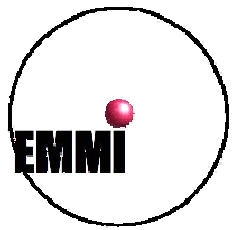
Structure and Dynamics of Highly-charged Ions: Physics at Extreme Fields

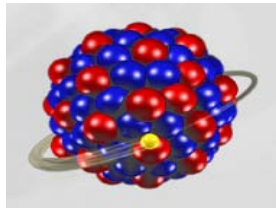
Alexandre Gumberidze

ExtreMe Matter Institute, EMMI



Atomic Physics at Extreme Fields with Highly Charged Heavy Ions

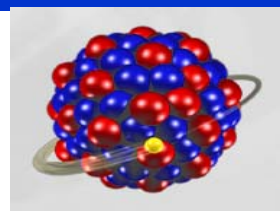
Scaling factors:		**from H to U^{91+}**
• level energy	$E_n \approx Z^2$	10^4
• hyperfine splitting	$\sim Z^3$	10^6
• nuclear size effects	$\sim Z^6$	10^{12}
• QED contributions	$\sim Z^4$	10^8



H-like Uranium
<E>~ 10^{16} V/cm

- Fundamental phenomena:
  - become accessible in some cases due to:
    simpler electronic structure
    scaling of effects with high powers of Z
    (QED, nuclear size,…)
- Laboratory and astrophysical plasmas:
  Almost all luminous matter is ionized
- X-ray standards, fundamental constants
- Sensitivity to nuclear parameters

Physics at Extreme Fields with Highly Charged Heavy Ions



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ATOMIC SPECTROSCOPY
QED, many body effects
critical fields

PLASMA DIAGNOSTICS
X-ray spectr.,temperature,
density, spectra interpretation

ATOMIC REACTIONS AND DYNAMICS
in strong perturbative regime

NUCLEAR GROUND STATE PROPERTIES
masses, nuclear moments, charge radii

PHYSICS AT EXTREME FIELDS
with
HIGHLY CHARGED IONS

COOLING Techniques

X-RAY SPECTROMETERS DETECTORS

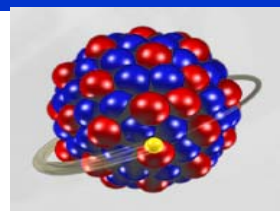
STORAGE RING TECHNIQUES

REACTION SPECTROMETERS

TRAP TECHNIQUES

HIGH-POWER LASERS X-RAY LASERS

Physics at Extreme Fields with Highly Charged Heavy Ions



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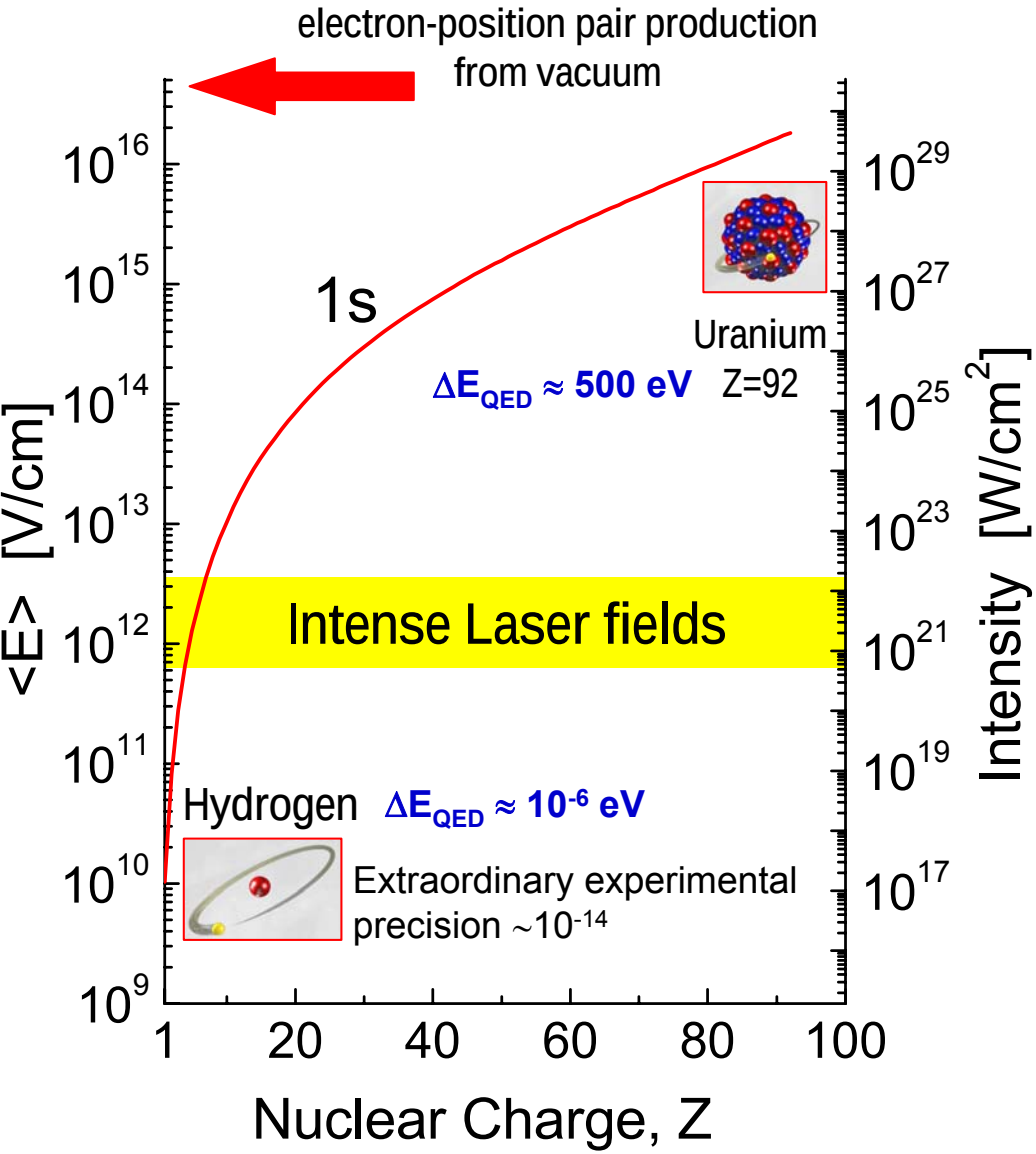
Physics in Extremely Strong Fields



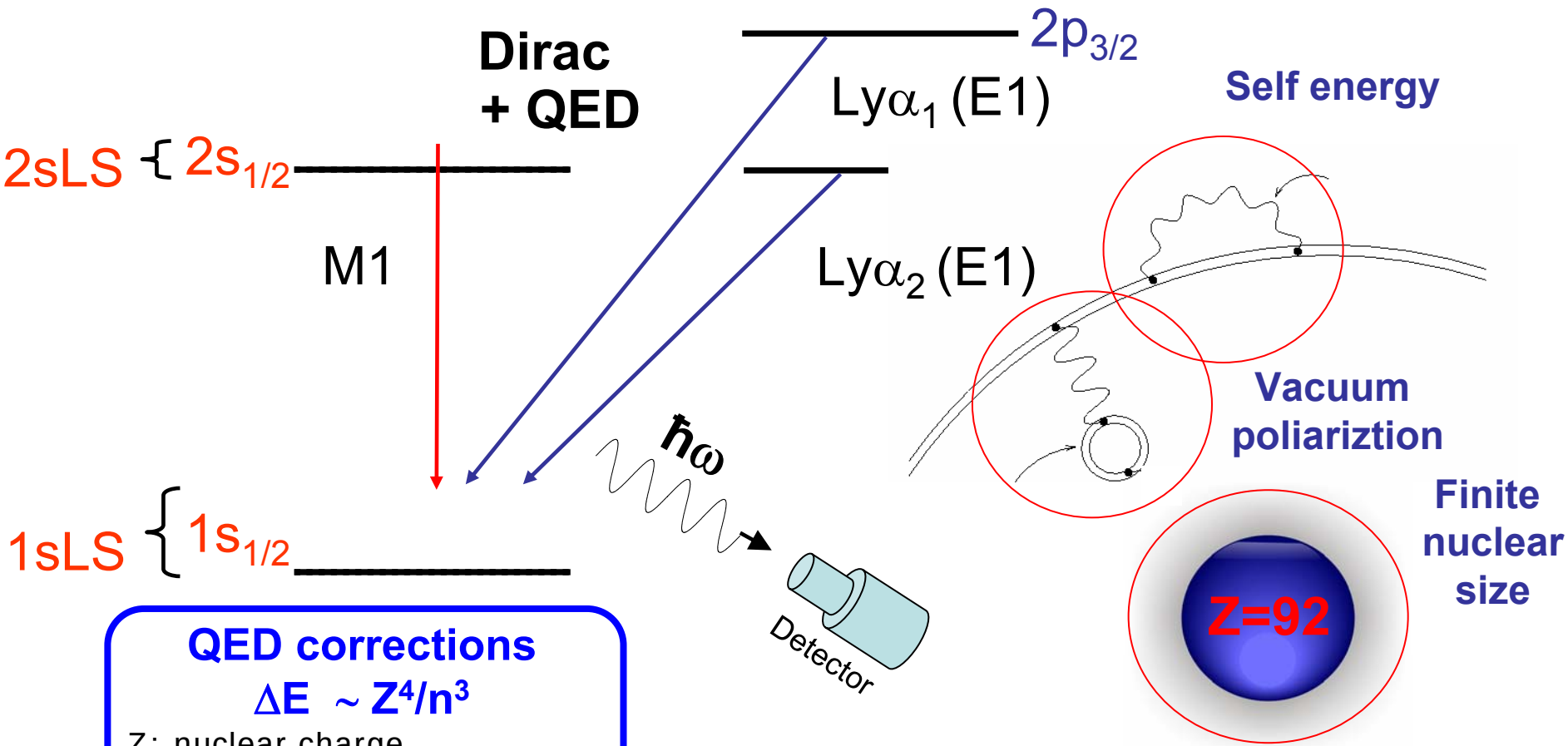
Atomic Structure at High-Z

- 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 Structure of One-electron System



