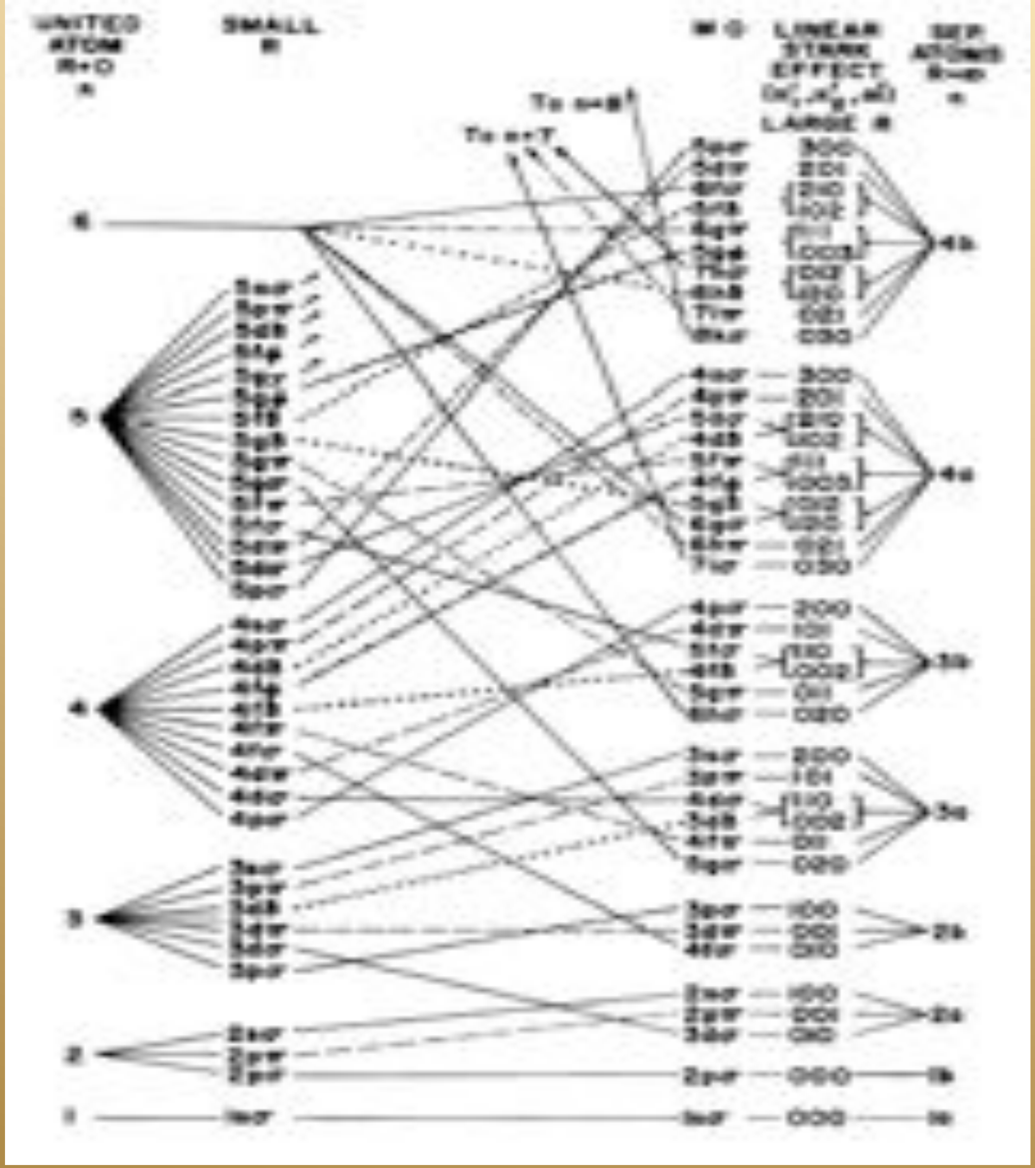
R(t) = **R(**R(t),θ(t)**)** →

$$\frac{\partial}{\partial t} = \dot{R}\frac{\partial}{\partial R} + \dot{\theta}\frac{\partial}{\partial \theta}$$

Radial coupling

Rotational coupling

Correlation diagrams – pathways for electronic transitions



Electron Binding Energy

United Atom

R = 0

R(t)

