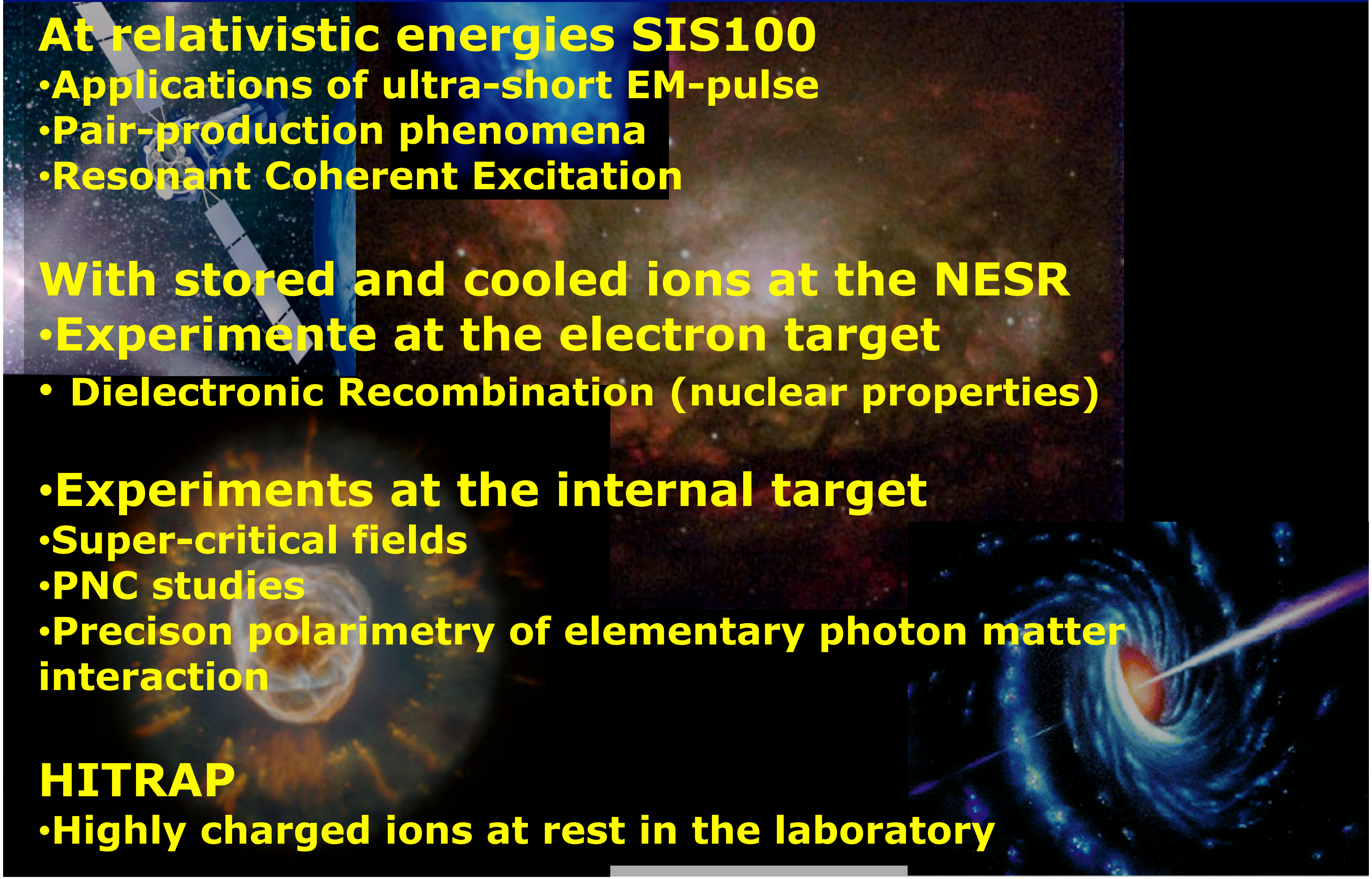
The Science Program of the Atomic Physics Collaborations at FAIR

Stored Particles Atomic Physics Research Collaboration

Strong links to: materials science, plasma and nuclear physics collaborations

Atomic Physics with Highly Charged Ions at FAIR



At relativistic energies SIS100

- Applications of ultra-short EM-pulse
- Pair-production phenomena
- Resonant Coherent Excitation

With stored and cooled ions at the NESR

- **Experimente at the electron target**
- Dielectronic Recombination (nuclear properties)

- **Experiments at the internal target**
- Super-critical fields
- PNC studies
- Precison polarimetry of elementary photon matter interaction

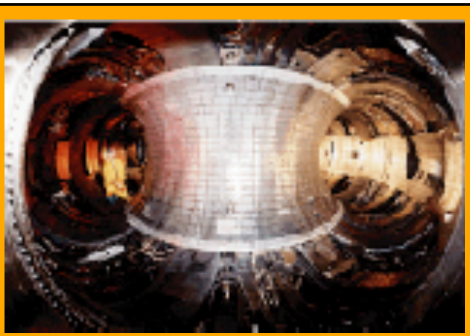
HITRAP

- Highly charged ions at rest in the laboratory

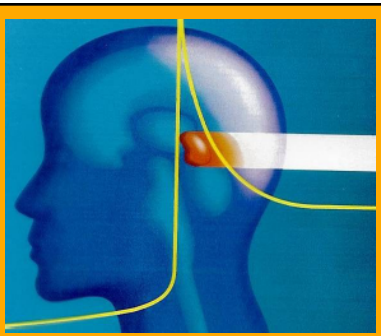
Research Focus: Matter under Extreme Conditions

Highest Charge States	*Extreme Static Fields*
Relativistic Energies	*Extreme Dynamical Fields and Ultrashort Pulses*
High Intensities	*Very High Energy Densities and Pressures*
High Charge at Low Velocity	*Large Energy Deposition*

Contributions to



Energy



Health

Aeronautics, Space

fusion energy research

... behaviour of compound materials

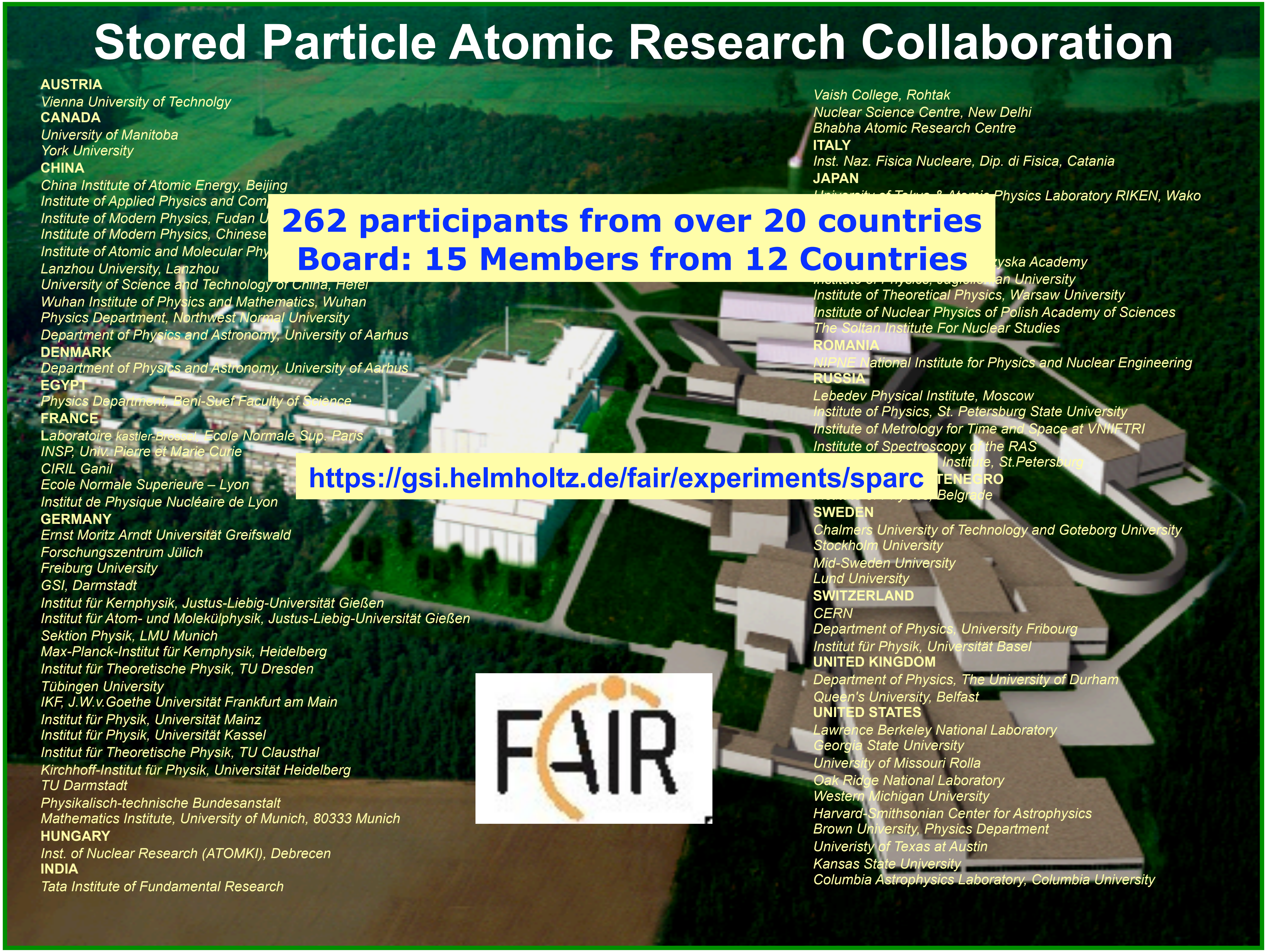
cancer therapy

... response of cells to irradiation by heavy ions

aerospace engineering

... active and passive radiation shielding of cosmic radiation

Stored Particle Atomic Research Collaboration



262 participants from over 20 countries
Board: 15 Members from 12 Countries

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

FAIR

AUSTRIA
Vienna University of Technolgy
CANADA
University of Manitoba
York University
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China Institute of Atomic Energy, Beijing
Institute of Applied Physics and Com
Institute of Modern Physics, Fudan U
Institute of Modern Physics, Chinese
Institute of Atomic and Molecular Phy
Lanzhou University, Lanzhou
University of Science and Technology of China, Hefei
Wuhan Institute of Physics and Mathematics, Wuhan
Physics Department, Northwest Normal University
Department of Physics and Astronomy, University of Aarhus
DENMARK
Department of Physics and Astronomy, University of Aarhus
EGYPT
Physics Department, Beni-Suef Faculty of Science
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INSP, Univ. Pierre et Marie Curie
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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
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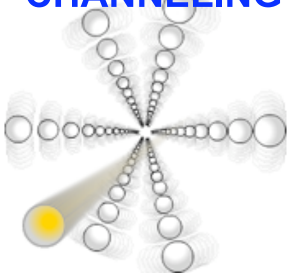
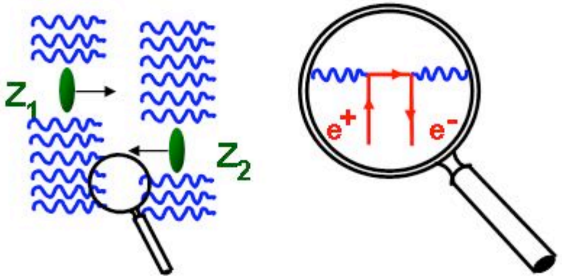
INDIA
Tata Institute of Fundamental Research
Vaish College, Rohtak
Nuclear Science Centre, New Delhi
Bhabha Atomic Research Centre
ITALY
Inst. Naz. Fisica Nucleare, Dip. di Fisica, Catania
JAPAN
University of Tokyo & Atomic Physics Laboratory RIKEN, Wako
zyska Academy
Institute of Physics, Jagiellonian University
Institute of Theoretical Physics, Warsaw University
Institute of Nuclear Physics of Polish Academy of Sciences
The Soltan Institute For Nuclear Studies
ROMANIA
NIPNE National Institute for Physics and Nuclear Engineering
RUSSIA
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
Institute, St.Petersburg
TENEGRO
Institute of Physics, Belgrade
SWEDEN
Chalmers University of Technology and Goteborg University
Stockholm University
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

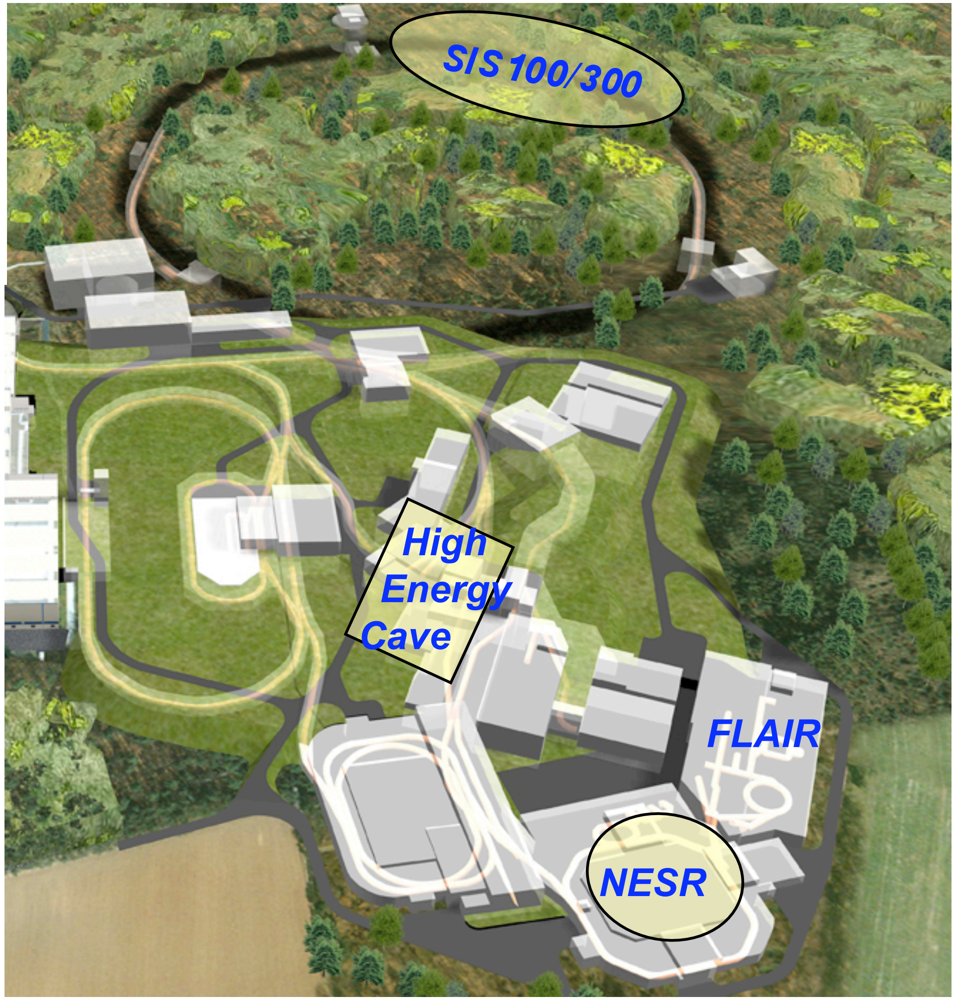
Experimental Facilities

CHANNELING



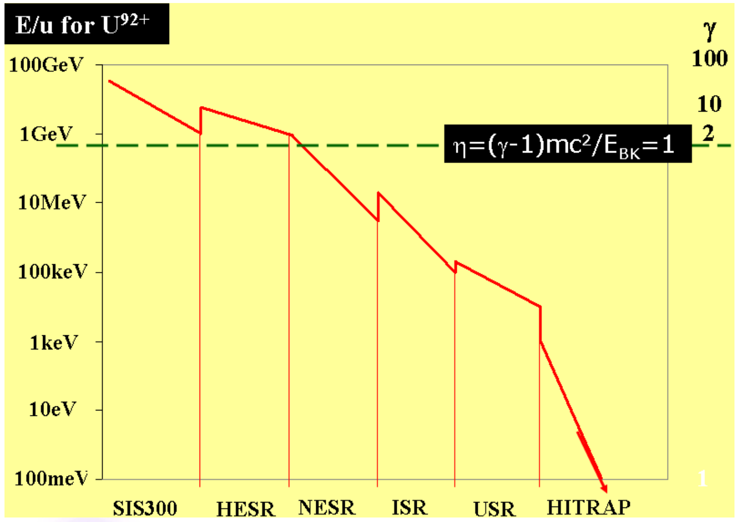
PAIR PRODUCTION





Stored and Cooled

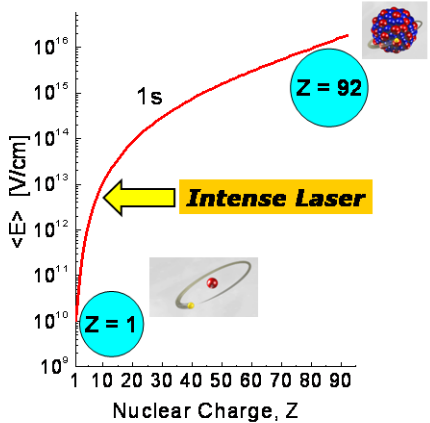
From Rest to Relativistic Energies:
Highly-Charged Ions and Exotic Nuclei
Intense Beams of Radioactive Isotopes
Intense Source of Virtual X Rays
XUV Energies via Lorentz Boost of Optical Wavelengths



Novel Instrumentation

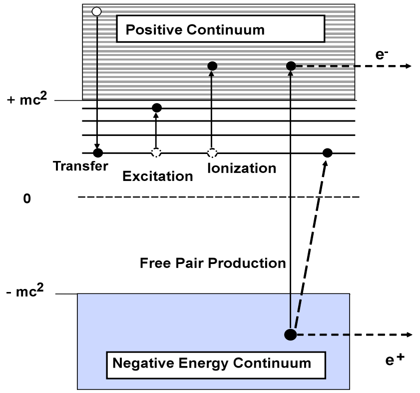
Atomic Physics in Strong Coulomb Fields

Structure Studies



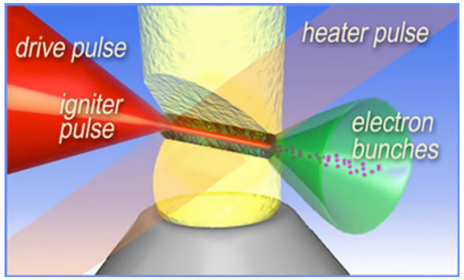
- bound state quantum electrodynamics (QED)
- nuclear effects on the atomic structure
- effects of relativity on the atomic structure
- electron correlation in strong fields
- supercritical fields

Dynamics



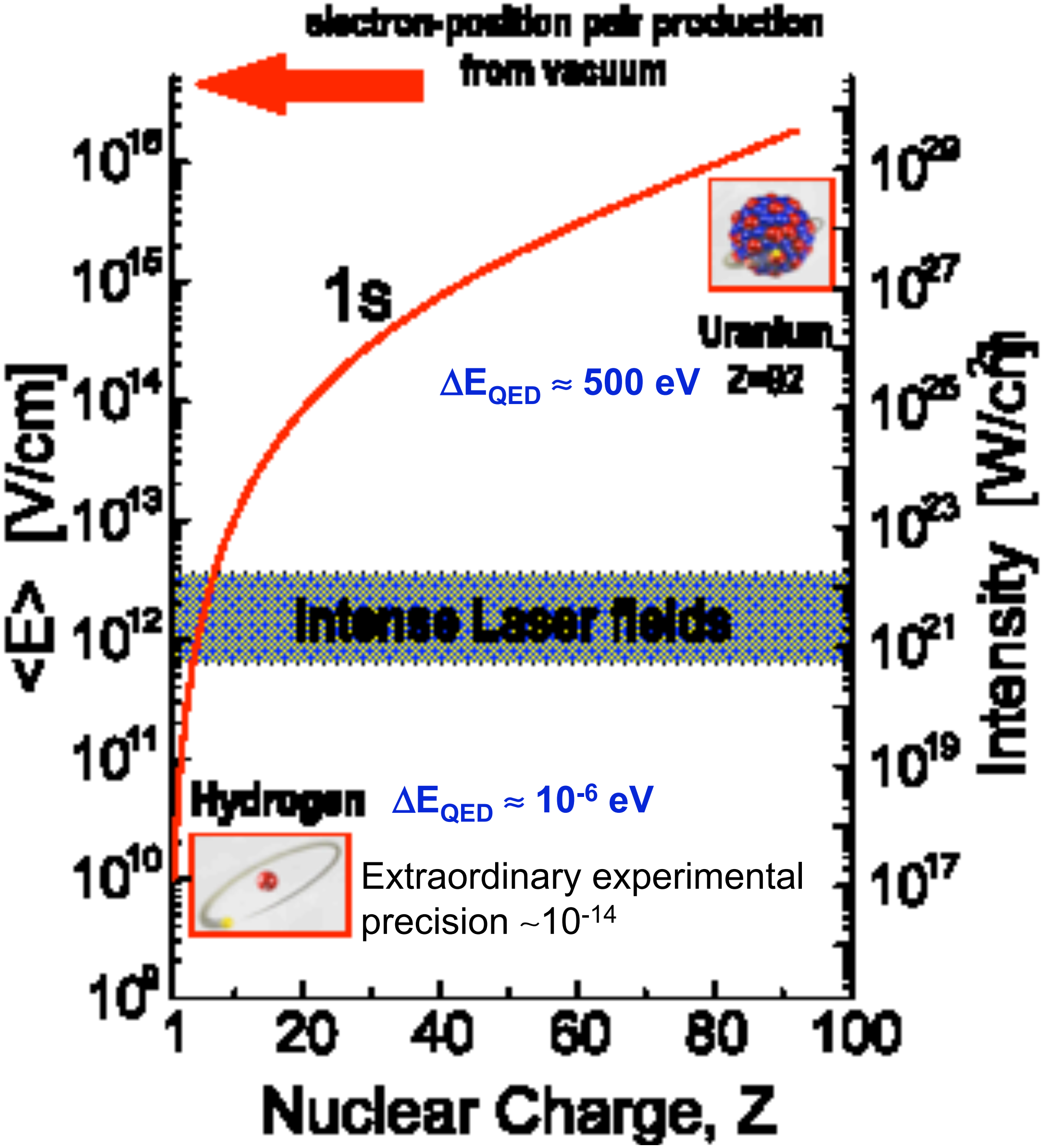
- dynamically induced strong field effects
- correlated many body dynamics
- elementary atomic processes at high Z
- photon matter interaction, e.g. photon polarization correlation

Applications



- ion cooling techniques
- storage and trapping techniques
- laser and spectrometer development
- photon, electron, ion detection techniques

Atomic Physics in Extremely Strong Fields



Atomic Structure at High-Z

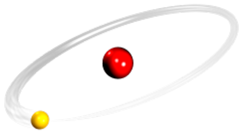
- Bound state quantum electrodynamics (QED) in extreme fields
- Effects of relativity on the atomic structure
- Electron correlation in the presence of strong fields

Atomic Collision at High-Z

- Correlated many-body dynamics
- Photon matter interaction: e.g., photon polarization effects
- Dynamically induced strong field effects

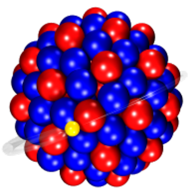
Atomic Physics: Quantum Electrodynamics in the Extreme Field Limit

hydrogen

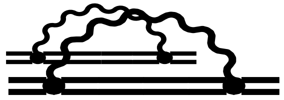


Z=1
E_b = 13.6 eV
Z·α « 1

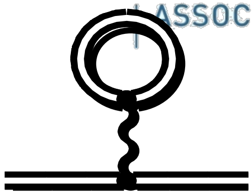
uranium ion

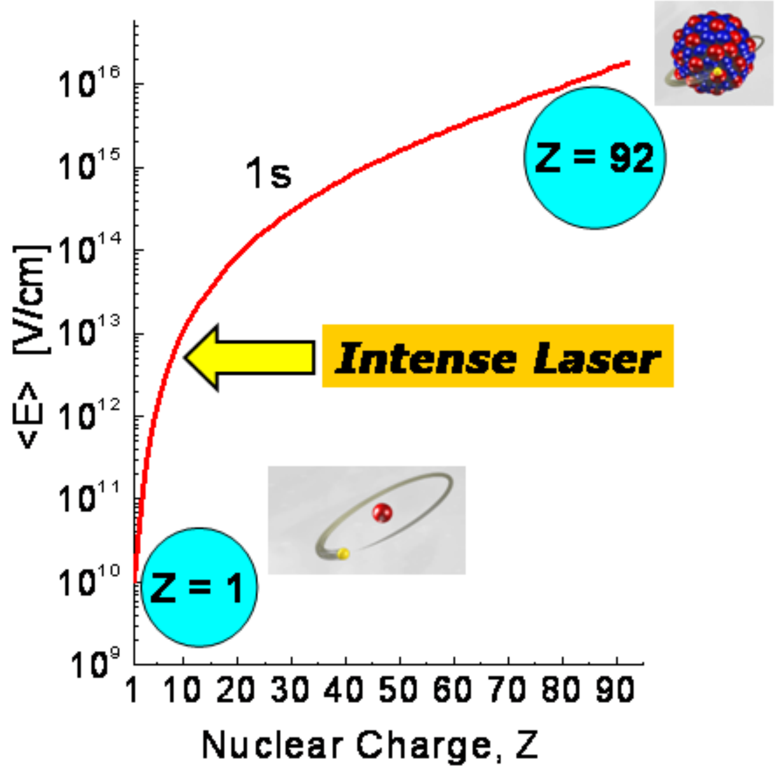


Z=92
E_b = 132 keV
Z·α ≈ 1



Strong Field QED

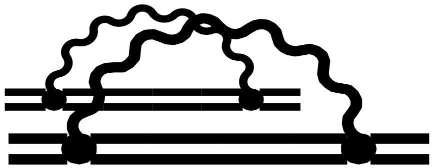




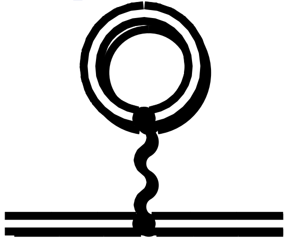
- **1s-Lamb Shift**
- **g-factor**
- hyperfine structure
- towards super-critical fields
- border line to nuclear physics

Bound-State QED: 1s Lamb Shift at High-Z

Self energy



Vacuum polarization



U^{91+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

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

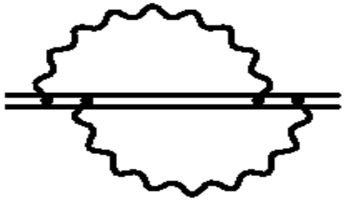
Low Z-Regime: $\alpha Z << 1$

$F(\alpha Z)$: series expansion in αZ

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

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

Goal:



±1 eV

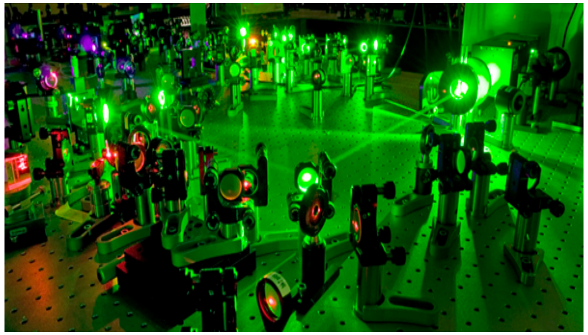
Quantum Electrodynamics

Richard Feynman
1918-1988

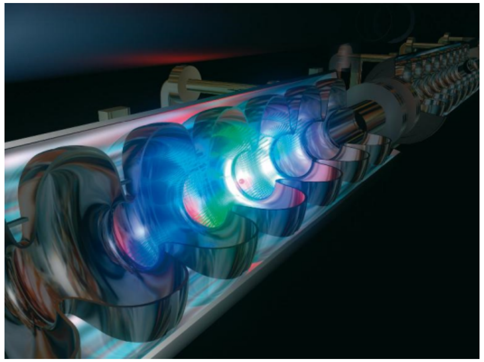
The theory of quantum electrodynamics is, I would say, the jewel of physics – our proudest possession.
R. Feynman, 1983

… having to resort to such hocus-pocus [renormalization] has prevented us from proving that the theory of QED is mathematically self-consistent.
… [renormalization] is what I would call a dippy process.
R. Feynman, 1985

Sources of strong EM fields

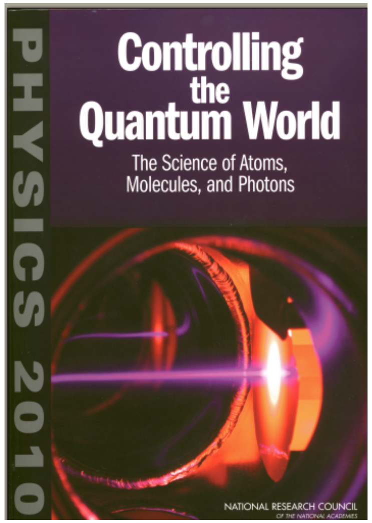


Novel intense laser sources (e.g. Vulcan facility in UK, POLARIS at FSU, DRACO at FZD)



Free electron lasers (e.g. XFEL)

Advanced particle acceleration facilities (e.g. GSI and FAIR, DESY)



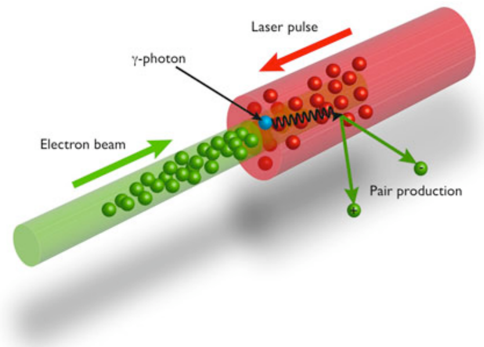
"... Thus the technologies are complementary [intense light sources and ion beams] and both are likely to lead to new insights in high-intensity science."

National Research Council, US on **AMO** Physics, 2008

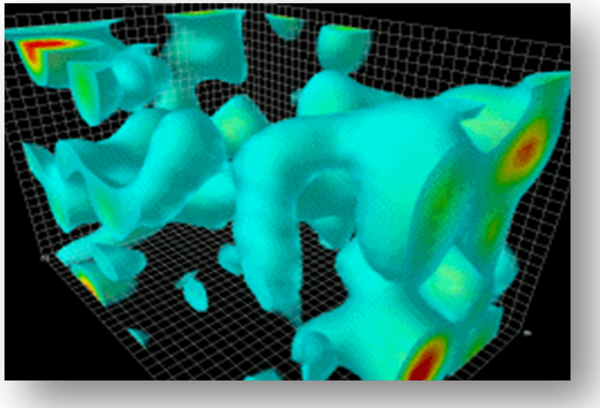
Physics of strong EM fields

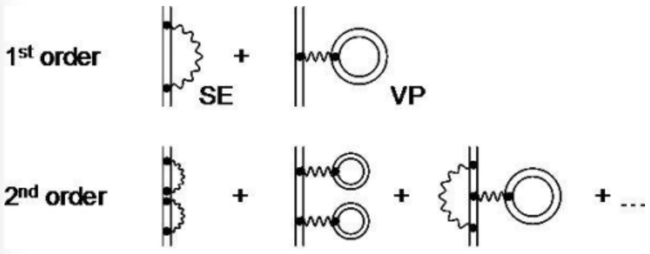
During the last decades significant interest has been growing in the physics of (extremely) strong electromagnetic fields. These fields provide a unique tool for studying a large number of fundamental problems in modern physics:

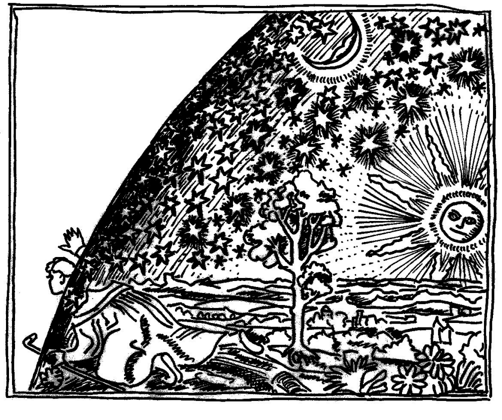
- Structure of matter under extreme conditions
- Non-linear phenomena in light-matter interaction
- Search for a new physics beyond the standard model



Picture from: www.extreme-light-infrastructure.eu





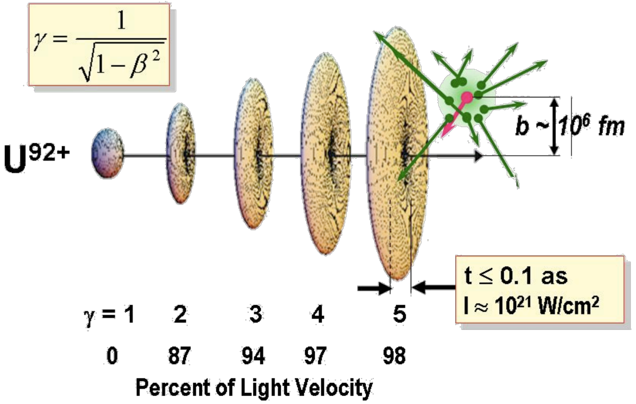


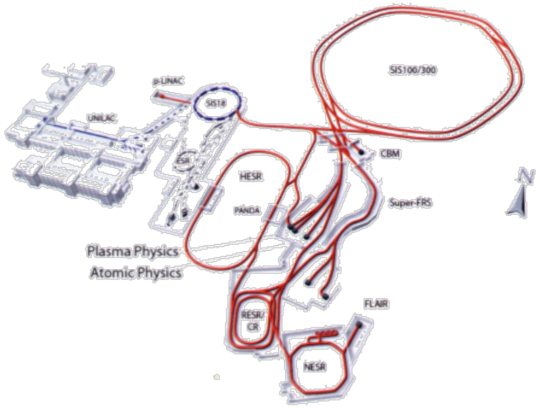
Is there anything beyond the Standard Model?

Complementarity: Extreme Light and Extreme Particle Beam Collisions

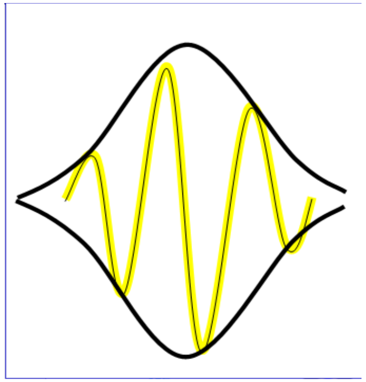
The fastest pulses

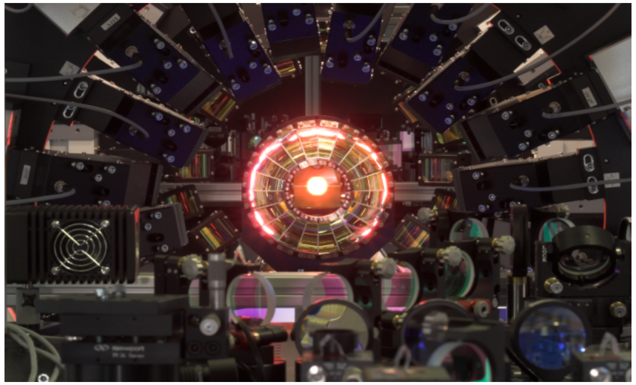
Ions: Sub Attosecond



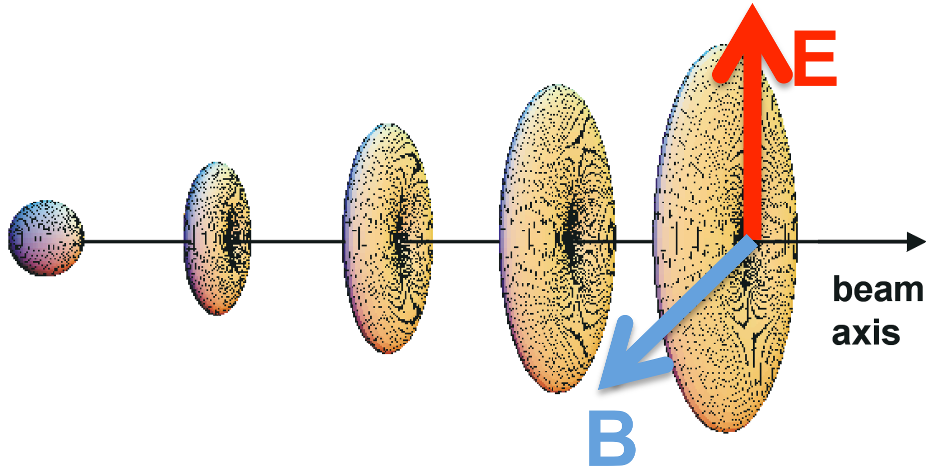


Laser: Femtosecond to Sub-Femtosecond



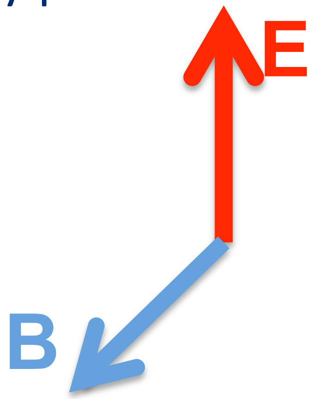


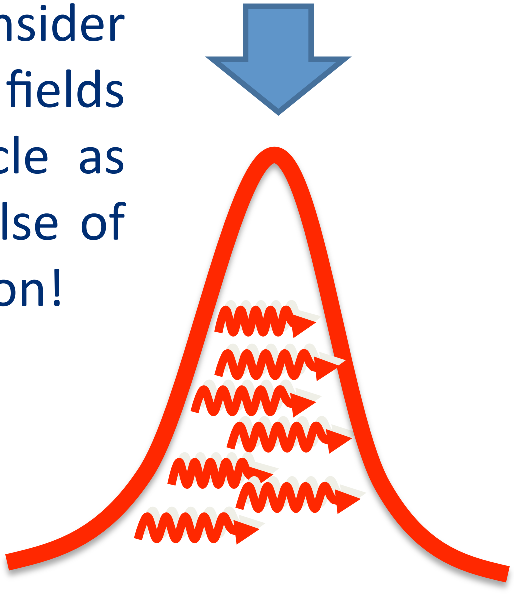
Equivalent (virtual) photons



The electric field produced by a moving charge (γ>>1) is almost transverse and is accompanied by transverse magnetic field (of almost equal strength).

Enrico Fermi: let us consider transverse (E and B) fields produced by fast particle as fields produced by a pulse of linearly polarized radiation!