QED corrections

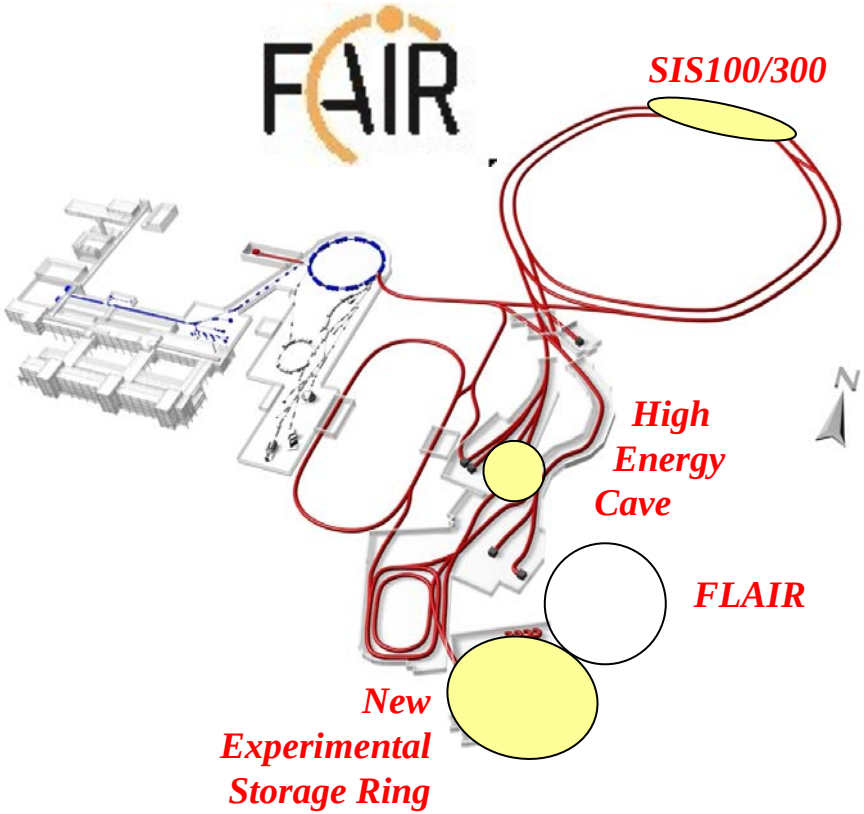
$\Delta E \sim Z^4/n^3$

Z: nuclear charge
n: principal quantum number

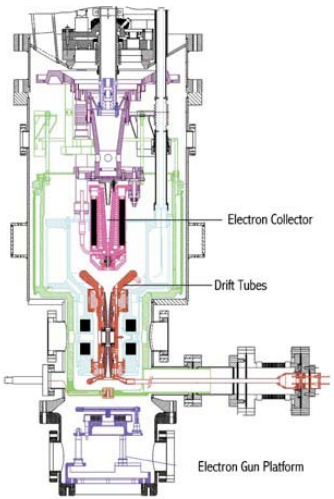
Important for s-states

- **Decrease of the binding energies**
- **dominantly for s-states**

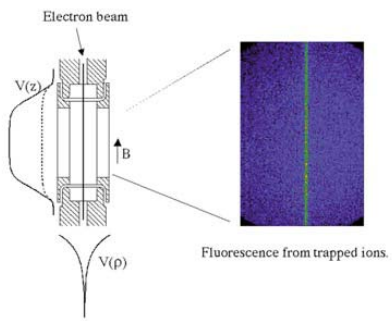
How to make HCI ?