Separated Atoms

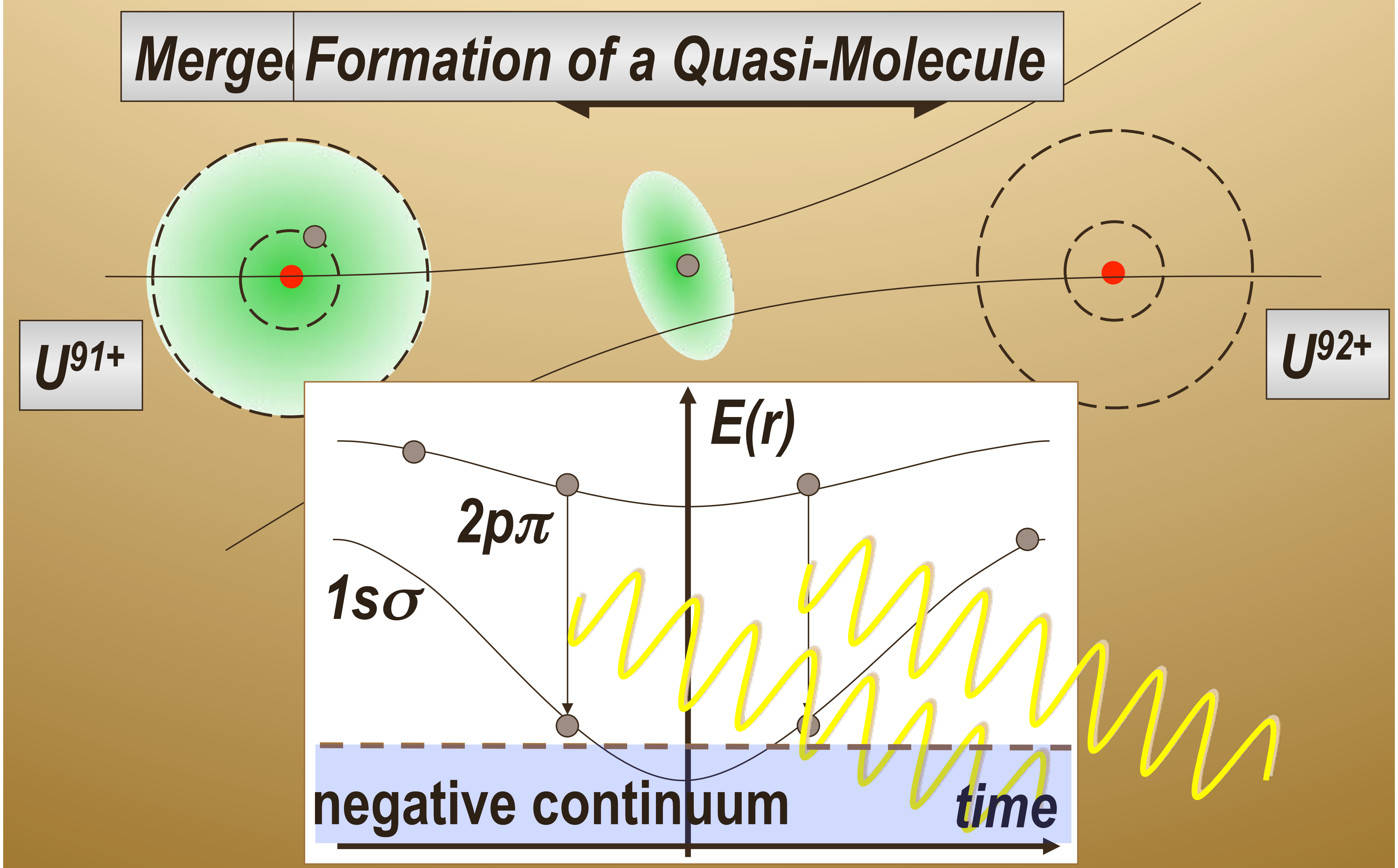
R = ∞

For a very short collision time, of about 10^{-20} sec, a quasi-atom is formed.

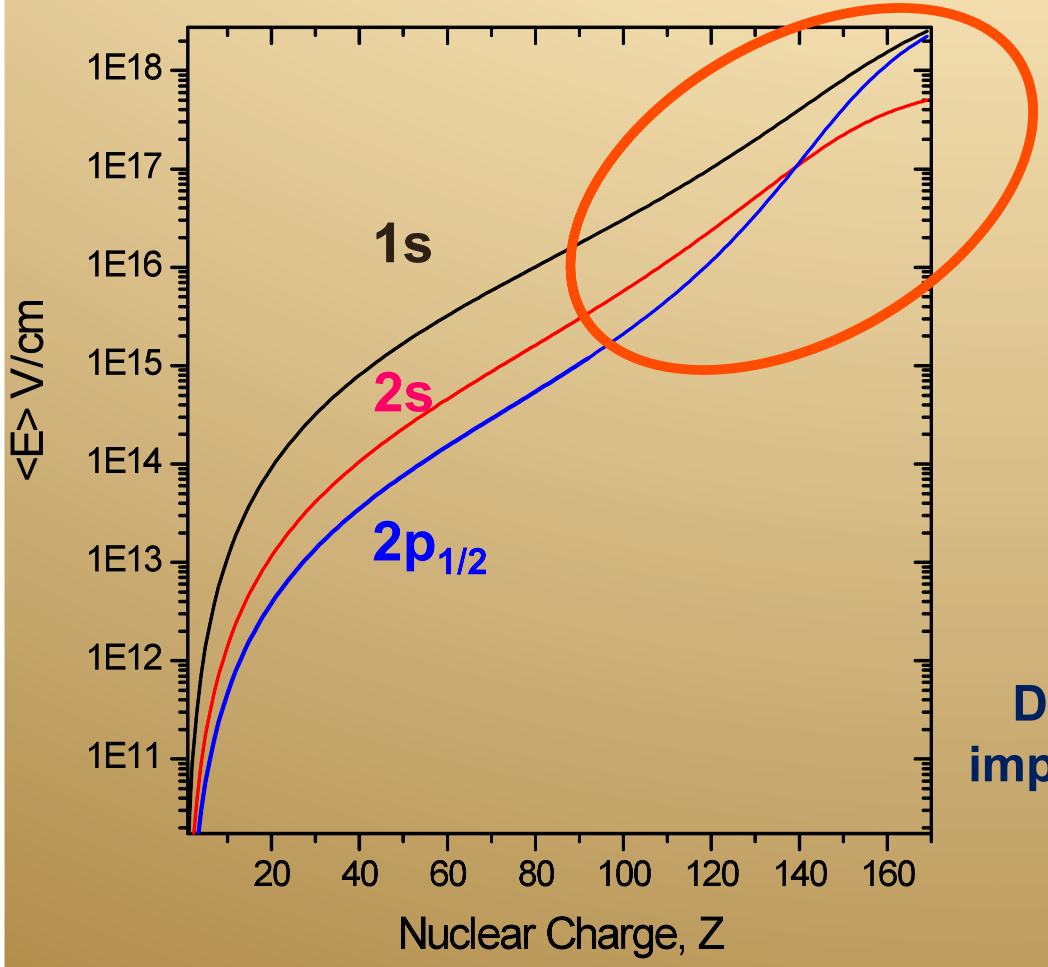
$$Z_1 + Z_2 = Z_{UA} \longrightarrow \approx 180 \longrightarrow E_B = ?$$