Sub-attosecond, half-cycle pulses

Parameters of the “pulse”:

Time duration: $\Delta t = b / v\gamma$

Maximal energy: $\hbar\omega = \hbar\gamma c / b$

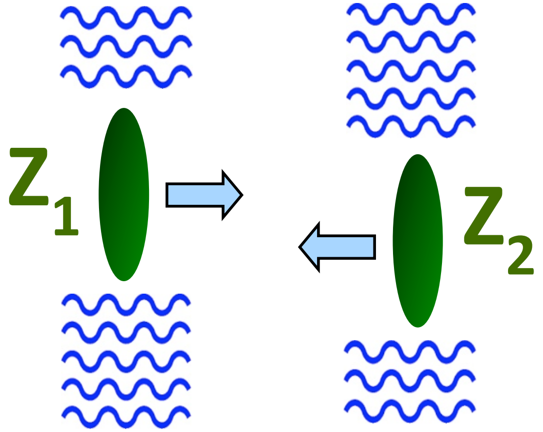
@ FAIR facility:

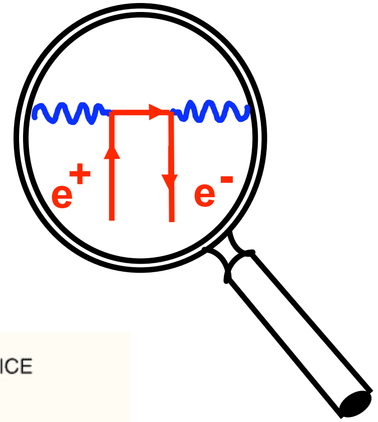
$$\Delta t \approx 1\, zs$$

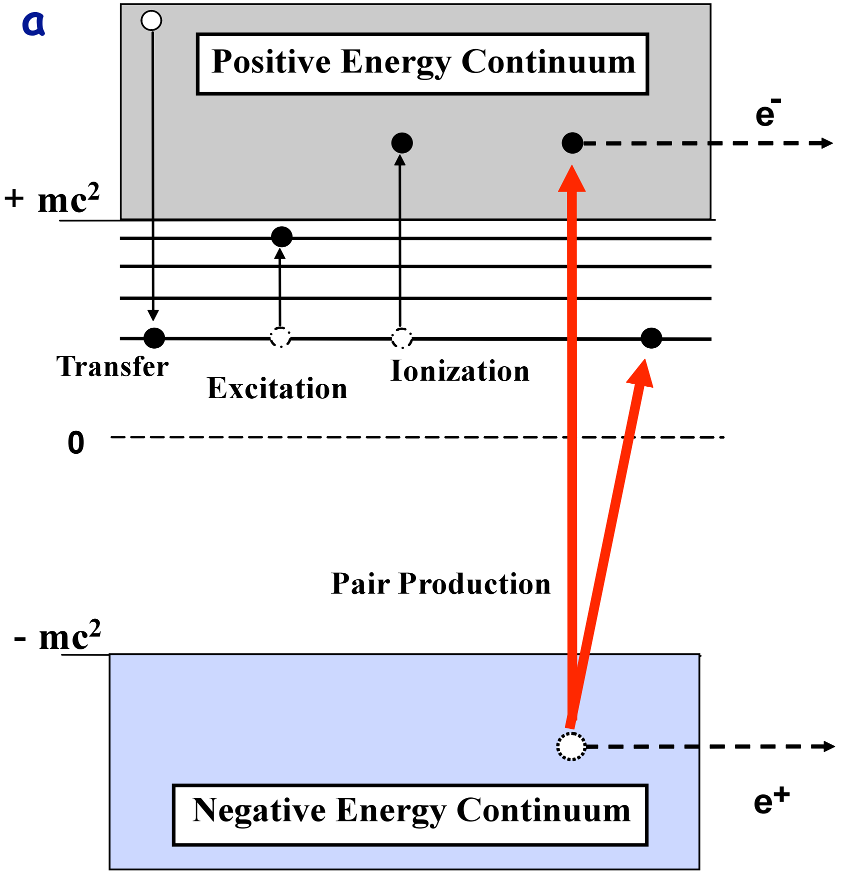
$$\hbar\omega \approx 800\, MeV$$

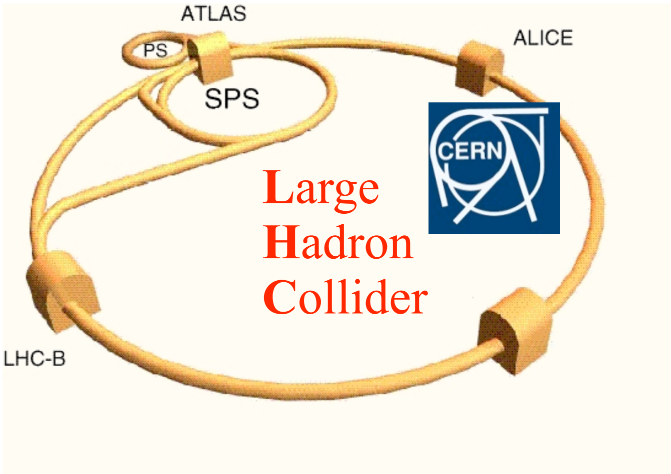
(Ultra) Relativistic Ion-Atom Collisions

- **Dynamically induced strong fields result in a large number of atomic processes**







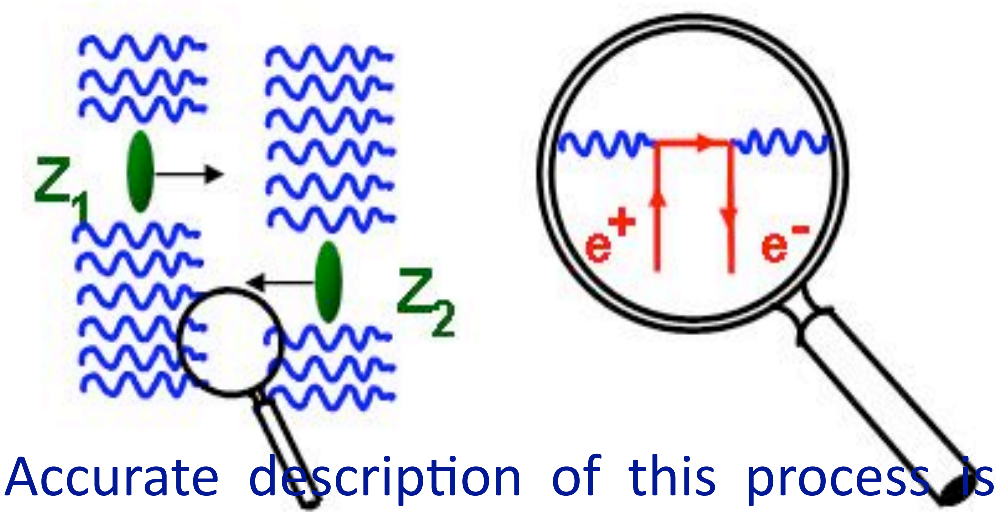


- Bound-free pair production limits the performance of the LHC at CERN!

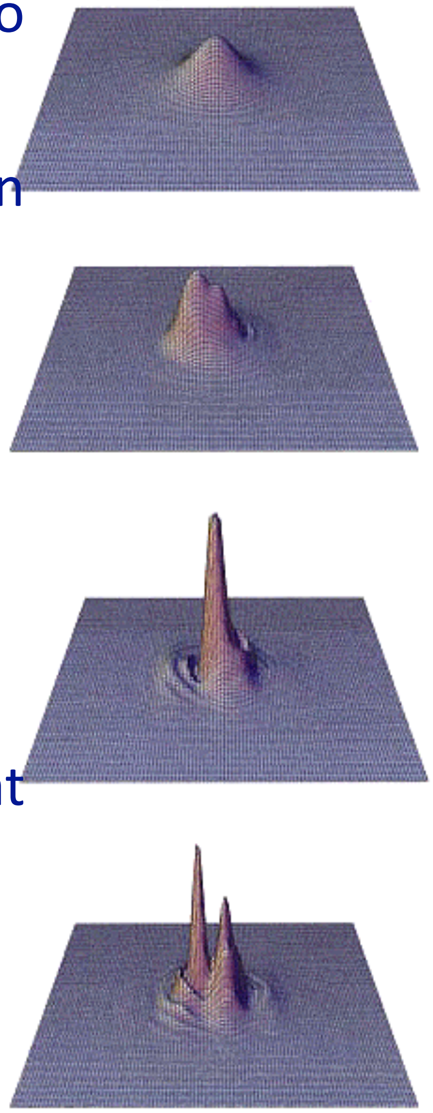
CERN Courier 47 (2007) 7

Pair production in ion collisions

- Dynamically induced strong fields may lead to electron-positron pair production.
- This process, again can be “understood” in equivalent photon picture.



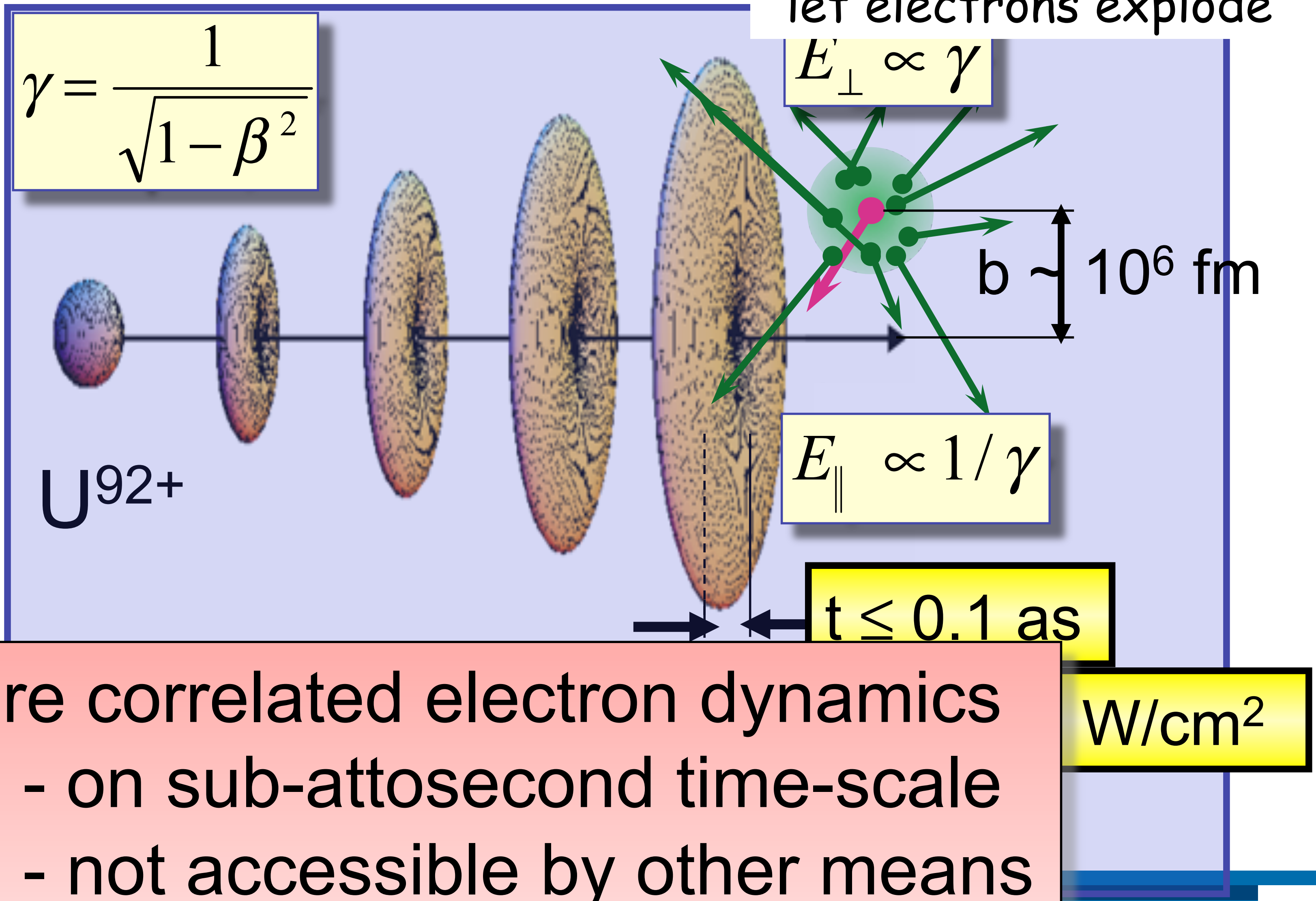
- Accurate description of this process is a great challenge for the QED-theory
- non-perturbative regime !
- Multiple Pair-Production?
- Recombination with the vaccum?



Calculations by A. Belkacem and D. Ionescu, LBNL

SPARC Module 1: Relativistic Collisions @SIS100

"Heisenbergs dream"
shot out the nucleus,
let electrons explode

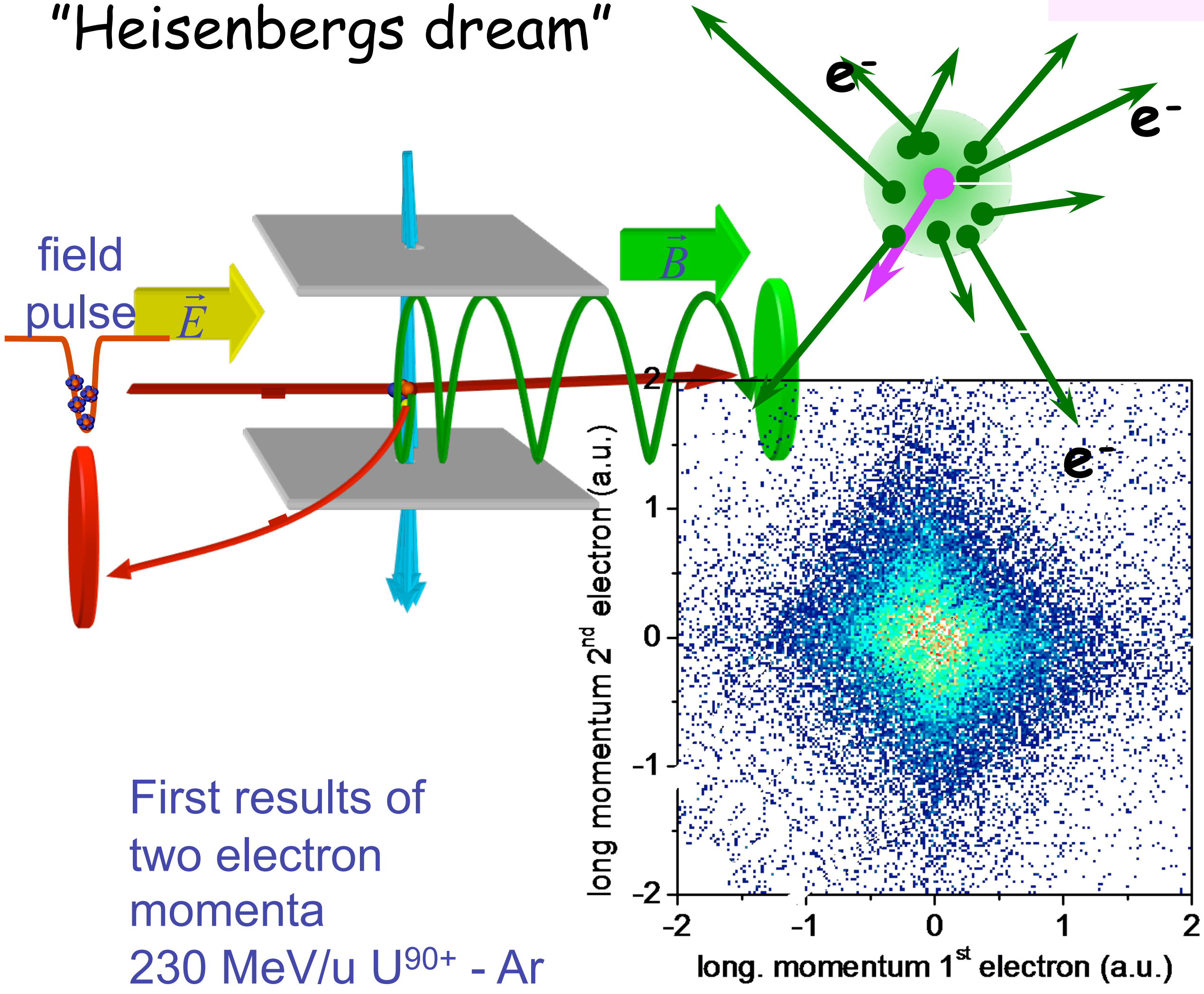


Explore correlated electron dynamics
- on sub-attosecond time-scale
- not accessible by other means

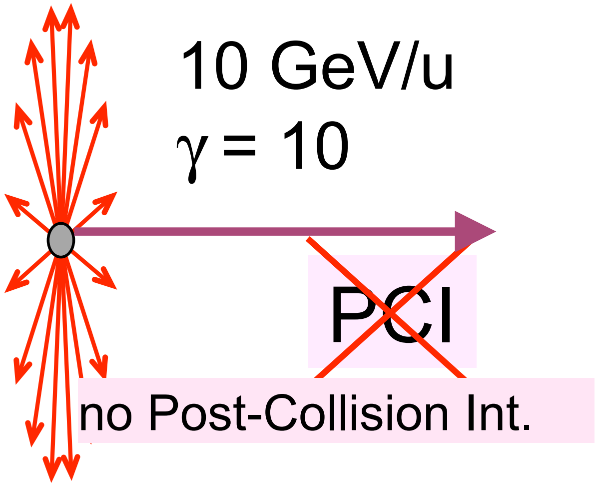
SPARC Module 1: Relativistic Collisions @SIS100

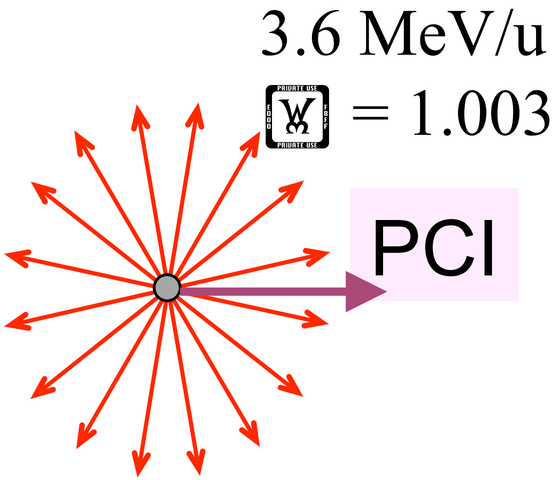
What makes the difference?

"Heisenbergs dream"



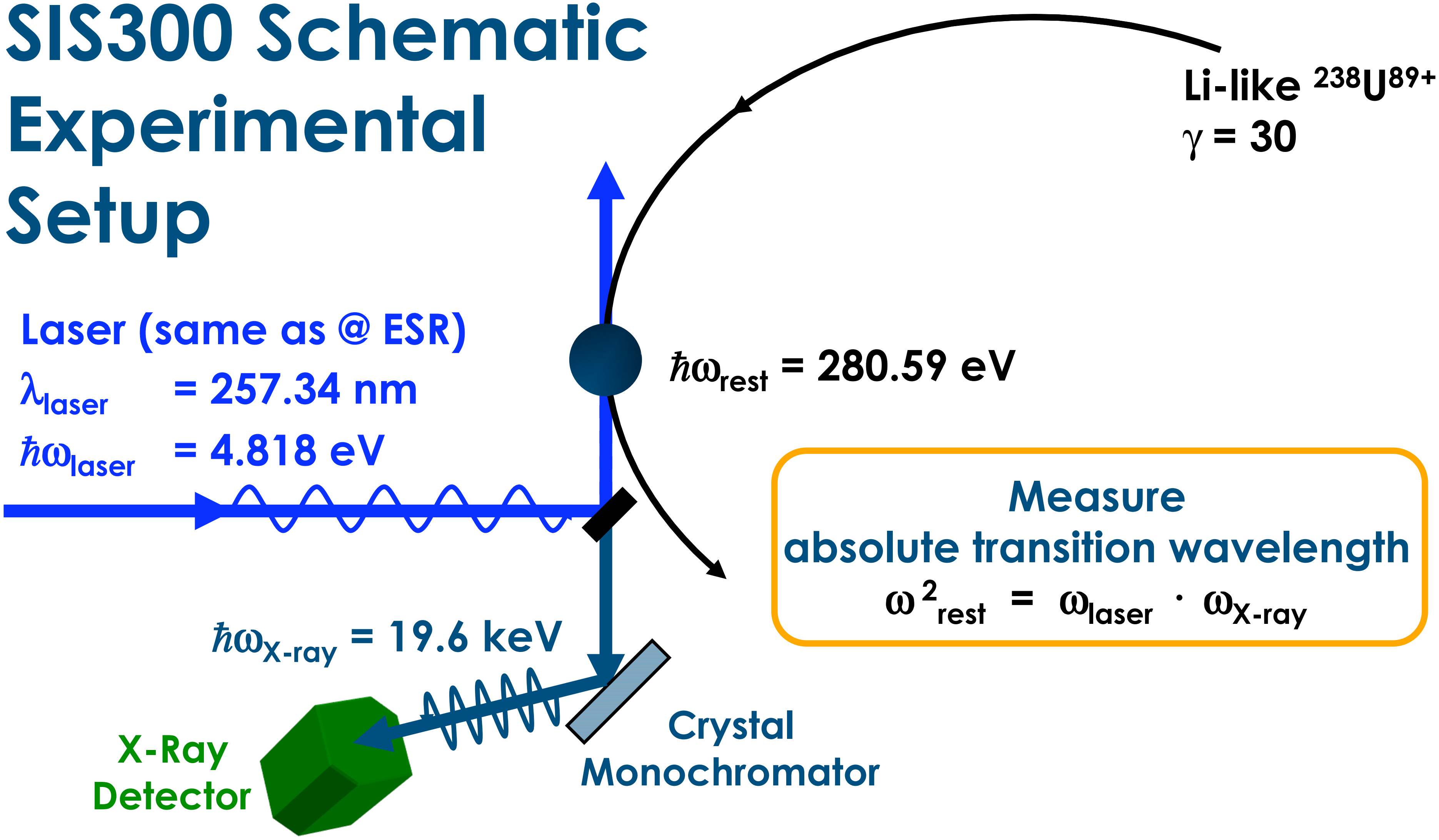
First results of
two electron
momenta
230 MeV/u U^{90+} - Ar





D. Fischer, S. Hagmann, J. Ullrich et al.

SIS300 Schematic Experimental Setup



Laser (same as @ ESR)

λ_{laser} = 257.34 nm

$\hbar\omega_{laser}$ = 4.818 eV

Li-like $^{238}U^{89+}$

γ = 30

$\hbar\omega_{rest}$ = 280.59 eV

Measure absolute transition wavelength

$$\omega^2_{rest} = \omega_{laser} \cdot \omega_{X\text{-ray}}$$

$\hbar\omega_{X\text{-ray}}$ = 19.6 keV

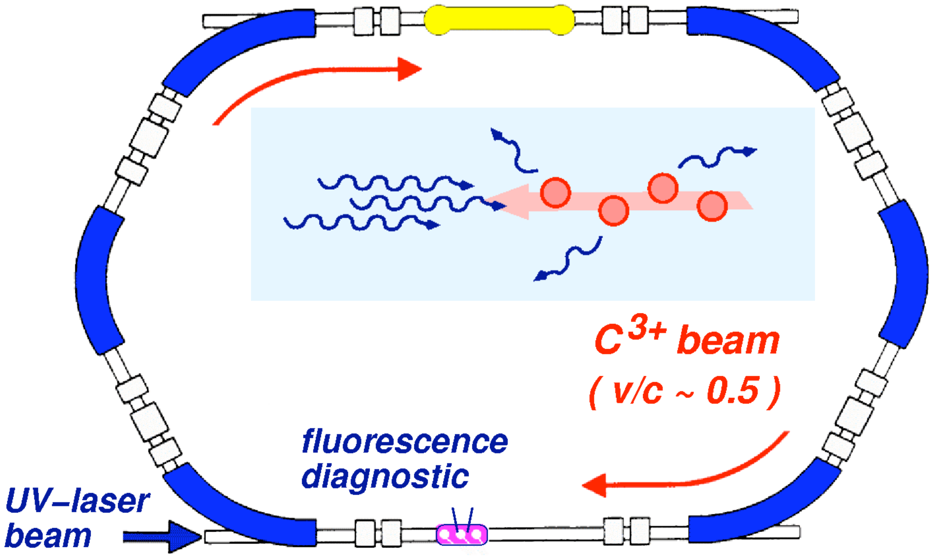
Crystal Monochromator

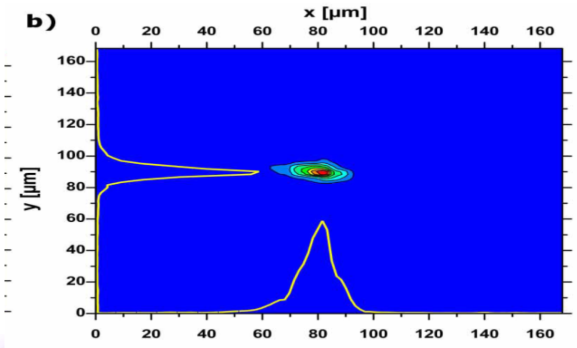
X-Ray Detector

SPARC07 M. Bussmann, U. Schramm, D. Habs et al. www.ha.physik.uni-muenchen.de/uschramm

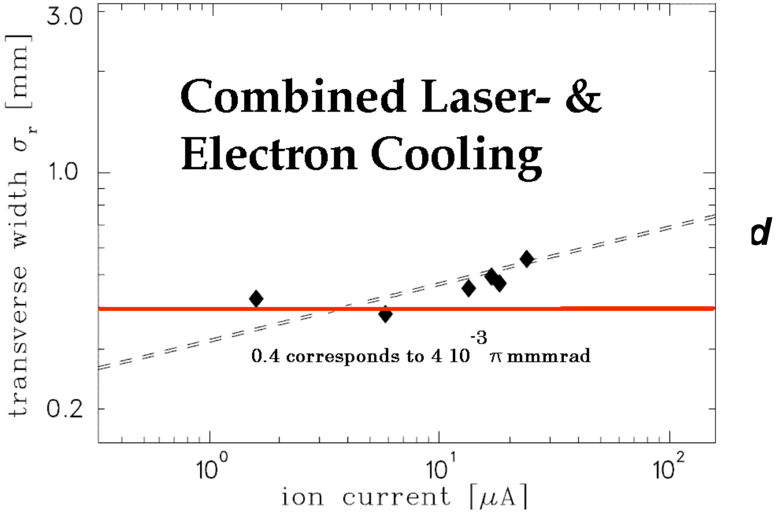
Laser cooling of C^{3+} beams

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





Demonstration of laser cooling of C^{3+} Ions at 122 MeV/u in the ESR for application at SIS 100/300 (2004)



bunch length reduced by a factor 2
beam diameter reduced by a factor 4
momentum spread reduced by a factor 10

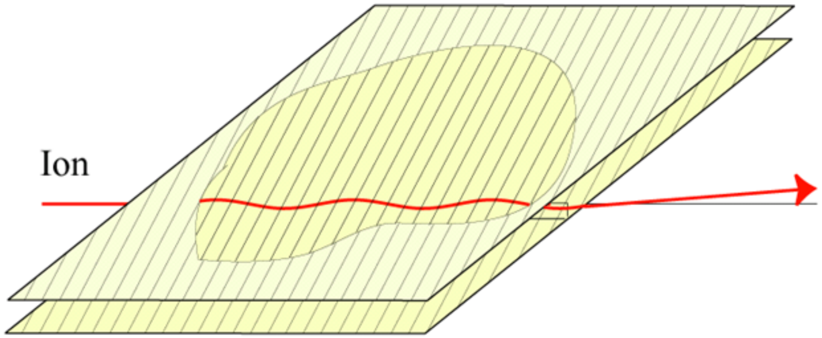
U. Schramm et al.,

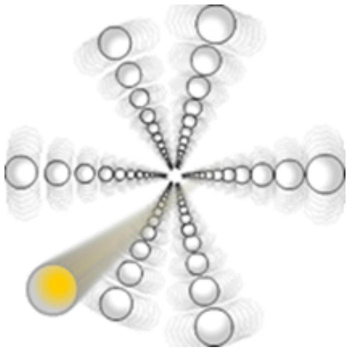
Resonant Coherent Excitation

A New Scheme for High Resolution Spectroscopy within the SPARC collaboration at FAIR

spokes person: Y. Yamazaki (RIKEN)

$$\boxed{E \sim \gamma h n(k\cos\theta + l\sin\theta)}$$





Characteristics of Resonant Coherent Excitation

✓ very high efficiency
→ ideal for low beam intensities: Radioactive Beams

✓ very high energy resolution not limited by detectors

Takes full advantage of cold ion beams

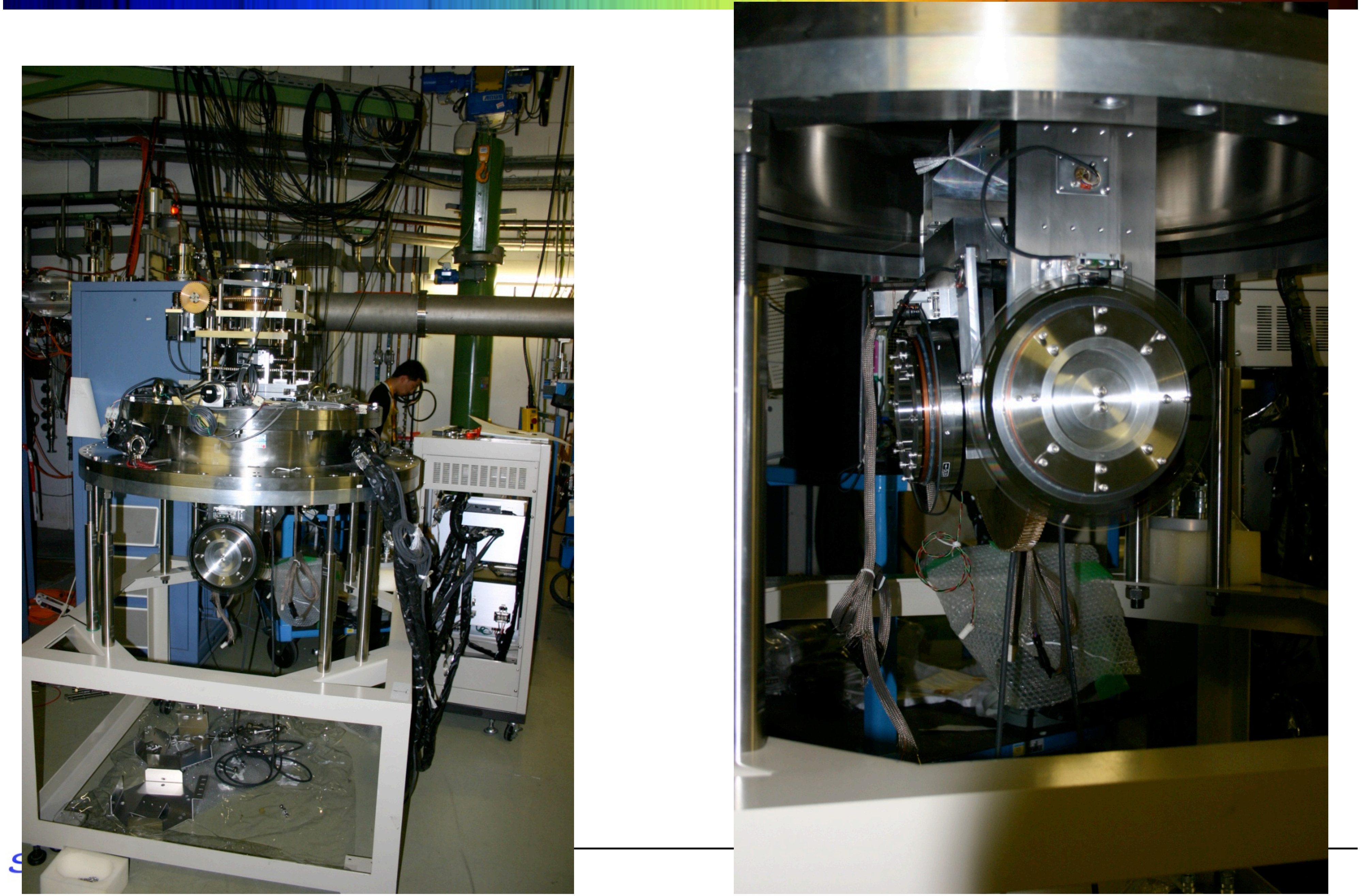
→ Major part of the SPARC activities at FAIR with

- heavy, highly charged ions
- beam energies up to 10GeV/u

A first test experiment with Li-like uranium at GSI is currently in preparation

FAIR SIS100: excitation of 1s-2p in U^{91+} possible for first time

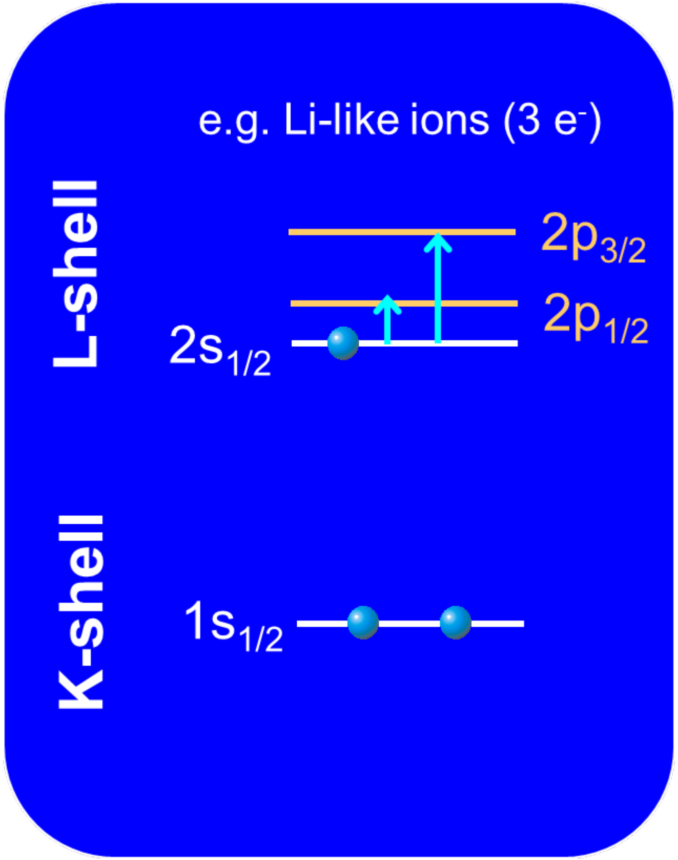
The high-precision goniometer has been shipped from Riken to GSI



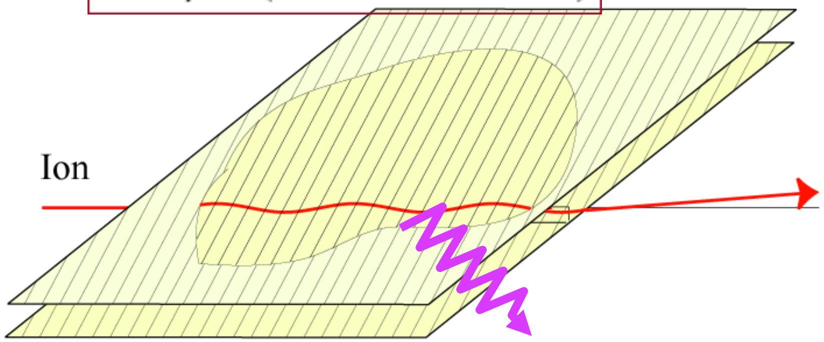
SPARC

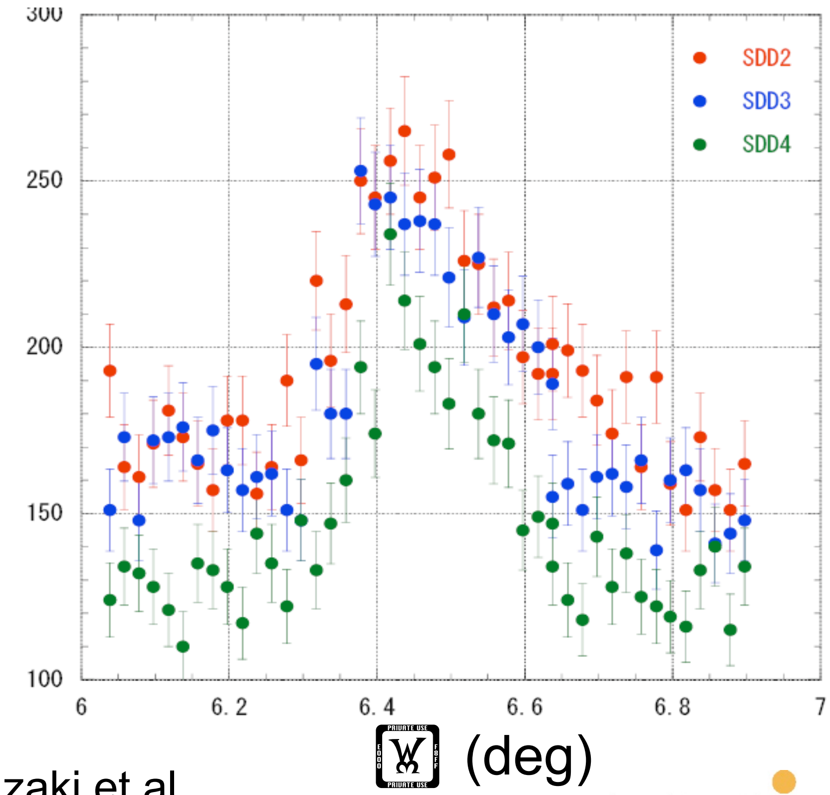
Virtual Photon Spectroscopy by Relativistic Channeling Heavy Ions

Li-like U^{89+} 2s-2p excit. for Lamb shift, Hyperfine (SIS18 September 2009)



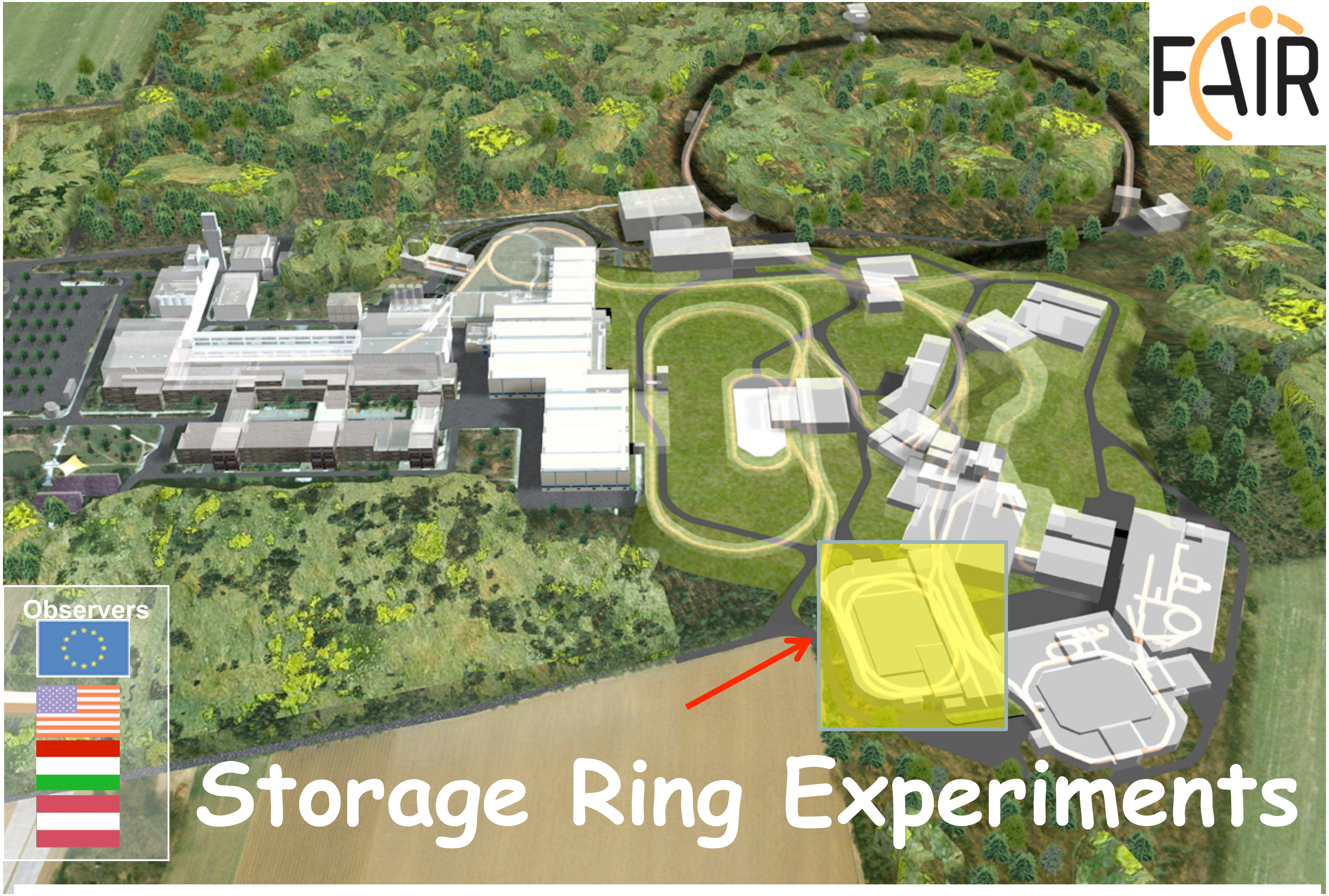
$$E \sim \gamma h n (k \cos\theta + l \sin\theta)$$