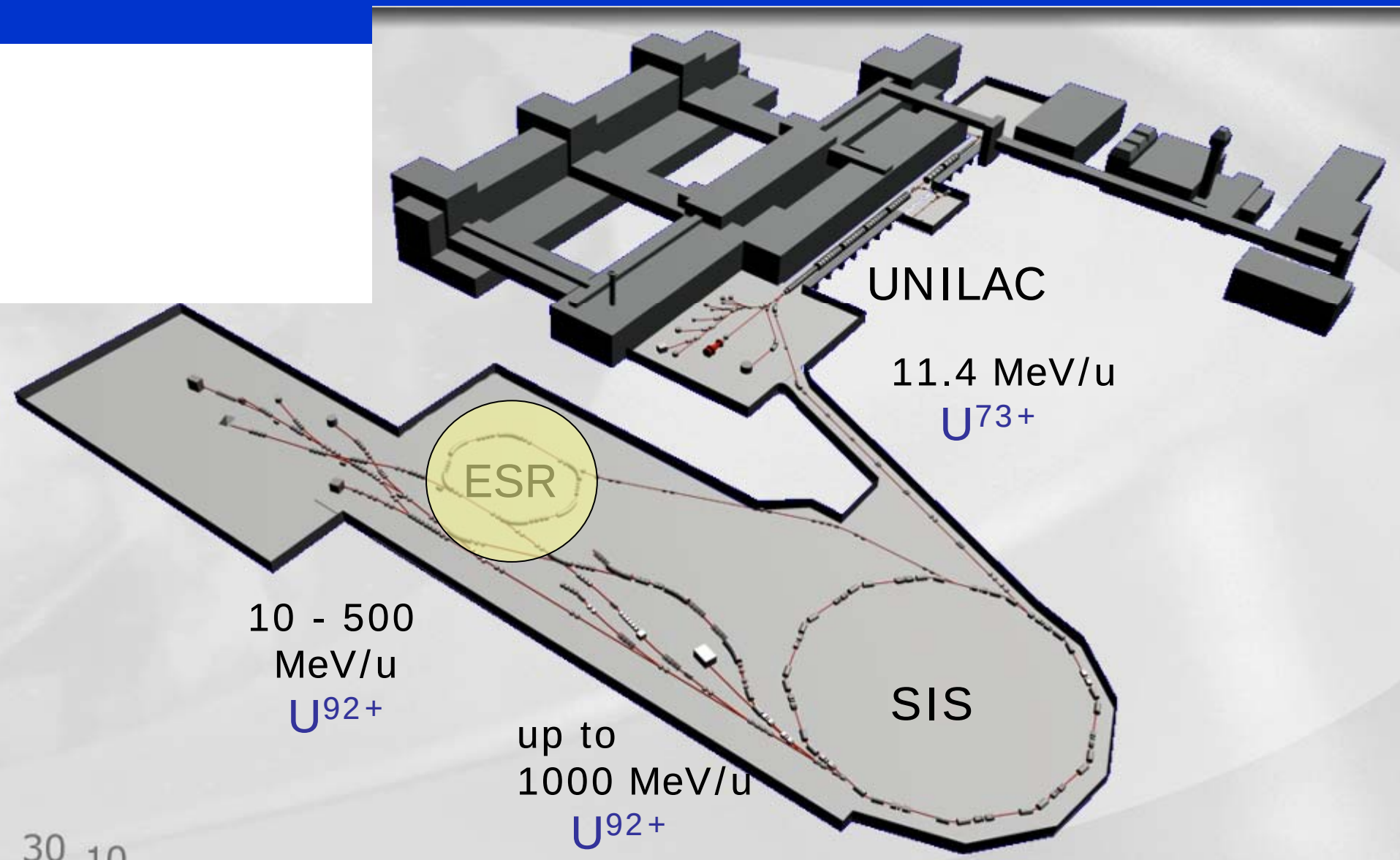
ECRIS



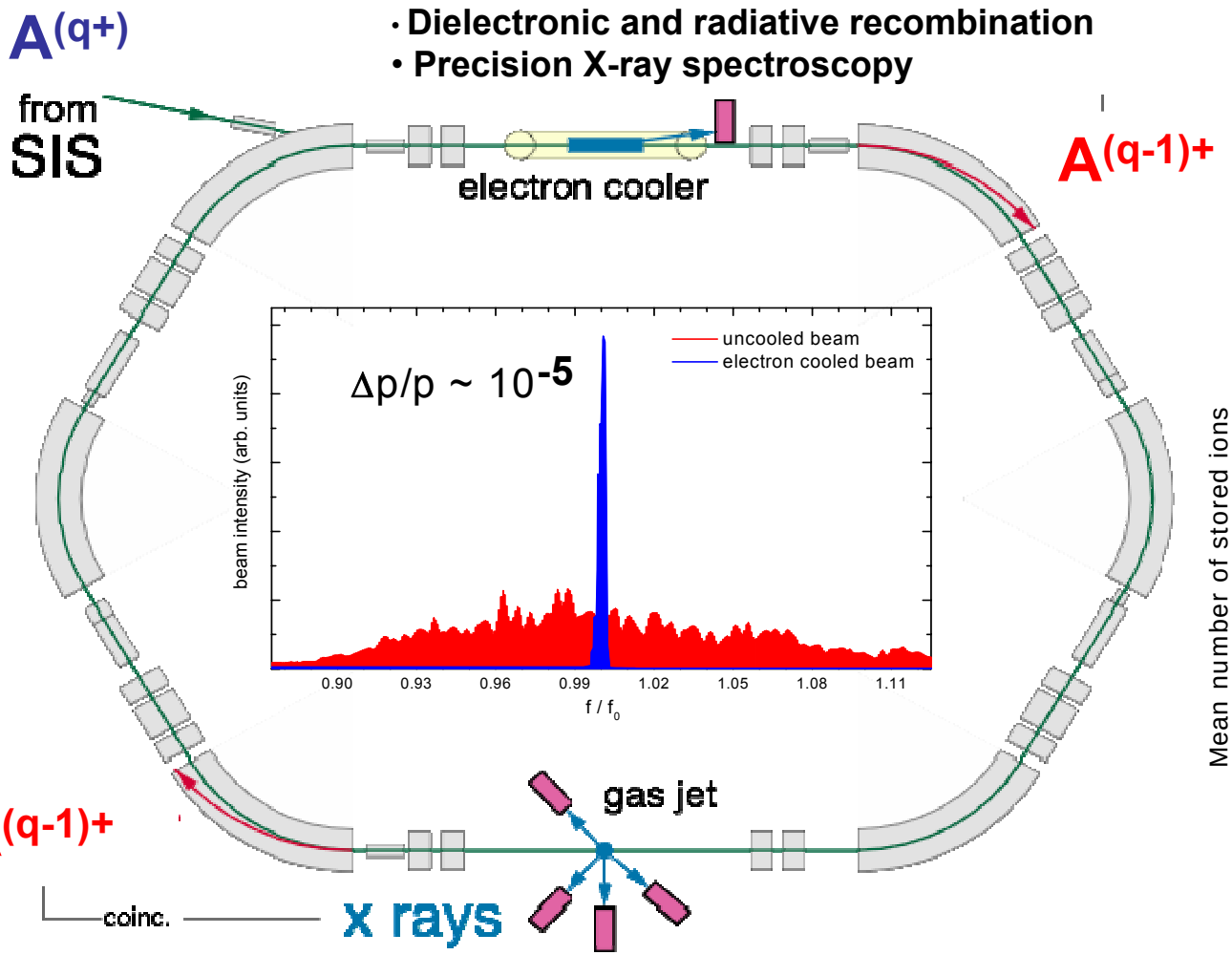
EBIT



HCI Production at GSI-ACCELERATOR FACILITY

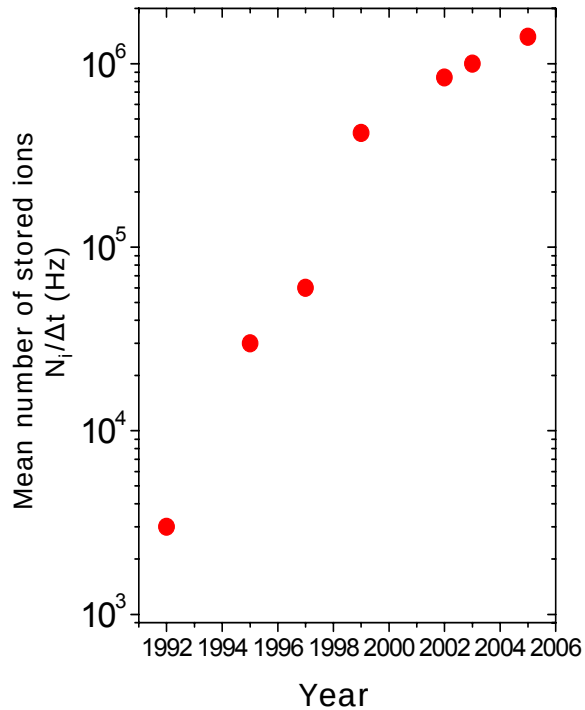


ATOMIC PHYSICS WITH STORED HIGHLY-CHARGED IONS AT THE ESR



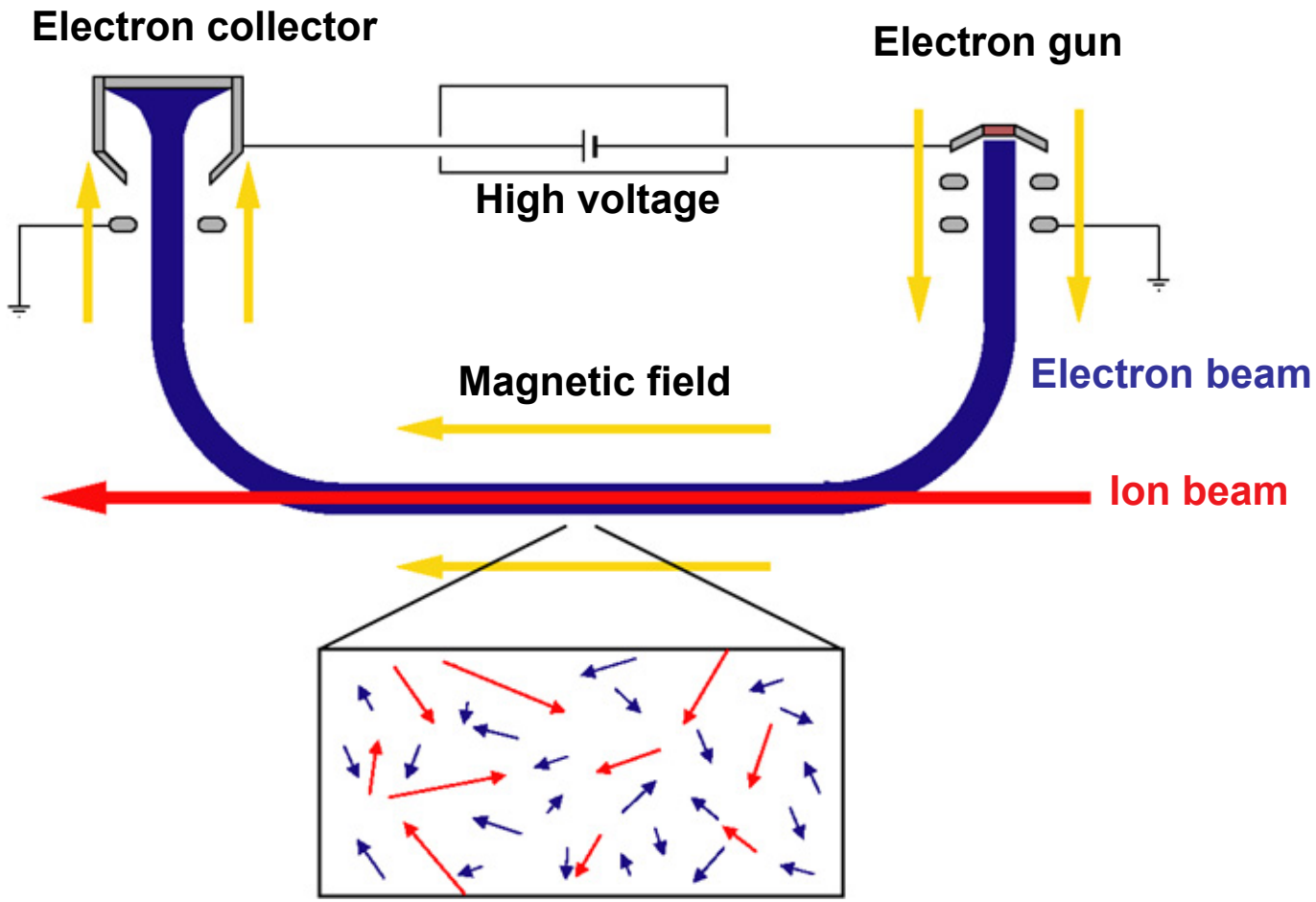
- STORING
- COOLING

→ **PRECISION**

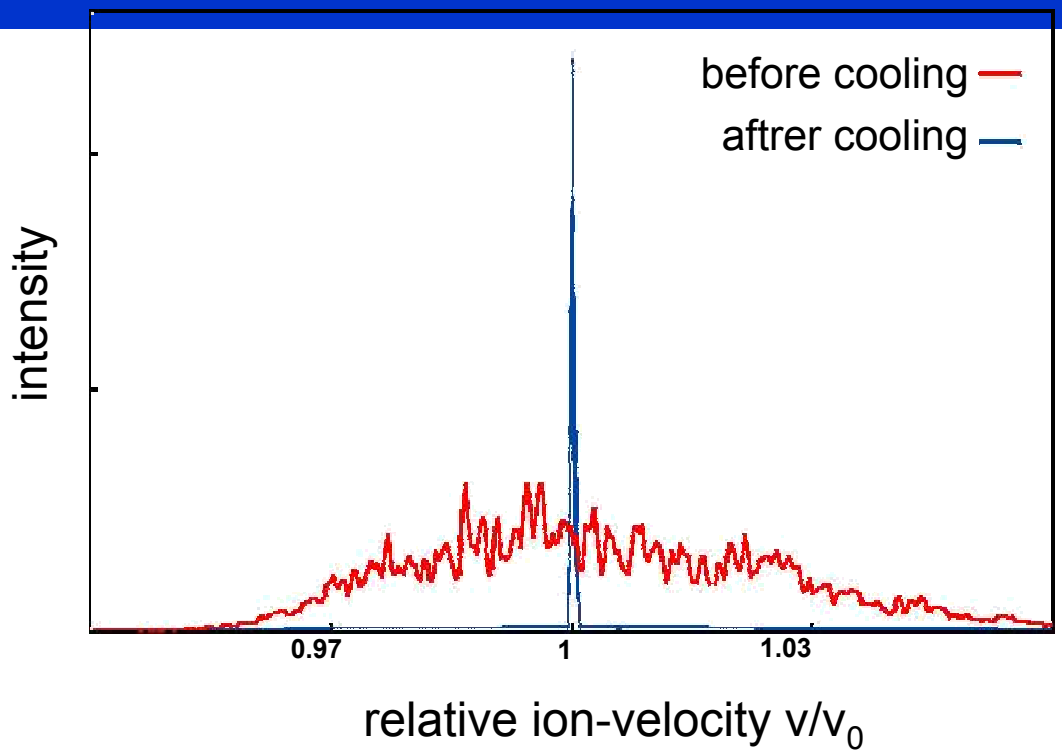


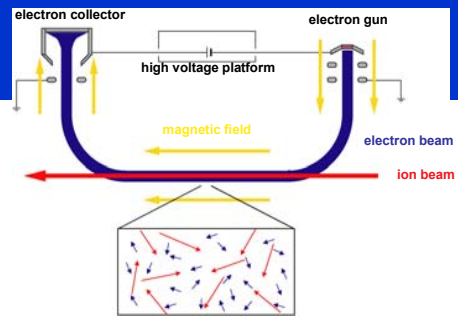
- **Relativistic atomic collision dynamics**