Merge

Formation of a Quasi-Molecule



Critical- and Super-Critical Fields



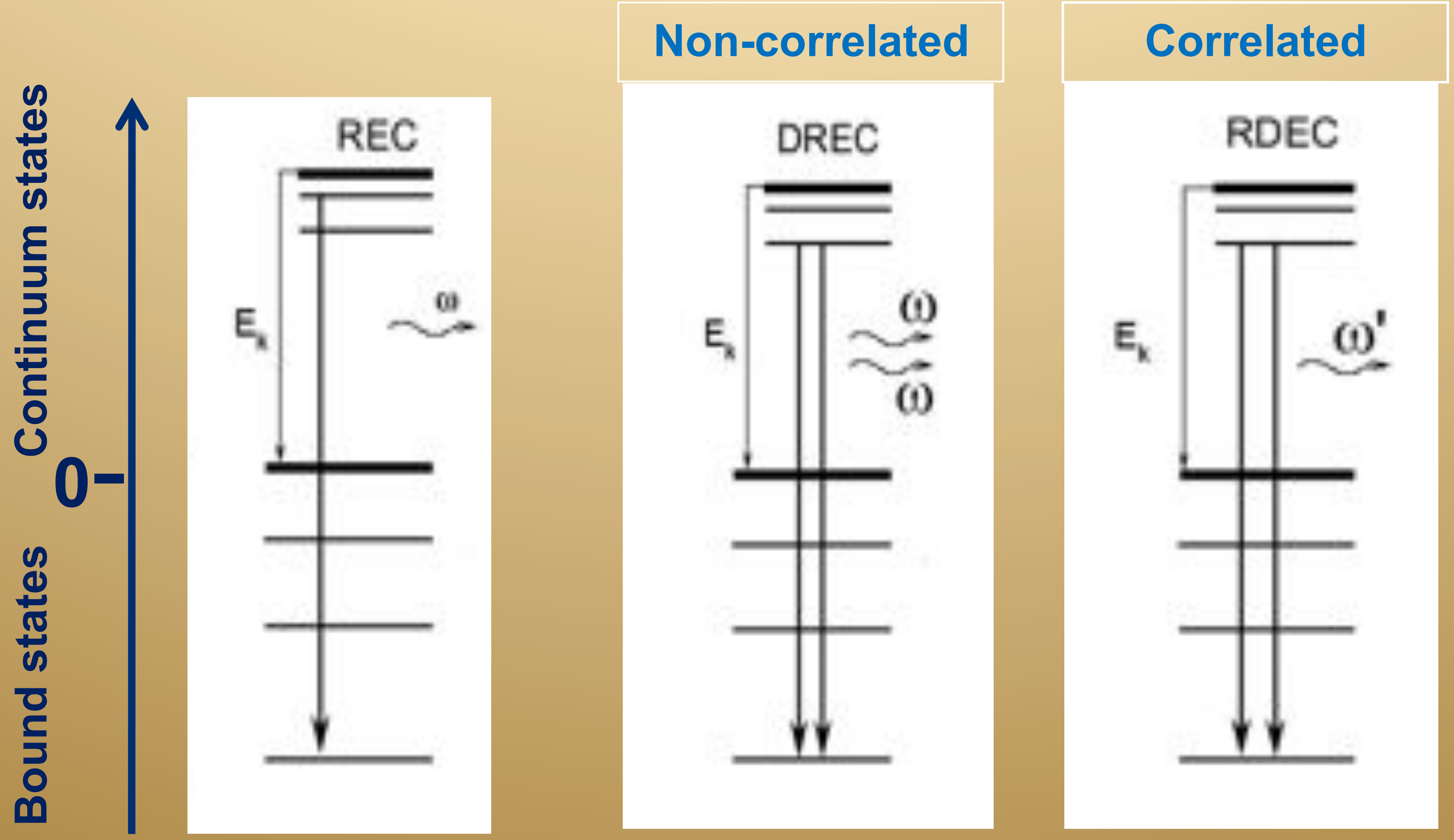
$U^{92+} \rightarrow U^{91+}$ =>

U^{91+} + MO-X-Ray...