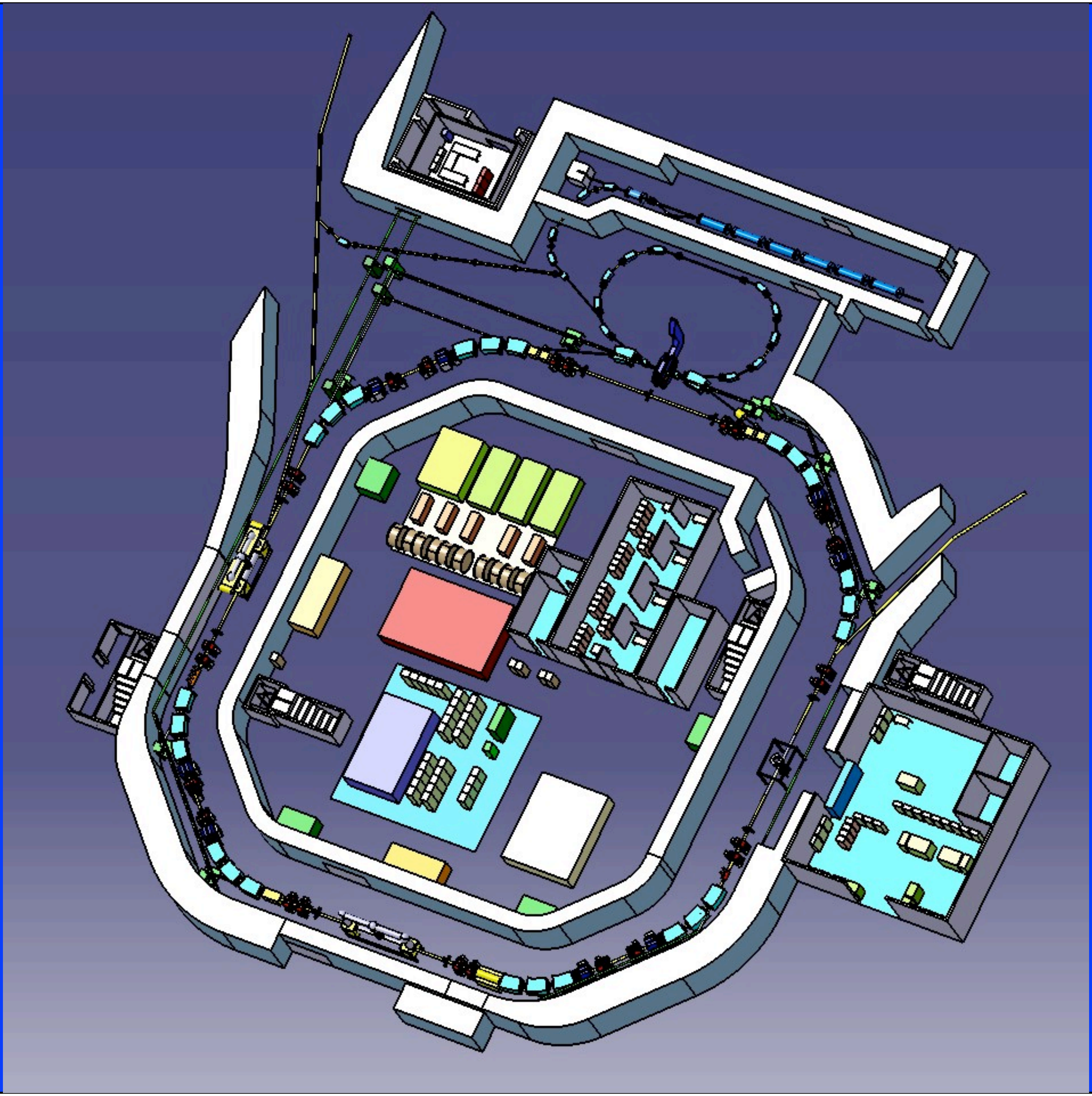


T. Azuma, A. Bräuning-Demian, H. Bräuning, Y. Yamazaki et al.

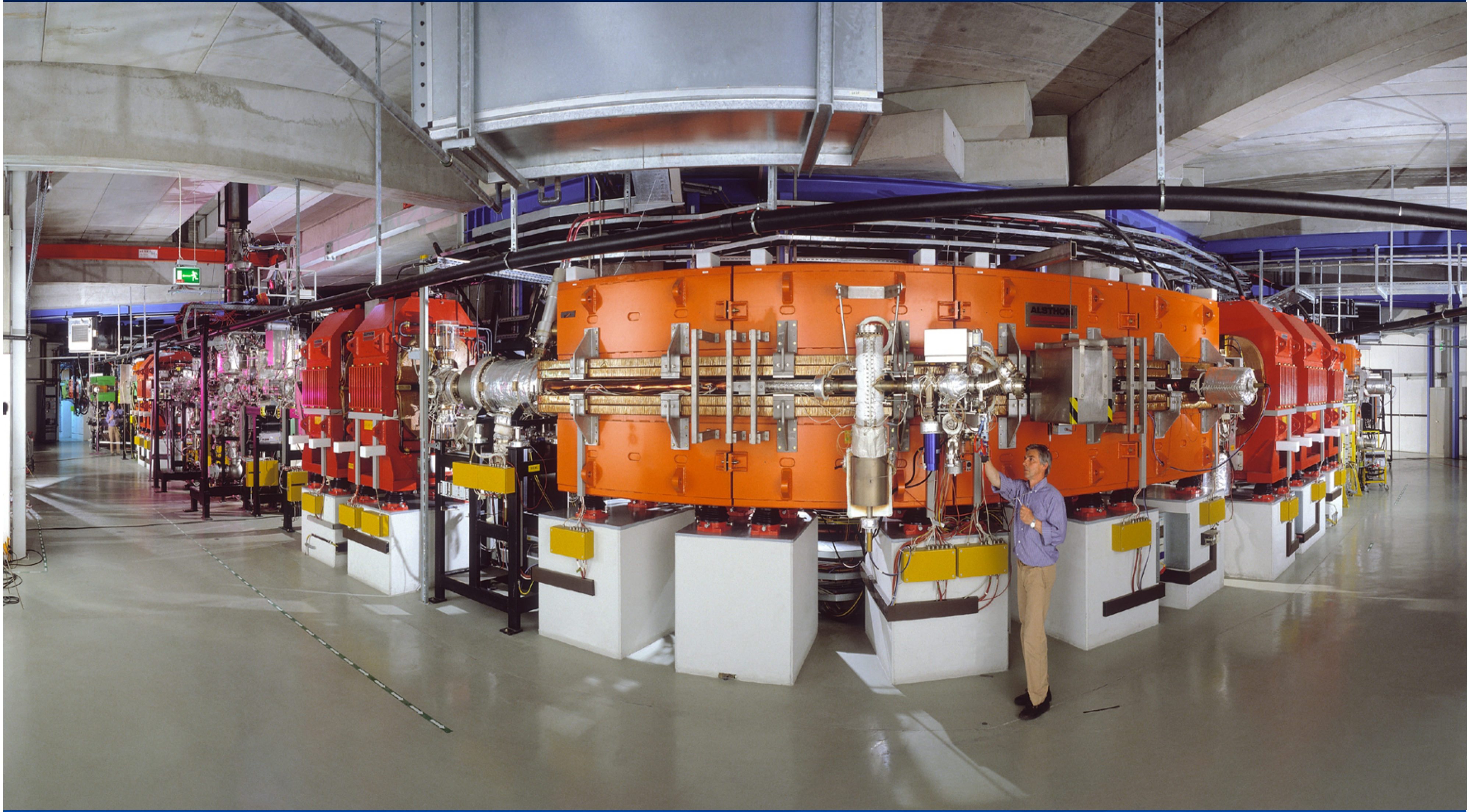
Storage Ring Experiments



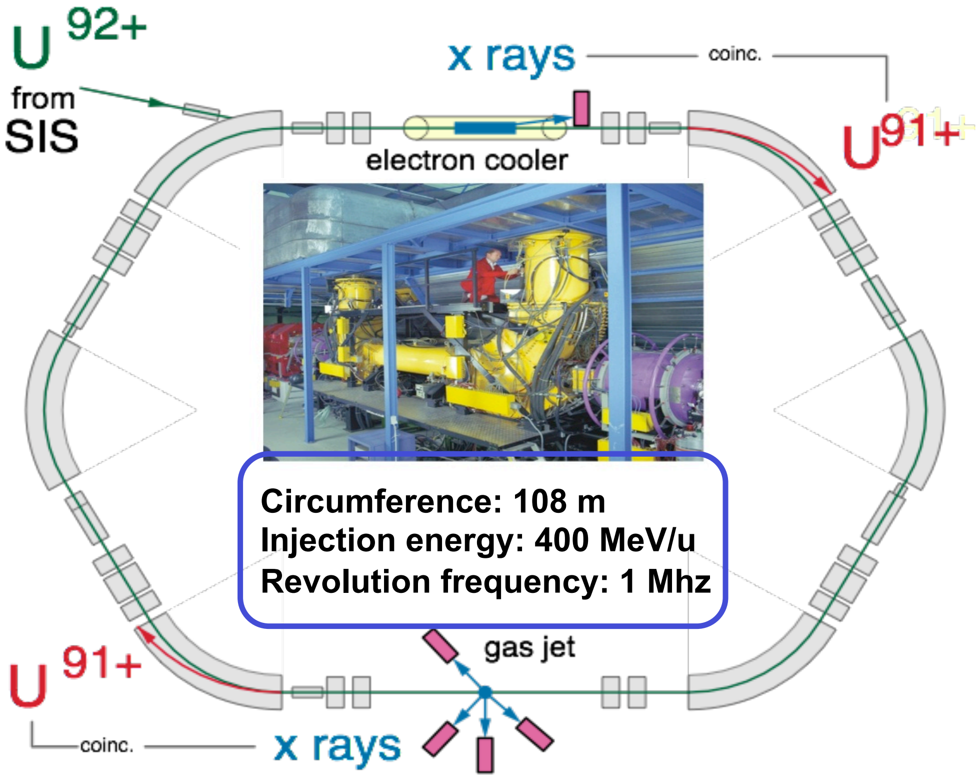
CN DE ES FI FR GB GR IN IT PL RO RU SE



The Experimental Storage Ring, ESR

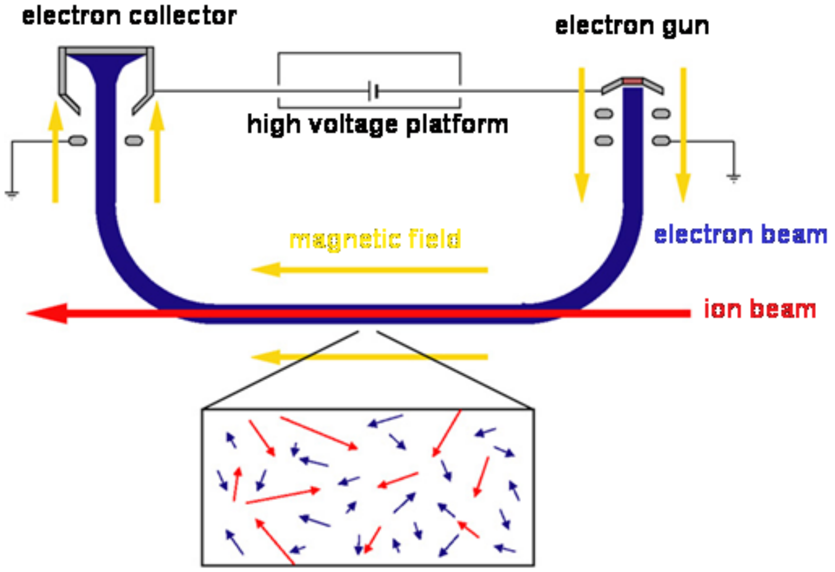


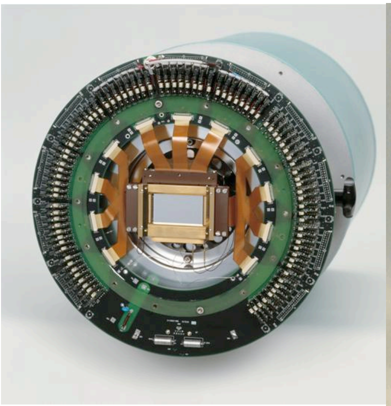
The Experiment Storage Ring ESR

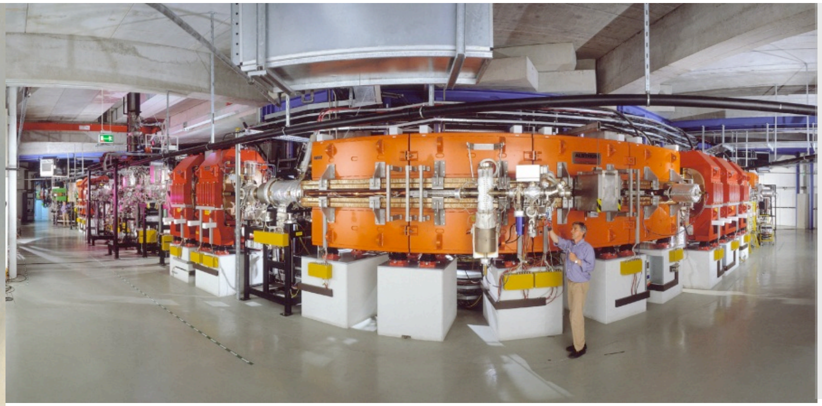


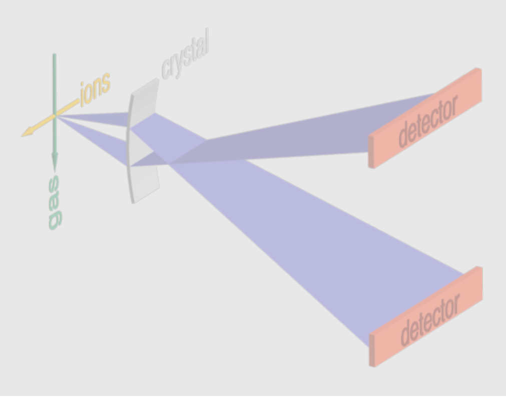
Circumference: 108 m
Injection energy: 400 MeV/u
Revolution frequency: 1 Mhz

Electron Cooling





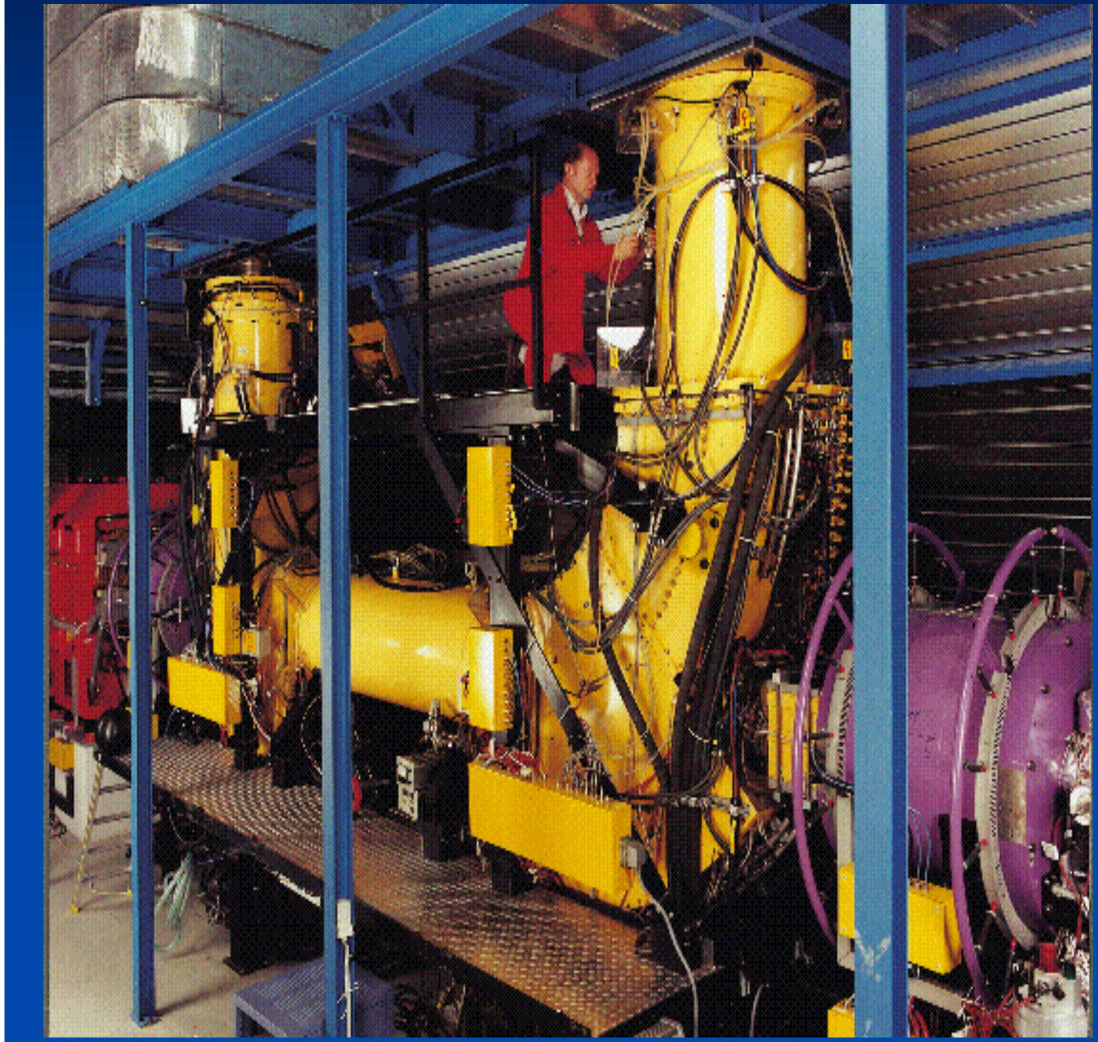


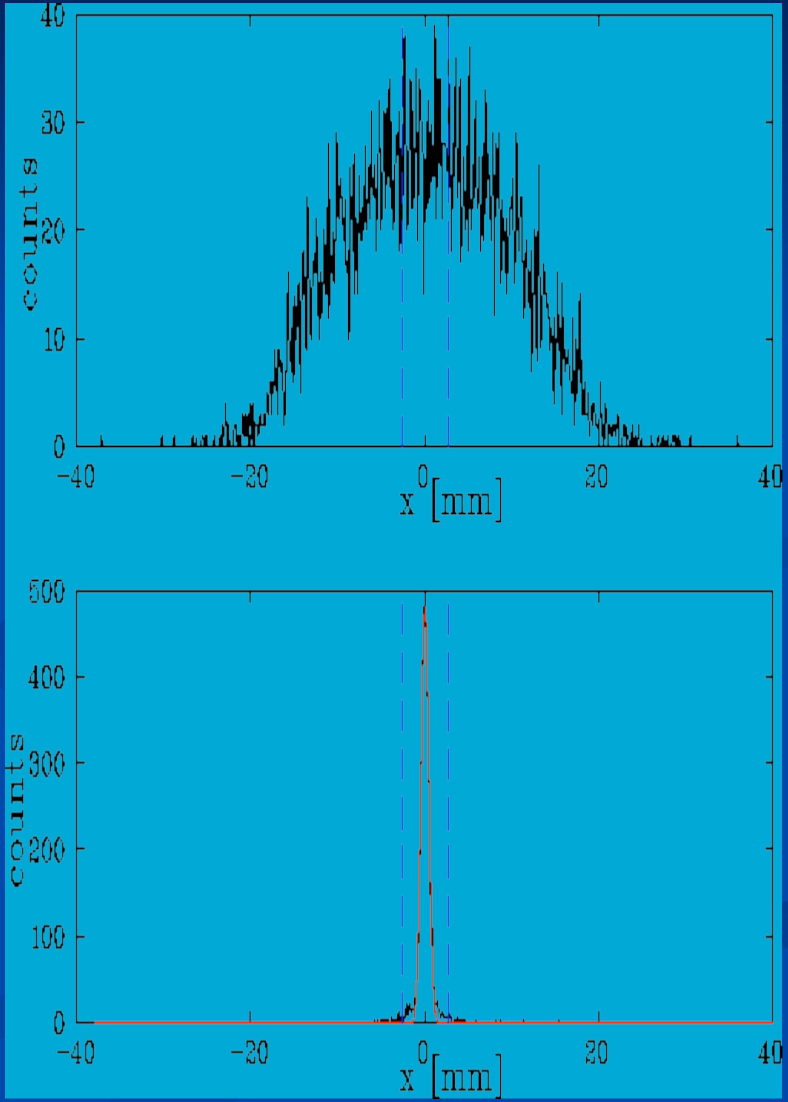


Storing and Cooling

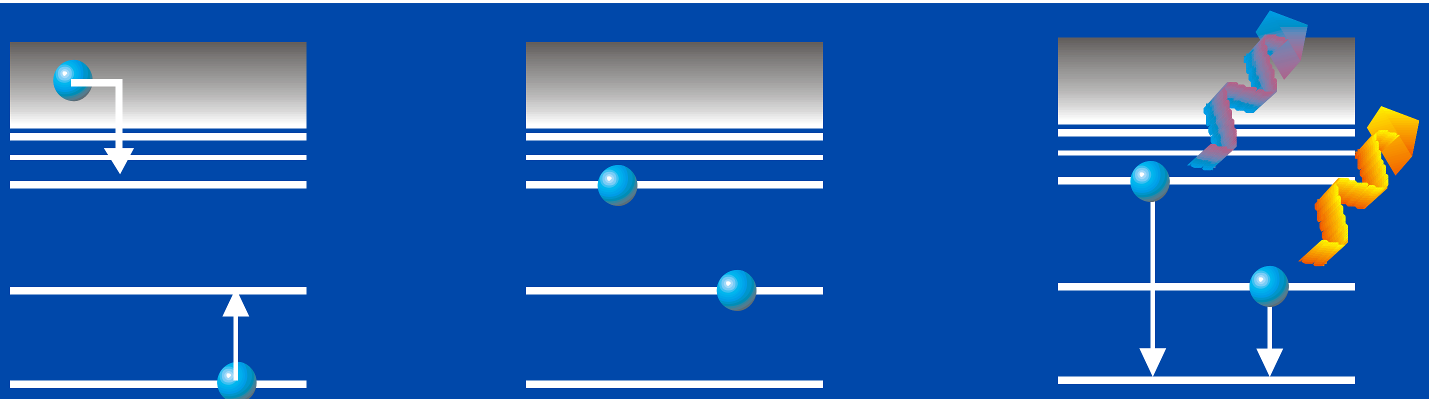
Detector and Spectrometers

Cooling = narrowing the velocity, the size, and the divergence of the stored ion beam

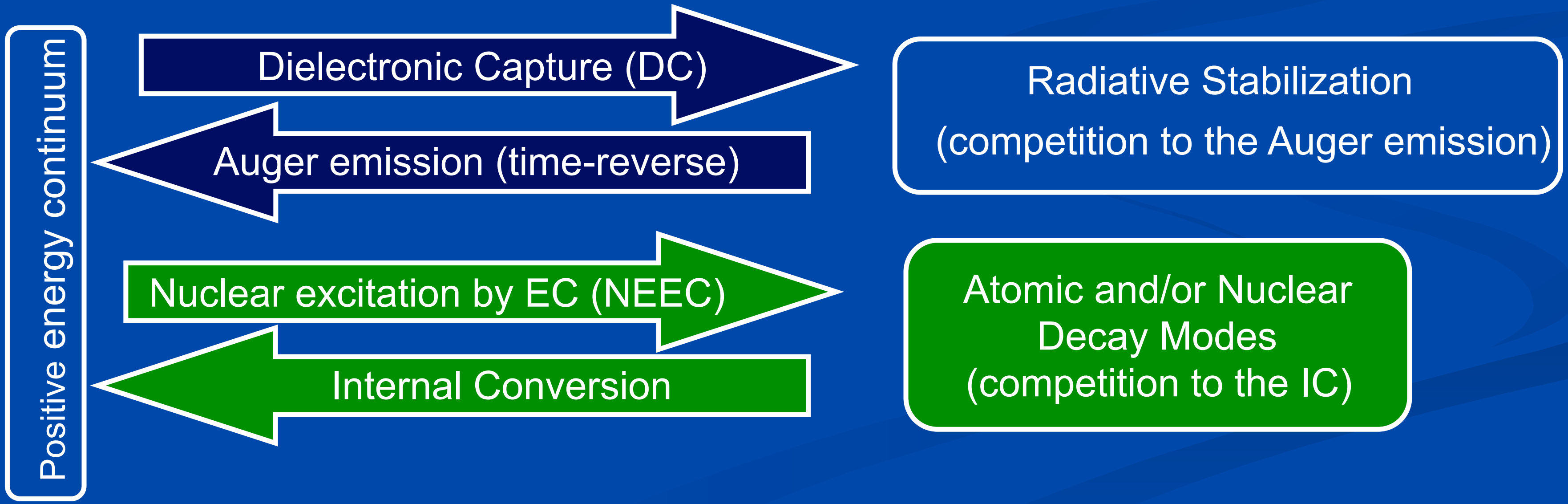




Photorecombination/Dielectronic Recombination = = Inverse Auger Spectroscopy



$$A^{q+} + e^- \rightarrow [A^{(q-1)+}]^{**} \rightarrow A^{(q-1)+} + n \cdot h\nu$$



Positive energy continuum

Dielectronic Capture (DC)

Auger emission (time-reverse)

Nuclear excitation by EC (NEEC)

Internal Conversion

Radiative Stabilization

(competition to the Auger emission)

Atomic and/or Nuclear Decay Modes
(competition to the IC)

Photorecombination in Cosmic Plasmas

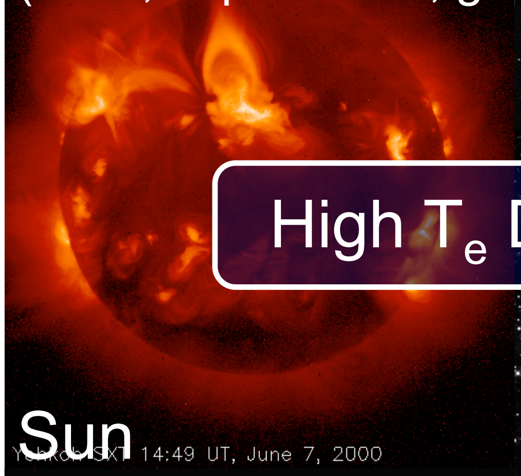
Courtesy D.W. Savin, Columbia Astrophysics Lab (CAL), New York, N.Y.

electron ionized
(stars, supernovae, galaxies, …)

photoionized (radiation field)
(PNebulae, x-ray binaries, AGNs,…)

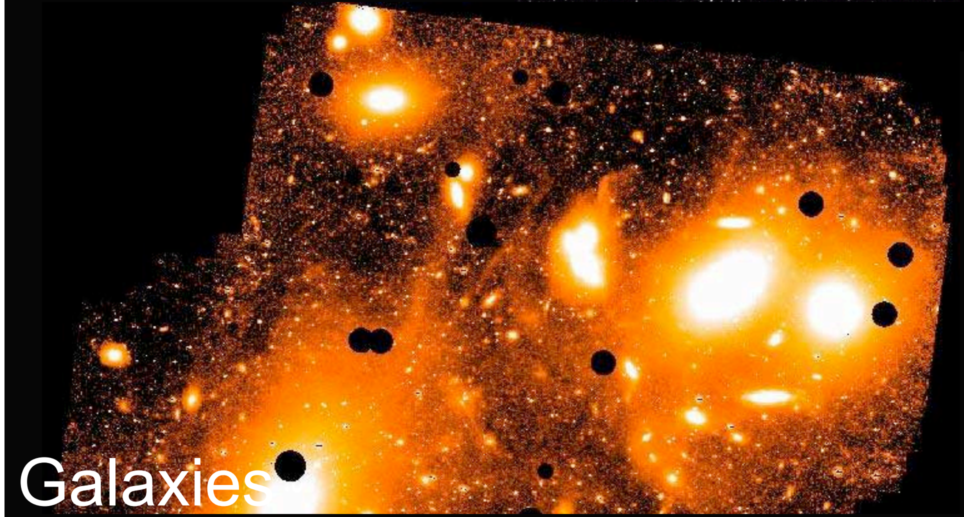
High T_e DR

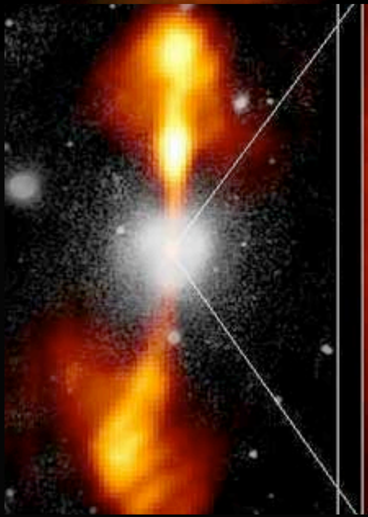
Low T_e DR


Sun


SNR

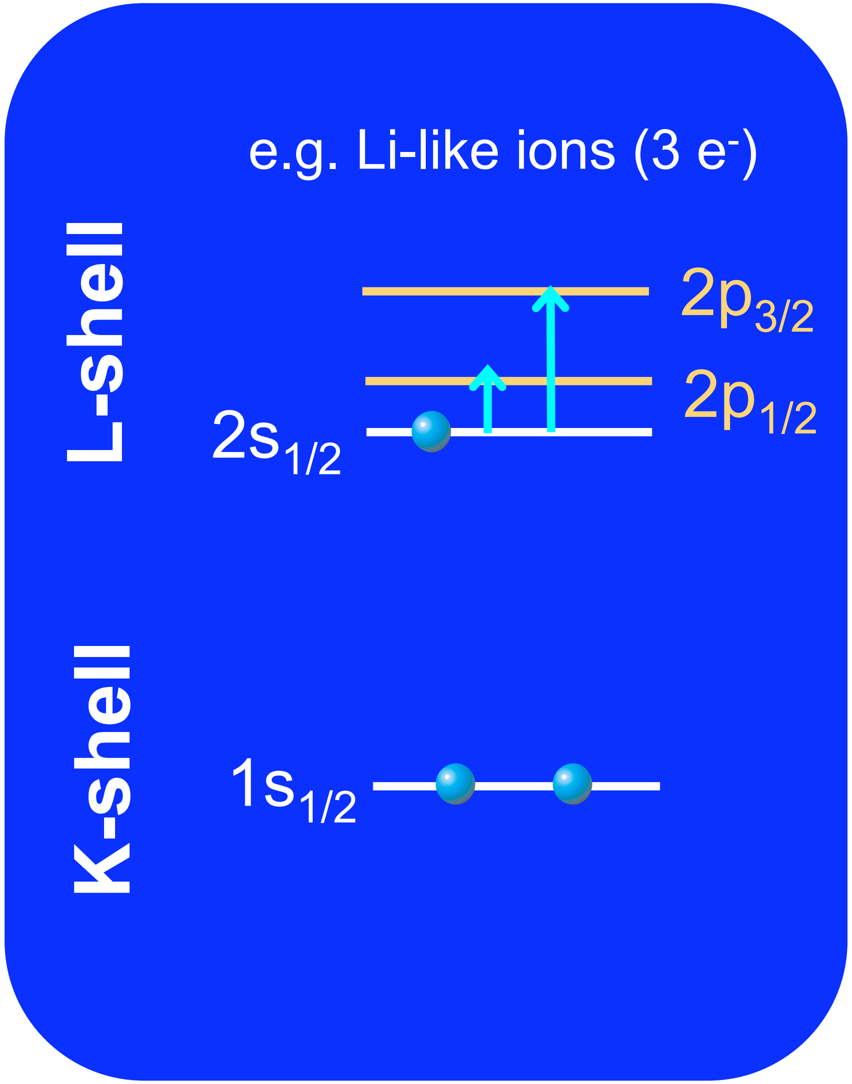

XRBs


Galaxies



Christophor Kozhuharov et al.

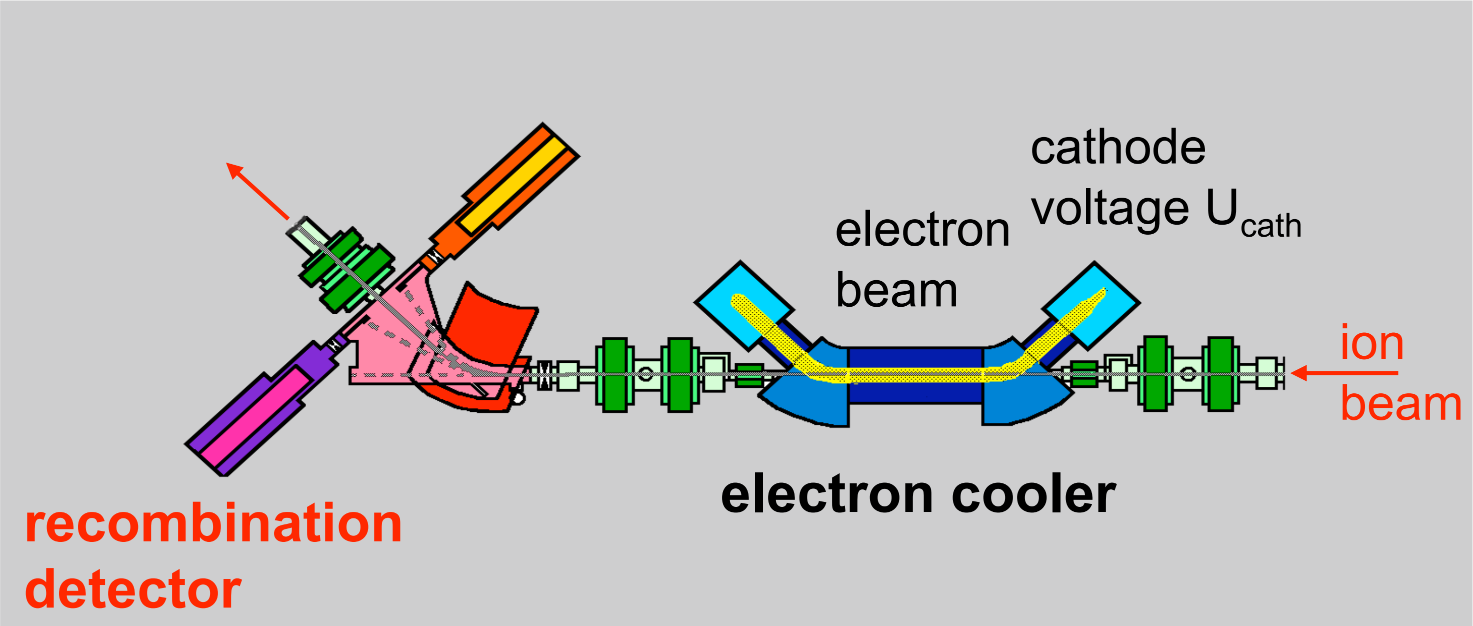
Why Investigate L-shell Ions (Li-like, Be-like,…)?



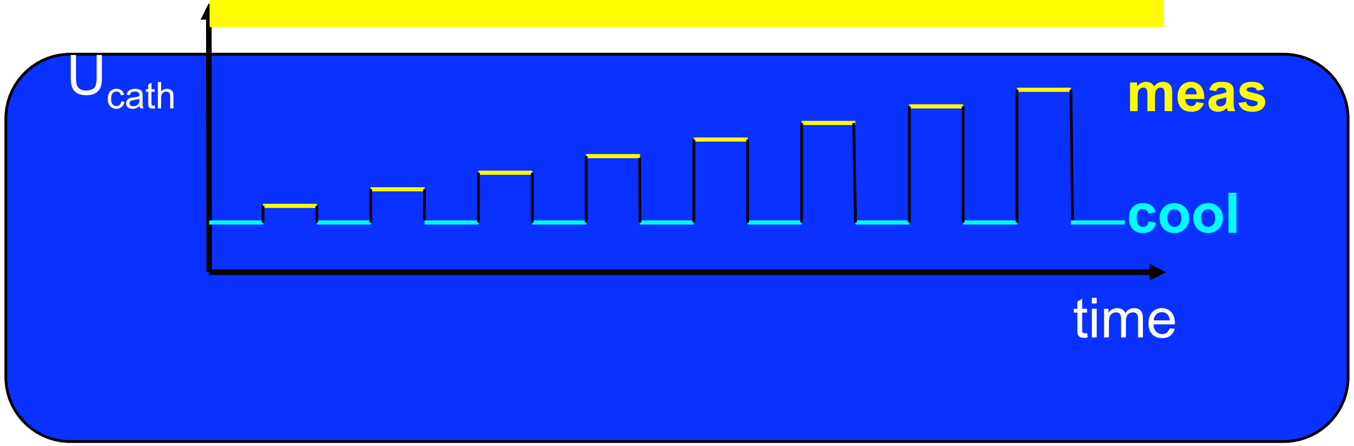
- simplest atomic systems with „low-energy“ intra-shell transitions ($\Delta n = 0$)
- large contributions from QED and nuclear size

  ⇒ high sensitivity
- simple to describe theoretically, e.g. Li-like
  ⇒ 1 „valance“ electron with small contributions from e-e-interaction

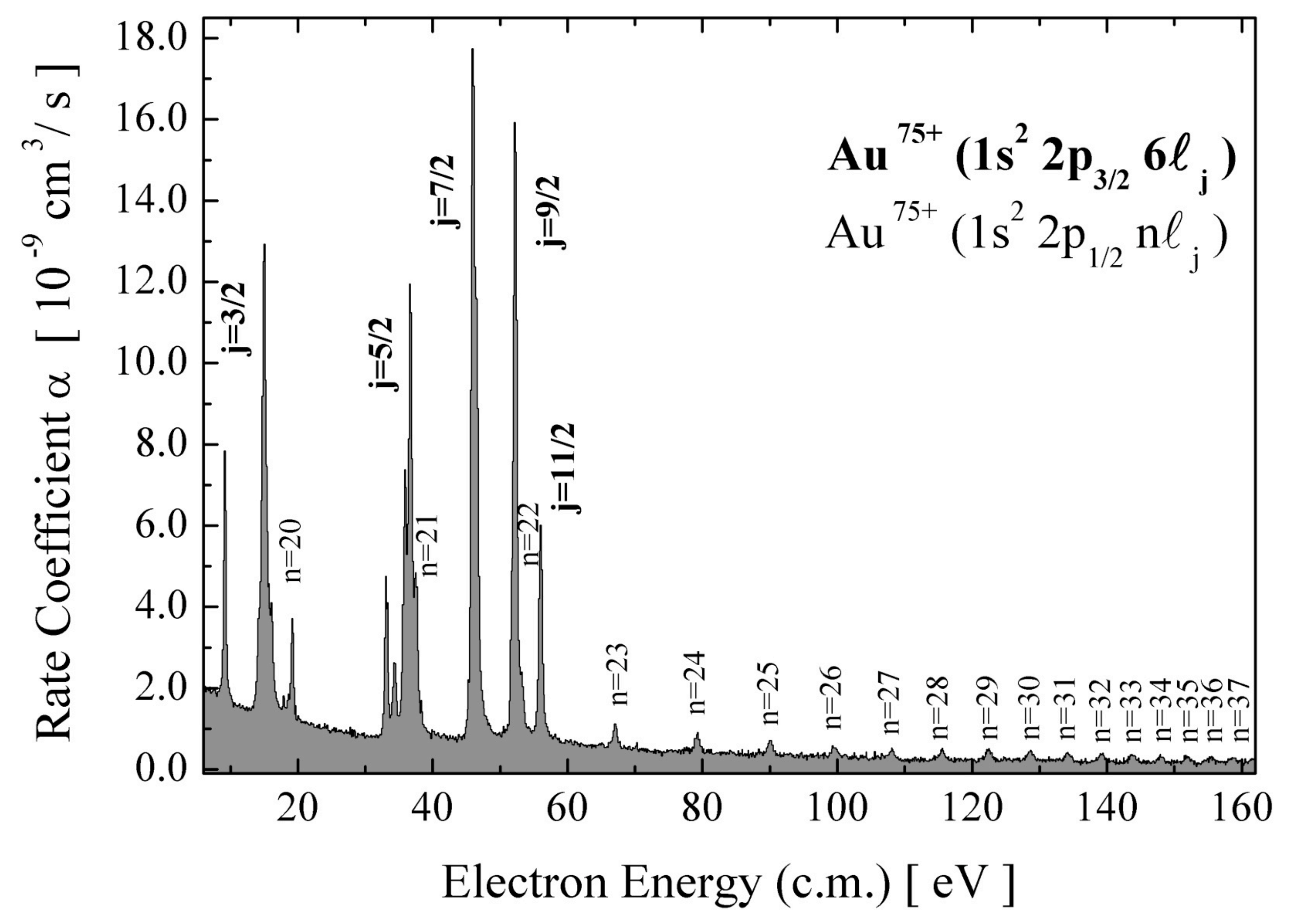
Dielectronic Recombination: The Technique



merged-beams rate coefficient: $\alpha = \langle \sigma v \rangle$

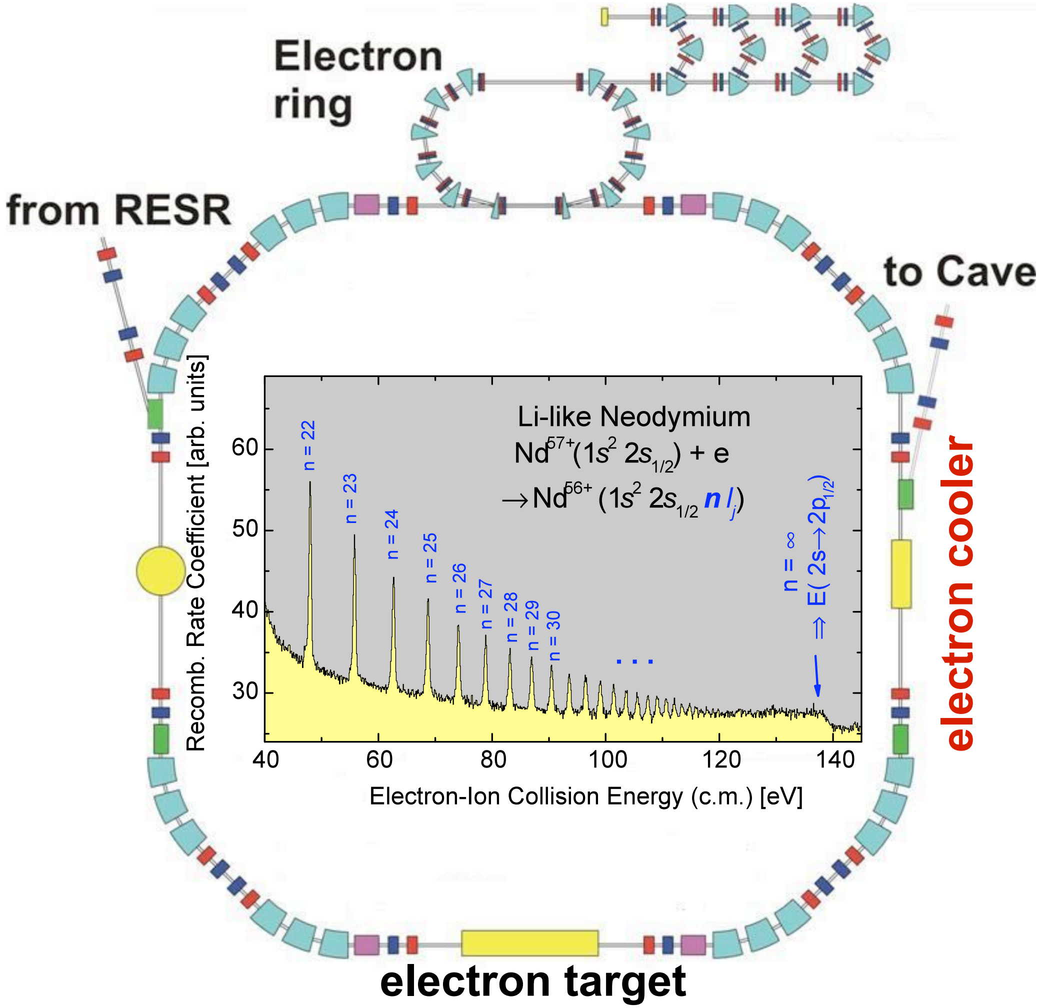


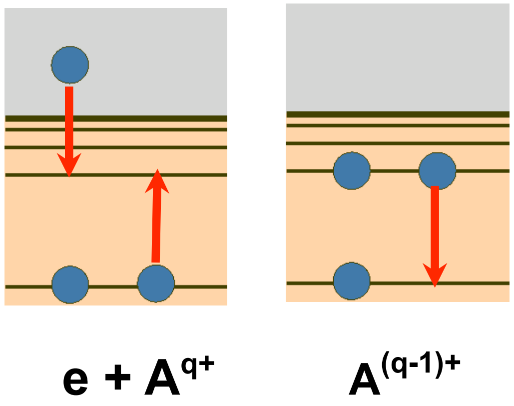
Dielectronic Recombination of Li-like Gold
Spectroscopy with no Photons in Sight



Christophor Kozhuharov et al.