- **Polarization and alignment phenomena**
- **Novel high-resolution X-ray detection devices**

The electron cooler



Cooled heavy-ion beams



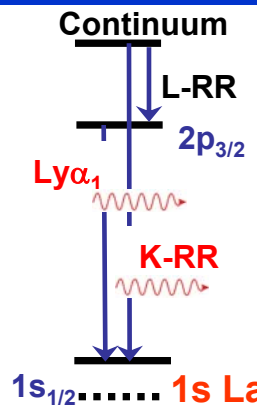


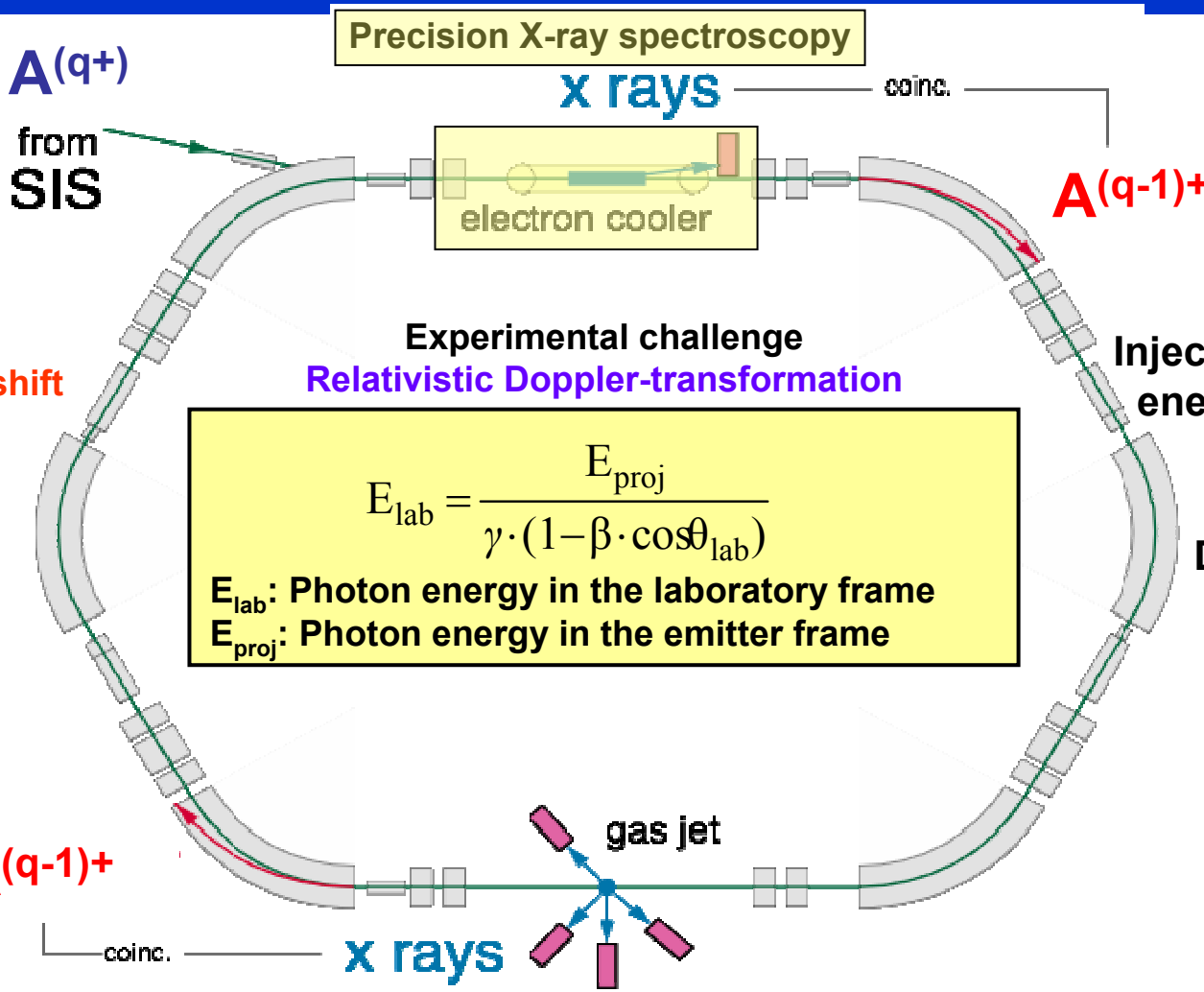
ions interact 10^6 1/s with the collinear cold electron beam

properties of cold ion beams

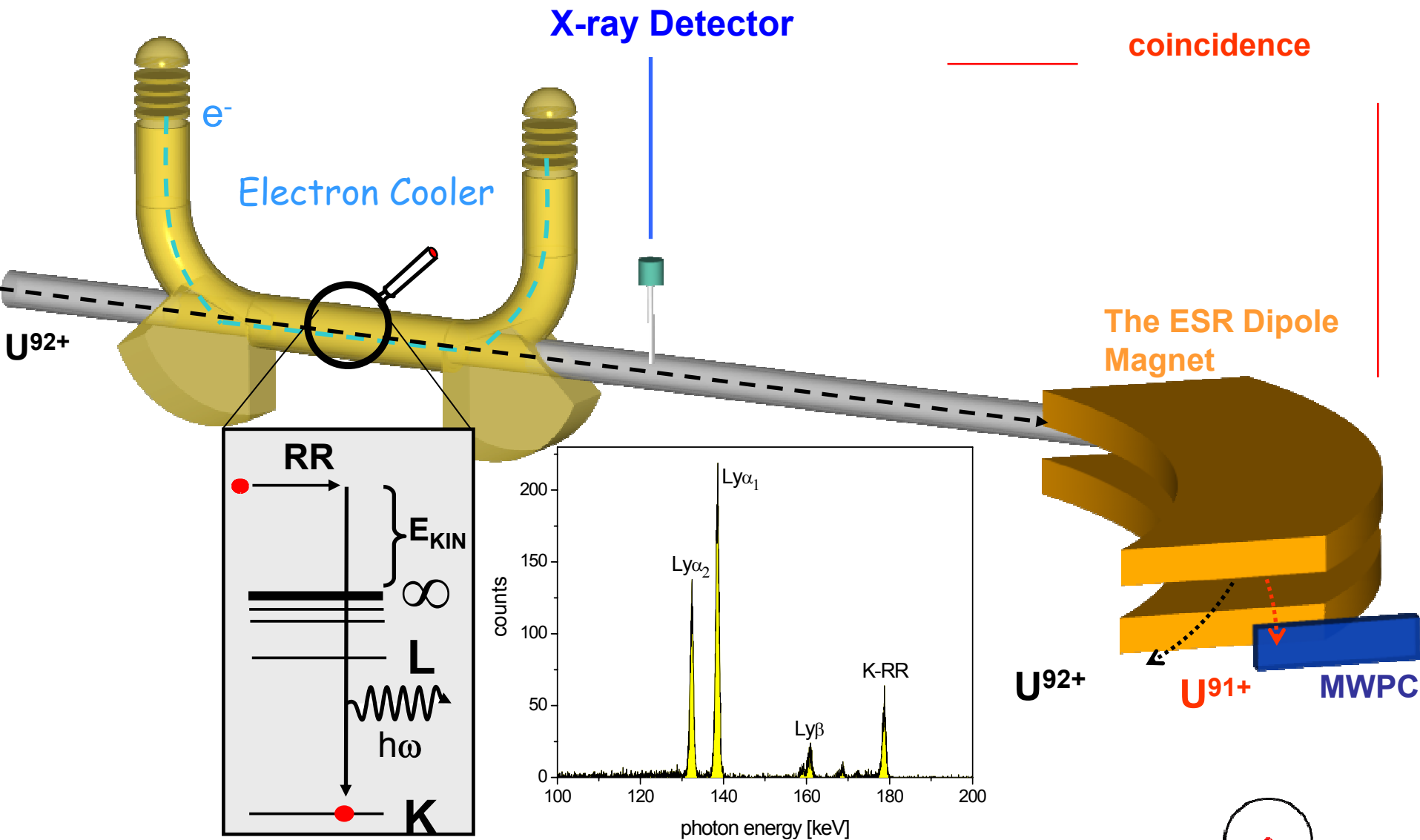
momentum width $\Delta p/p$: 10^{-4} – 10^{-5}
size 2 mm

PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS:
Lamb shift in H-like uranium

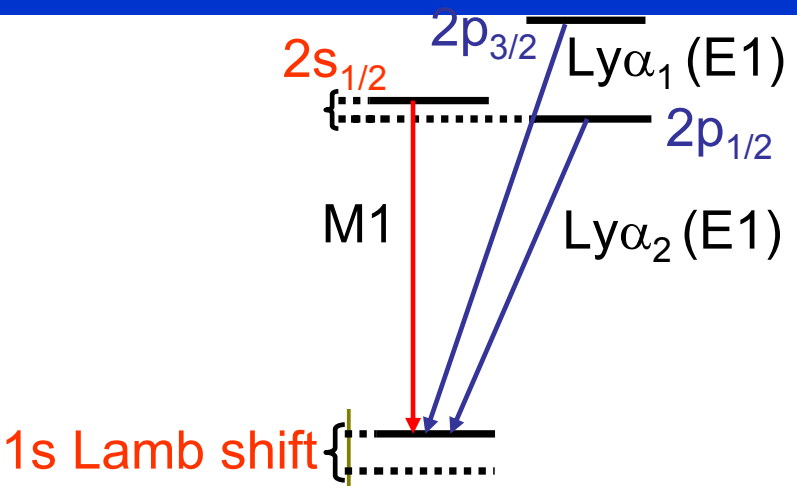


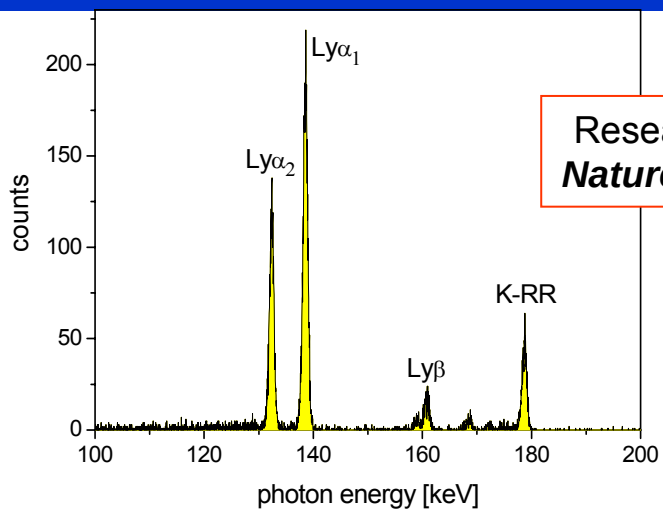


PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS:
The Two-electron Contribution to the Ground State Binding-Energy in He-like Uranium

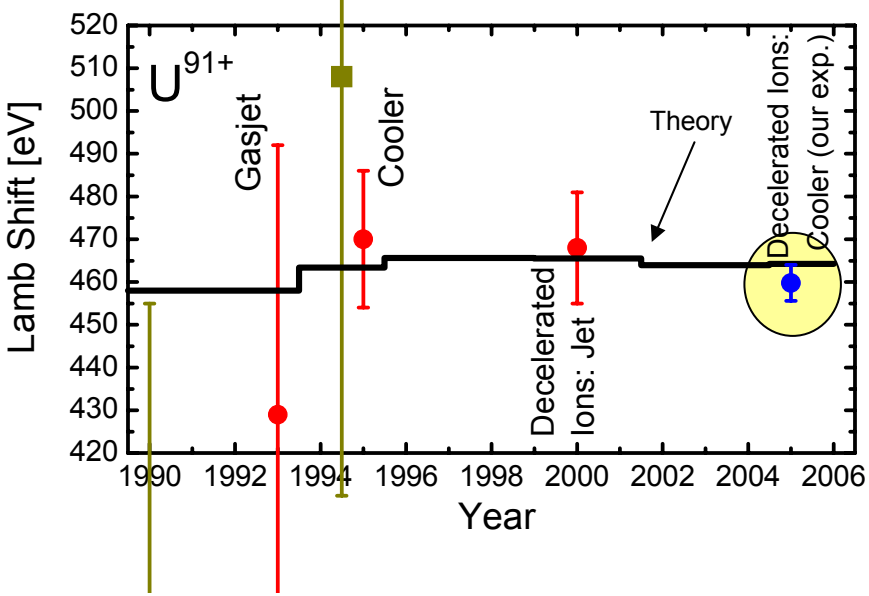


PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS: Lamb shift in H-like uranium measured at the ESR electron cooler



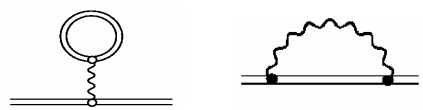


Research Highlights
***Nature* 435**, 858-859



Experiment : 460.2 ± 4.6 eV

Theory : 464.26 ± 0.5 eV



→ **1% sensitivity to the 1s Lamb shift**

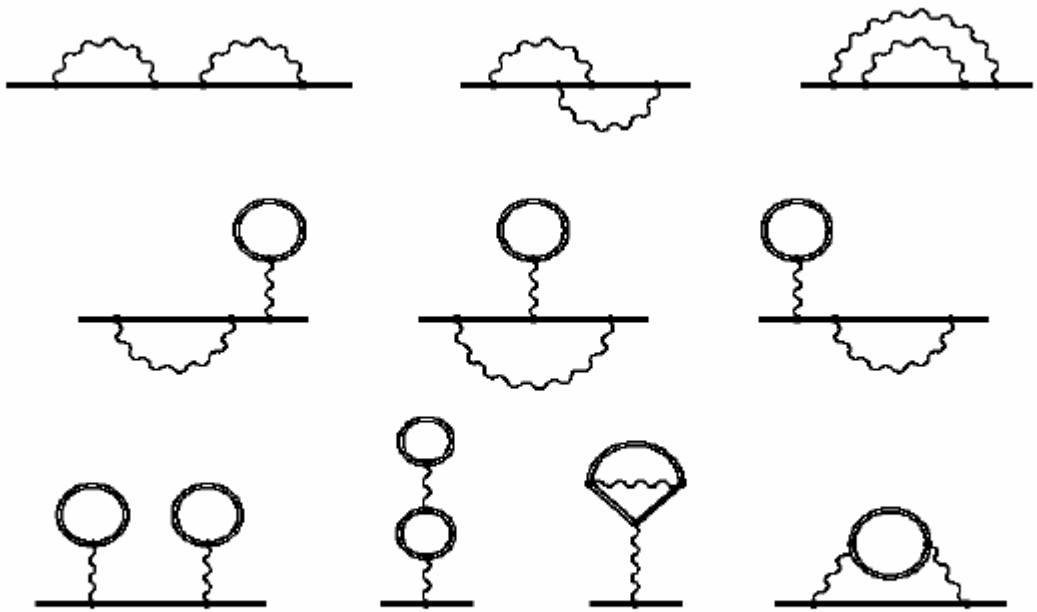
→ **Most stringent test of bound-state QED for one-electron high-Z systems**

A. Gumberidze et al.,PRL 94, 223001 (2005)
V. A. Yerokhin et al., EPJ D 25, 203 (2003)

QED effects on the energy levels of high-Z few-electron systems

One-electron QED corrections of second order in α

Non-perturbative calculations (in $Z\alpha$)