as function of
impact parameter

Development of in-ring detectors for impact parameter sensitive experiments

Radiative Double Electron Capture (access to correlation effects)



Continuum states

0

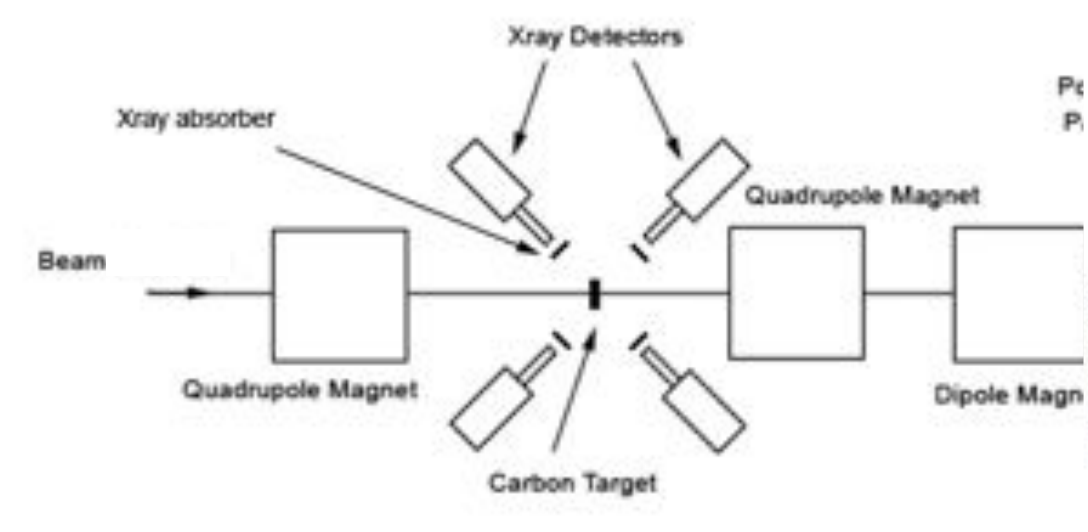
Bound states

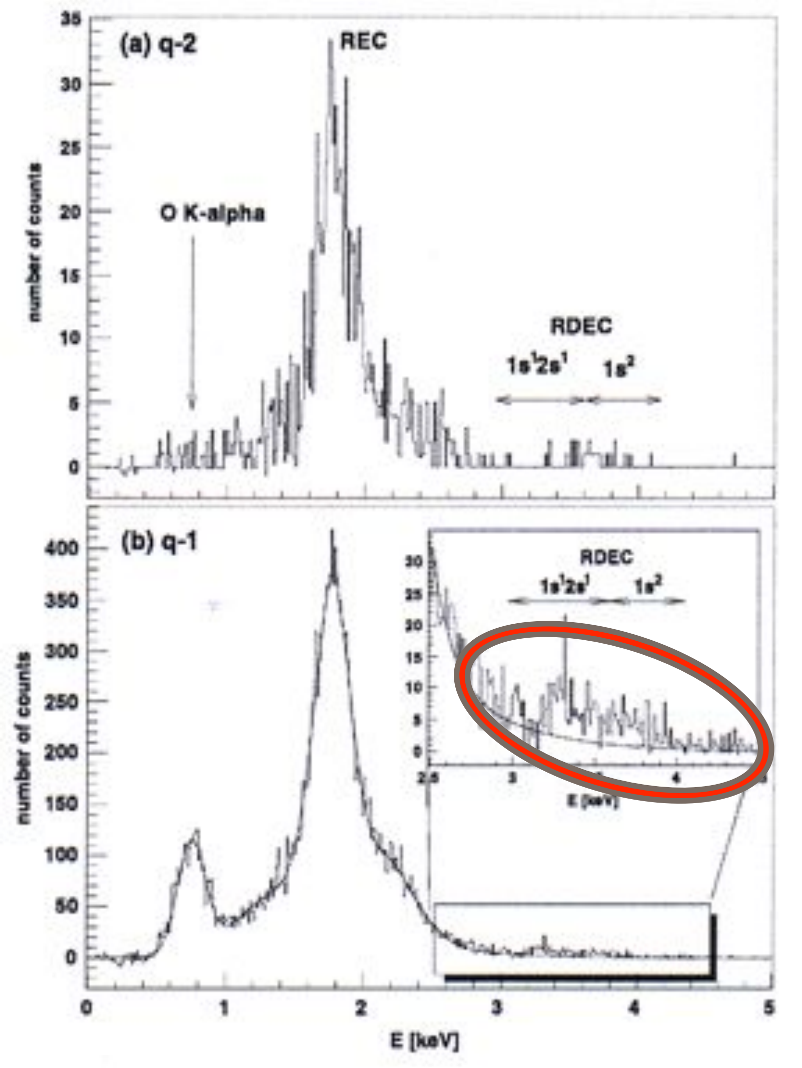
Non-correlated

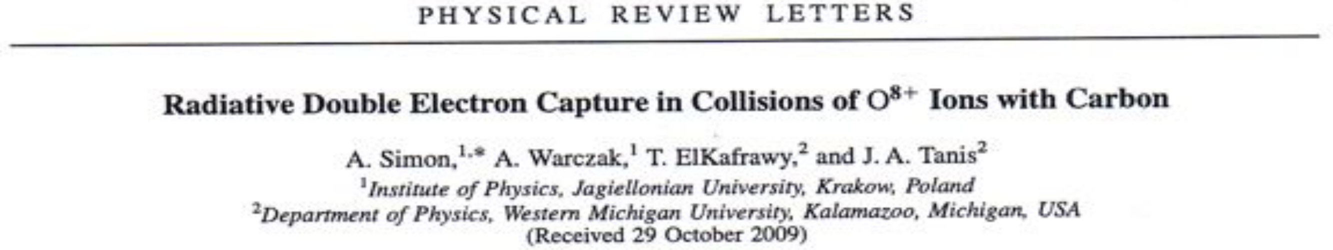
Correlated

Promissing measuremen

O^{8+} + C @ 38 MeV