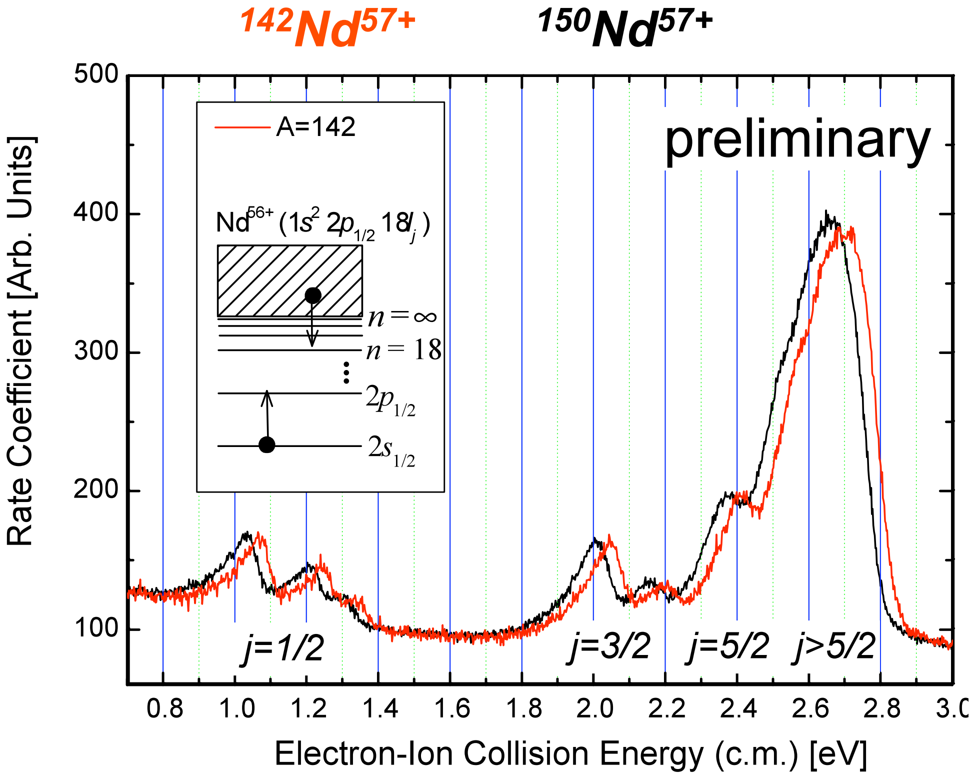
Experiments – at the Electron Target
Dielectronic Recombination





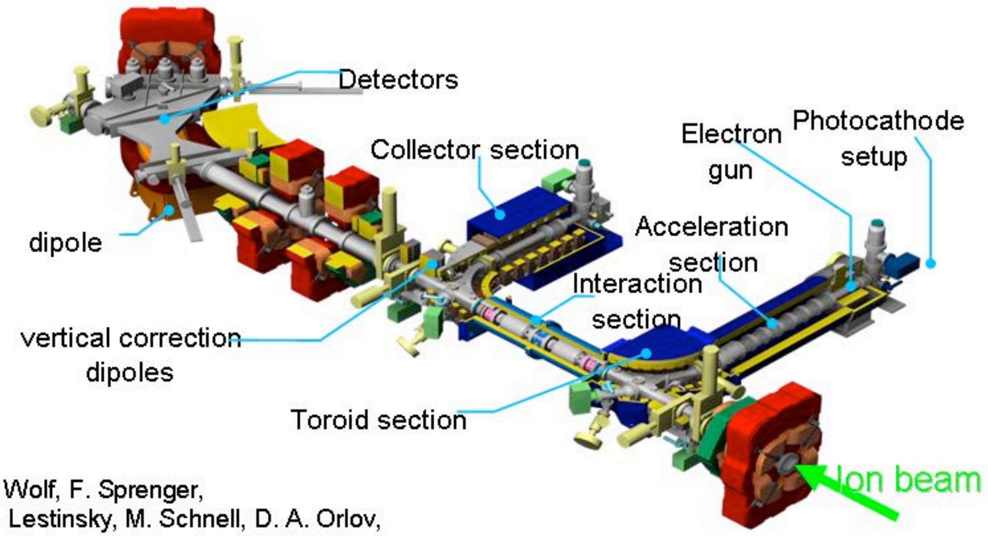
DR experiments for Li-like heavy ions at the ESR: The already achieved accuracy is comparable with the most precise x-ray experiments

DR, a novel technique to measure charge radii of stable and exotic heavy nuclei



C. Brandau, C. Kozhuharov et al., PRL, 2008

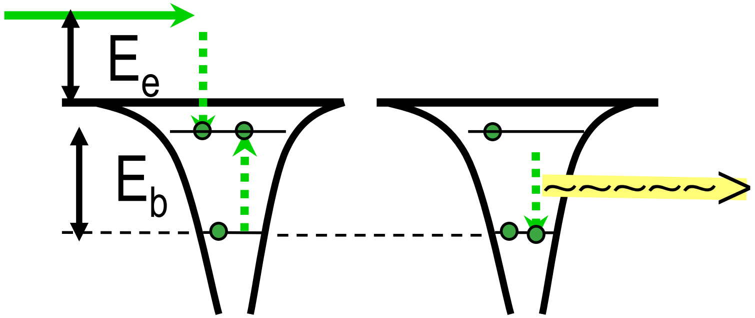
3rd“ generation electron target (dedicated and optimized with respect to experiments)
Adiabatic expansion / adiabatic acceleration of electrons

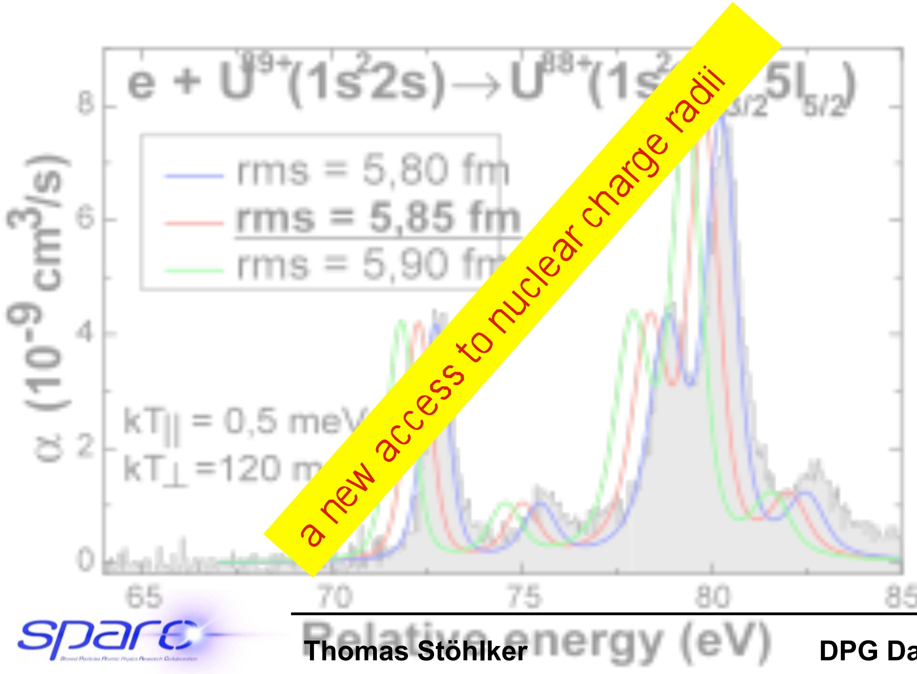


A. Wolf, F. Sprenger,
M. Lestinsky, M. Schnell, D. A. Orlov,
U. Weigel, D. Schwalm, MPI-K HD

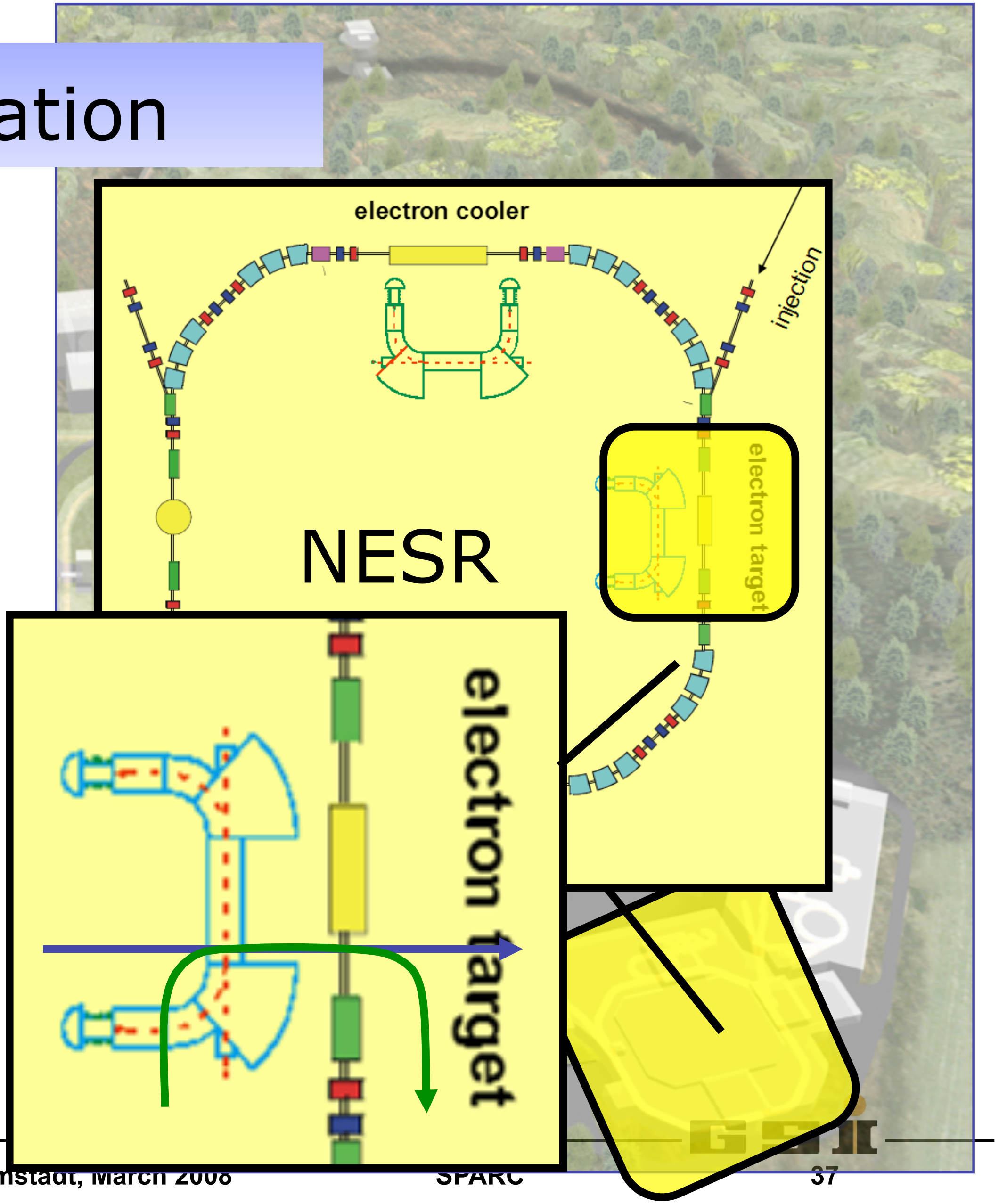
Explore the Nucleus

Dielectronic Recombination

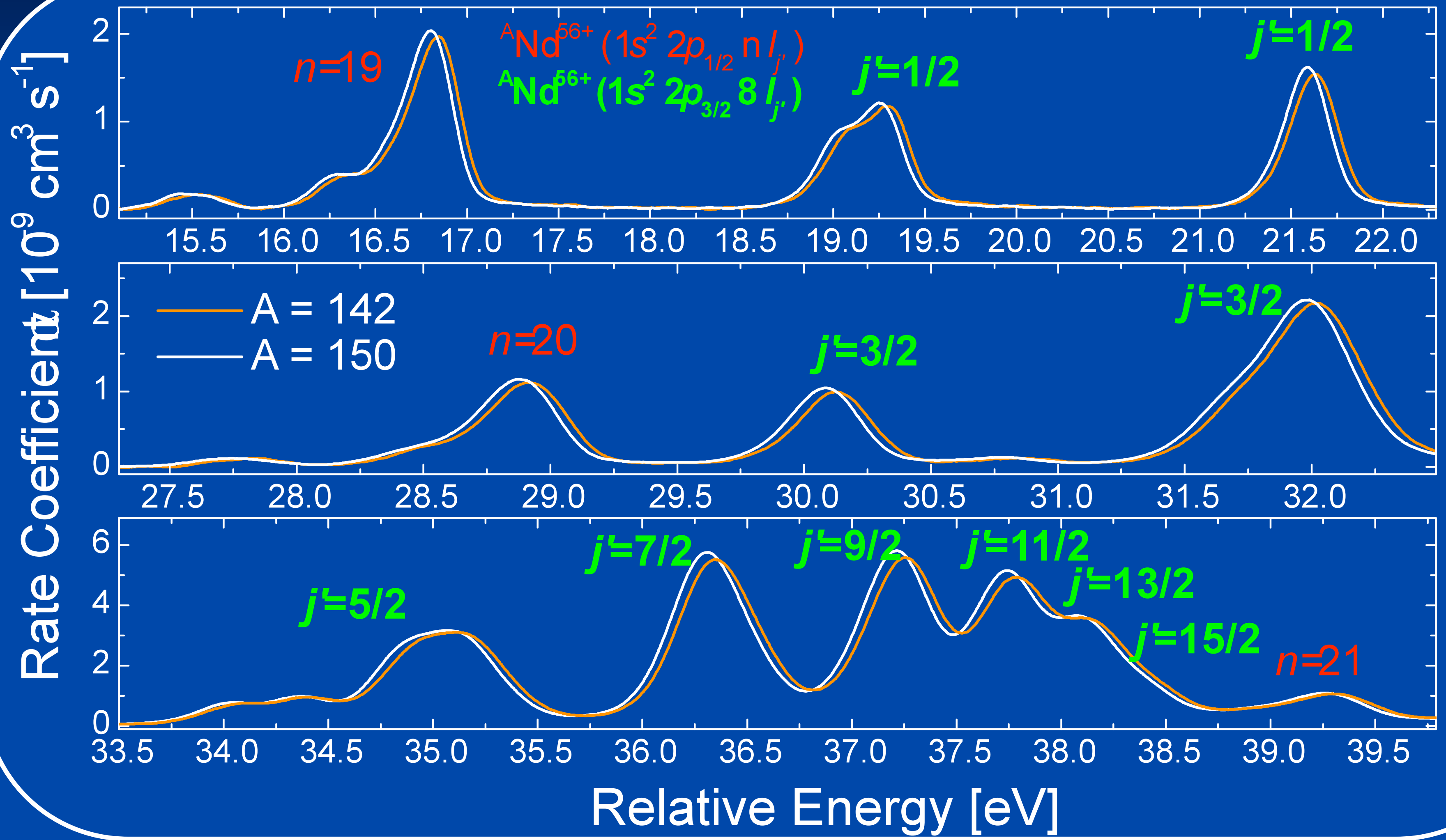




a new access to nuclear charge radii

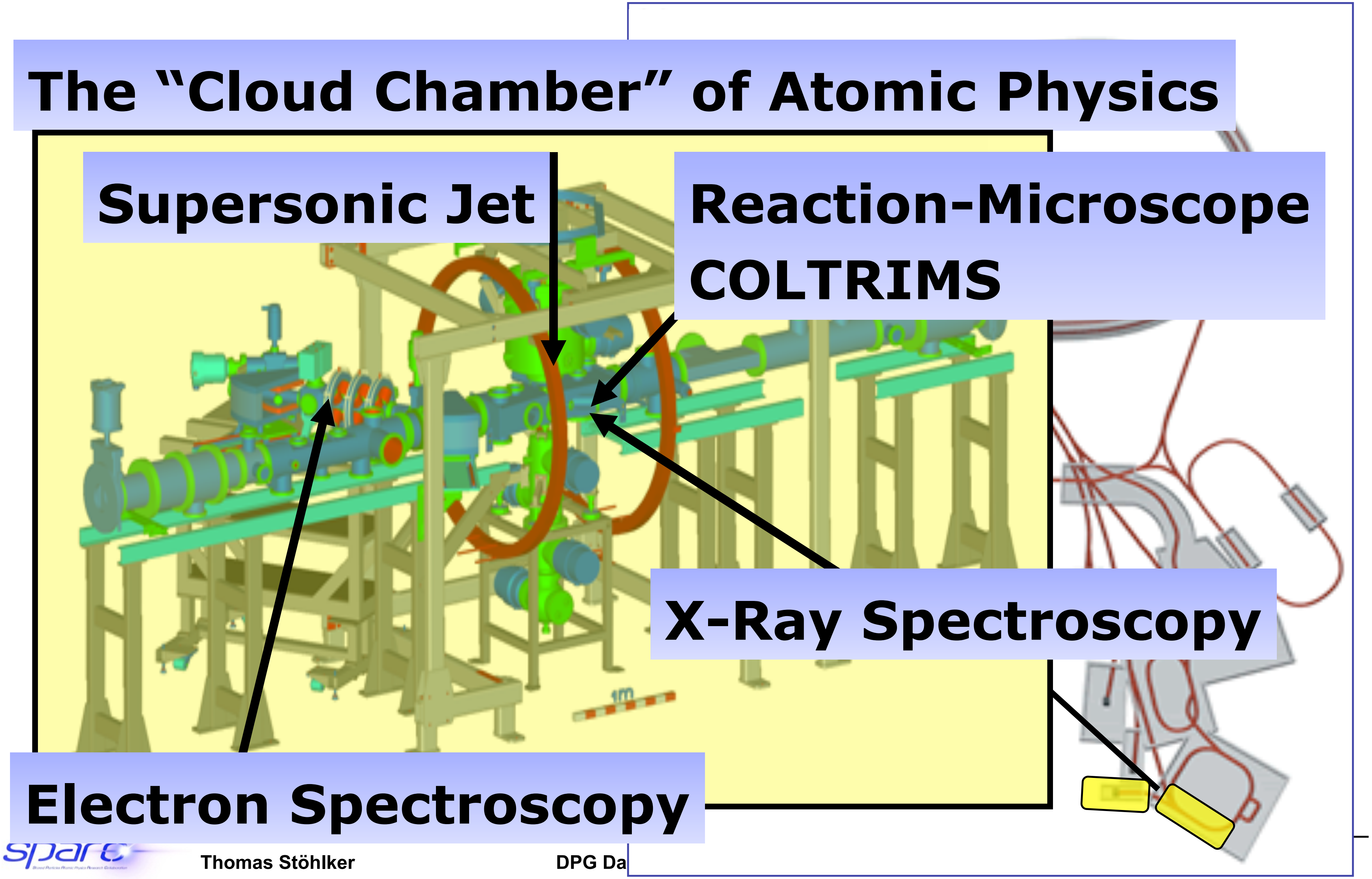


Li-like ^{142}Nd^{57+} vs. ^{150}Nd^{57+}



C. Brandau, et al., PRL **100** (2008) 073201

In-Ring Spectrometers



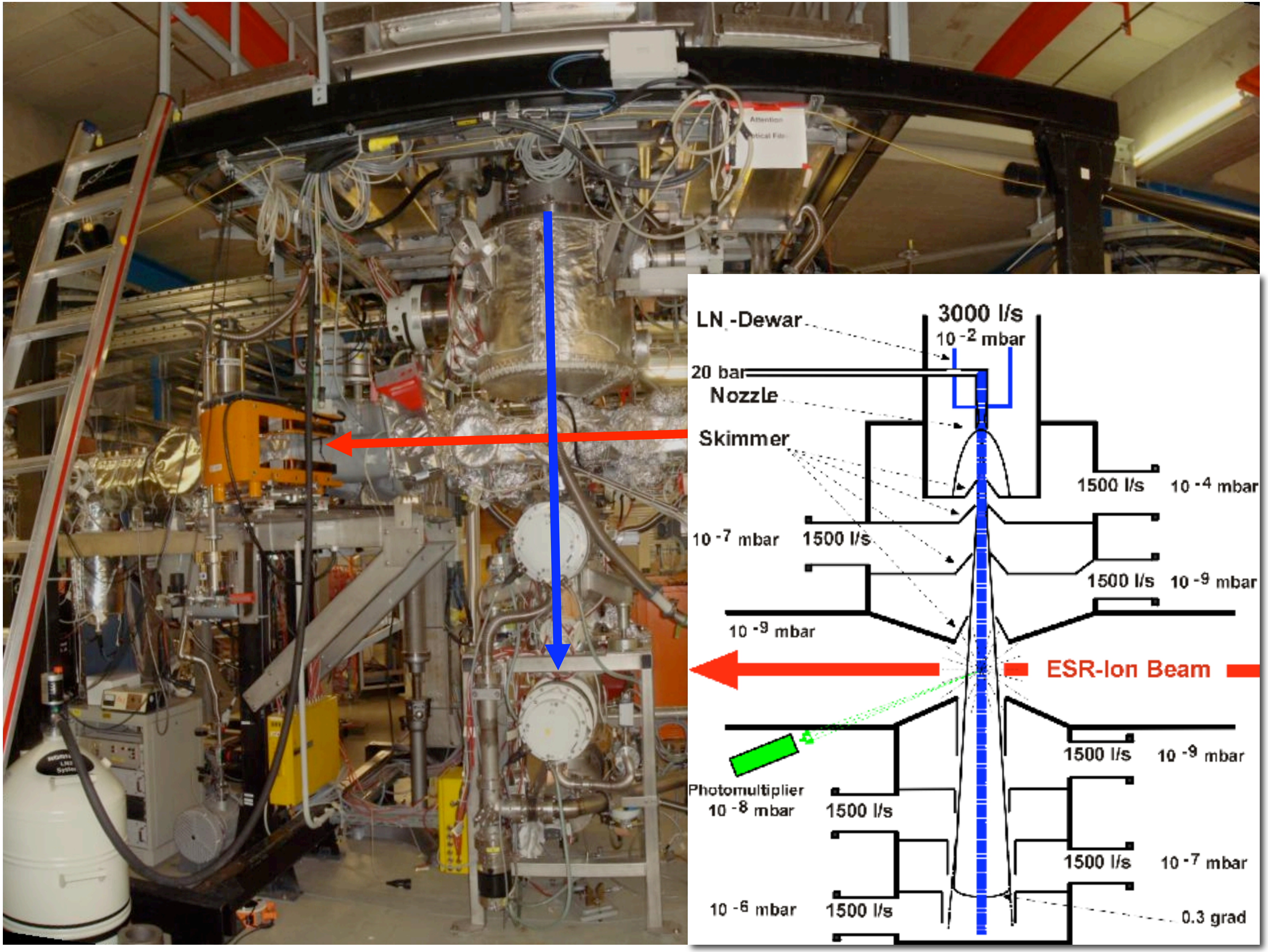
The “Cloud Chamber” of Atomic Physics

Supersonic Jet

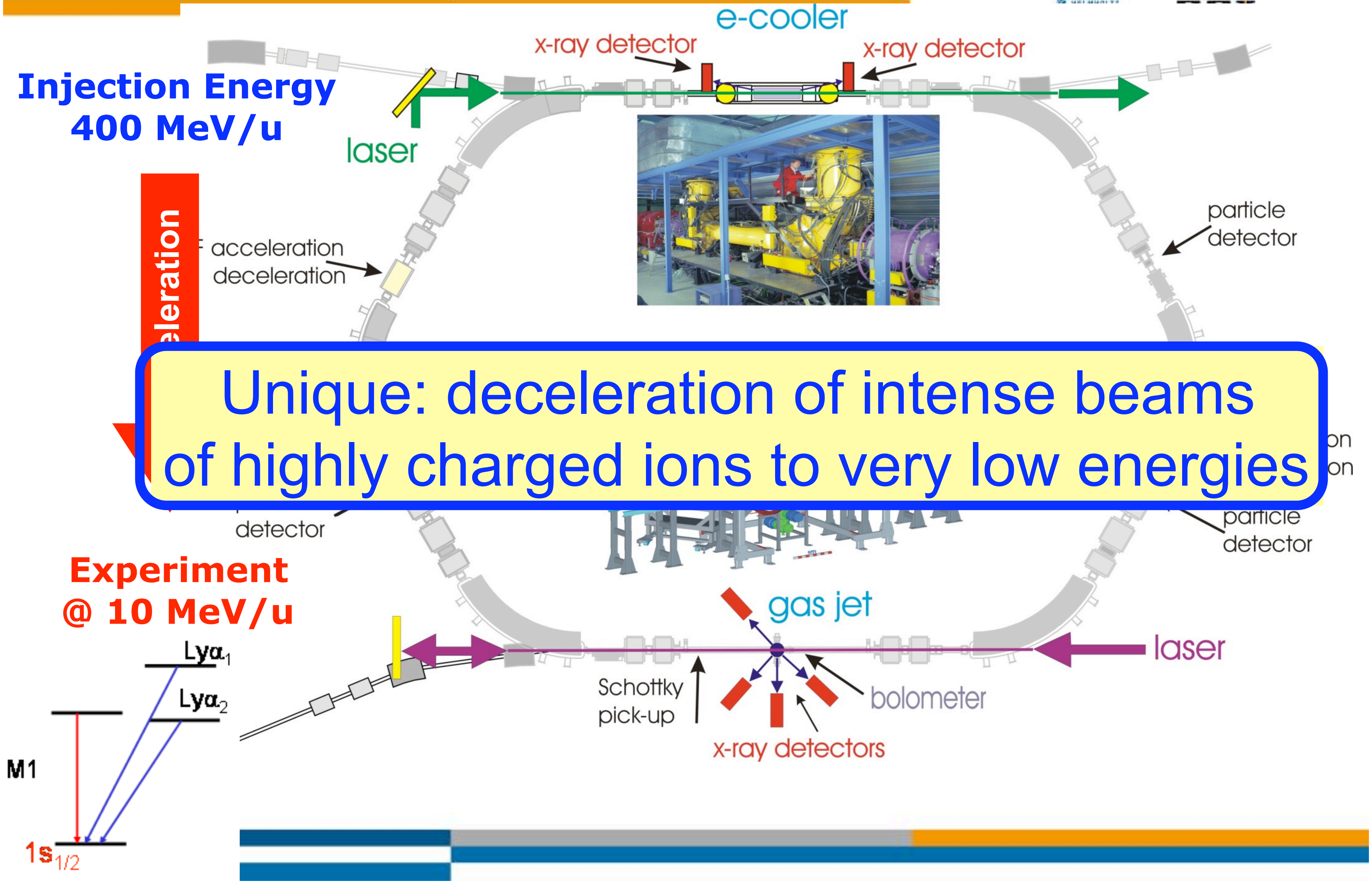
Reaction-Microscope
COLTRIMS

X-Ray Spectroscopy

Electron Spectroscopy


LN -Dewar
3000 l/s
10 -2 mbar
20 bar
Nozzle
Skimmer
1500 l/s
10 -4 mbar
10 -7 mbar
1500 l/s
1500 l/s
10 -9 mbar
10 -9 mbar
ESR-Ion Beam
1500 l/s
10 -9 mbar
Photomultiplier
10 -8 mbar
1500 l/s
1500 l/s
10 -7 mbar
10 -6 mbar
1500 l/s
0.3 grad
Attention
Optical Fib

X-Ray Spectroscopy at the ESR



Injection Energy
400 MeV/u

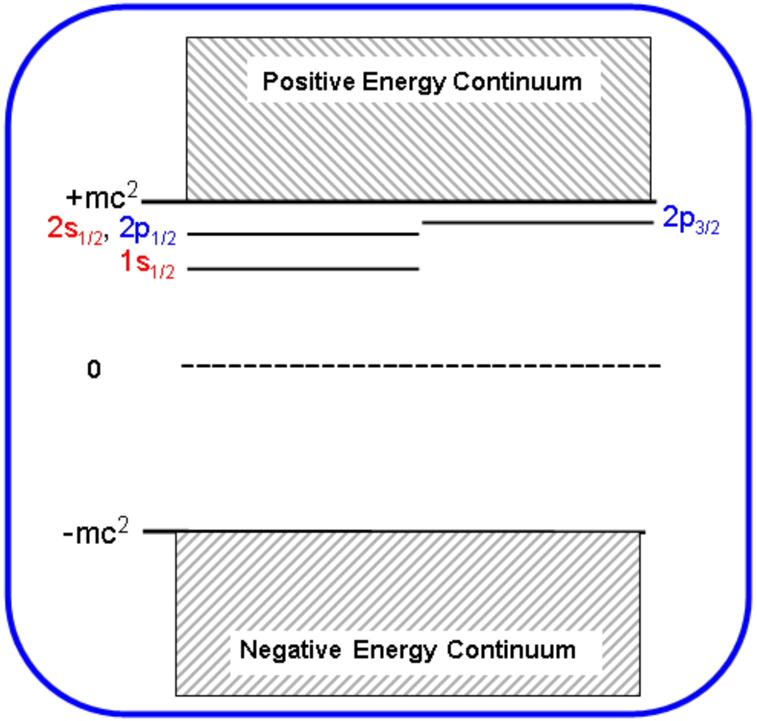
Unique: deceleration of intense beams of highly charged ions to very low energies

Experiment
@ 10 MeV/u

Dirac

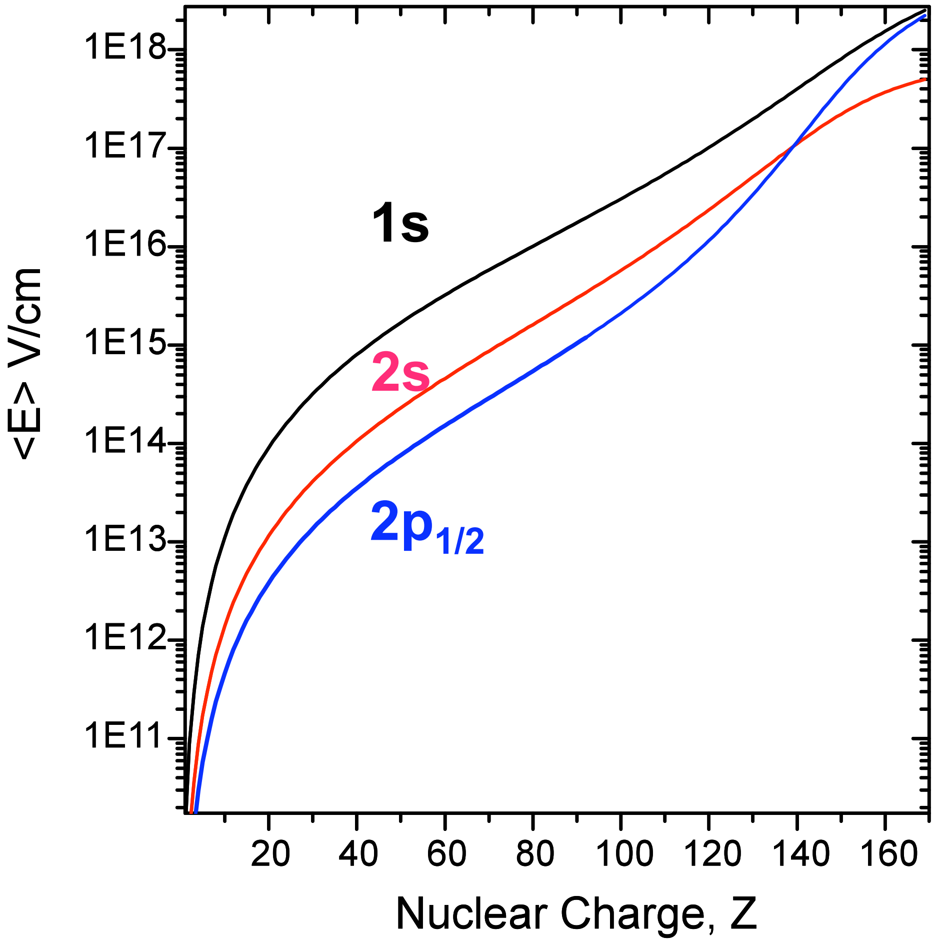
$$E_{1s} = mc^2\sqrt{1-(Z\alpha)^2}$$ (total energy)

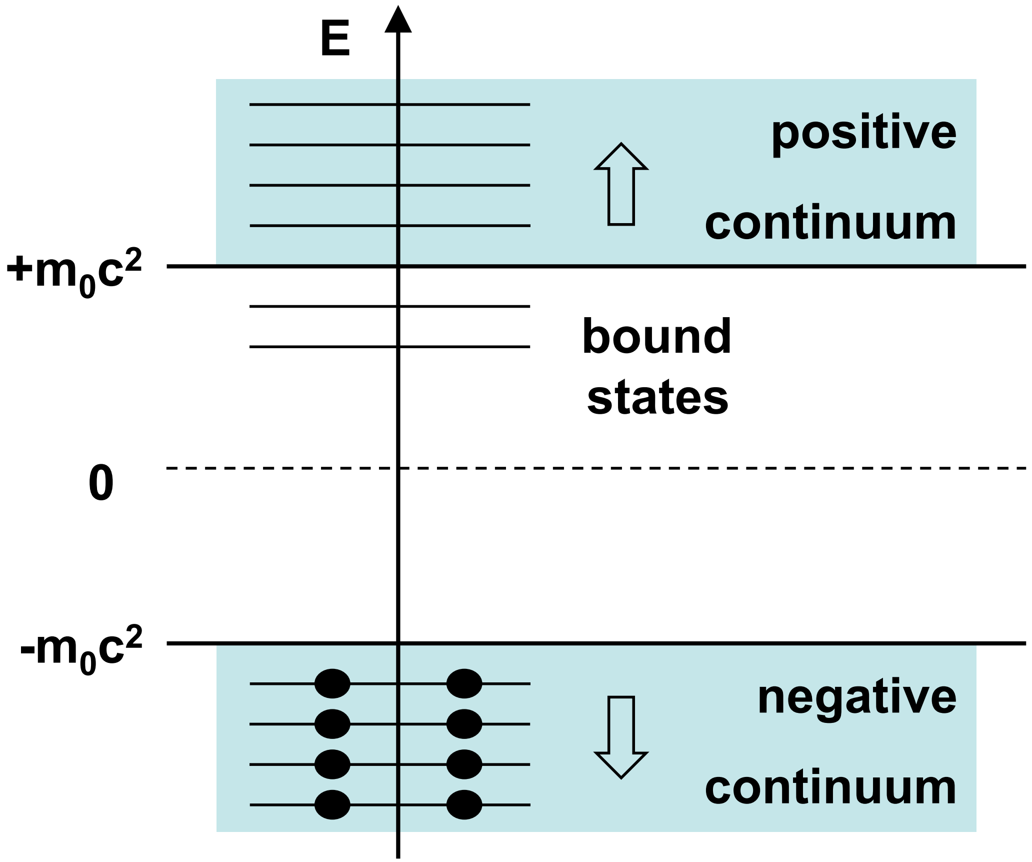
First excited states of one-electron ions



What about supercritical fields ?

Critical- and Supercritical Fields

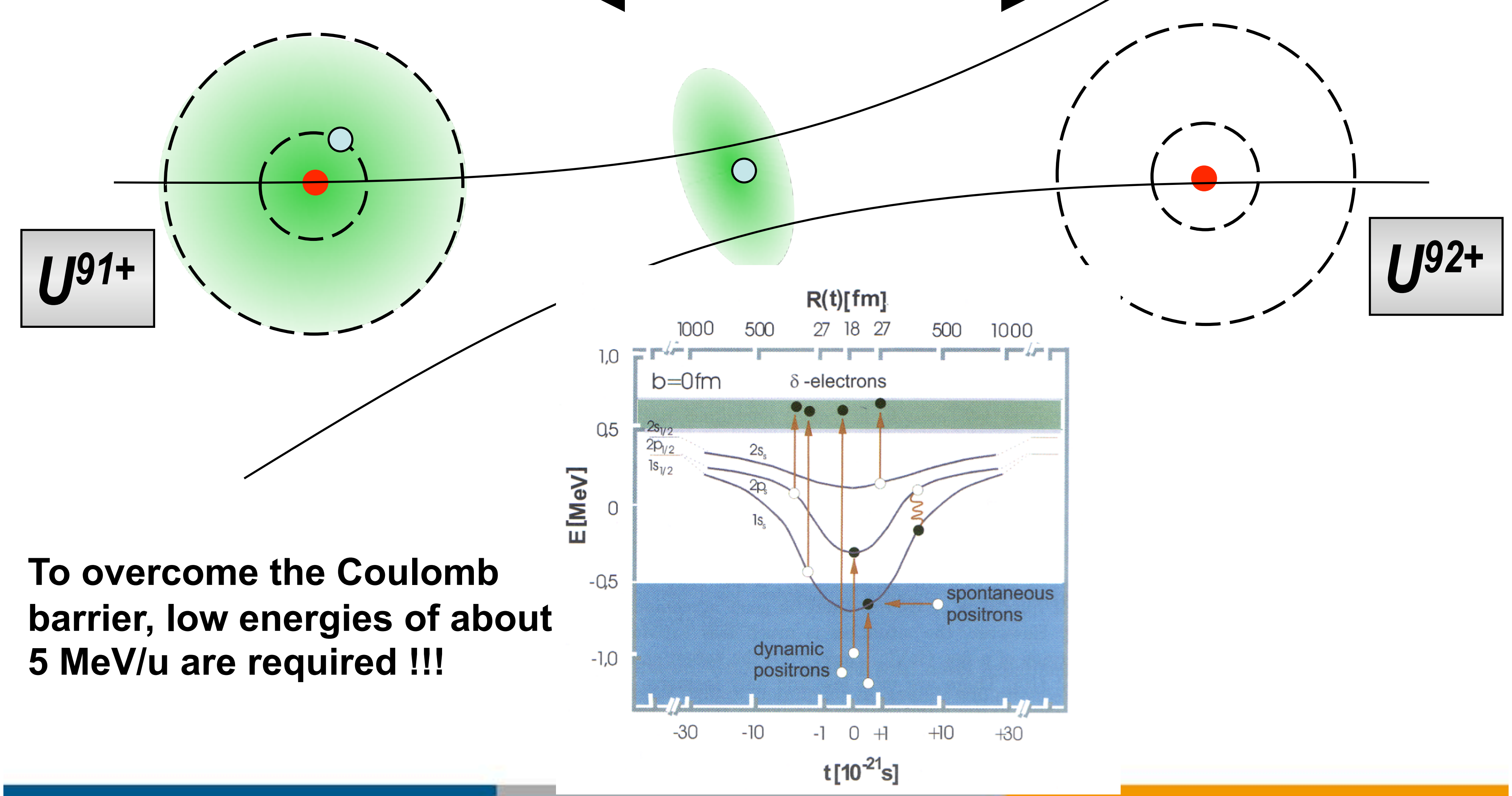




Supercritical fields

Merge

Formation of a Quasi-Molecule

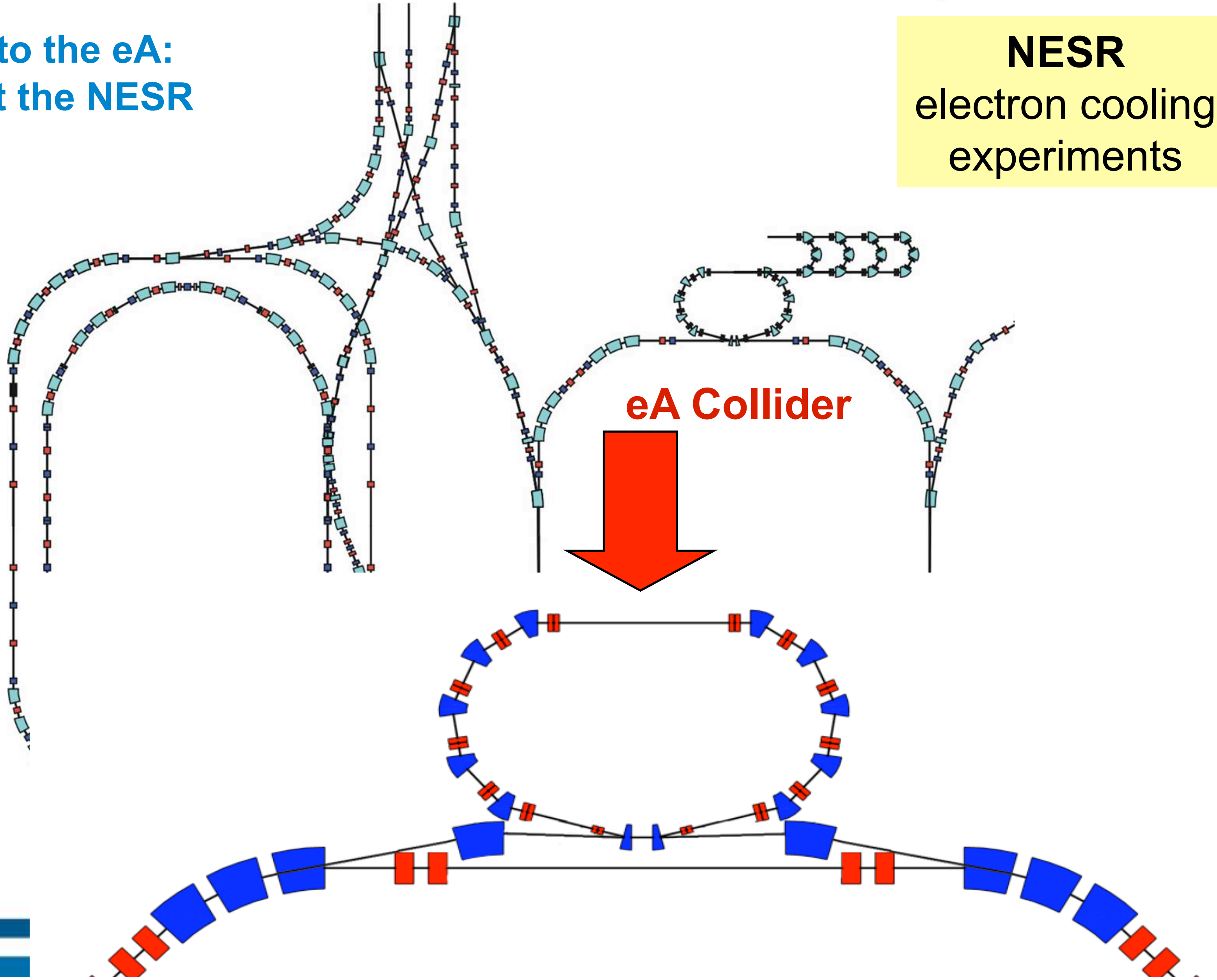


To overcome the Coulomb barrier, low energies of about 5 MeV/u are required !!!