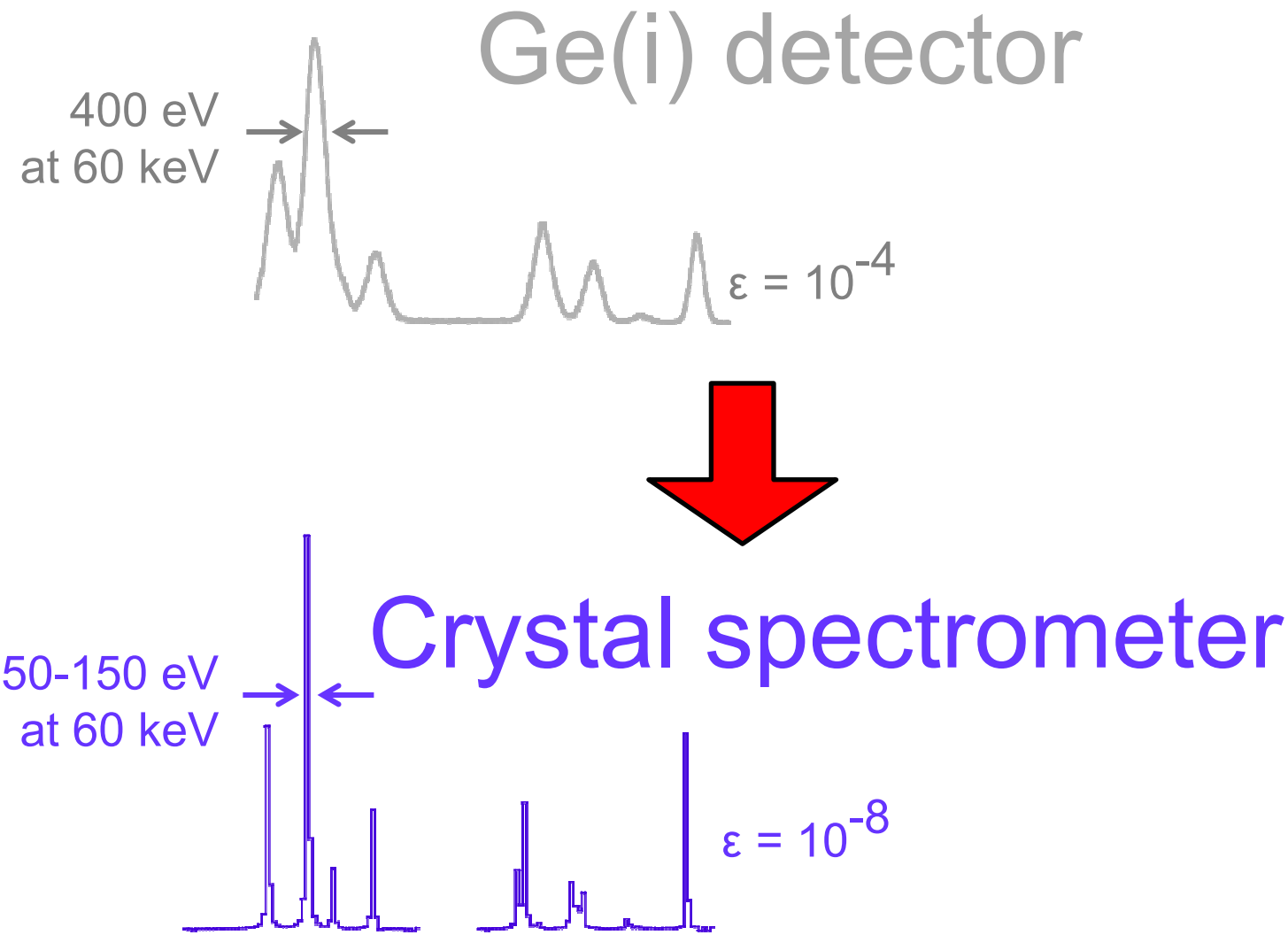
Goal

~1 eV

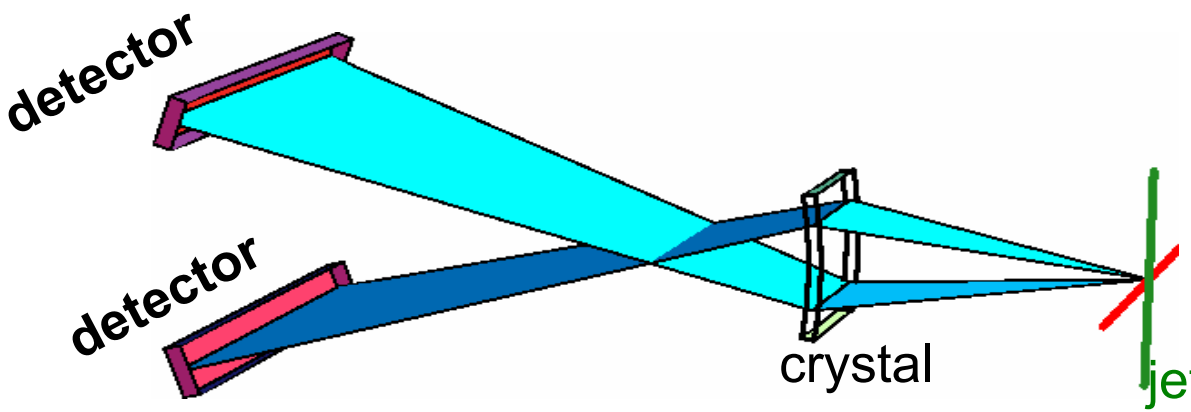
Recent progress: Evaluation of the two-loop self-energy diagrams

(V.A. Yerokhin, P. Indelicato, and V.M. Shabaev, JETP, 2005; PRL, 2006).

Towards an accuracy of 1 eV



Transmission crystal spectrometer
towards an accuracy of 1 eV



H.F. Beyer et al

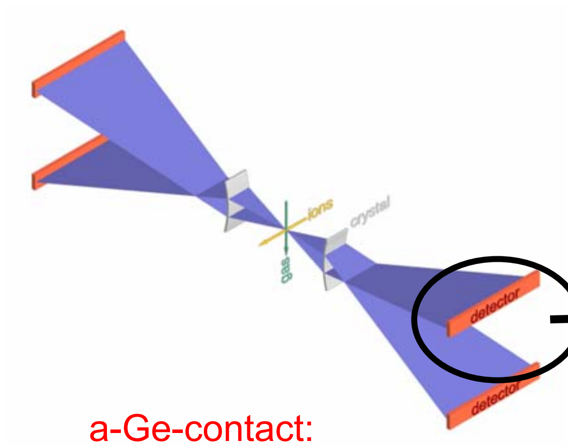
Bragg-Laue relation

$$n \cdot \lambda = 2 \cdot d \cdot \sin\theta$$

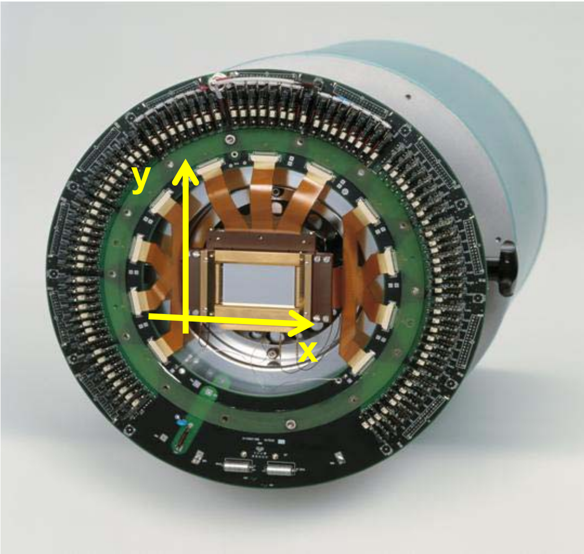
FOCAL spectrometer: $\varepsilon \approx 10^{-8} \Rightarrow$ 5 events per hour

~~gas counters (drift chambers)~~

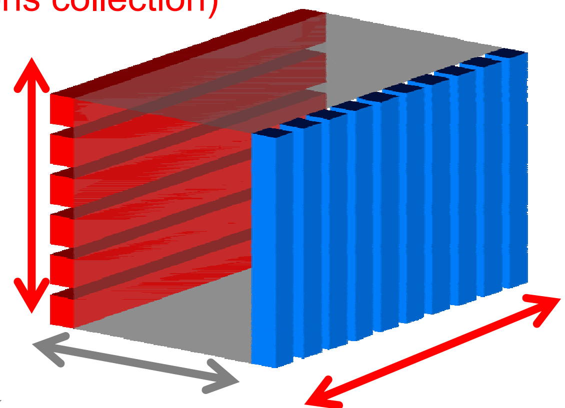
Micro-strip semiconductor detector



2D µSTRIP
germanium detector
-GSI



a-Ge-contact:
48 strips in the back side
(electrons collection)



p^{+}-contact:
128 strips in the front side
("holes" collection)

Ge(i) crystal
11 mm thick

2D detector [1,2]
Ge(i) crystal
128 X 48 Strips
Δx ~ 1167 µm
Δy ~ 250 µm (< 150 eV)
ΔE ~ 2.1 keV
Δt ~ 50 ns