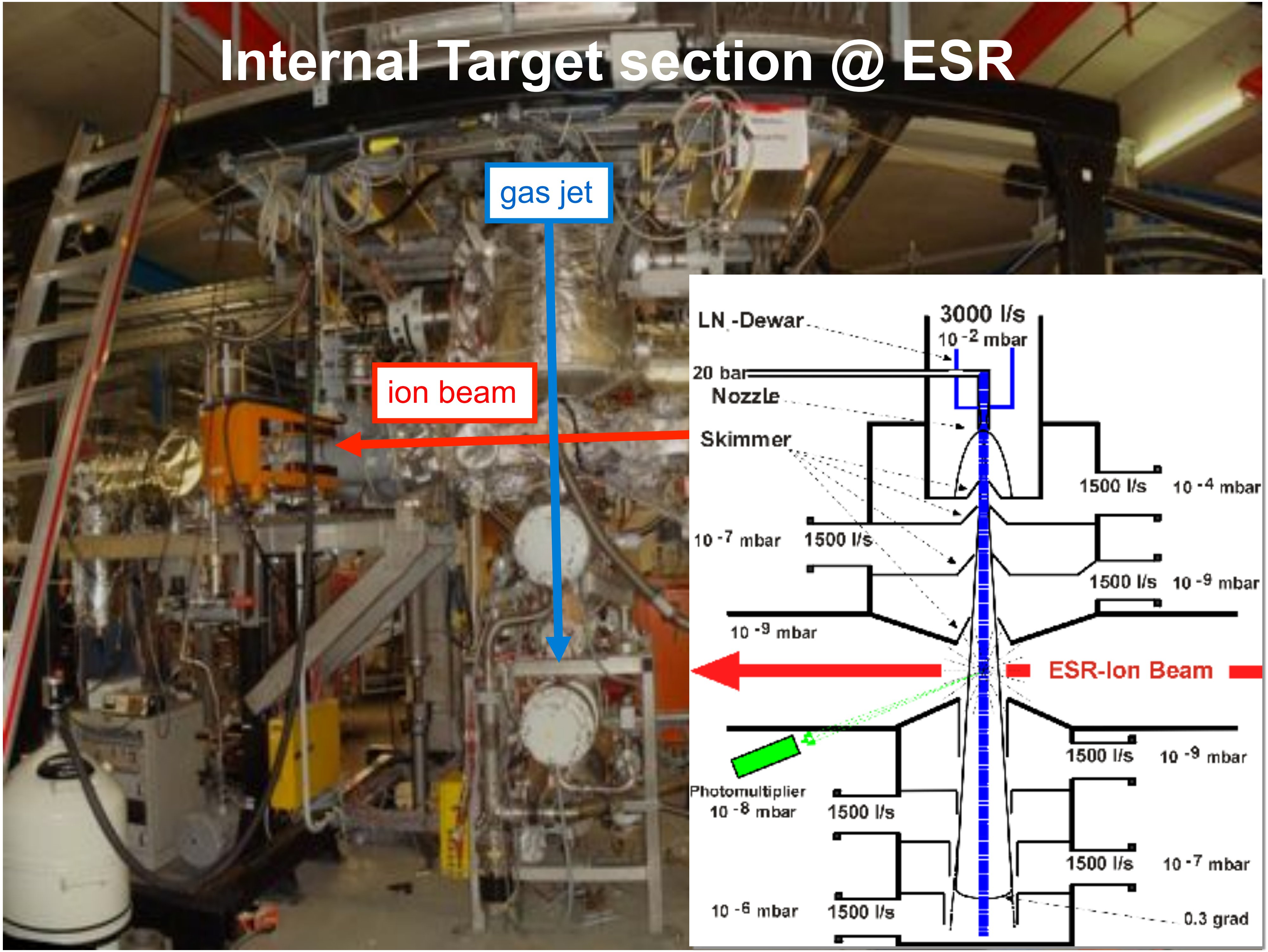


PHYSICAL REVIEW LETTERS

Radiative Double Electron Capture in Collisions of O^{8+} Ions with Carbon

A. Simon,[1,*] A. Warczak,[1] T. ElKafrawy,[2] and J. A. Tanis[2]
[1] *Institute of Physics, Jagiellonian University, Krakow, Poland*
[2] *Department of Physics, Western Michigan University, Kalamazoo, Michigan, USA*
(Received 29 October 2009)