The Ring Branch

Alternative to the eA:
Ion target at the NESR

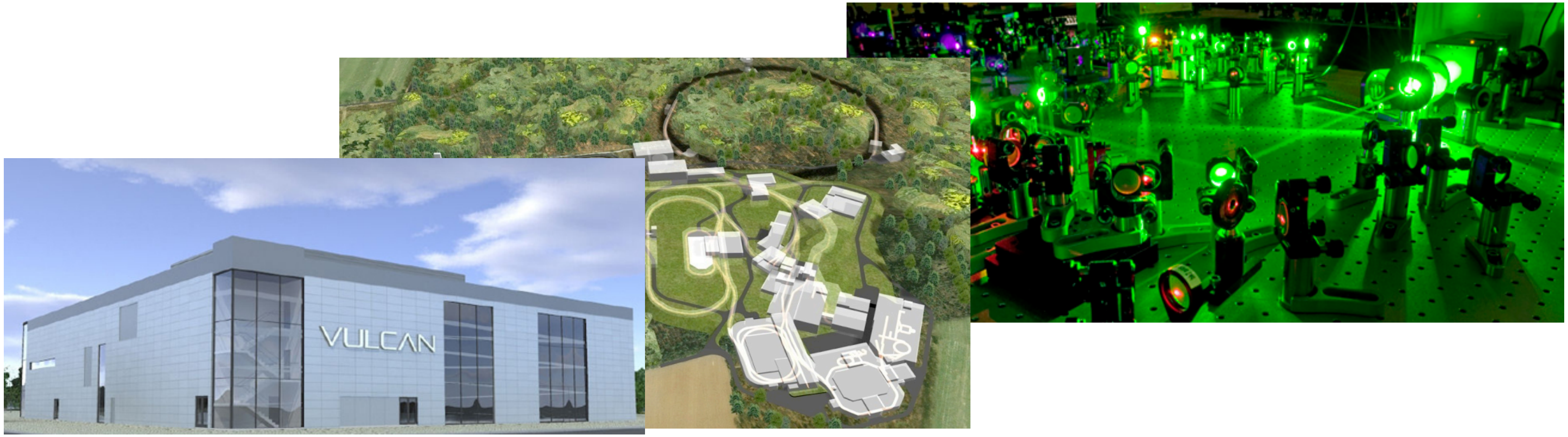
NESR
electron cooling
experiments



Physics of strong fields: Lasers and Ions

We shall briefly recall four case studies in strong-field physics:

- Pair production in strong electromagnetic fields
- Search for parity non-conservation in atomic systems
- Non-linear phenomena in quantum vacuum
- Multi-photon processes with highly-charged ions



Unified electro-weak interaction

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c²**	**Electric charge**
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

Strong	
	Residual
	See Residual Strong Interaction Note
	Hadrons
	Mesons
	Not applicable to quarks
	20

η_c	eta-c	$c\bar{c}$	0	2 .980	0

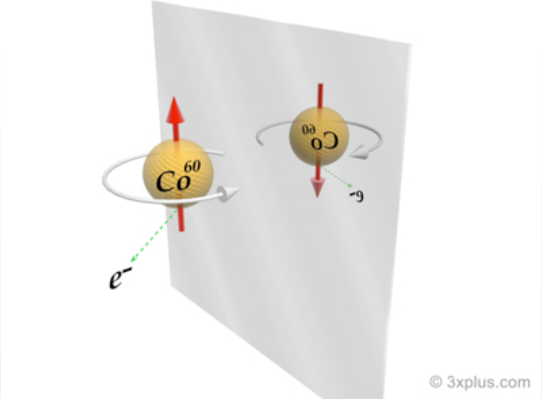
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Note: electromagnetic interaction preserves parity while weak interaction – not!

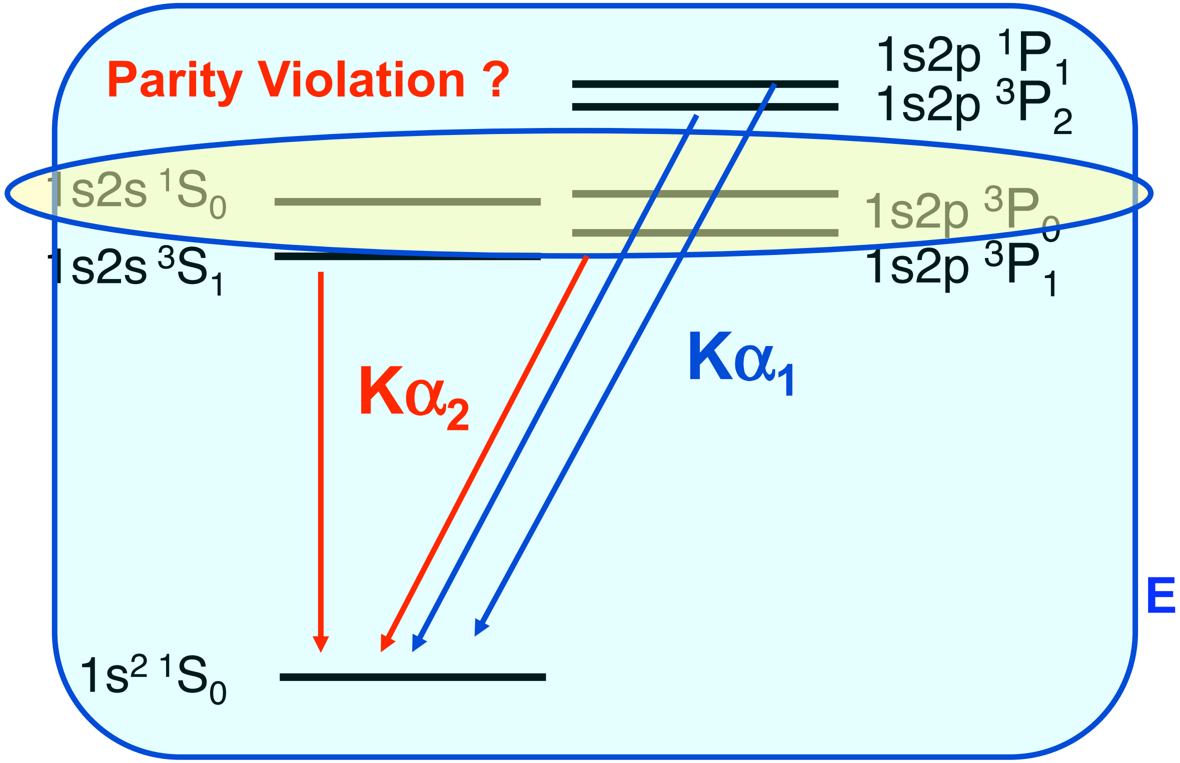


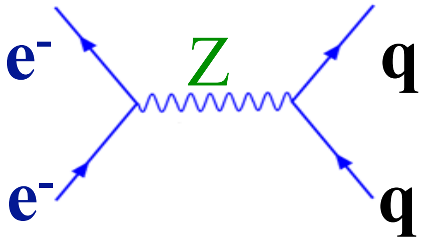
First time observed in famous Wu experiment on the beta-decay of cobalt nuclei.

- Weinberg angle is the key parameter of electro-weak theory

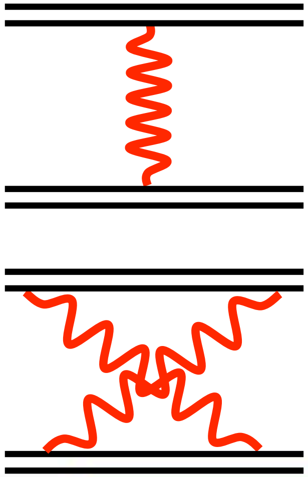
$$\sin^2\theta_W = \frac{\alpha_{em}}{\alpha_{weak}}$$

Atomic Structure of He-like Ions

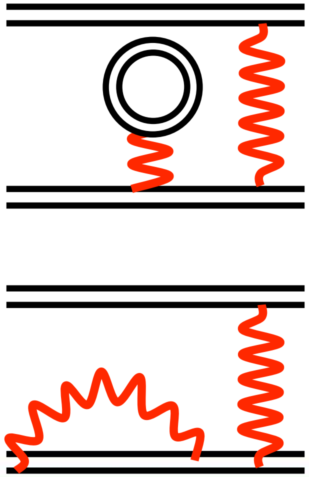




Electron-electron interaction



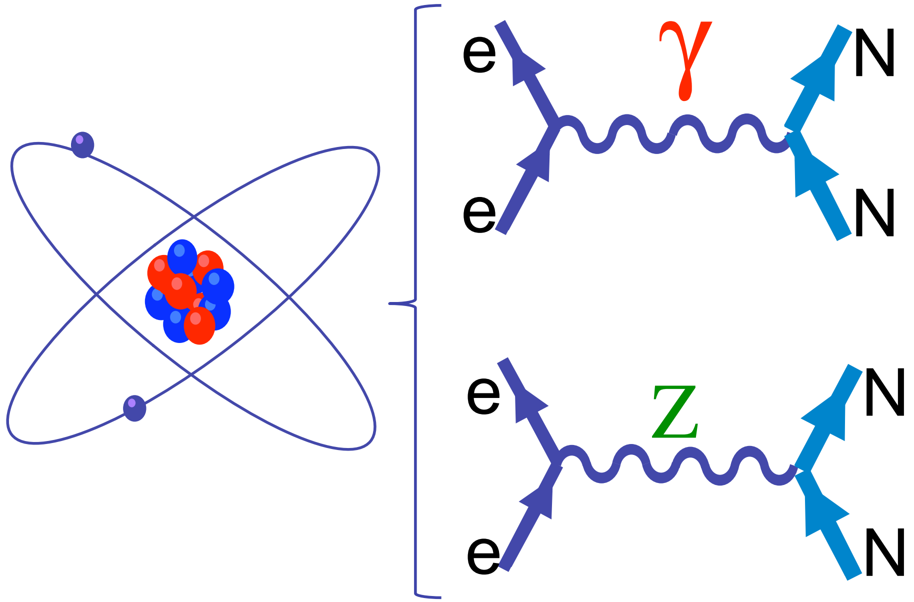
Two electron QED



- **exotic decay modes:** **M2, 2E1, E1M1**

- **electron correlation and QED in the relativistic domain**

Atomic parity violation studies

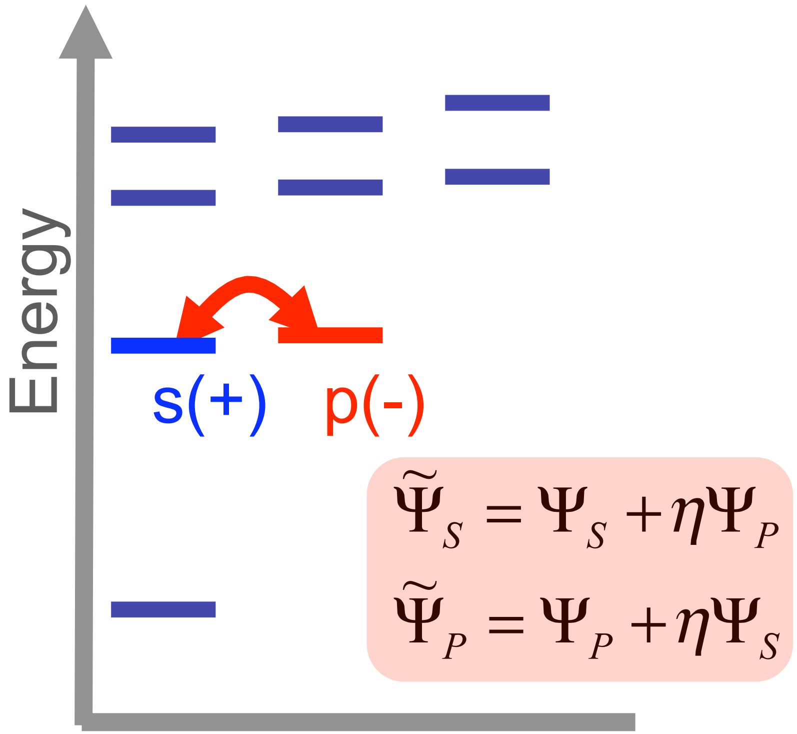


- Mixing coefficient for the states with opposite parities:

$$\eta \propto \frac{1}{E_S - E_P}$$

Energy splitting should be small!

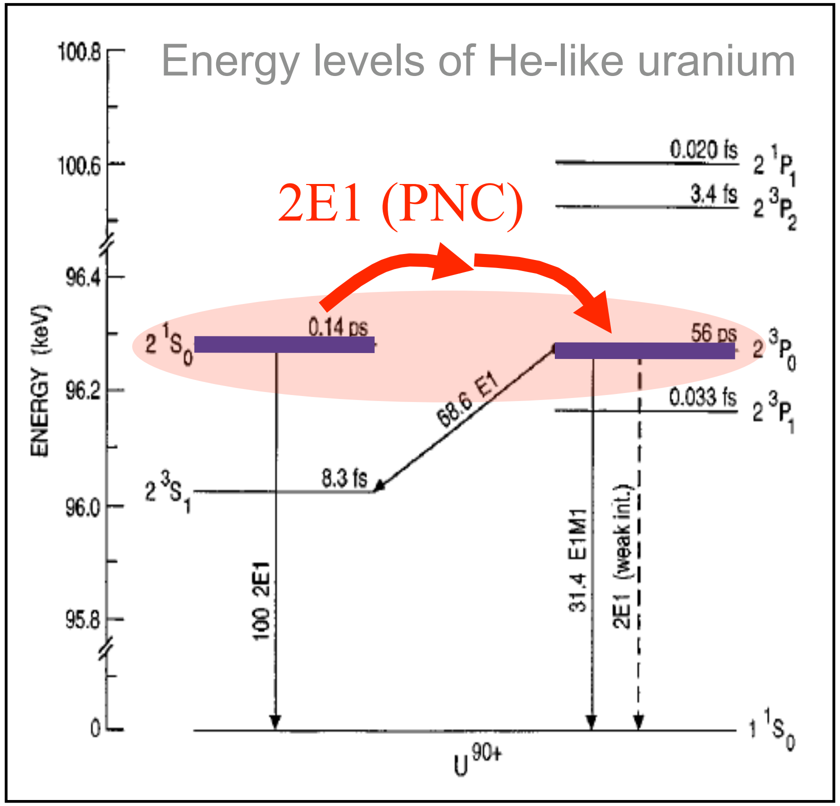
- Exchange of neutral Z boson between nucleus and electrons leads to the mixing of atomic levels with different parities.



$$\tilde{\Psi}_S = \Psi_S + \eta \Psi_P$$

$$\tilde{\Psi}_P = \Psi_P + \eta \Psi_S$$

PNC transitions in He-like ions


Energy levels of He-like uranium

- Many-body relativistic calculations show that for the case of Uranium ion:

$$\Gamma_{2\gamma} = I^2 (\varepsilon_1 \cdot \varepsilon_2) \times 0.26 \cdot 10^{-42}\ ns^{-1}$$

$$I = 10^{20} - 10^{22}\ W/cm^2$$

- To "compete" with spontaneous decay channels we have to induce two-photon PNC transition by polarized light with intensity:

Theory: F. Fratini, A. Surzhykov (Uni-HD, GSI)
S. Fritzsche (Uni Oulu, GSI)

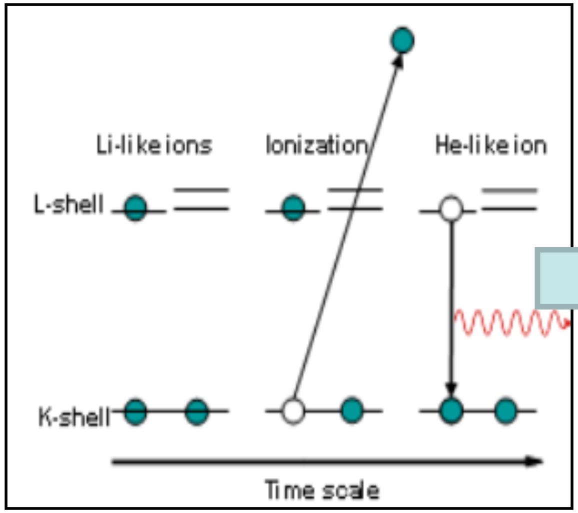
PNC experiments with He-like ions: Proposal

- We may think of three steps to study PNC phenomena in He-like ions

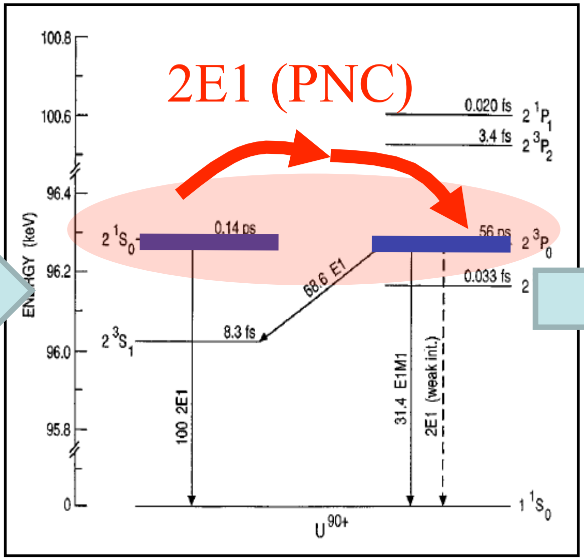
Production of 2^1S_0 state by means of inner-shell ionization (of Li-like ions)

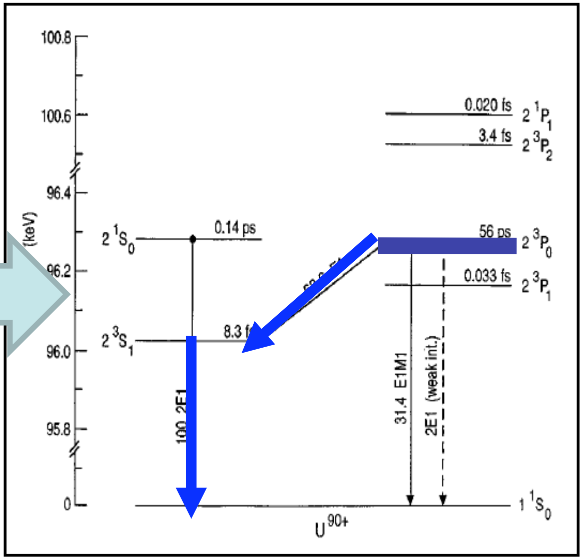
Stimulation of two-photon transition from 2^1S_0 to 2^3P_0

Measurement stabilization of 2^3P_0 metastable state



S. Trotsenkov et al, PRL (2010)





population of states

(high selectivity for s-states required)

(induced) PNC

(atomic structure, photon intensity)

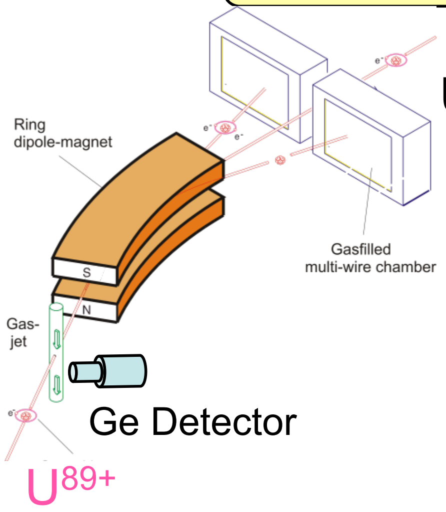
detection

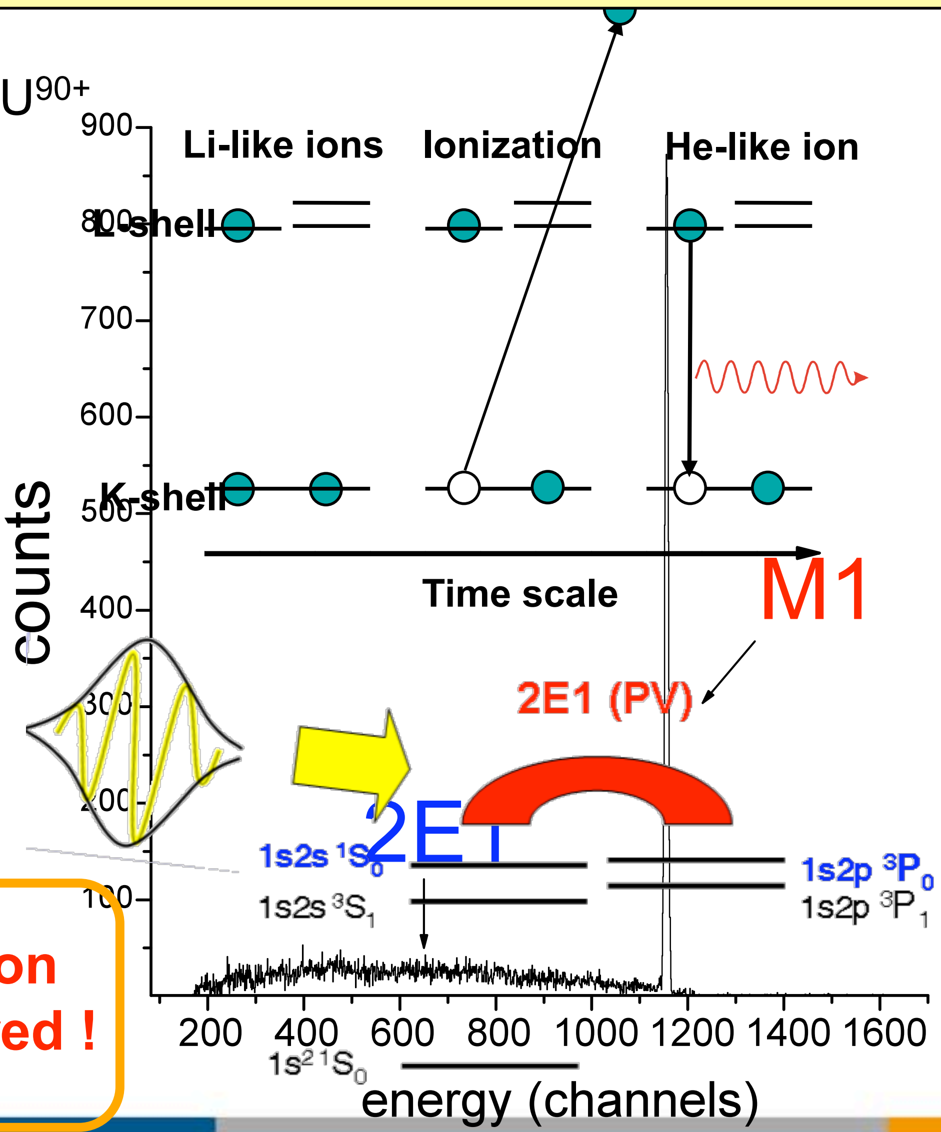
(decay properties)

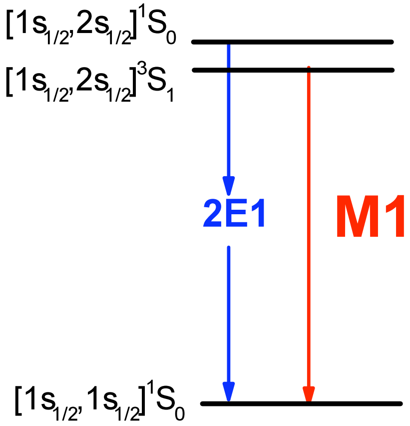
- Important question: which intensity of incident light do we need to make 2E1 PNC transition “visible”? Some theory predictions are required!

Parity Violation: Selective Production of 2s-States

Isolation of s-states in He-like heavy ions





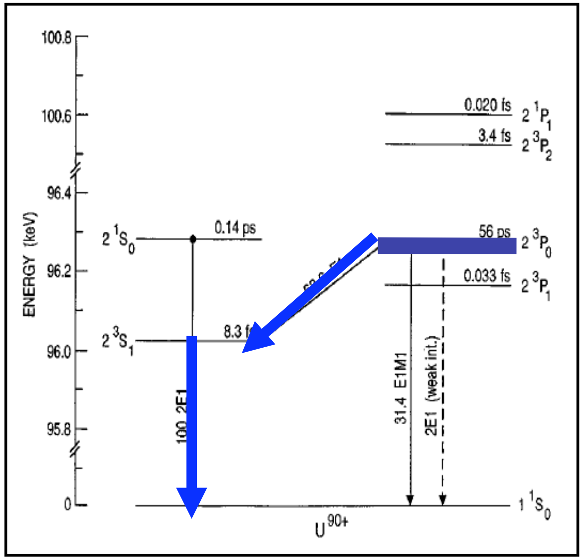


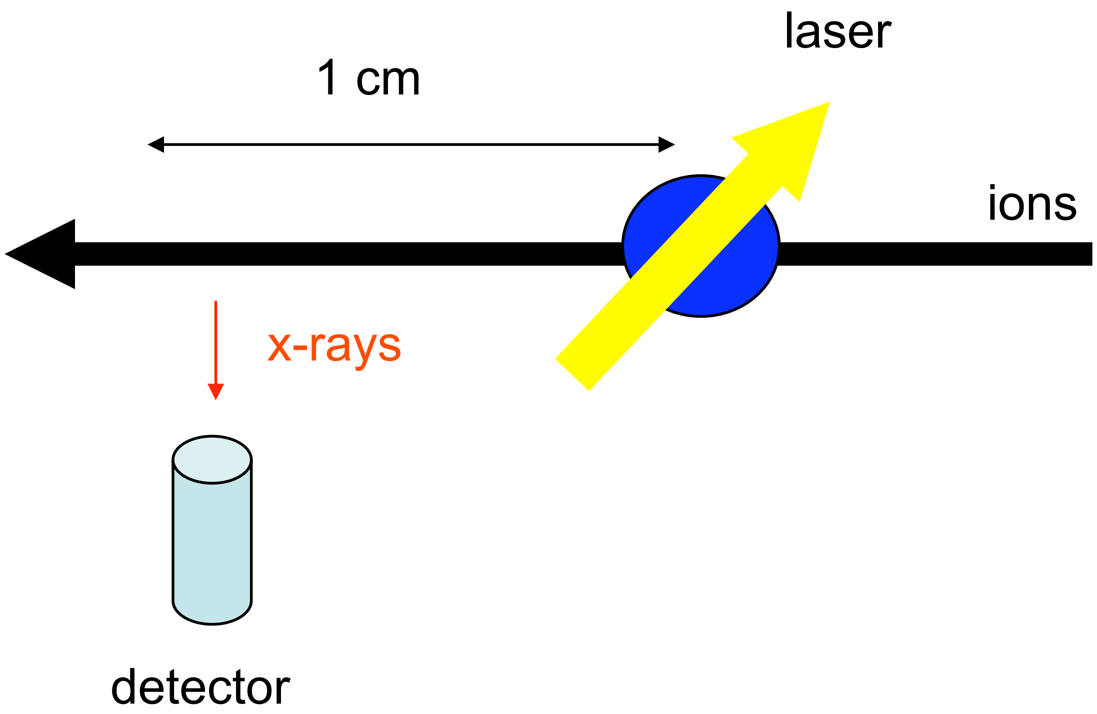
Intense photon pulse is required !

Due to the long lifetime, the decay of the $^3P_0$ can easily be detected !

Measurement of the decay of the metastable $^3P_0$

Radiative stabilization of 2^3P_0 metastable state via the $^3S_1$ decay

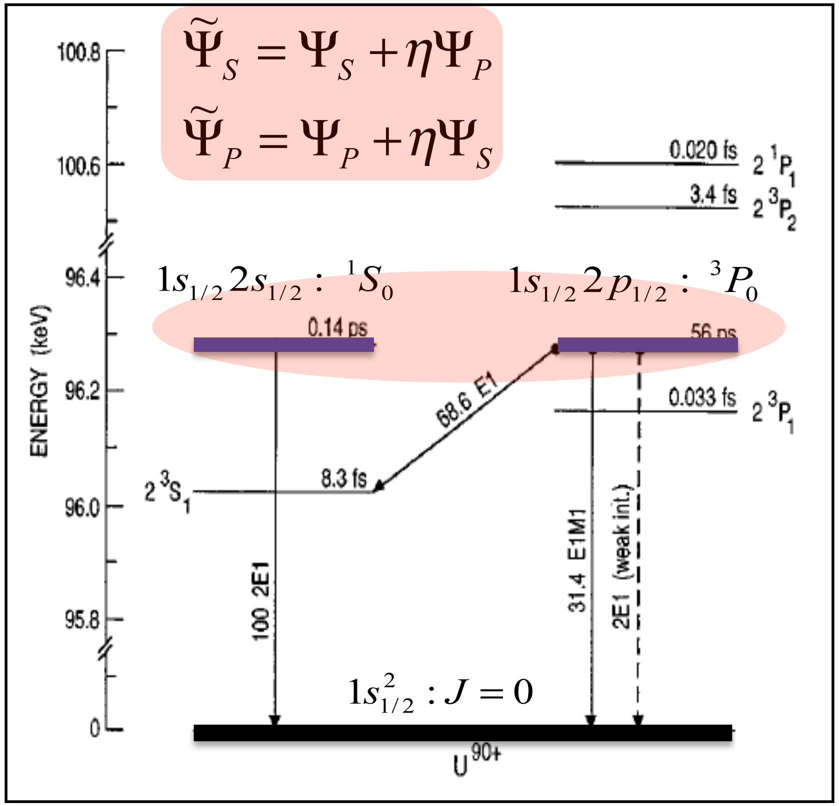




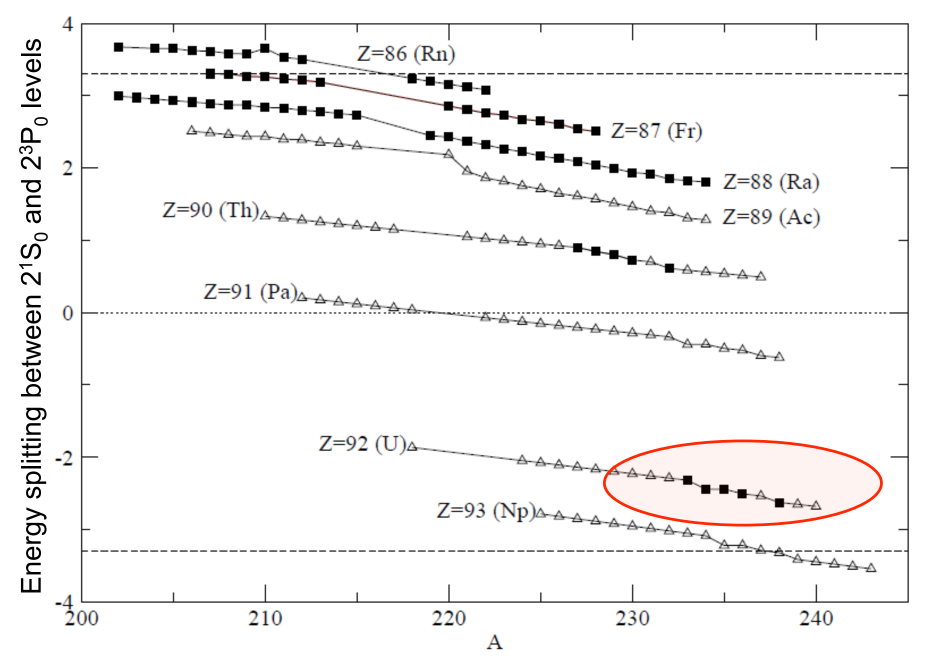
detection of the delayed x-ray emission
upstream from the target

We need FAIR ! and a high-power laser

- Helium-like ions provide a unique tool for studying parity-violation phenomena in atomic systems.



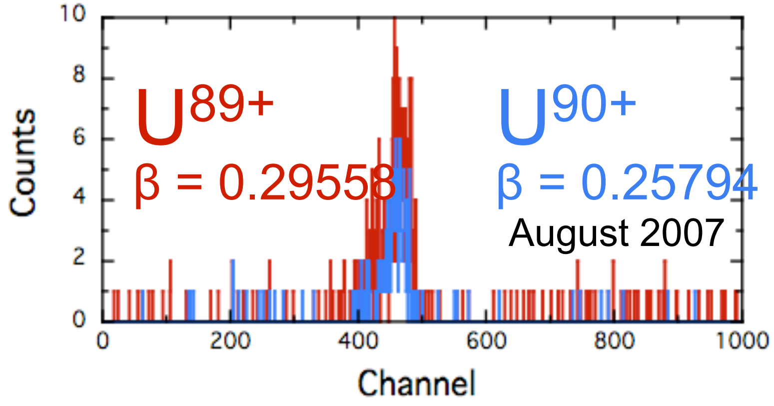
Energy levels of He-like uranium

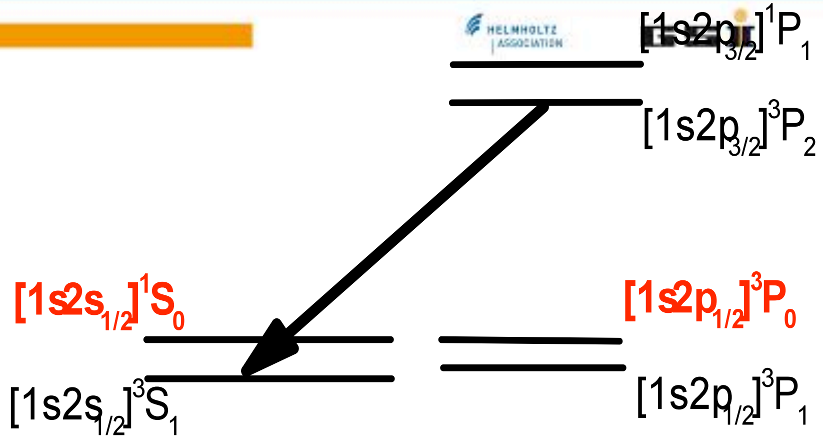


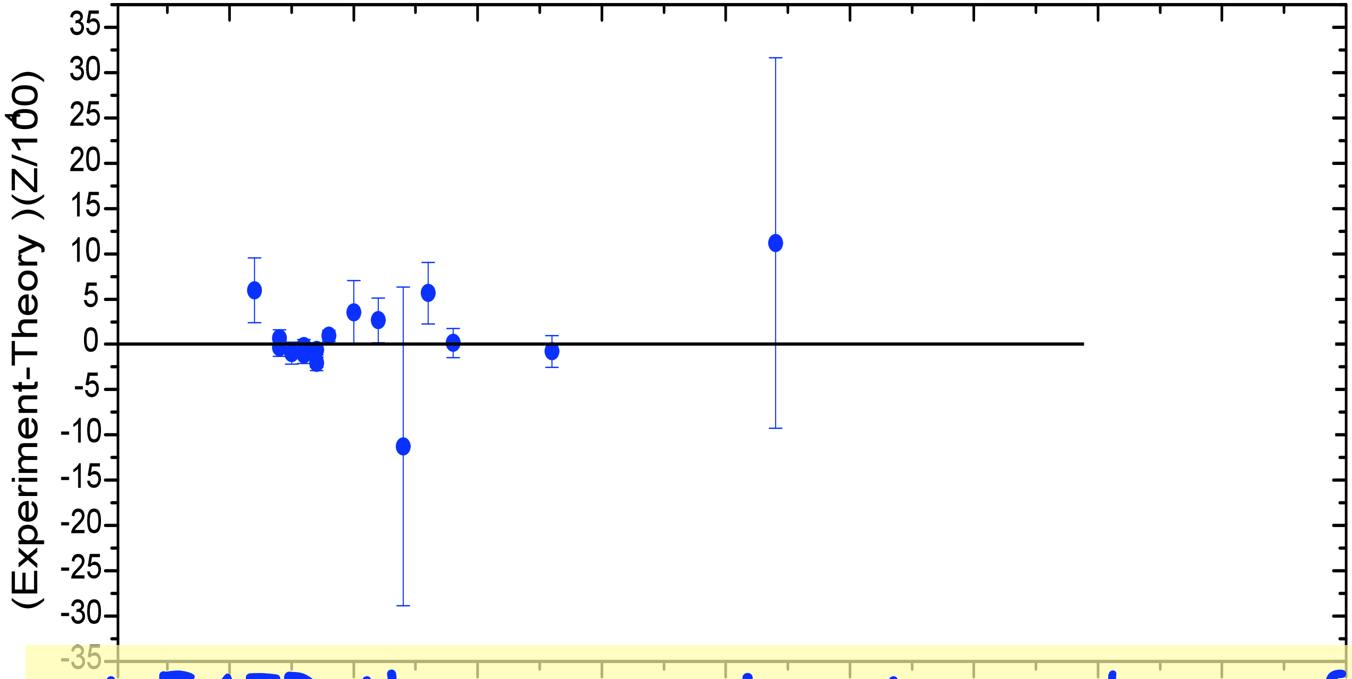
F. Ferro, A. Artemyev, Th. Stöhlker and A. Surzhykov
Phys. Rev. A 81 (2010) 062503

- In He-like ions there are two (almost degenerate) levels with opposite parities: 2^1S_0 and 2^3P_0.
- … but! How to induce 0 ➡ 0 transition?

First observation of the Δn=0 $^3P_2 \rightarrow {}^3S_1$ in He-like uranium (ESR 2008)



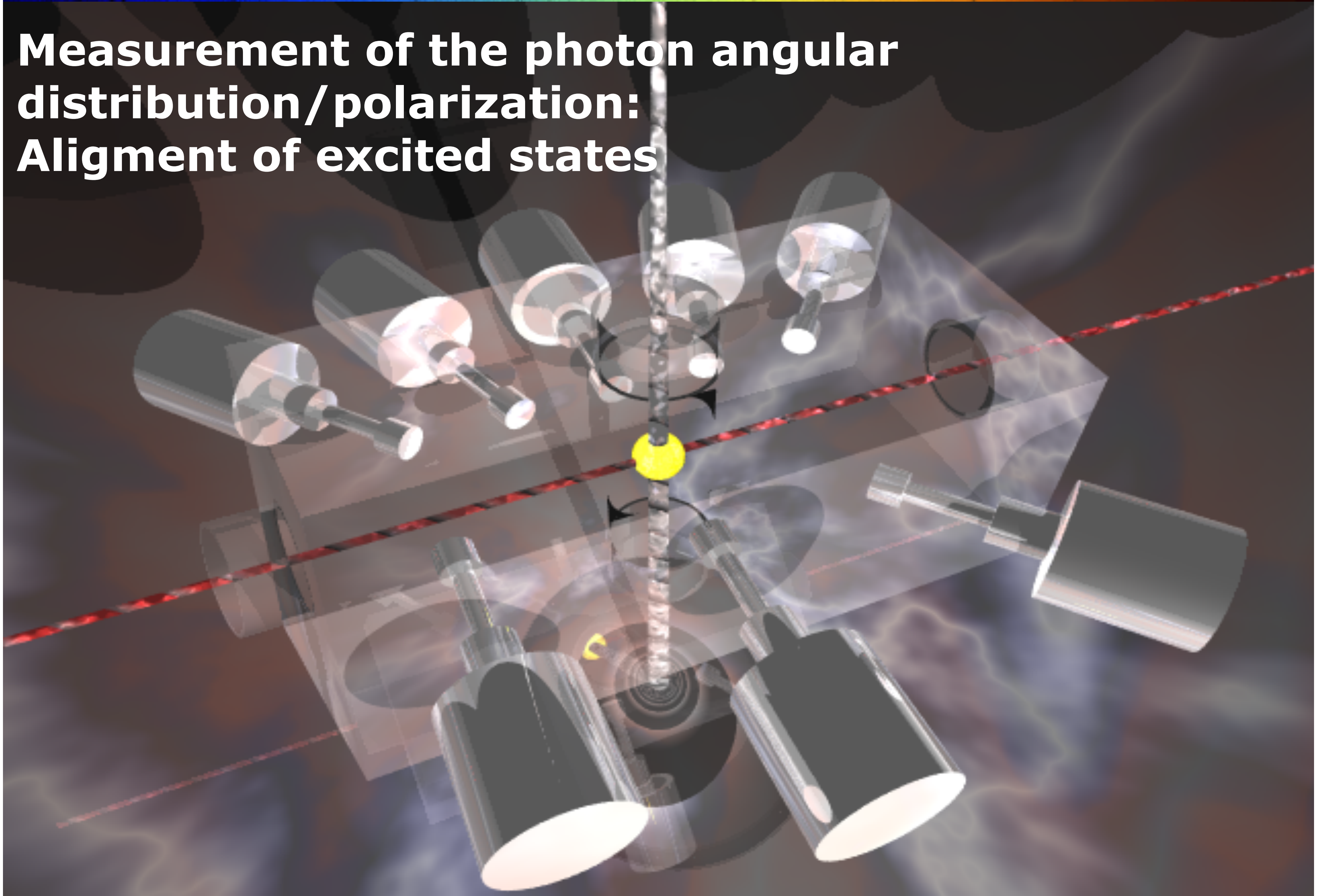




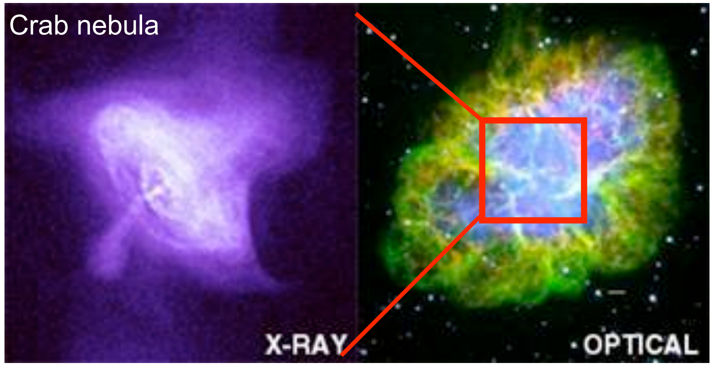
at FAIR these experiments can be performed for different isotopes

Photon Angular Distribution/Polarization

Measurement of the photon angular distribution/polarization:
Aligment of excited states

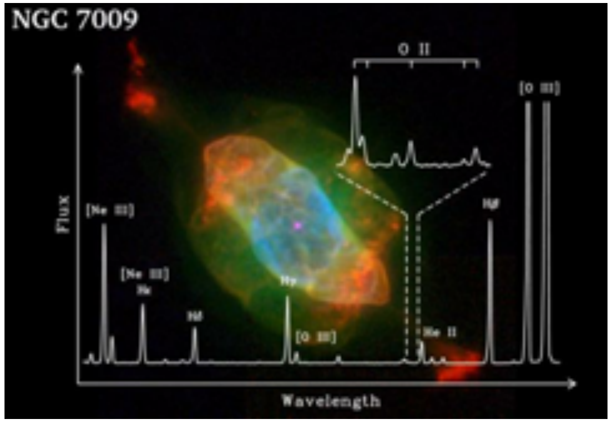


Polarization Spectroscopy



↔

Direct insight into celestial plasmas



Spectra provide knowledge of temperature, density, element abundance, etc.