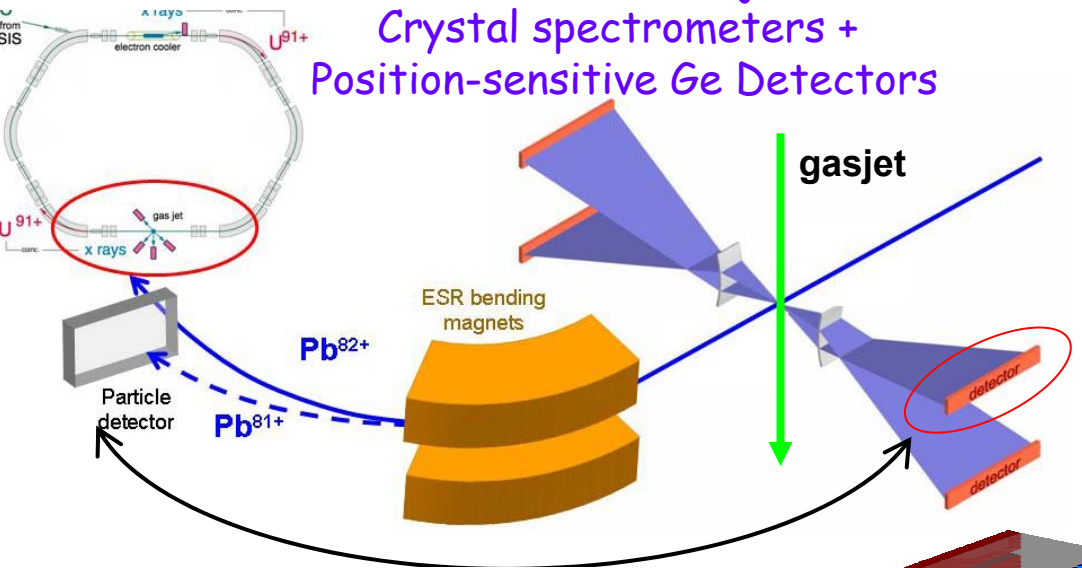
2D/3D position-sensitivity

energy resolution

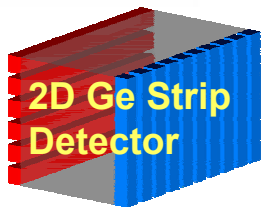
timing

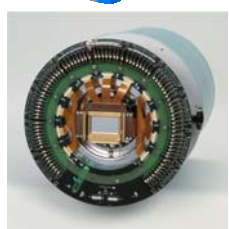
PRECISION TESTS OF BOUND-STATE QED IN EXTREME FIELDS
HIGH-RESOLUTION DETECTION DEVICES AT THE ESR

The **FOCAL** Project
Crystal spectrometers +
Position-sensitive Ge Detectors

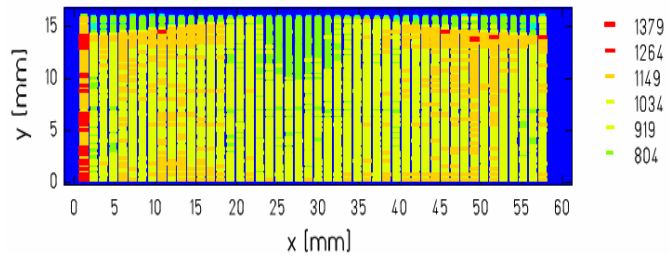


coincidences between particle and x-ray detectors

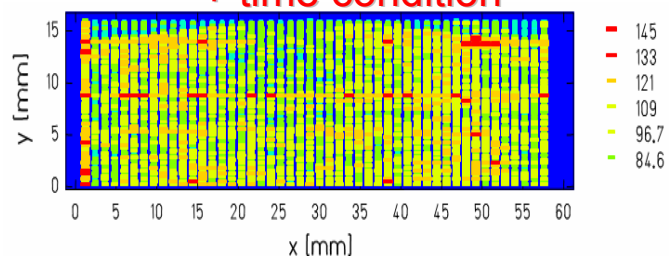




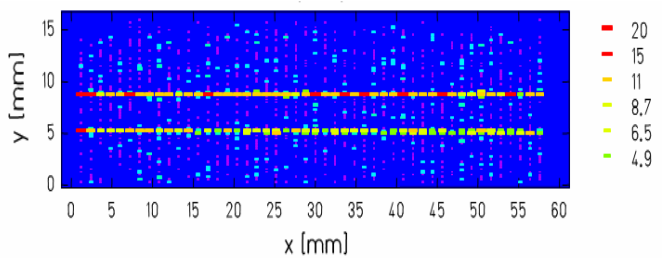
x-ray image (10 keV to 130 keV)



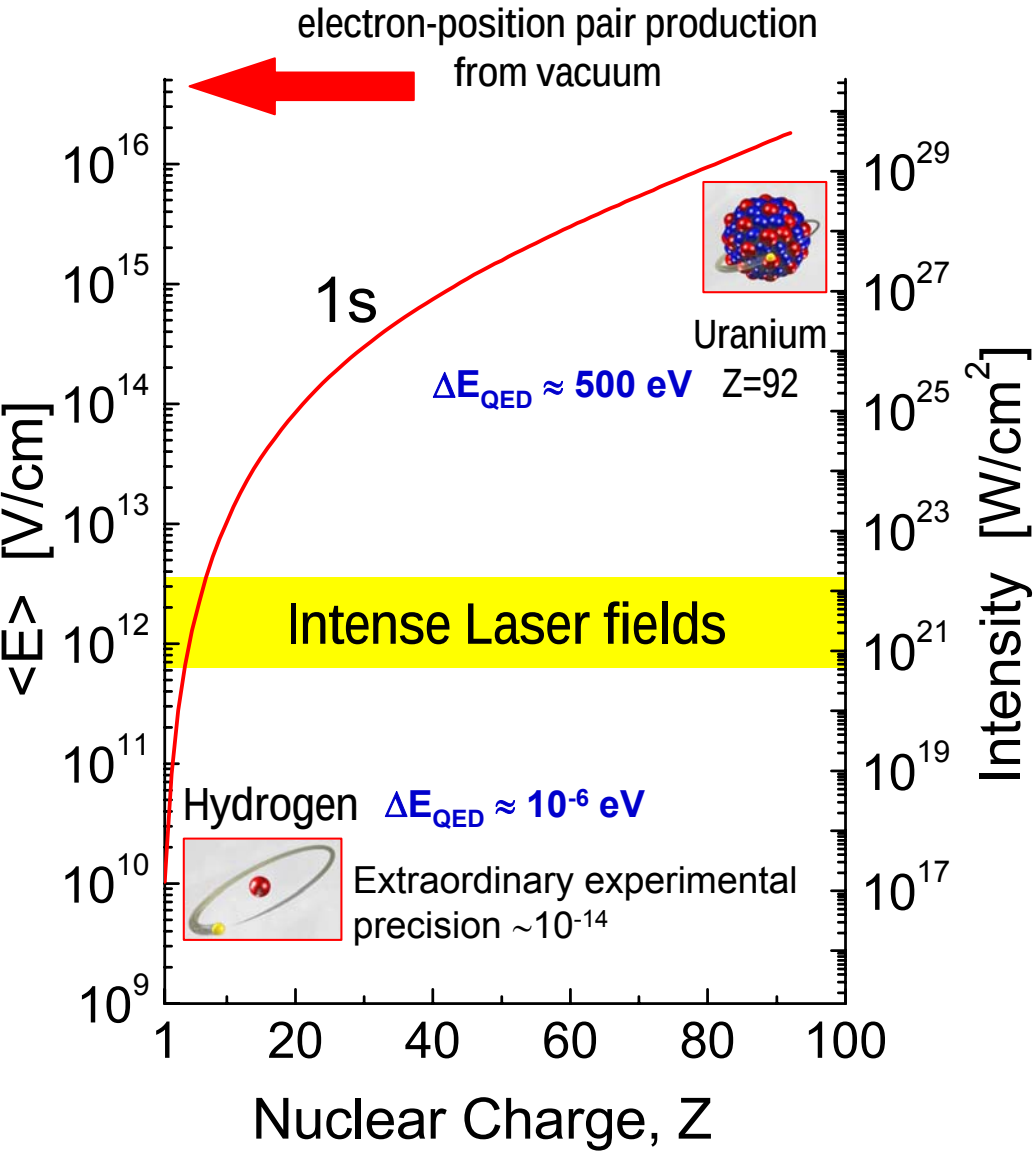
x-ray image (10 keV to 130 keV)
+ time condition