Internal Target section @ ESR



Target Development for In-Ring Experiments

Design goal for NESR:

jet-diameter below 1 mm;

densities between 10^{11} and 10^{16} cm^{-3}

R. Grisenti et al. (University Frankfurt)

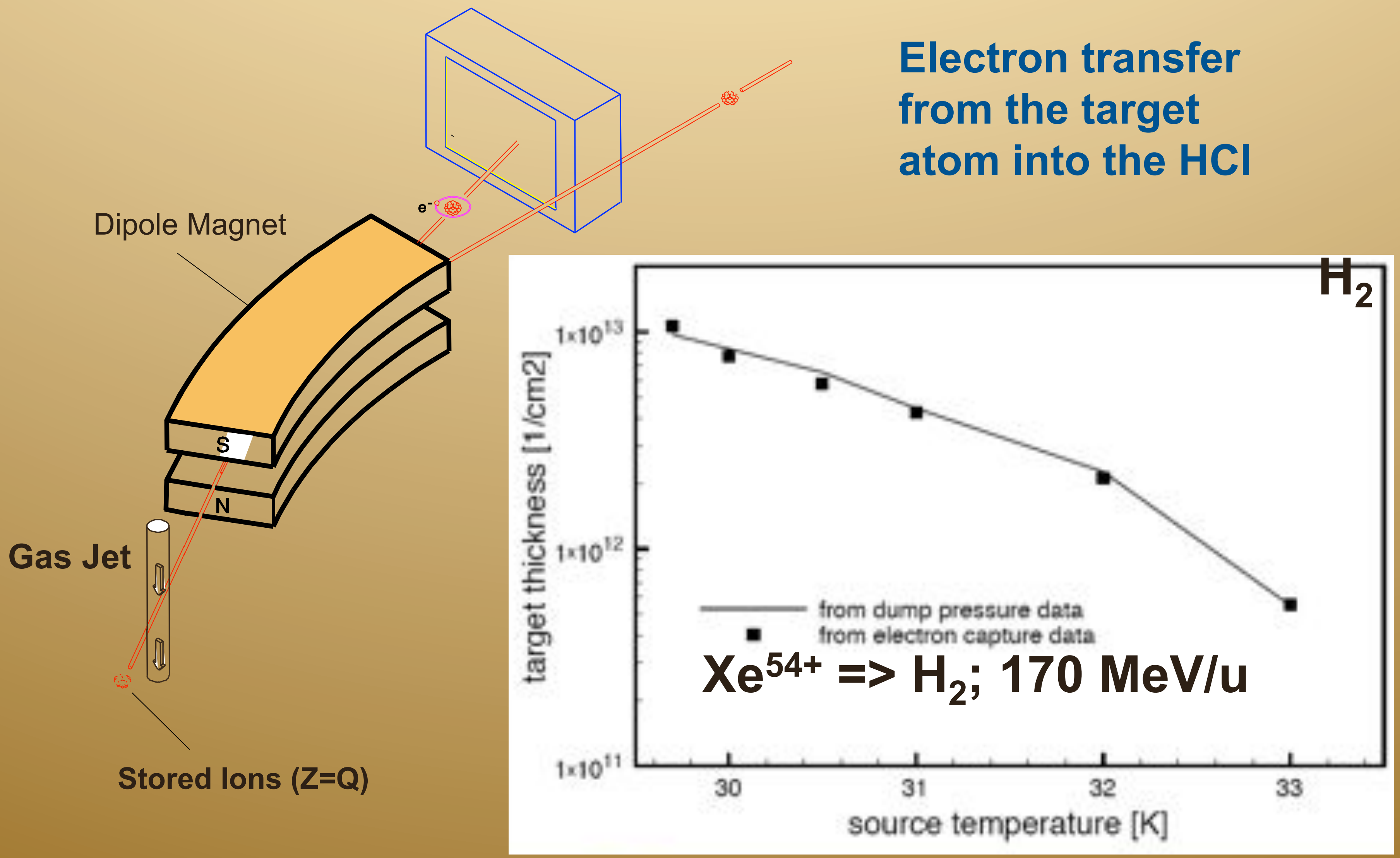
micro-droplet (cluster) targets (H_2, He)

cluster diameters ~ 1µm

target densities up to ~ 10^{14}

Density tests at the internal target

Electron transfer from the target atom into the HCI



Particle Counter (MWPC)