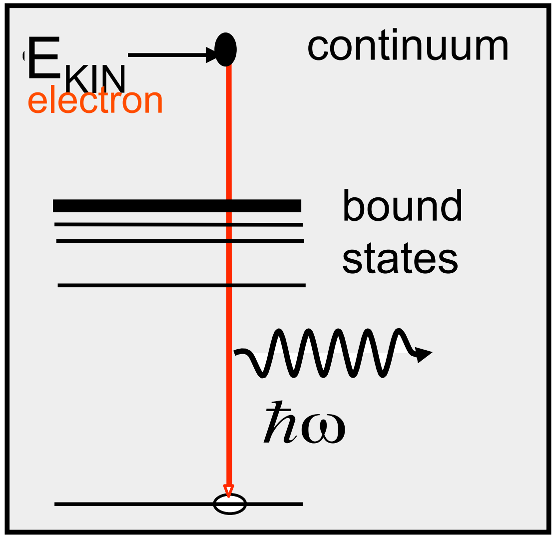
↔

Laboratory Astrophysics

Radiative processes: **Main photon matter interaction processes exhibit distinct photon polarization features (Synchrotron Radiation, Bremsstrahlung, Recombination, Inverse Compton Scattering)**

Dynamics in Strong Fields: Radiative Processes

e.g. Radiative Recombination/Electron Capture

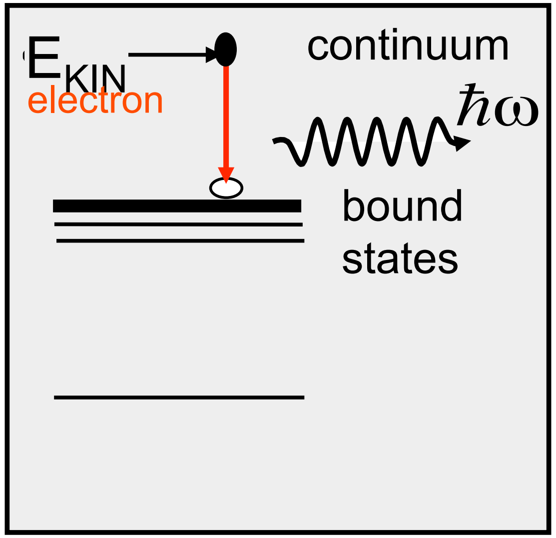


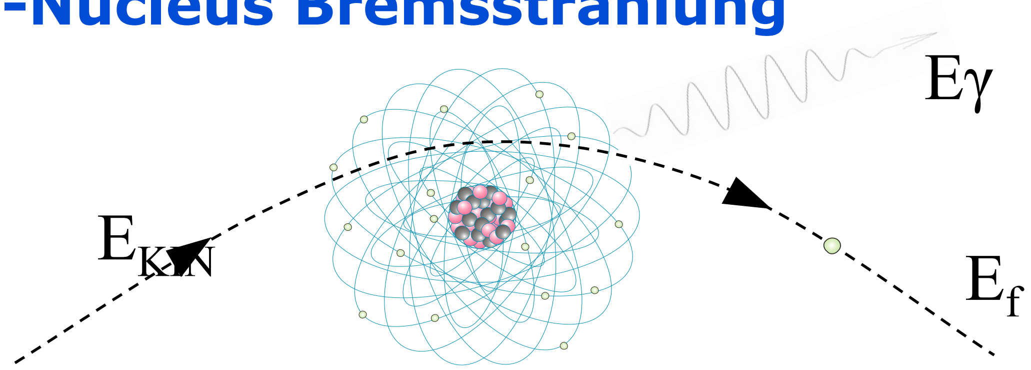
- *Electron capture into a bound ionic state by emission of a photon*

$$\hbar\omega = E_B + E_{KIN}$$

- *Time-reversed photonization*

e.g. Electron-Nucleus Bremsstrahlung

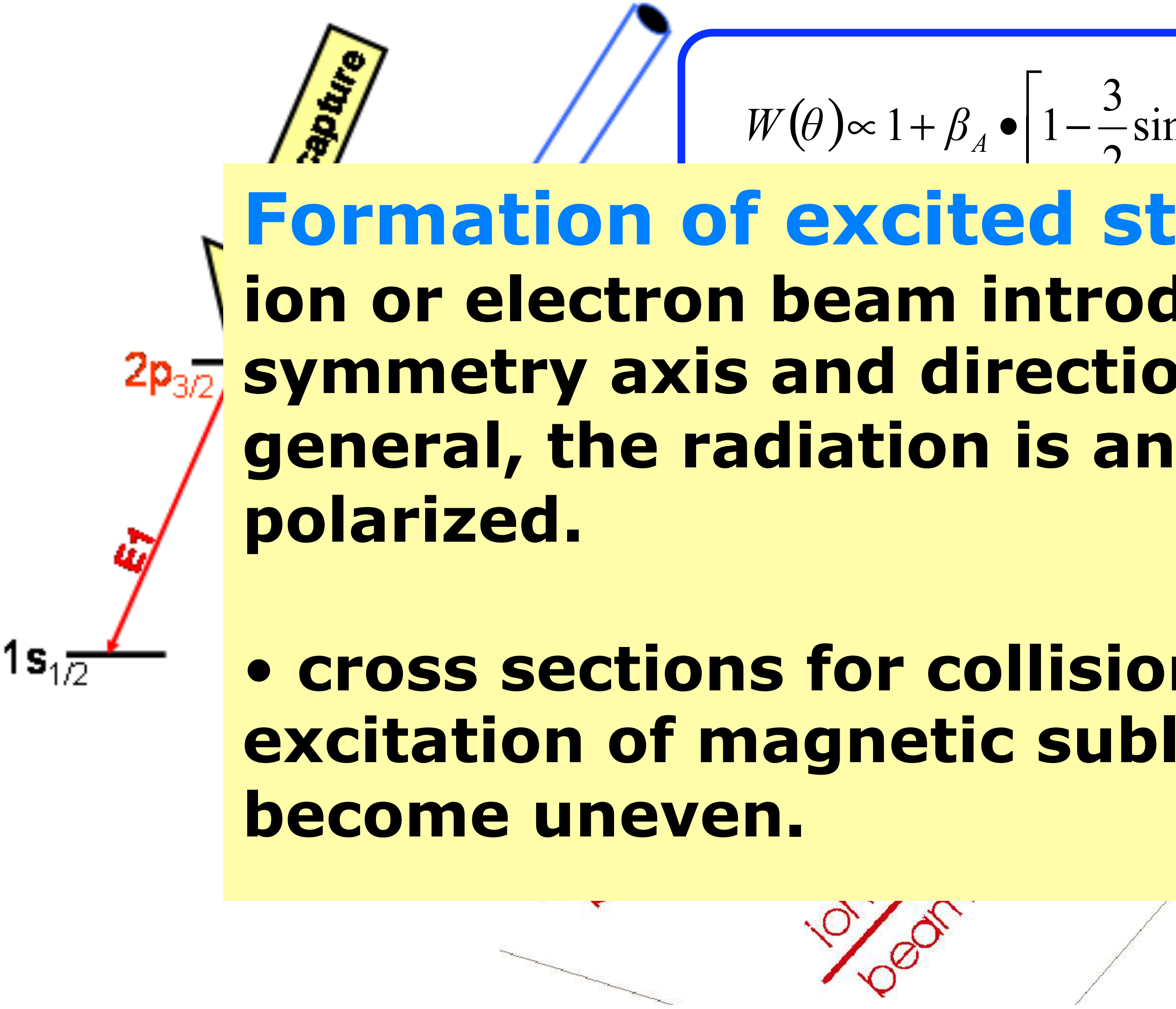




$$E_{KIN} = E_f + E\gamma$$

Radiation is emitted in every collision in which the electron changes velocity.

Excited States



$$W(\theta)\propto 1+\beta_A\bullet\left[1-\frac{3}{2}\sin^2\theta\right]$$

rameter

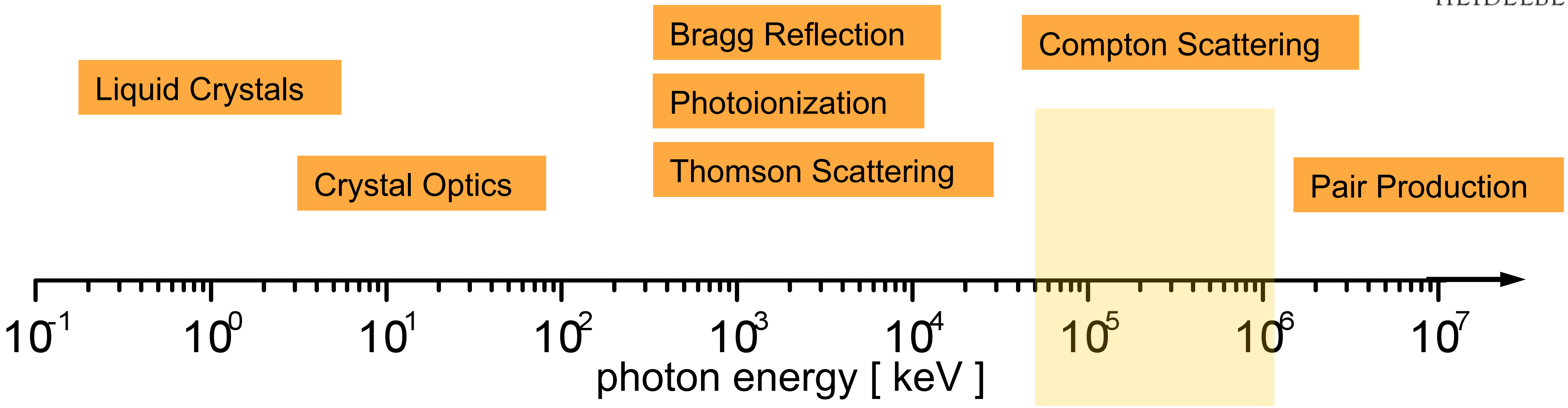
$$\frac{-\sigma\left(\frac{3}{2}\,\frac{1}{2}\right)}{+\sigma\left(\frac{3}{2}\,\frac{1}{2}\right)}$$

Formation of excited states: **The ion or electron beam introduces a symmetry axis and directionality. In general, the radiation is anisotropic and polarized.**

- **cross sections for collisional excitation of magnetic sublevels become uneven.**

angular distribution or polarization

Polarimetry Techniques



Liquid Crystals

Crystal Optics

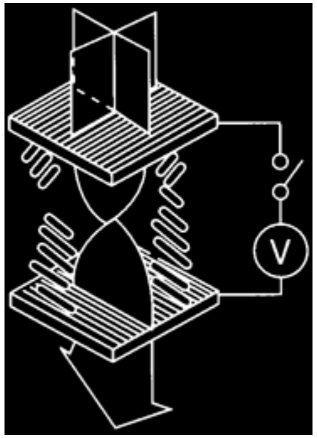
Bragg Reflection

Photoionization

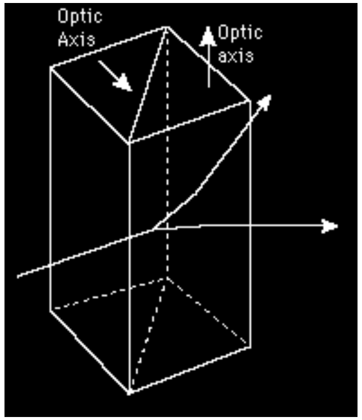
Thomson Scattering

Compton Scattering

Pair Production



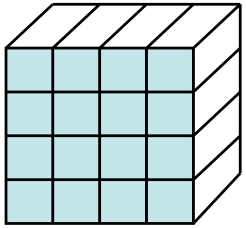
LCD



Prism

Micropattern Gas Counters

x-ray Optics



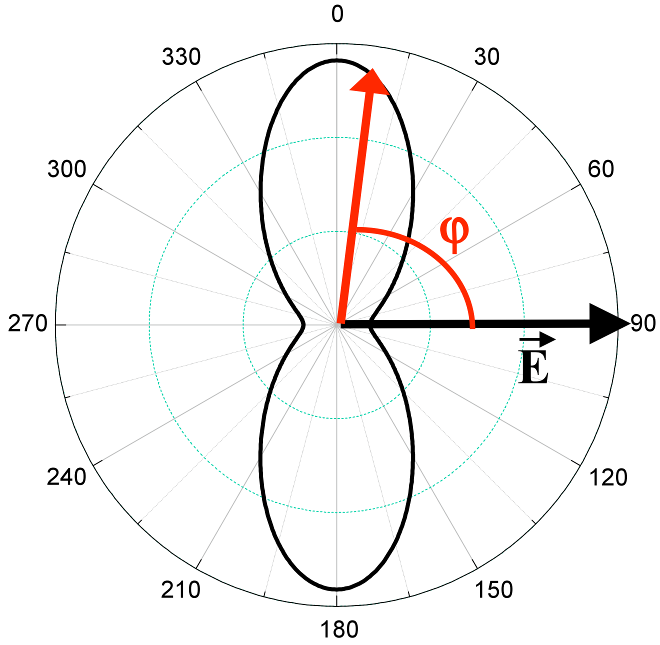
Segmented Solid State Detectors

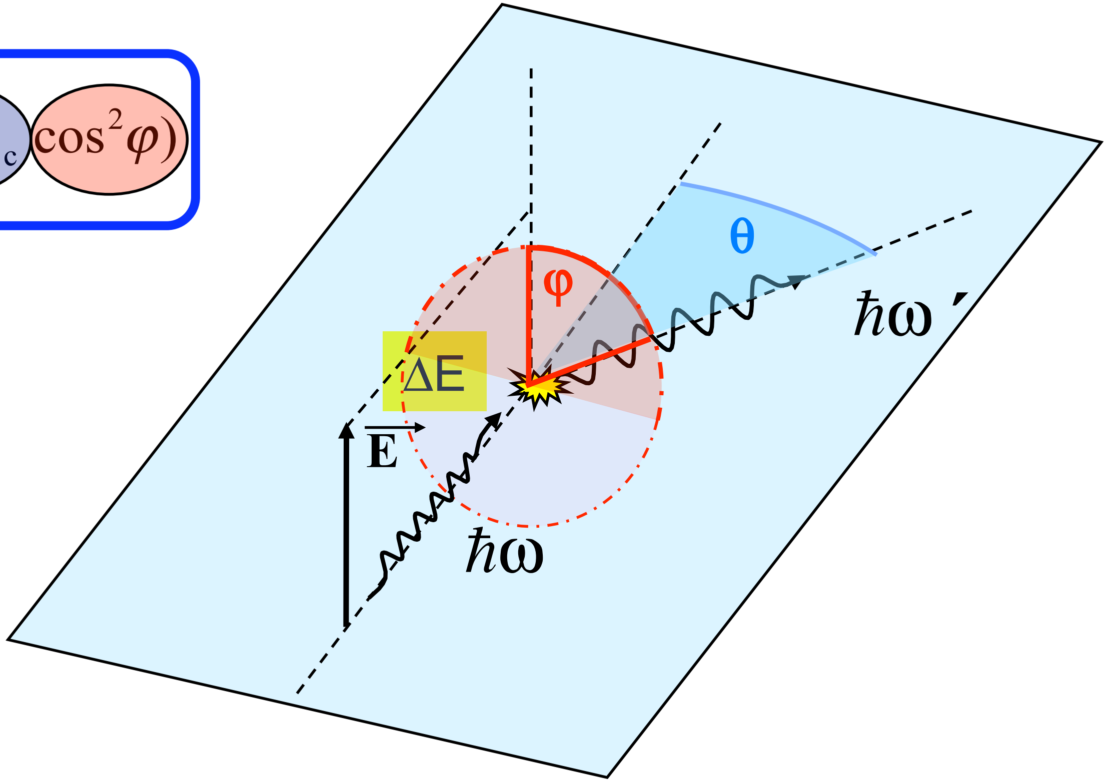
Polarization Measurement via Compton Scattering

Linearly polarized radiation

Klein-Nishina equation

$$\frac{d\sigma}{d\Omega}=\frac{1}{2}r_0^2\left(\frac{\hbar\omega'}{\hbar\omega}\right)^2\left(\frac{\hbar\omega'}{\hbar\omega}+\frac{\hbar\omega}{\hbar\omega'}-2\sin^2\theta_c\cos^2\varphi\right)$$

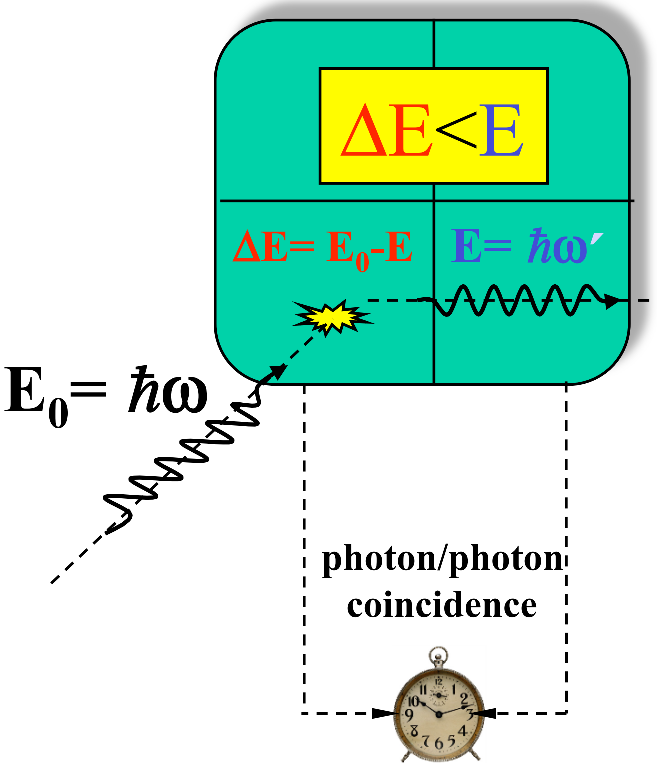


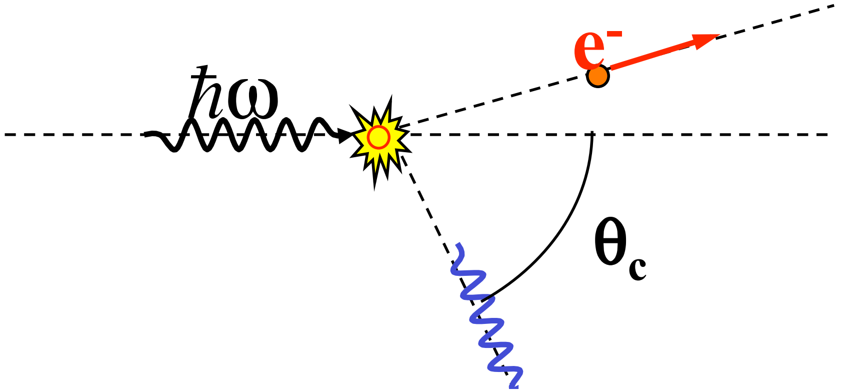


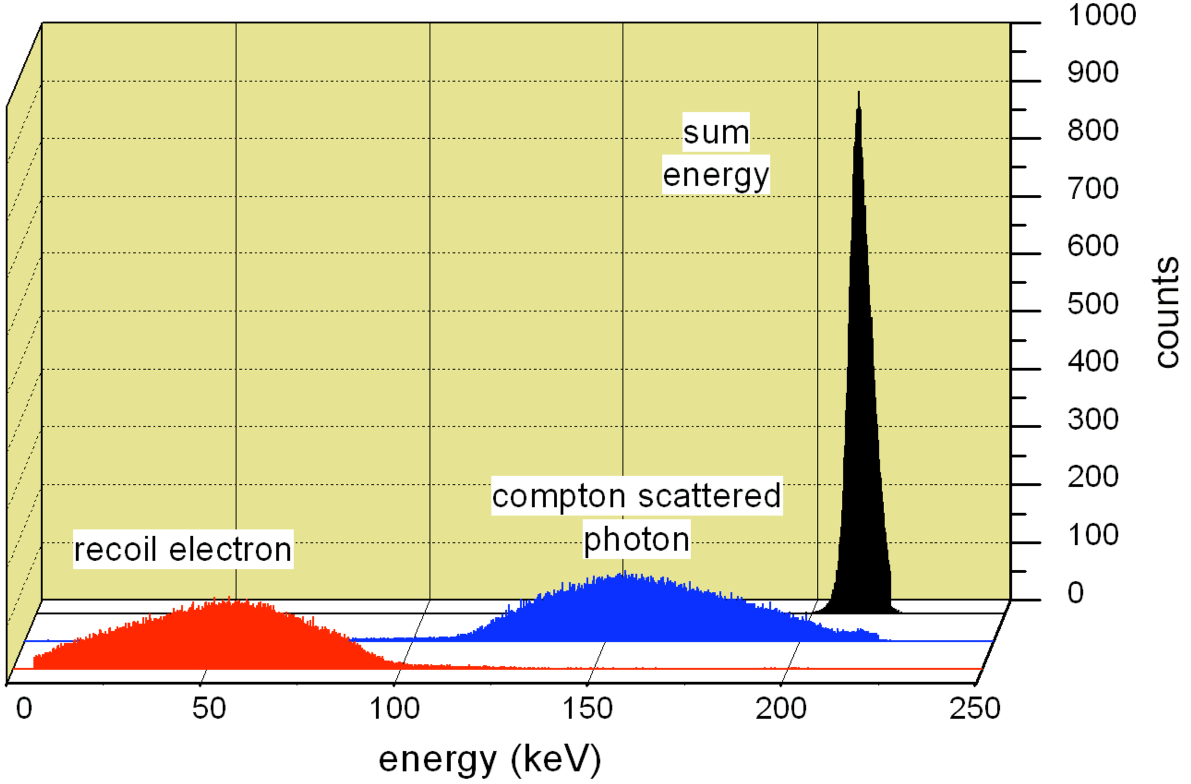
$$\hbar\omega=\hbar\omega' + \Delta E$$

ΔE : electron recoil energy

Detection of Compton Scattered Photons





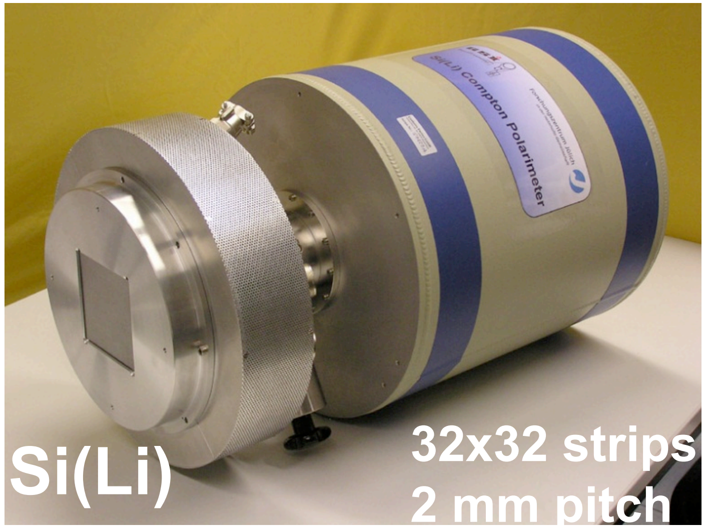


energy deposition in two independent parts of the detector

⬇

reconstruction of compton events

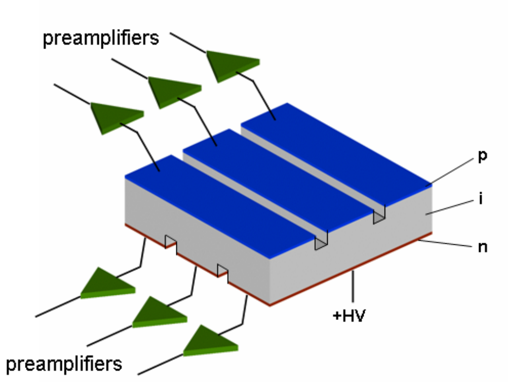
2D/3D Si(Li)-Detector for Compton Polarimetry

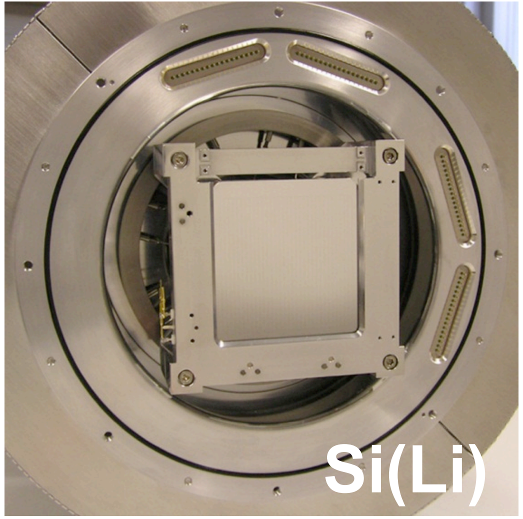


Si(Li)

32x32 strips
2 mm pitch

Si(Li) and Ge(i) based Compton polarimeter

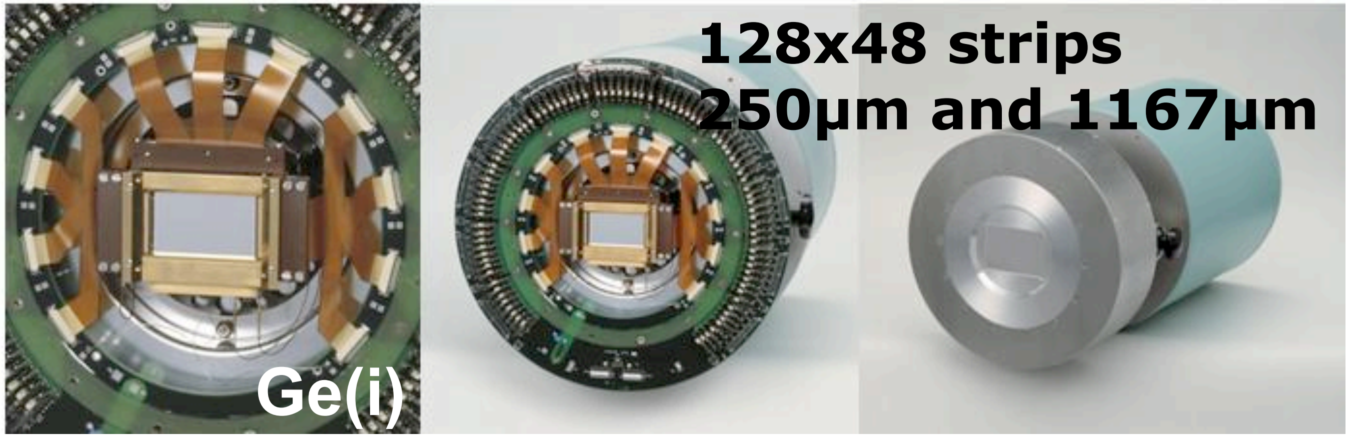




Si(Li)

crystall size: 4" x 4"

energy resolution – timing - 2D/3D position sensitivity – multihit

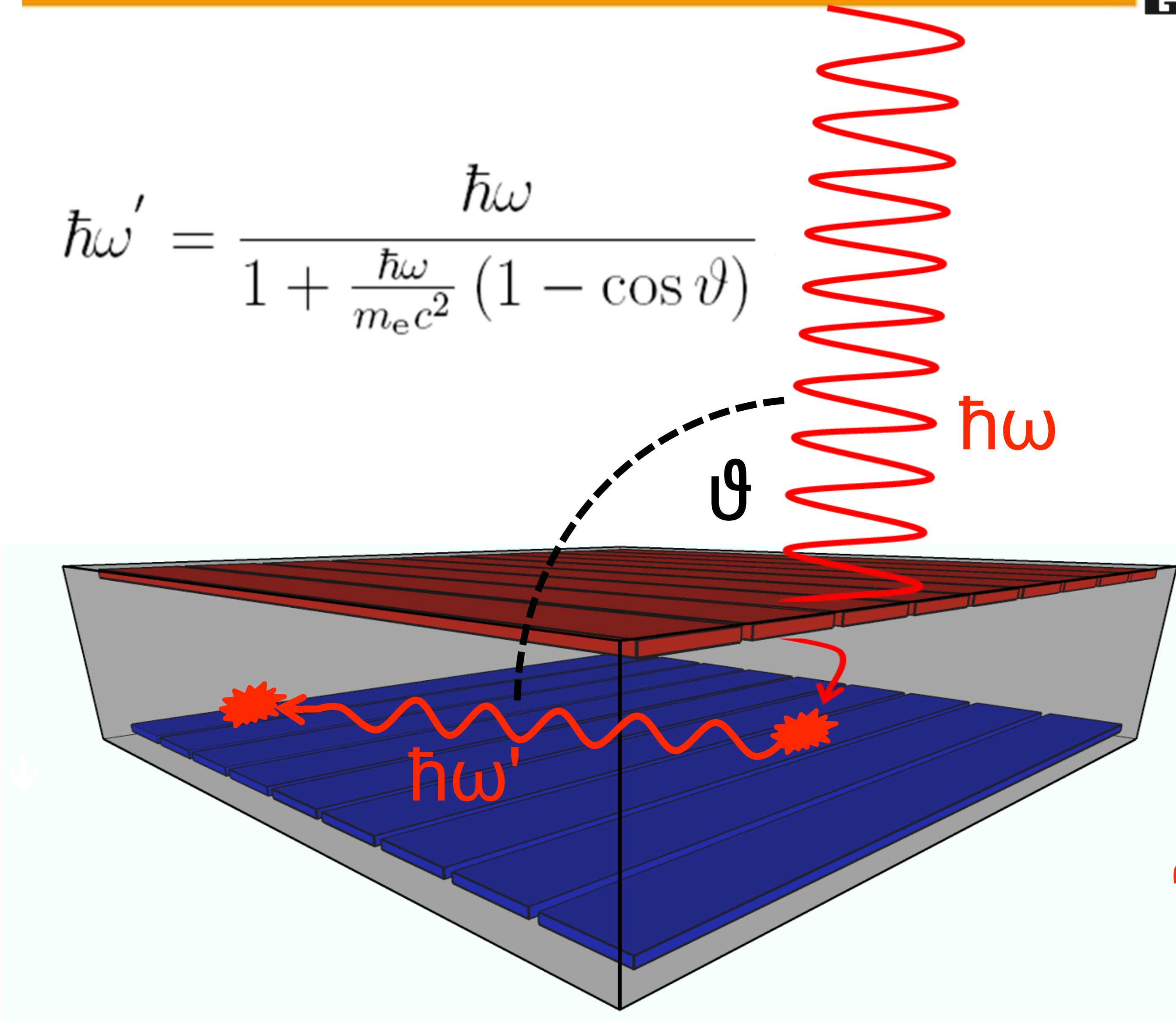


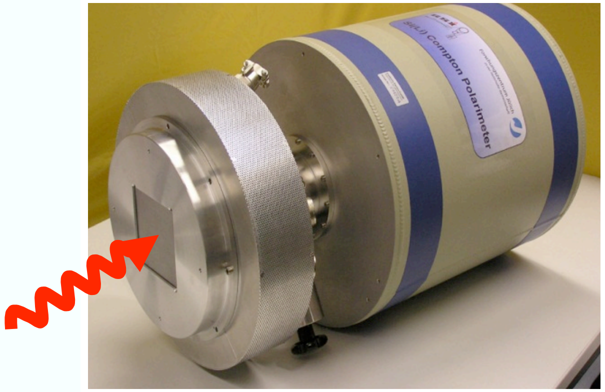
128x48 strips
250µm and 1167µm

Ge(i)

Position sensitive Si(Li) detector as a Compton Polarimeter

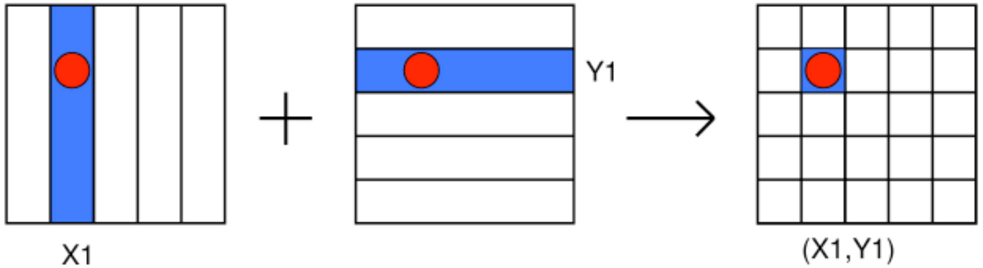
$$\hbar\omega' = \frac{\hbar\omega}{1+\frac{\hbar\omega}{m_e c^2}(1-\cos\vartheta)}$$



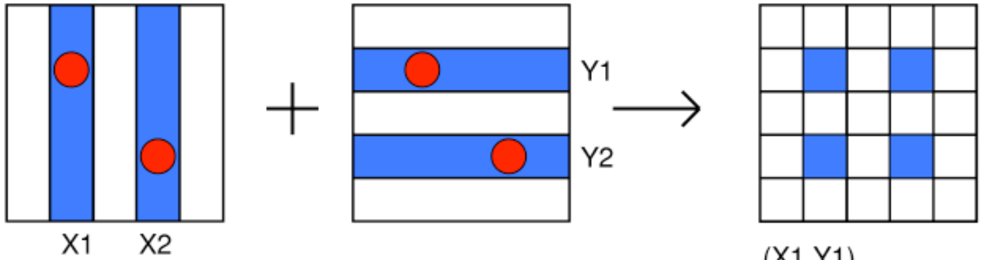


Simple position reconstruction in planar strip detectors

Photoabsorption



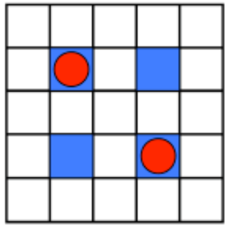
Compton Event



(X1,Y1)
(X1,Y2)
(X2,Y1)
(X2,Y2)

???

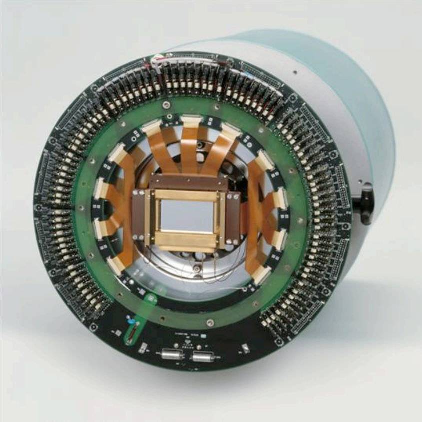
$E(X(i)) \overset{!}{=} E(Y(j)) \longrightarrow$



(X1,Y1)
~~(X1,Y2)~~
~~(X2,Y1)~~
(X2,Y2)

Exploiding Position and Energy Resolution

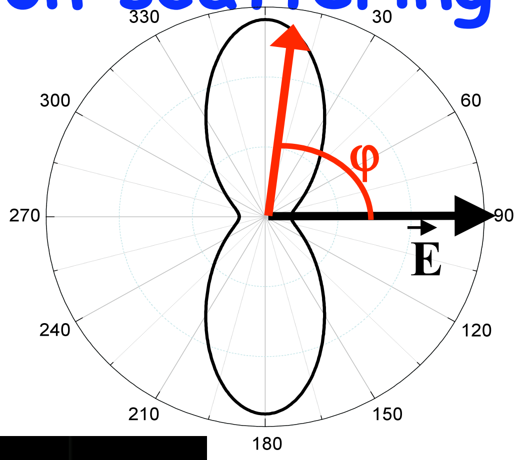
Polarization Measurement via Compton scattering

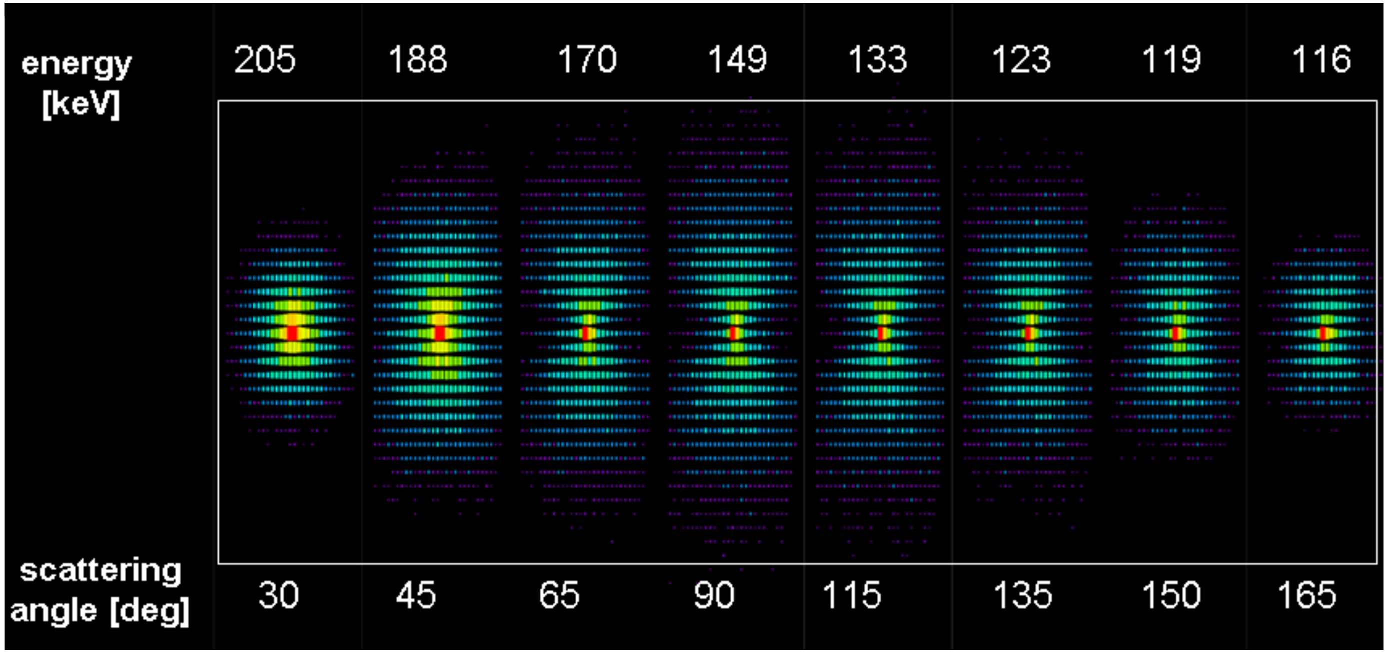


2D µSTRIP germanium detector

Angle / Energy

$$\hbar\omega' = \frac{\hbar\omega}{1+\frac{\hbar\omega}{m_{el}c^2}(1-\boxed{\cos\theta_c})}$$

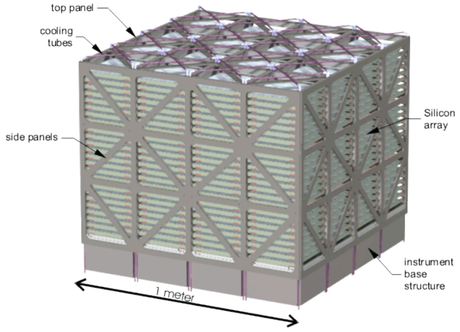


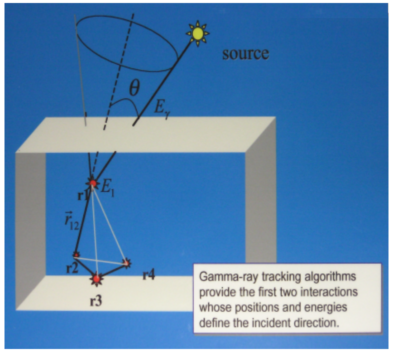


X-Ray images for Compton Scattering as a function of scattering angle

Compton Imager and Polarimeter

2D µSTRIP
germanium detector
-GSI

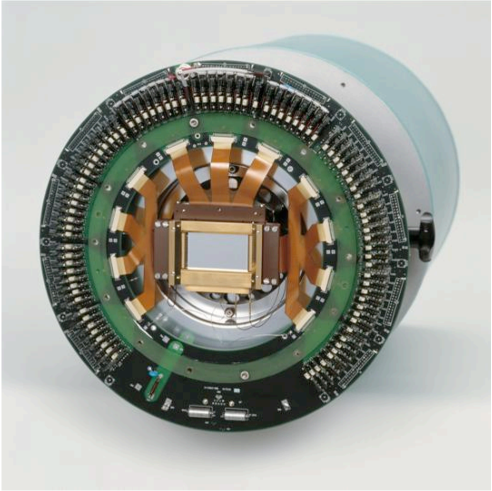




Gamma-ray tracking algorithms provide the first two interactions whose positions and energies define the incident direction.