Dipole Magnet

Gas Jet

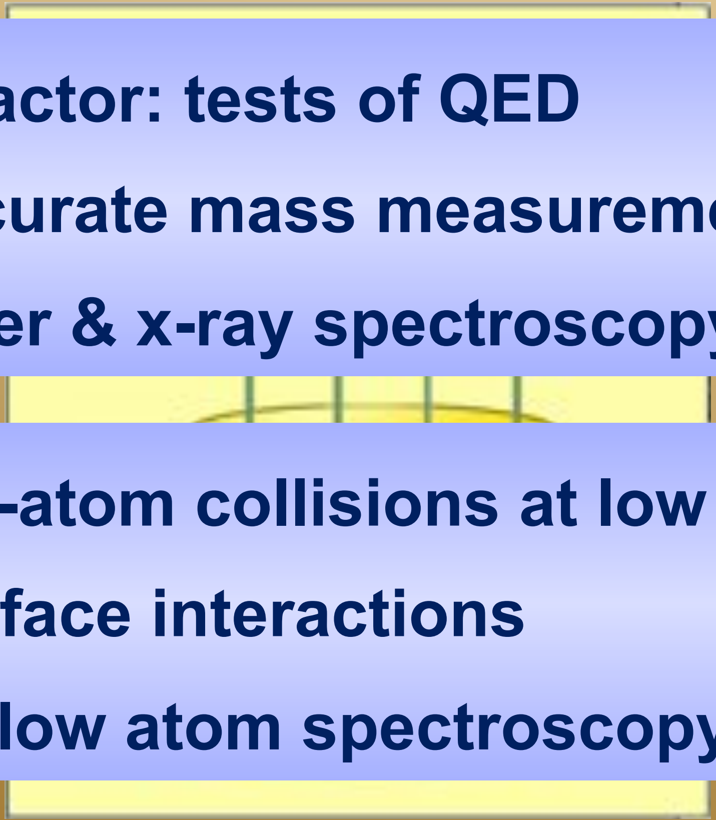
Stored Ions (Z=Q)

H_2

Xe^{54+} => H_2; 170 MeV/u

HITRAP project

The HITRAP facility:
highly charged
single ions "at rest"!

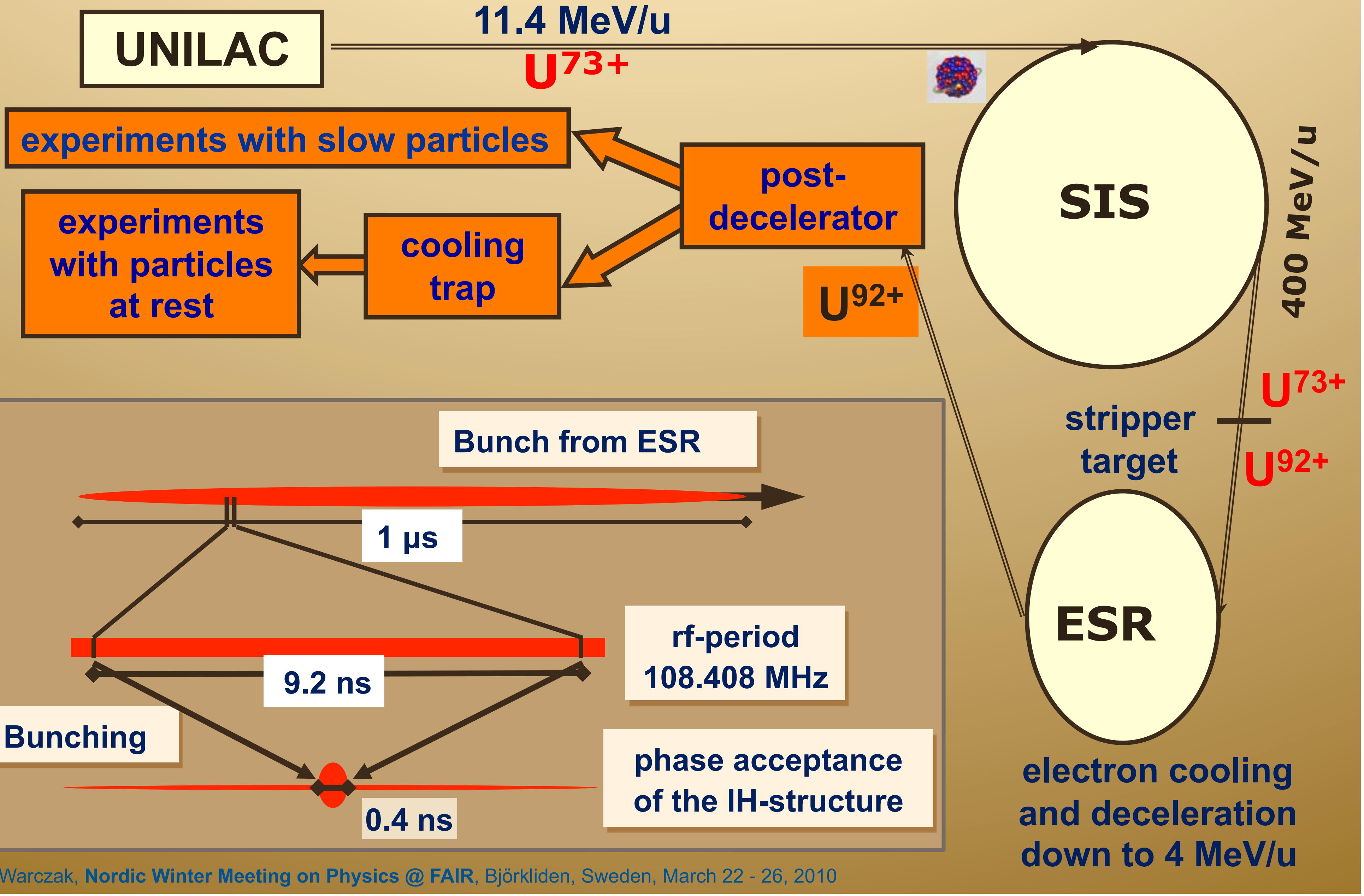


- **g-factor: tests of QED**
- **accurate mass measurements**
- **laser & x-ray spectroscopy**

- **ion-atom collisions at low velocities**
- **surface interactions**
- **hollow atom spectroscopy**

W. Quint, O. Kester et al.

HITRAP operation



UNILAC

11.4 MeV/u

U^{73+}

experiments with slow particles

experiments with particles at rest

cooling trap

post-decelerator

U^{92+}

SIS

400 MeV/u

U^{73+}

stripper target

U^{92+}

ESR

electron cooling and deceleration down to 4 MeV/u

Bunch from ESR

1 μs

rf-period 108.408 MHz

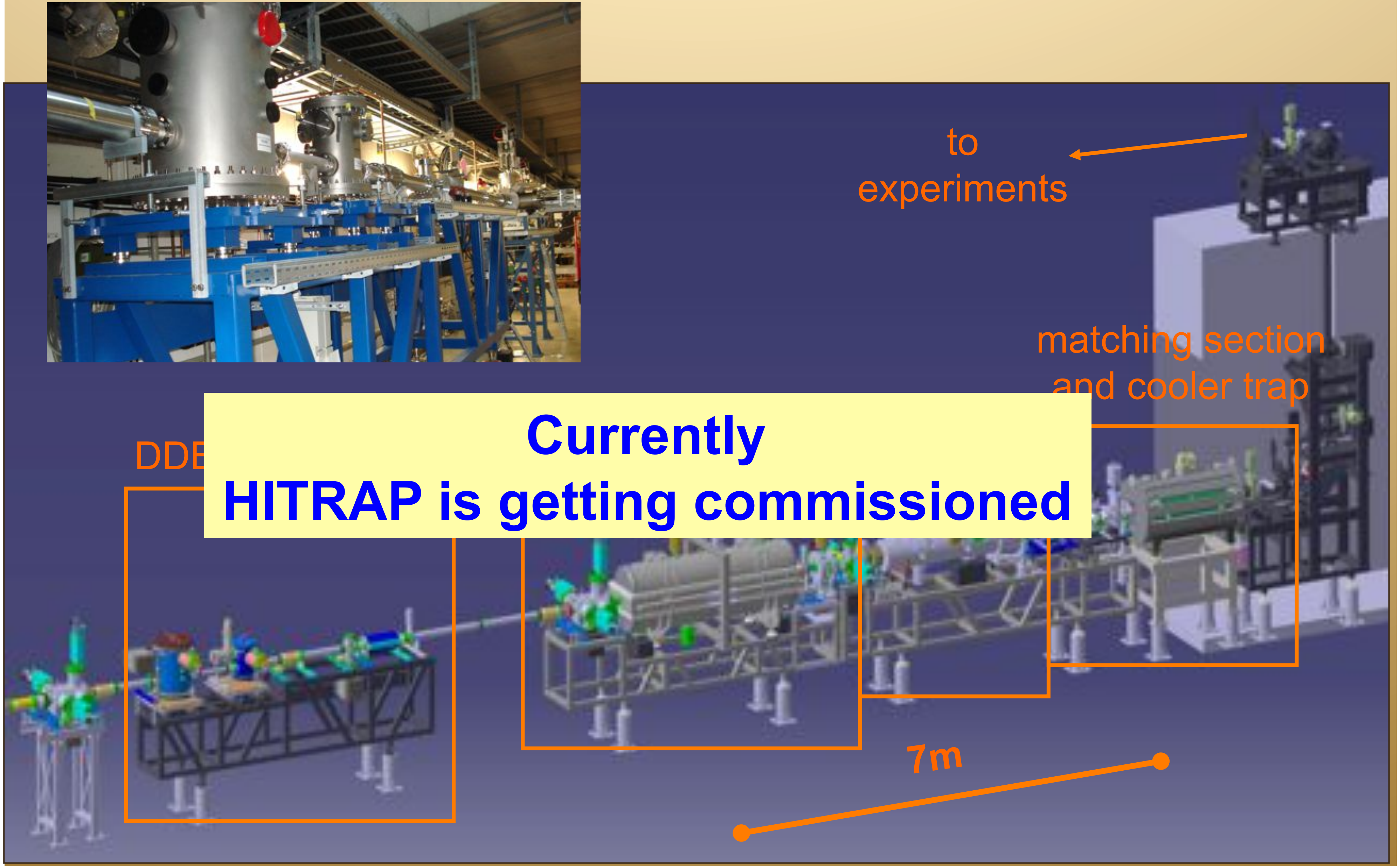
9.2 ns

Bunching

phase acceptance of the IH-structure

0.4 ns

HITRAP: technical design



Currently
HITRAP is getting commissioned

Summary

SPARC is well advanced to investigate:

- bound state quantum electrodynamics (QED)
- effects of relativity on the atomic structure
- electron correlation in strong fields
- dynamically induced strong field effects
- elementary atomic processes at high Z
- photon matter interaction,
- storage and trapping techniques
- spectrometer development
- photon, electron, ion detection techniques

Thank you for your attention