Similar projects based on planar position sensitive Germanium and Si(Li) detectors:

Compton imager and polarimeter
at Naval Research Lab.
(space missions,
Kroeger et al.)

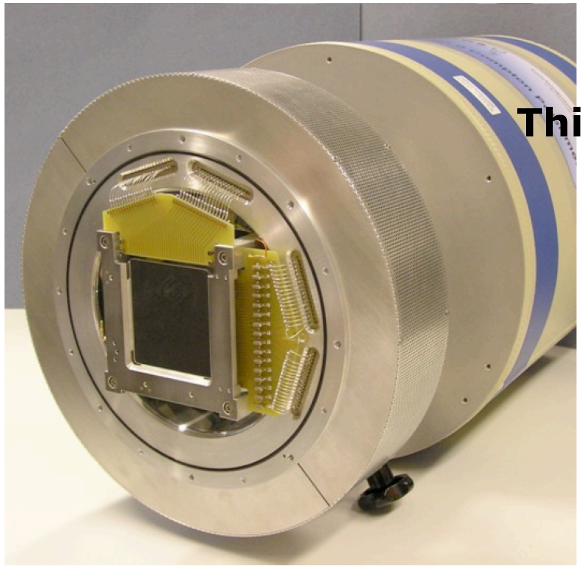


Compton imager at LLNL
(γ-ray imaging,
K. Vetter et al.)

Compton imager
(medical imaging,
Valenta et al.)

Planar structured semiconductor detectors

2D Si(Li)-strip-detector



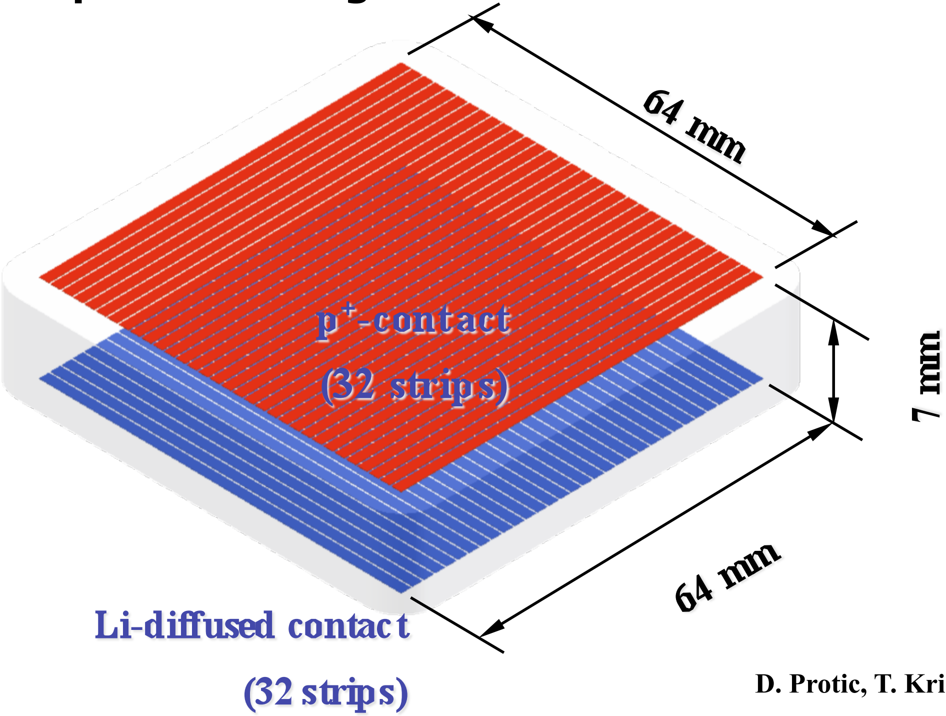
Crystal: p-type silicon

Thickness: 7 mm

Size: 74 x 74 mm²

Depletion voltage: 800V

Position sensitive structure



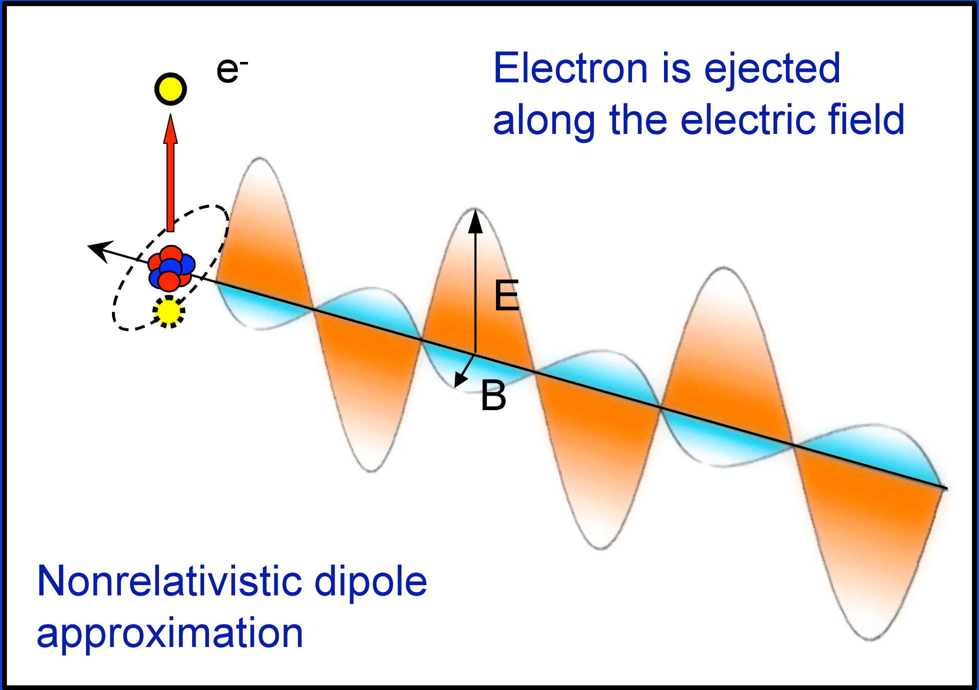
Stripes per contact :	32
Stripe length:	64 mm
Stripe width:	2 mm
=> 1024 stripsel total	
Isolation gap:	~50 µm
Active area:	4100 mm²

D. Protic, T. Krings;

IKP, JZ-Jülich (now Semikon GmbH)

Photoionization ⇔ Recombination

Linear Polarization



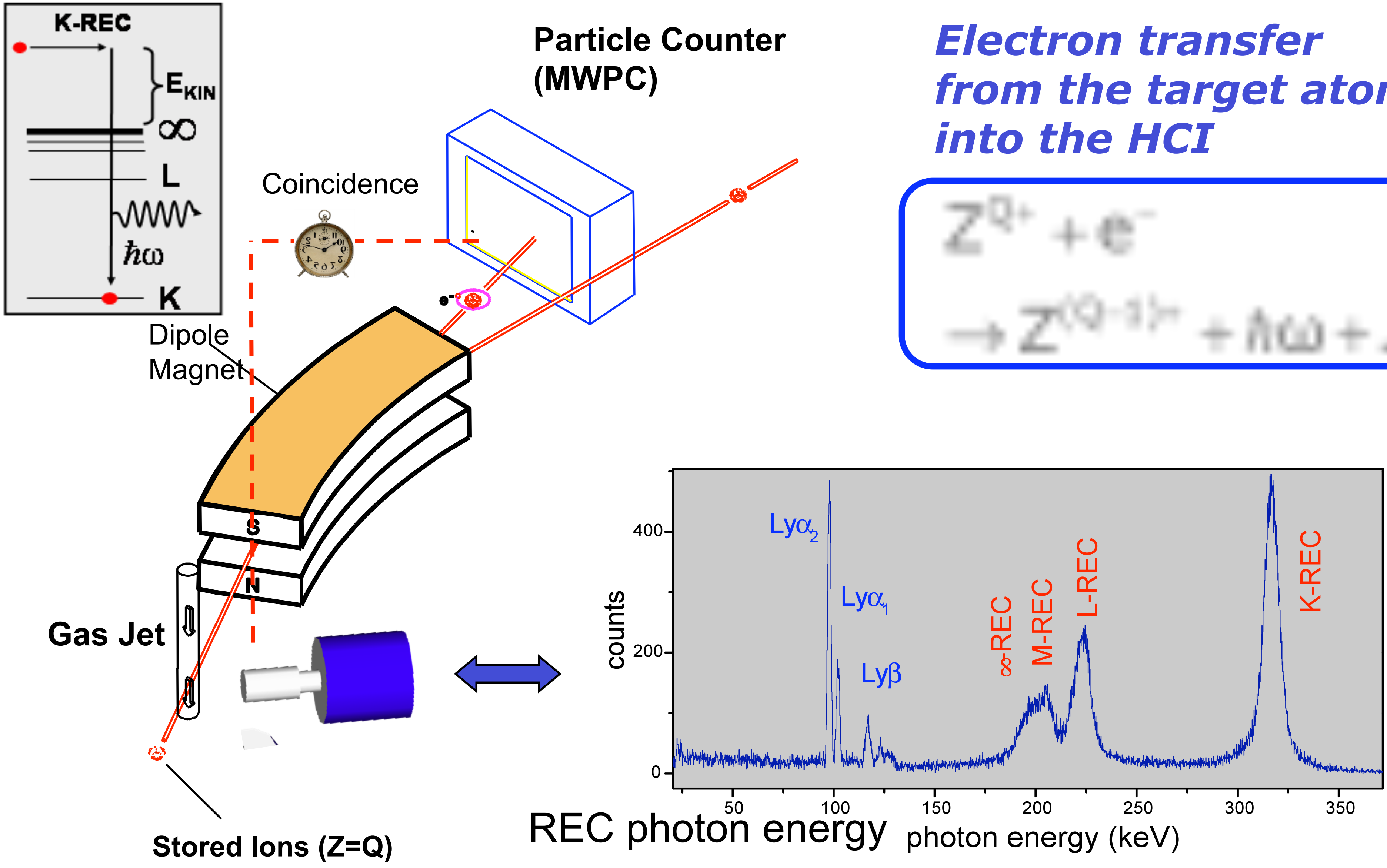
Photoionization

non-relativistic dipole approximation: 100 % polarization for all emission angles

Experiments at the Jet-Target

Electron transfer from the target atom into the HCI

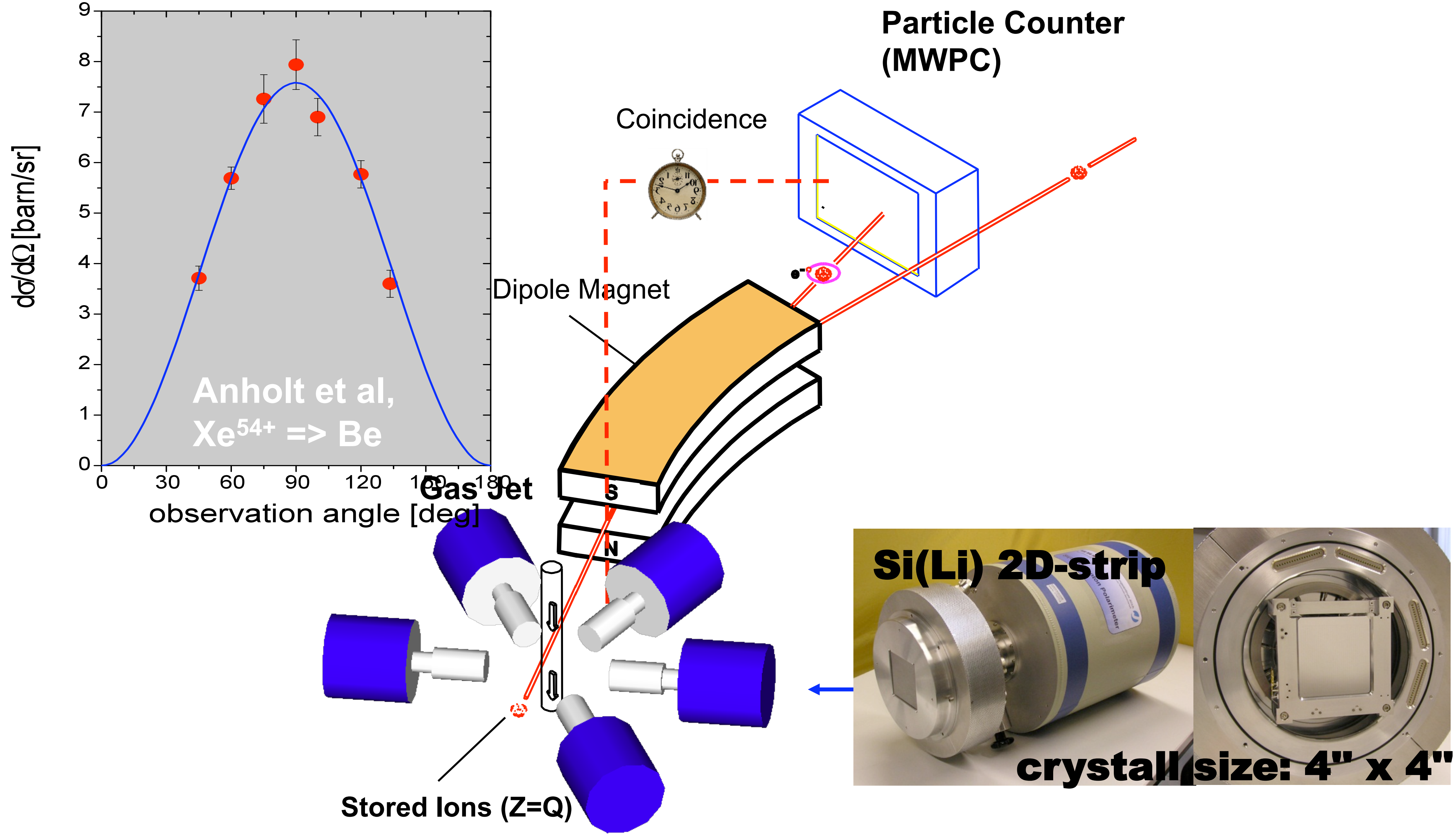
$$Z^{Q+} + e^- \rightarrow Z^{(Q-1)+} + \hbar\omega + \ldots$$



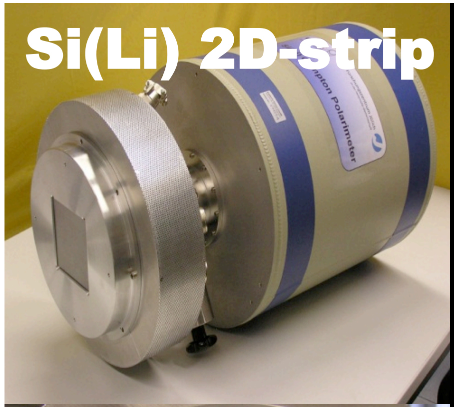
$$\hbar\omega_{REC} = E_B + m_e c^2(\gamma - 1) + \gamma(v_i p_z - E_T)$$

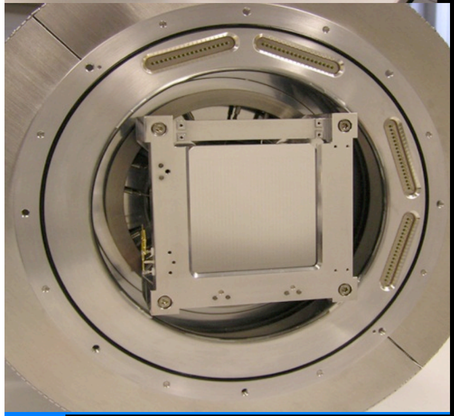
Angular Distributions and Polarisation Imaging

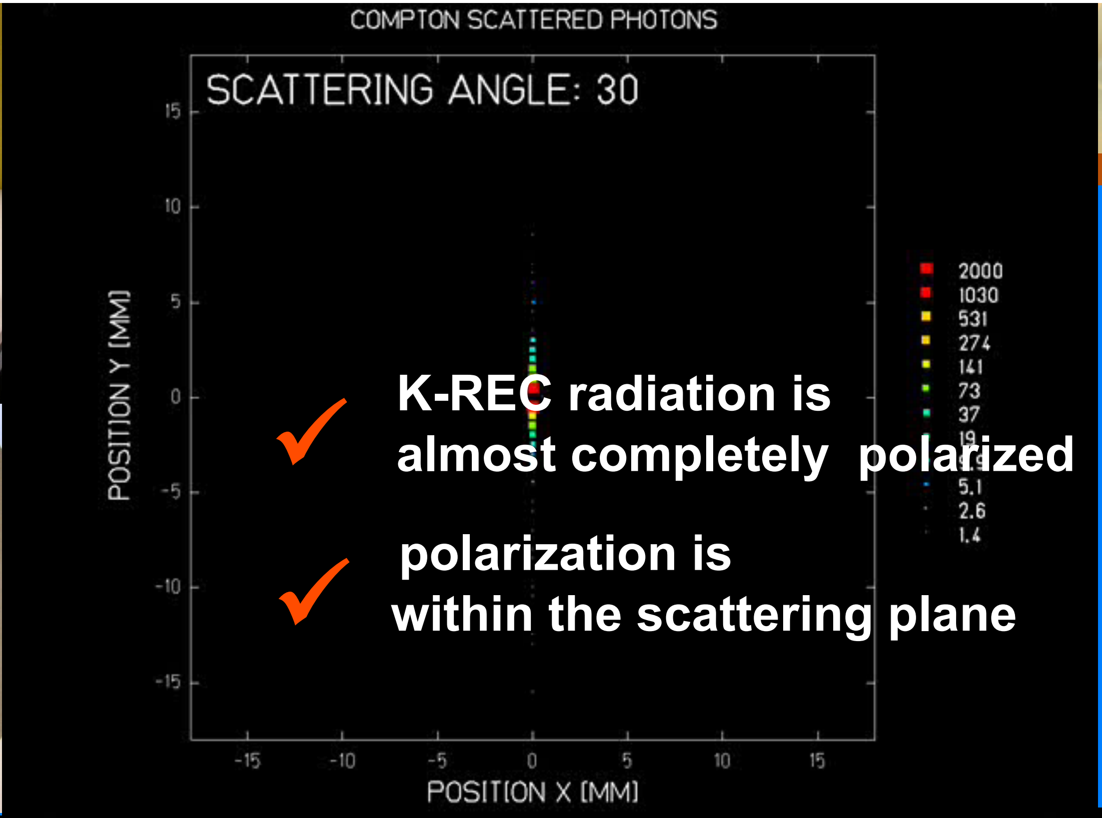
K-REC angular distribution



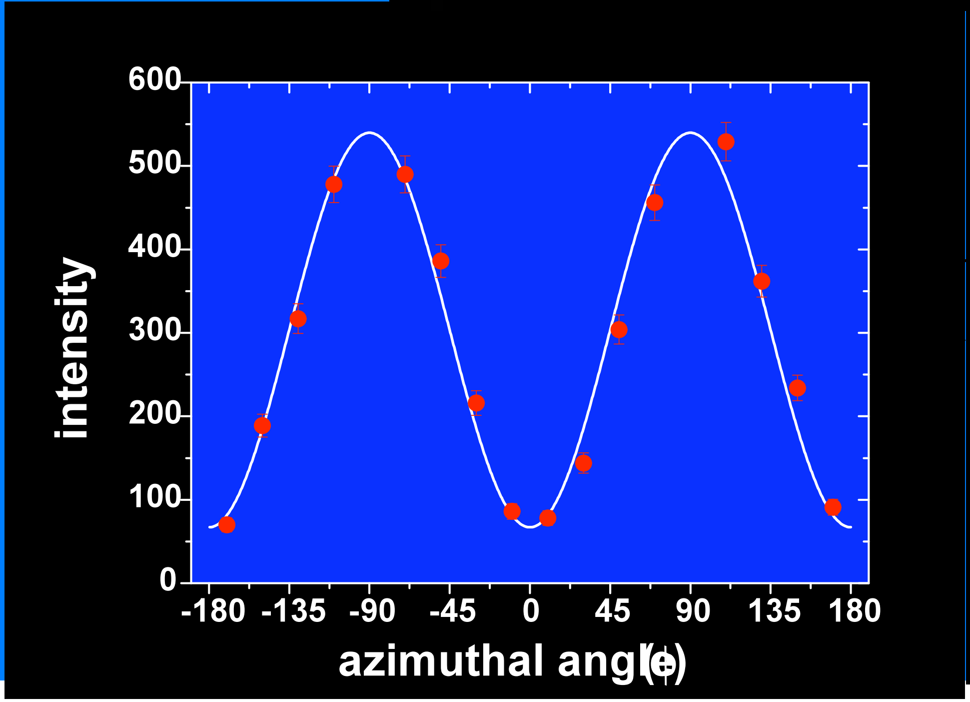
Si(Li) 2D-strip

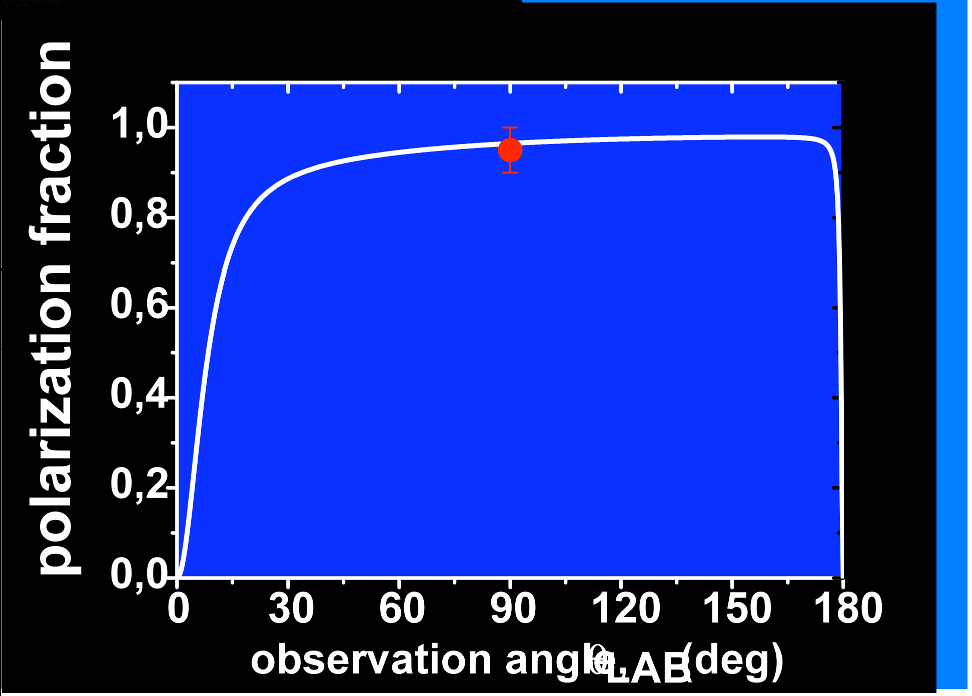






- ✓ K-REC radiation is almost completely polarized
- ✓ polarization is within the scattering plane





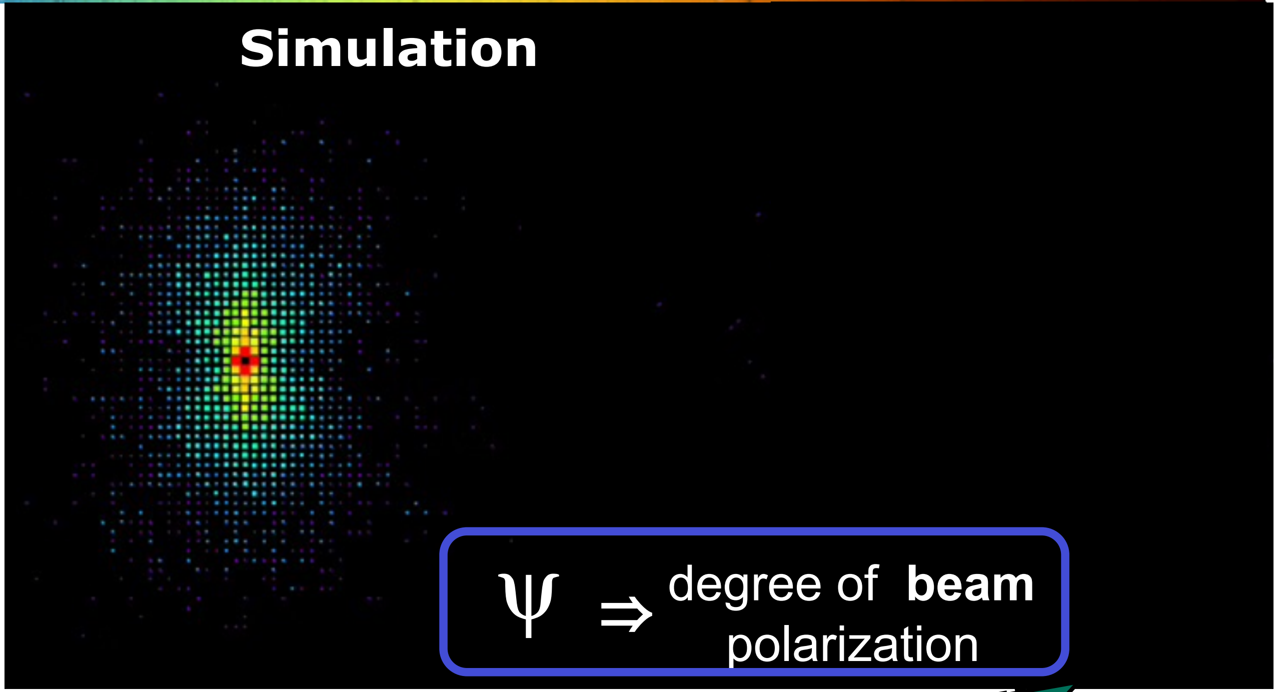
Recombination: spin polarization of particles

(ion or electron beam)

Spin Polarized Ion Beams

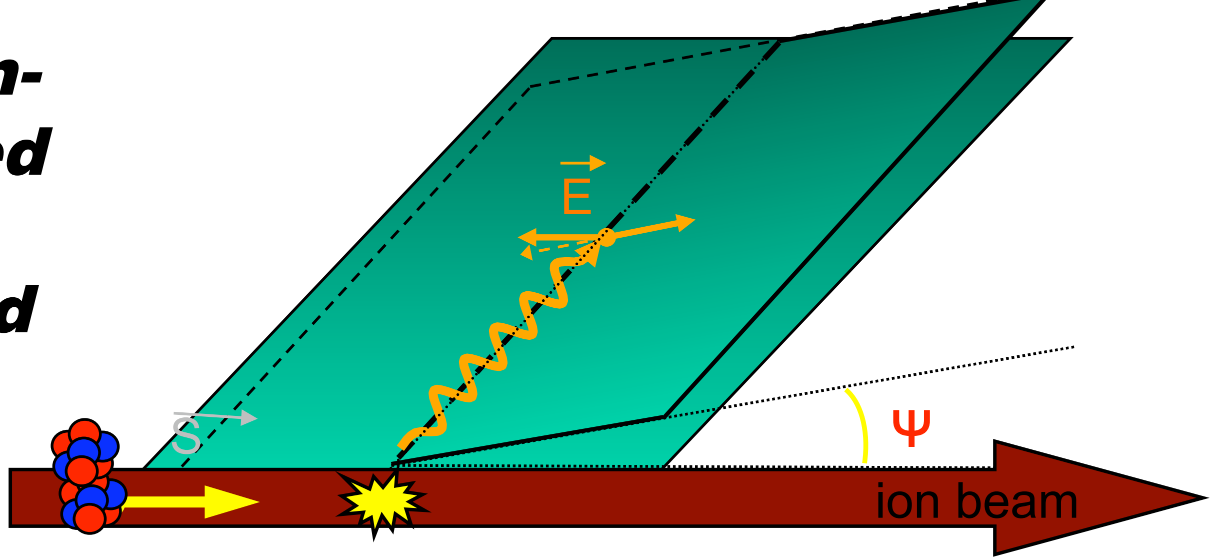
for spin polarized ions, the polarization plane and scattering plane are not equal for spin aligned ion beams

predictions by A.Surzhykov et al., PRL 94, 203202 (2005)

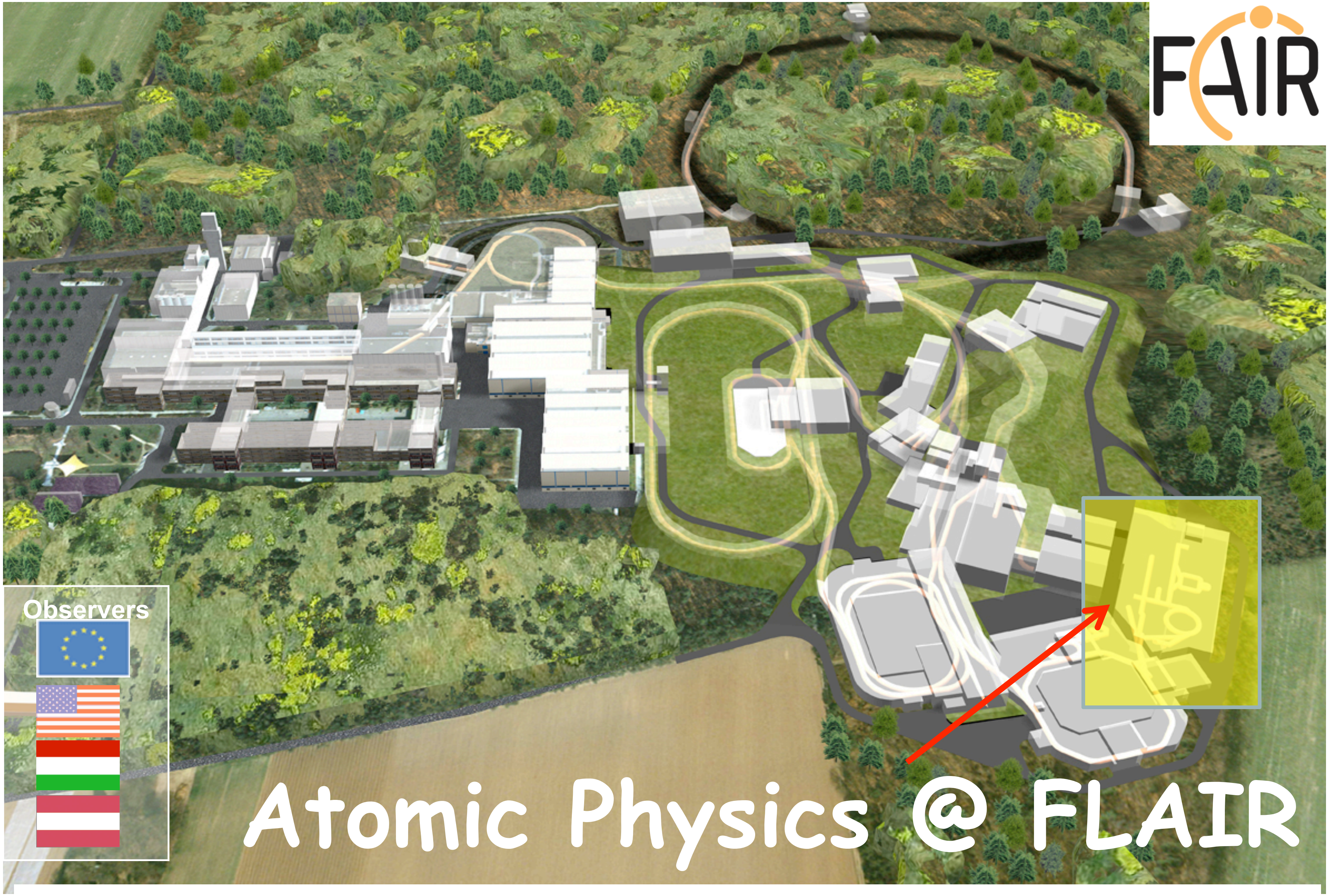


ψ ⇒ degree of **beam** polarization

control over the spin-polarization of stored ions:
required for EDM and PNC experiments



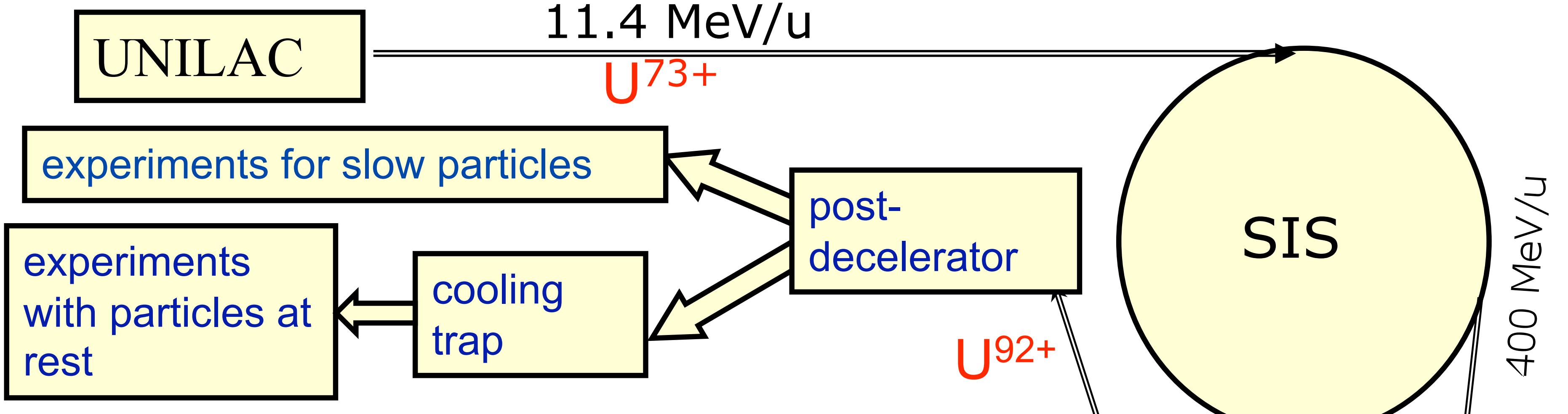
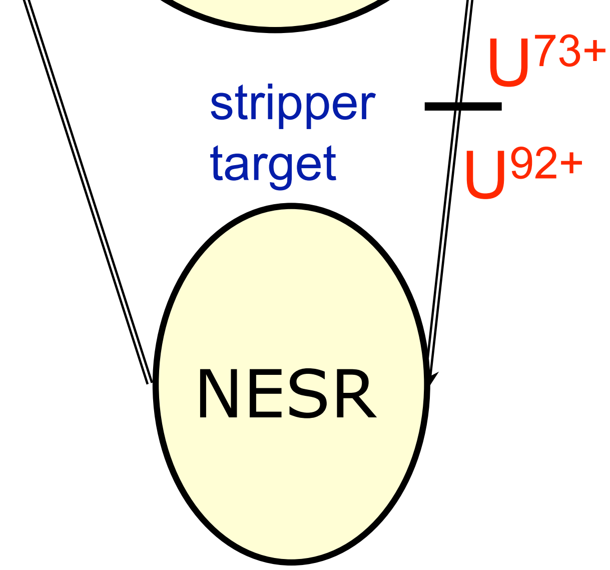
Atomic Physics @ FLAIR

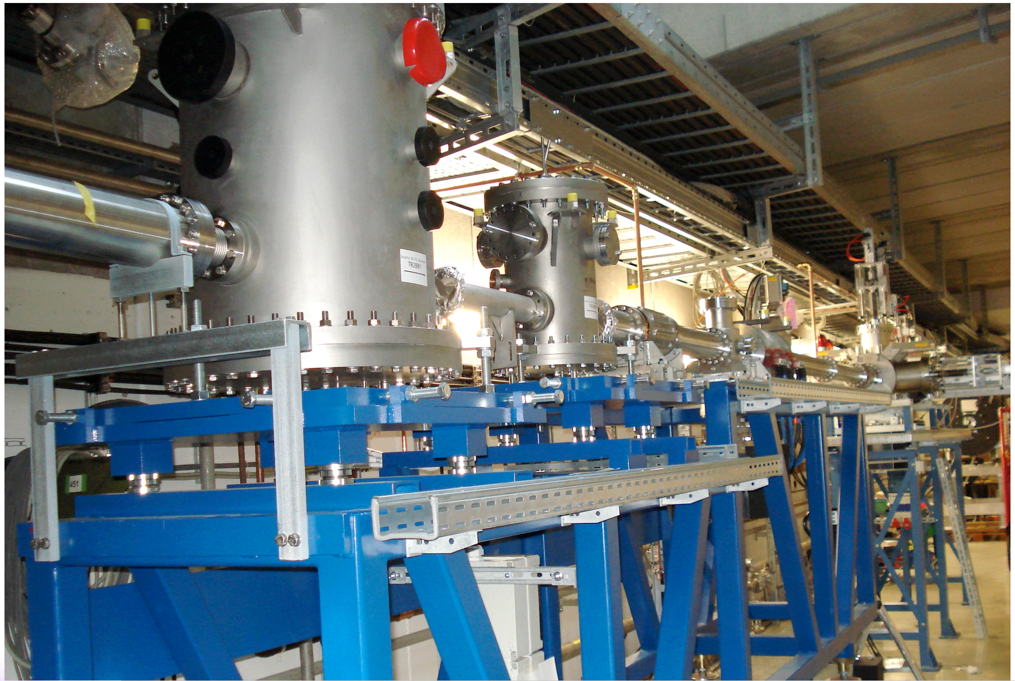


Observers

CN DE ES FI FR GB GR IN IT PL RO RU SE

The HITRAP Project

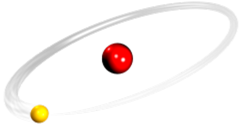





W. Quint, O. Kester et al.

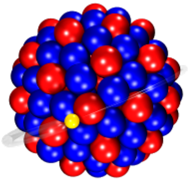
Quantum Electrodynamical Effects in Extreme Electromagnetic Fields

hydrogen

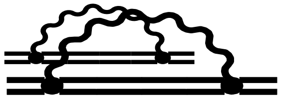


Z=1
E_b = 13.6 eV
Z·α « 1

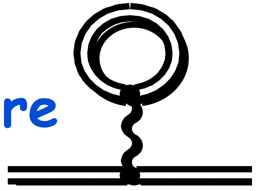
uranium ion

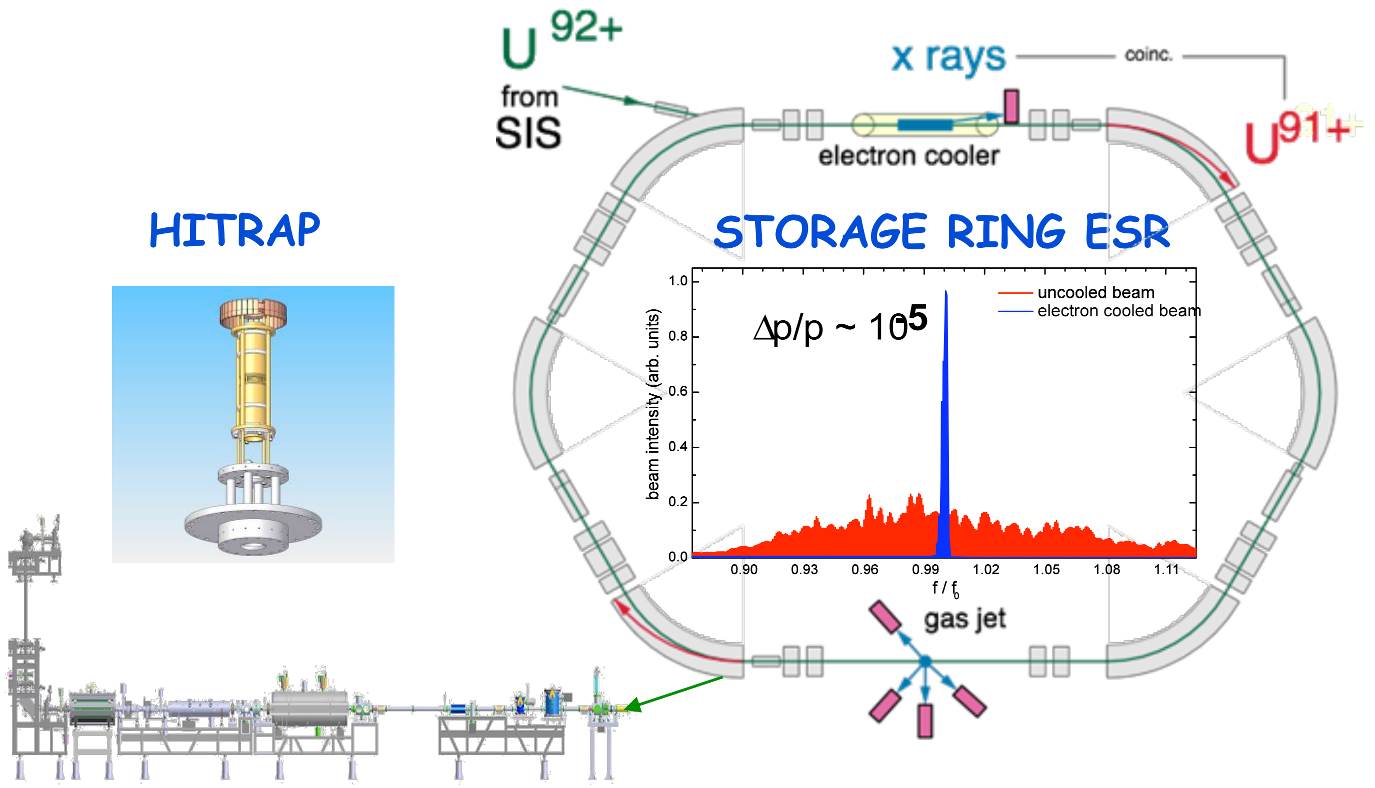


Z=92
E_b = 132 keV
Z·α ≈ 1

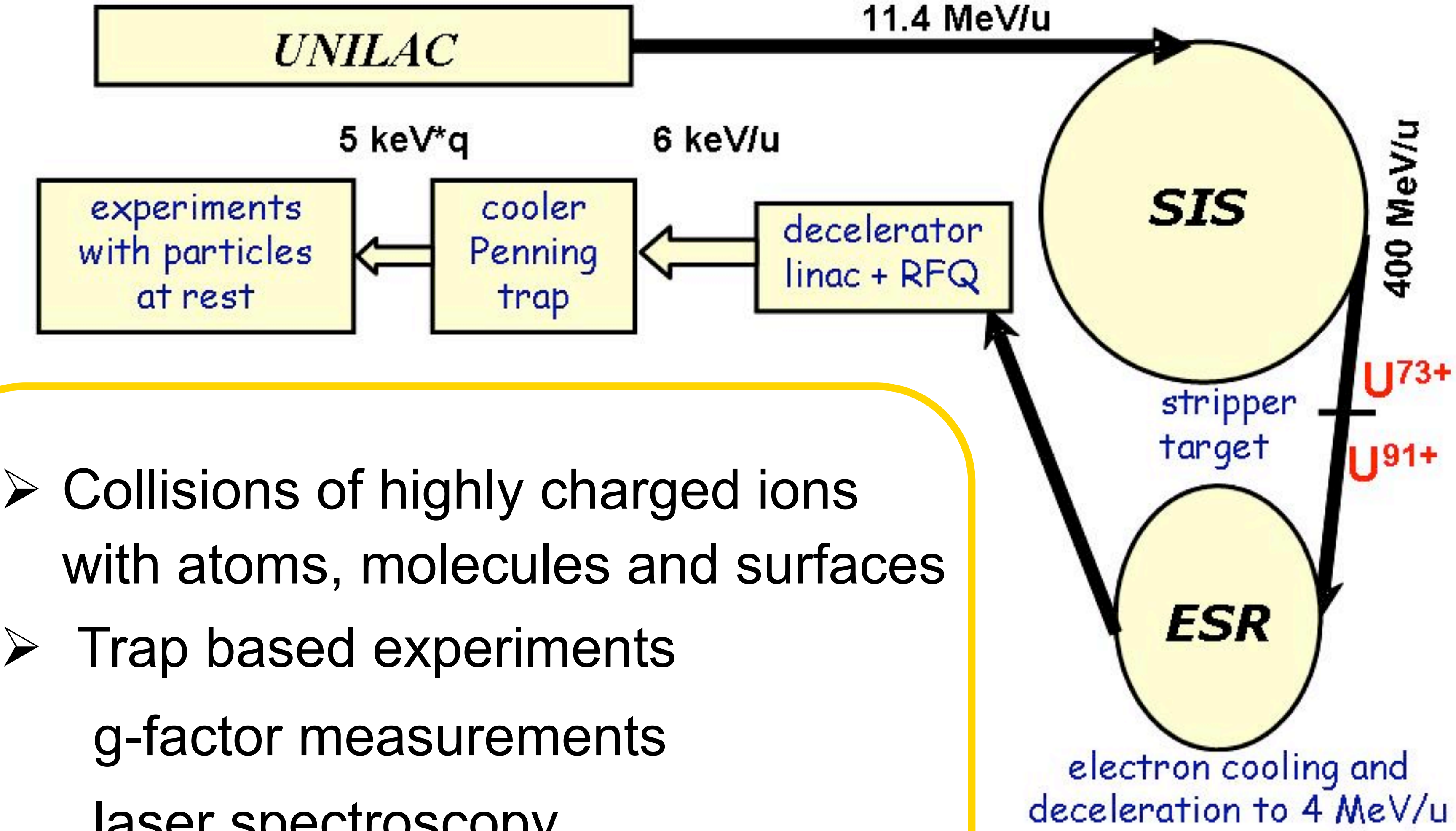


Lamb Shift
Hyperfine Structure
g-Factor





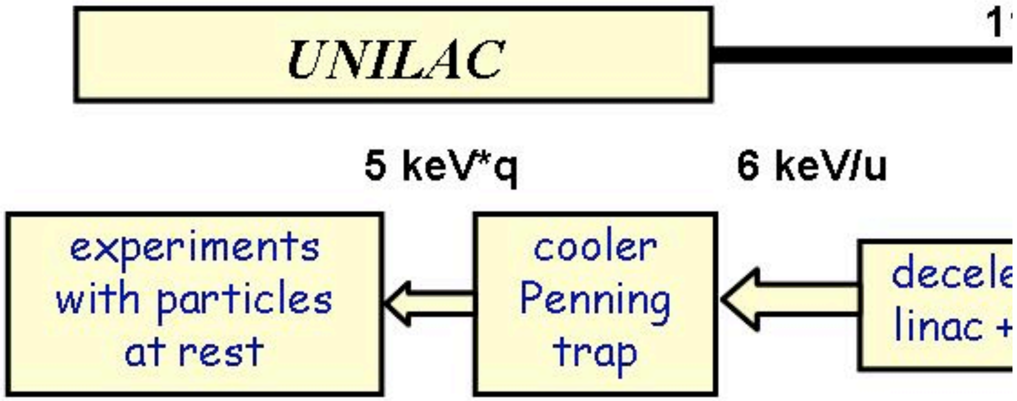
HITRAP – Trap facility for heavy highly charged ions



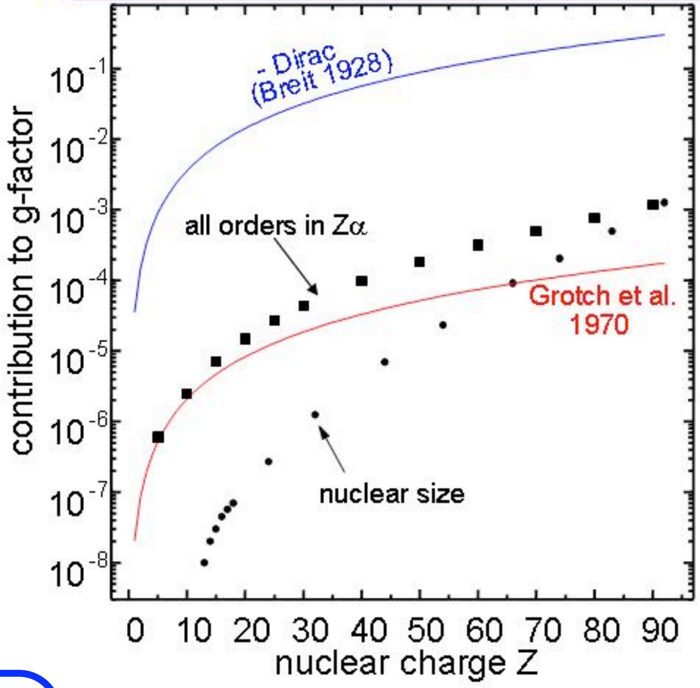
- Collisions of highly charged ions with atoms, molecules and surfaces
- Trap based experiments
  - g-factor measurements
  - laser spectroscopy
  - mass measurements

HITRAP - Trap facility for heavy highly charged ions

g-Factor of the bound electron in a hydrogen-like ion (hydrogenlike uranium at rest)



$$g_{bound}/g_{free} \approx 1 - \underbrace{(Z\alpha)^2/3}_{\text{Dirac theory}} + \underbrace{\alpha(Z\alpha)^2/4\pi}_{\text{bound-state QED}} + \ldots$$



Bound-state QED and fundamental constants
g-Factor measurements
***in a series of elements* up to U^{91+}**

- **low-Z → electron mass m_e**
- **medium-Z → fine-structure constant α**
- **high-Z → test of bound-state QED**

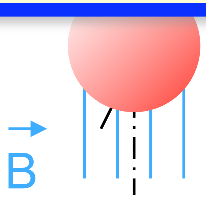
Theory: T. Beier, U.D. Jentschura, S. Karshenboim, H. Persson, V. Shabaev, V. Yerokhin, et al.

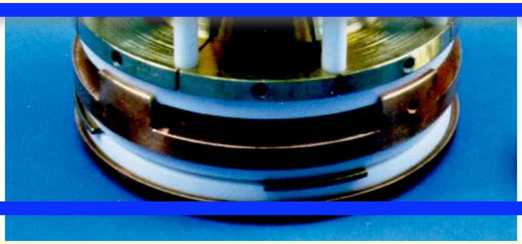
g-factor of the bound electron in a HCI

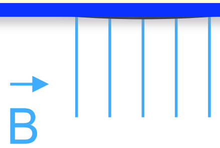
La

bound state electron g-factor for C^{5+}

theoretical value: 2.001 041 589 9(9)
experimental value: 2.001 041 596 4(10) {44}







assume QED is correct

m_e = 0.000548 579 909 2(4) u

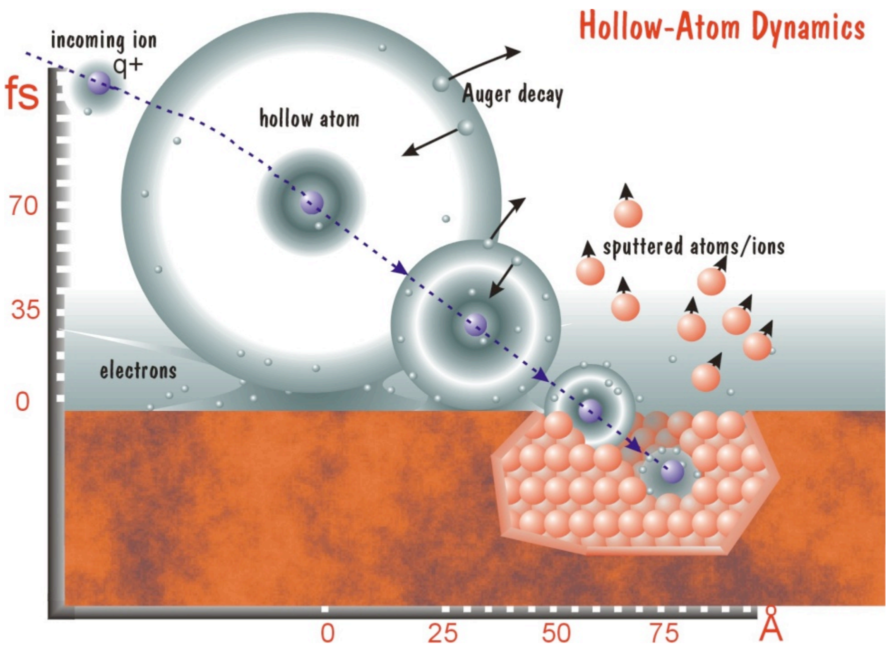
van Dyck (1995) m_e = 0.000548 579 911 1(12) u
CODATA (1998) m_e = 0.000548 579 911 0(12) u

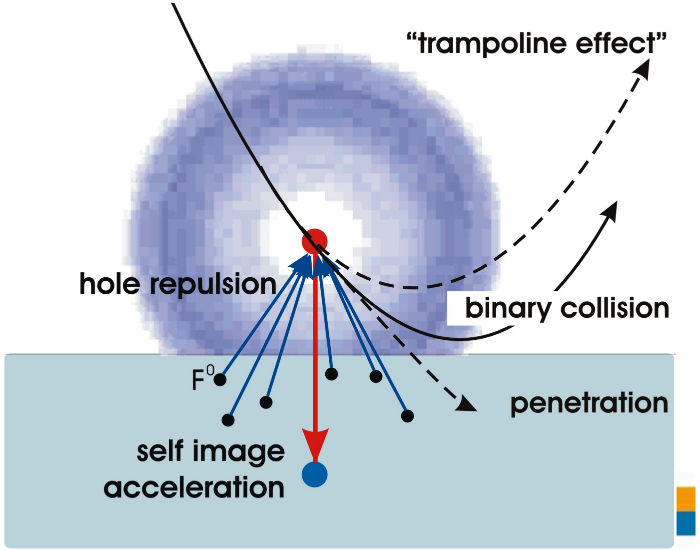
improvement by a factor of 4*

Ion-surface interaction

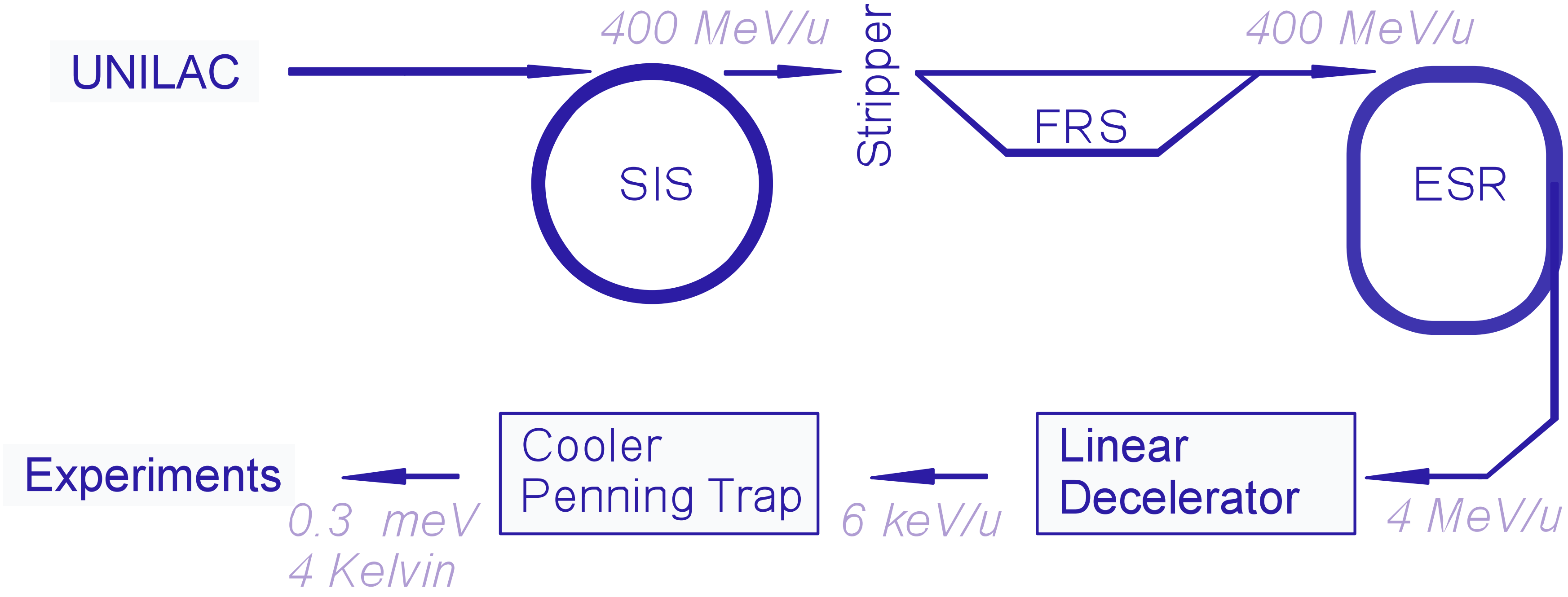
questions to be addressed:

- hollow atom spectroscopy
- high-spin states via electron capture from magnetised surfaces
- electron dynamics at surfaces and thin films
- trampoline effect existent above a critical charge state?
- surface lithography by means of HCI impact?





HITRAP @ GSI



UNILAC

400 MeV/u

SIS

Stripper

FRS

400 MeV/u

ESR

4 MeV/u

Linear Decelerator

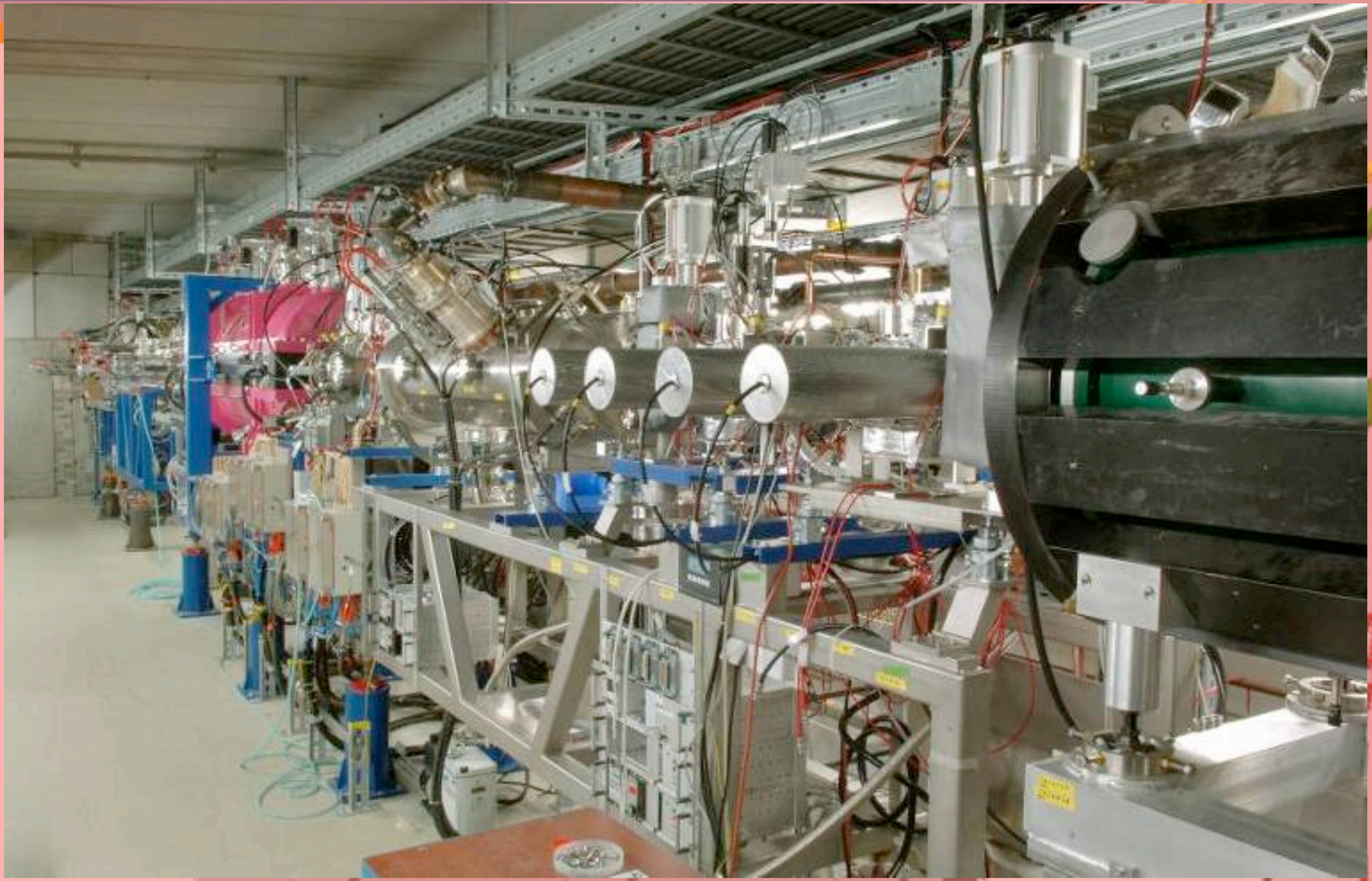
6 keV/u

Cooler Penning Trap

0.3 meV
4 Kelvin

Experiments

HITRAP

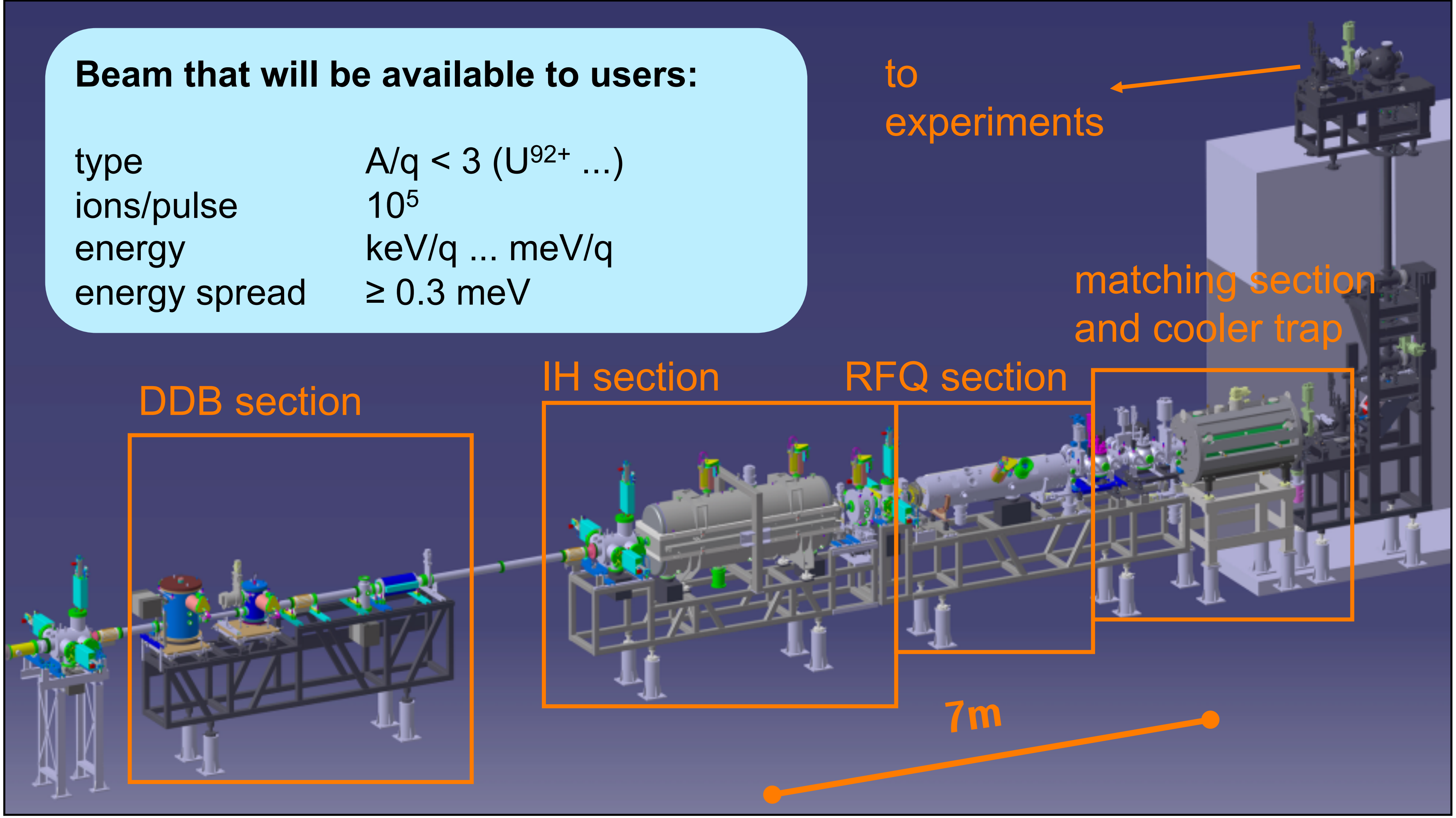


GeV/u

HITRAP – Linear Decelerator

Beam that will be available to users:

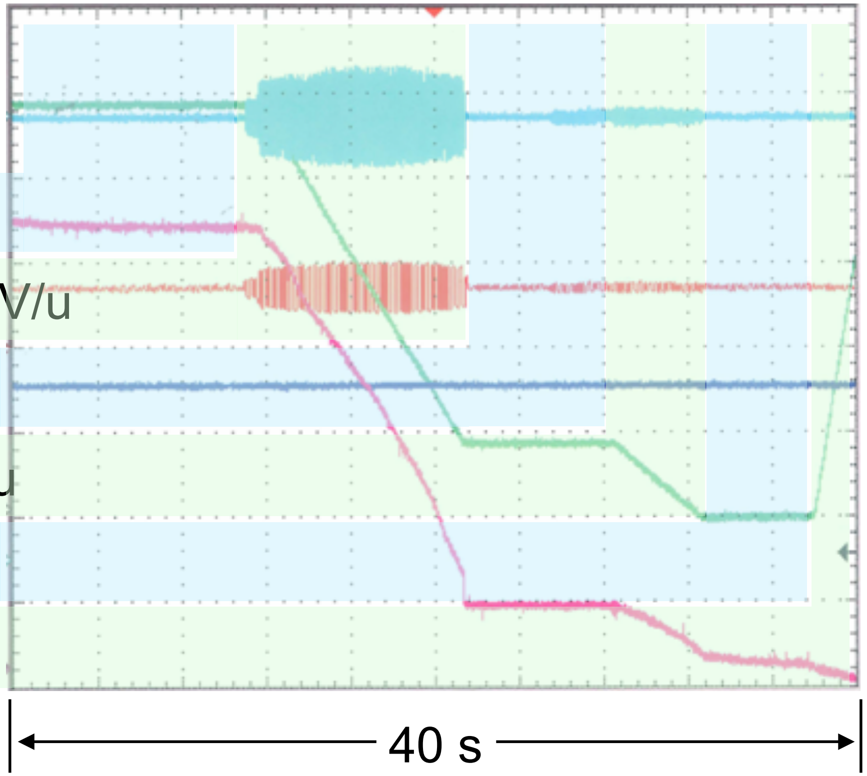
type	A/q < 3 (U^{92+} ...)
ions/pulse	10^5
energy	keV/q ... meV/q
energy spread	≥ 0.3 meV



ESR – From 400 to 4 MeV/u

ESR – Experimental Storage Ring at GSI with stochastic and electron cooling

time (s)	**ESR cycle during recent experiment**
5..20	injection, stoch. cooling
3..10	deceleration 400 – 30 MeV/u
2..6	e^- cooling, rebunching
2..5	deceleration 30 – 4 MeV/u
2..5	e^- cooling, ejection
3	reset magnets



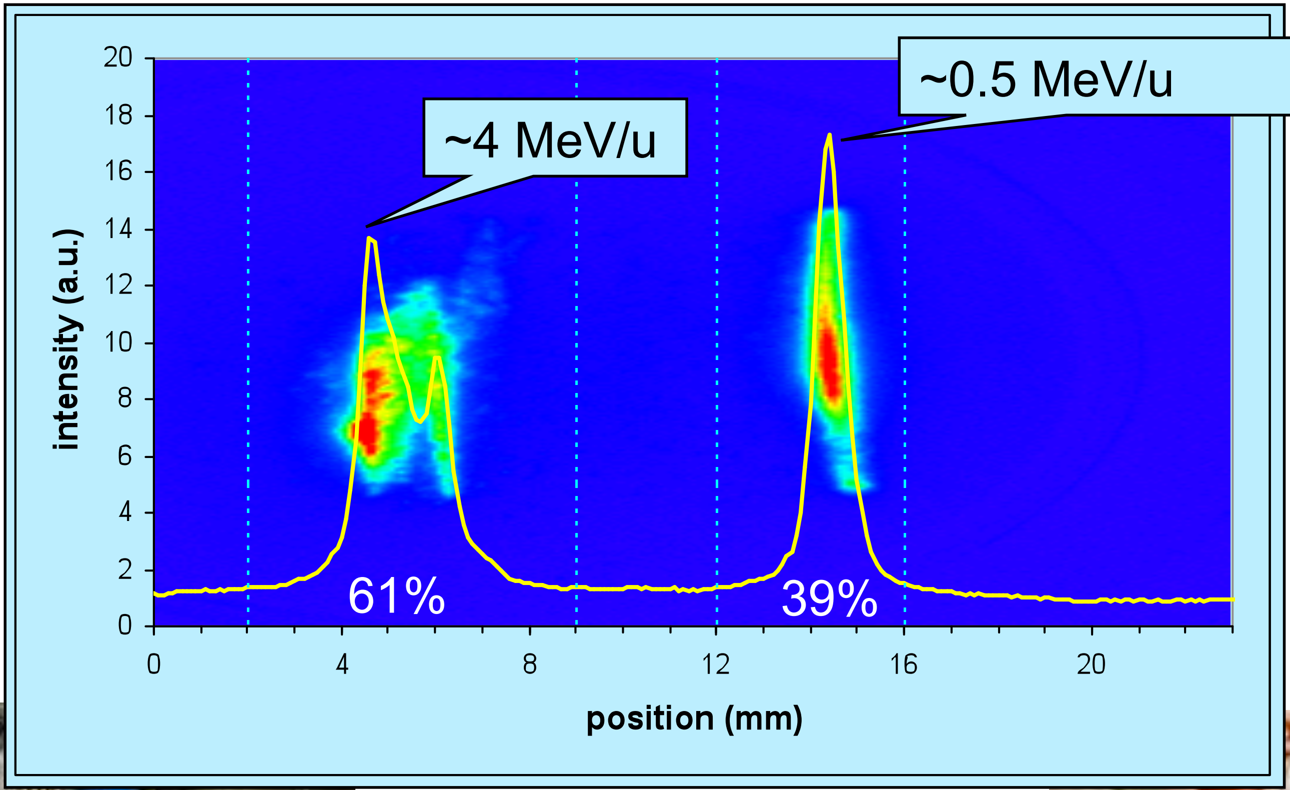
signal:

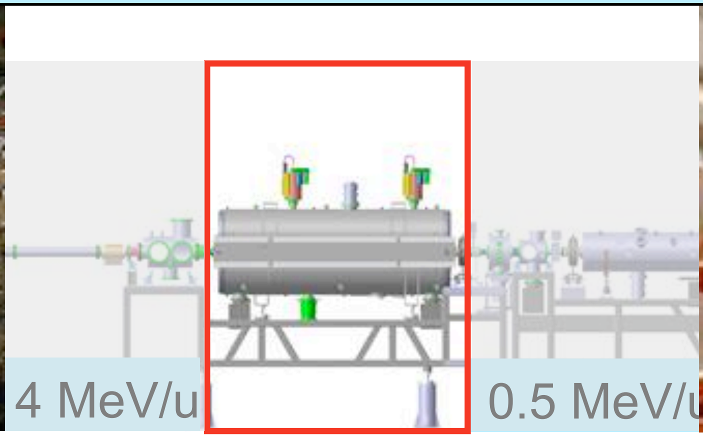
RF amplitude

magn.dipole field

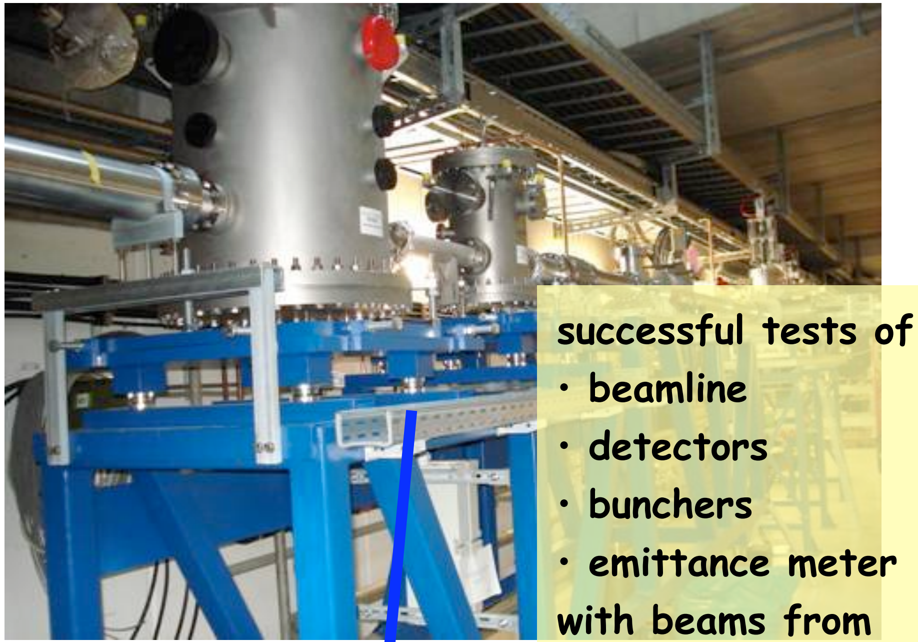
ion current

HITRAP – IH Structure



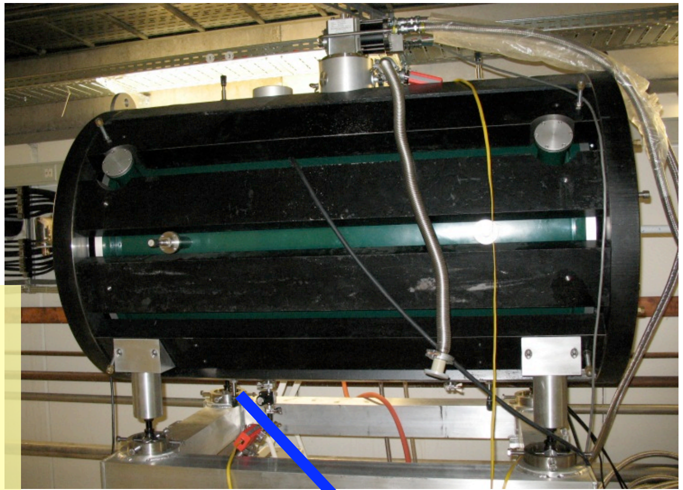


HITRAP overview in the re-injection channel at ESR

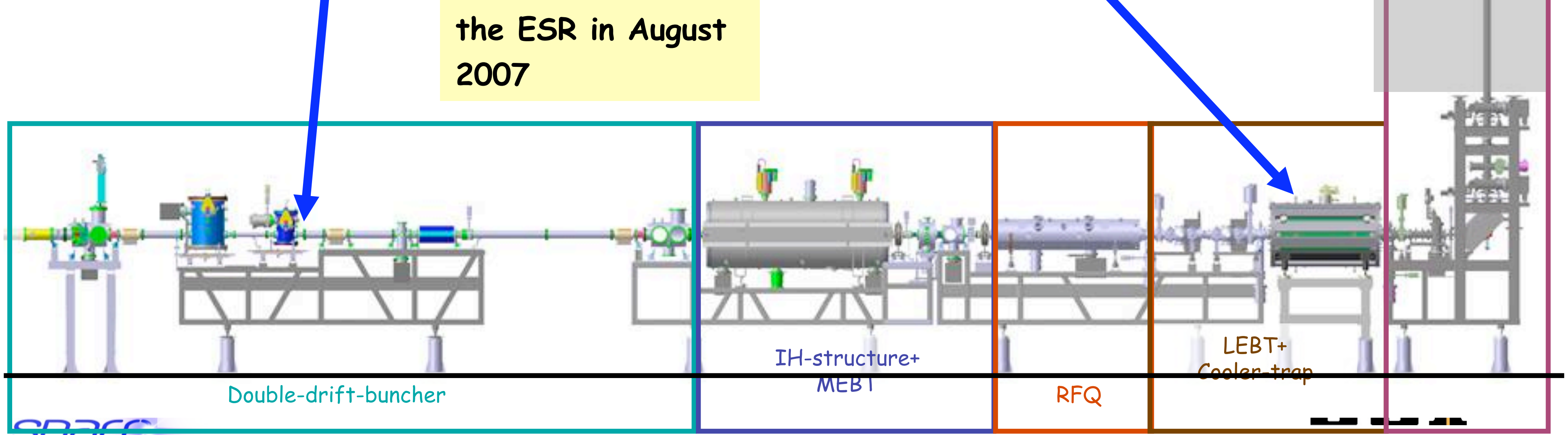


successful tests of
- beamline
- detectors
- bunchers
- emittance meter

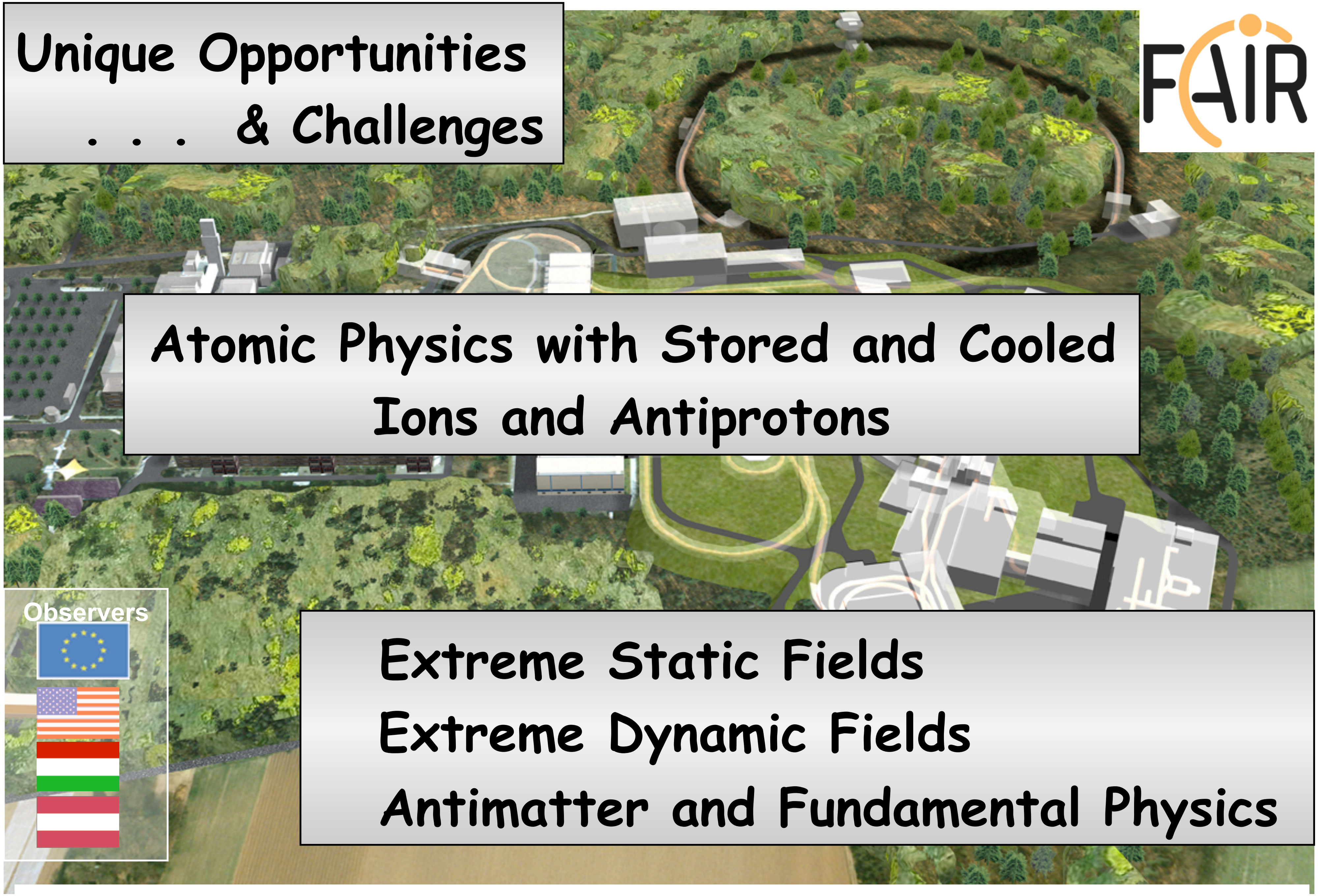
with beams from the ESR in August 2007



Cooler trap available:
- magnet
- electrodes
- HV-cage



Unique Opportunities . . . & Challenges



Atomic Physics with Stored and Cooled Ions and Antiprotons

Extreme Static Fields

Extreme Dynamic Fields

Antimatter and Fundamental Physics

Observers

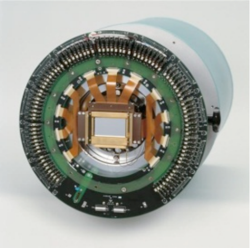
CN DE ES FI FR GB GR IN IT PL RO RU SE

Construction and Infrastructure

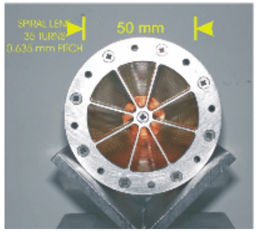
NESR, SIS100/300, HCAVE A, FLAIR-Building

R&D Activities Towards FAIR Required at

CAVE A, ESR, UNILAC



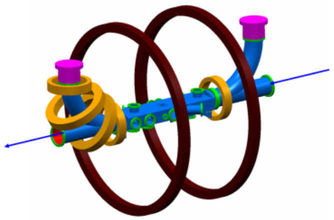
Detectors



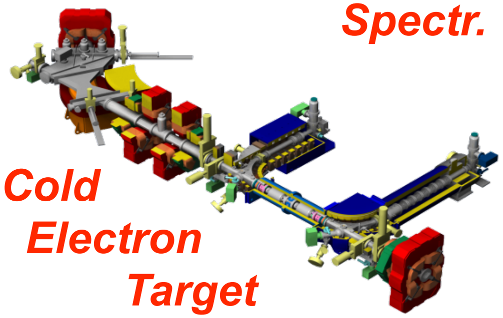
X-Ray Optics

R&D Towards FAIR at External Labs

Belfast (EBIT)
Cracow
ESRF, Grenoble (Synchrotron)
Groningen (ECR)
HASYLAB, Hamburg (Synchrotron)
Heidelberg (EBIT)
Stockholm (EBIT)
GANIL
Catania
Lanzhou (ECR)



Electron-, Recoil Ions Spectr.



Cold Electron Target