x-ray image (58 keV to 65 keV)
+ time condition



Atomic Physics in Extremely Strong Fields



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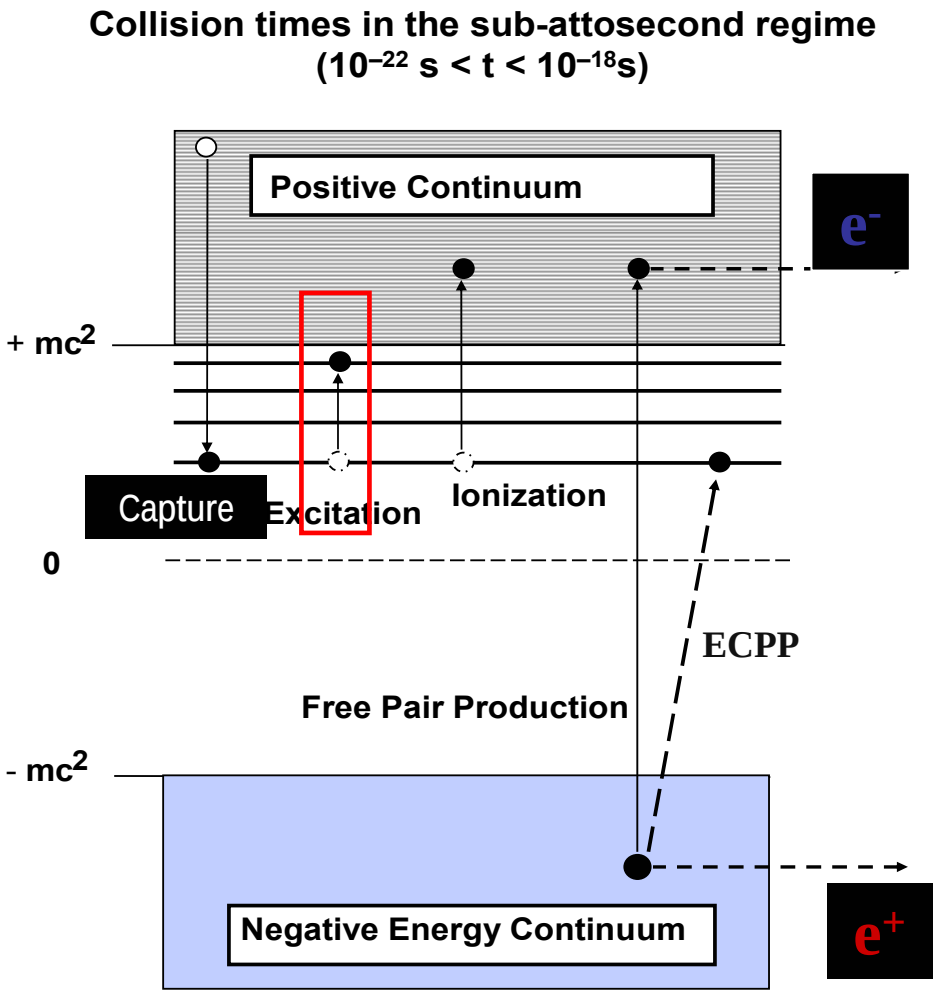
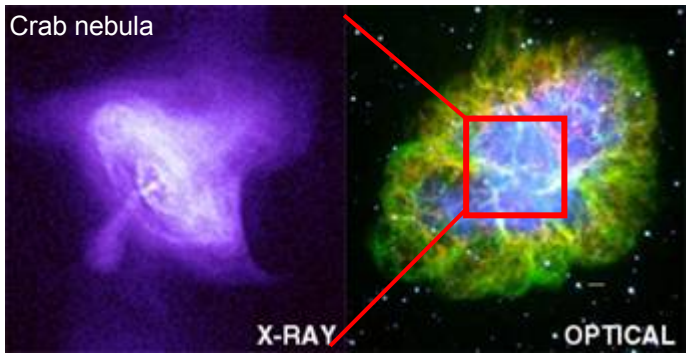
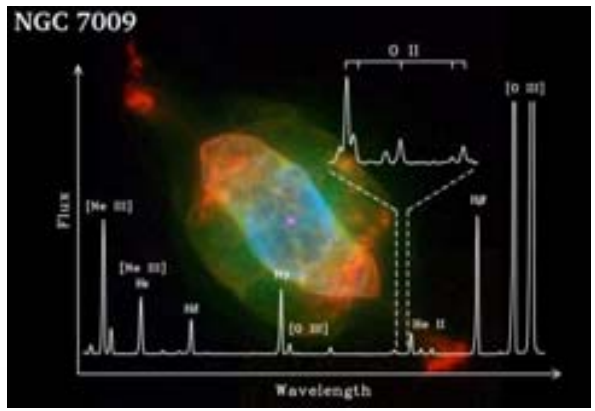
High-γ


Collision times in the sub-attosecond regime
(10⁻²² s < t < 10⁻¹⁸s)
Positive Continuum
e⁻
+ mc²
Capture
Excitation
Ionization
0
ECPP
Free Pair Production
- mc²
Negative Energy Continuum
e⁺



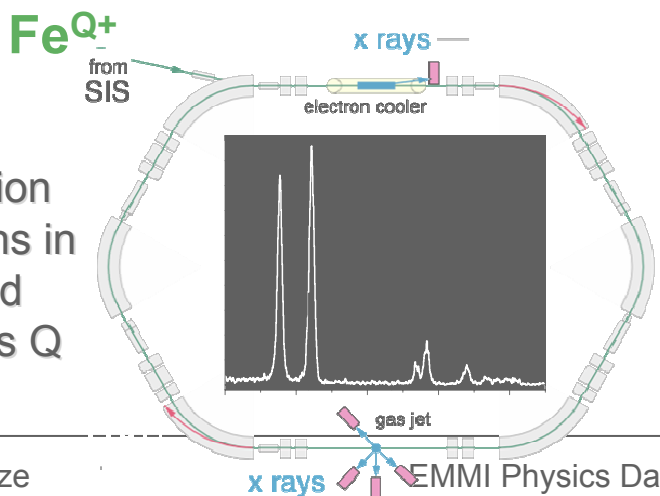
Direct insight into celestial plasmas

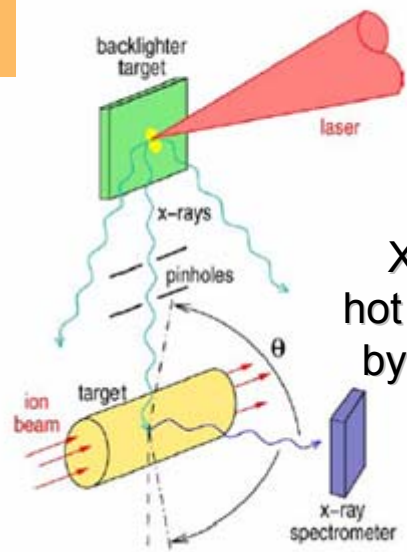


Spectra provide knowledge of temperature, density, element abundance, etc.

Laboratory Astrophysics

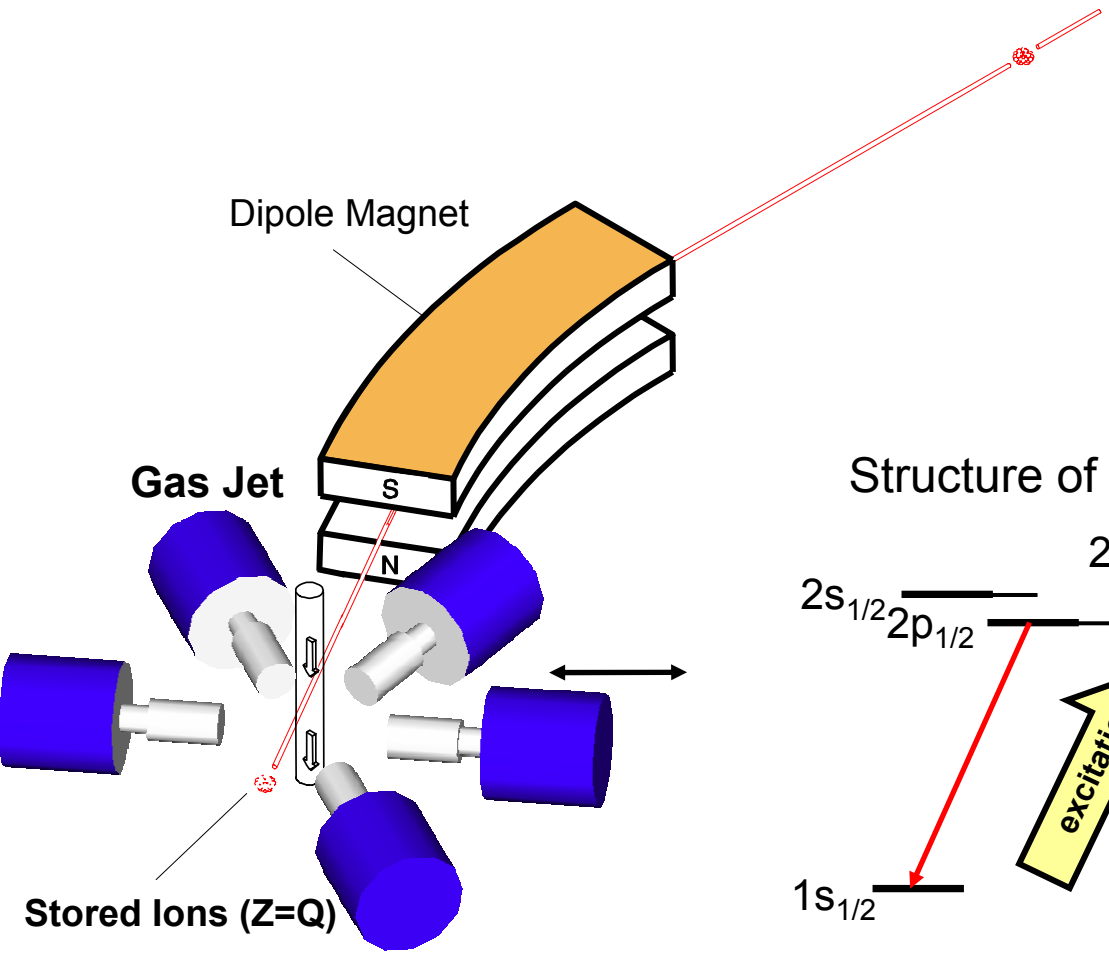
X-ray emission studies for ions in well defined charge-states Q





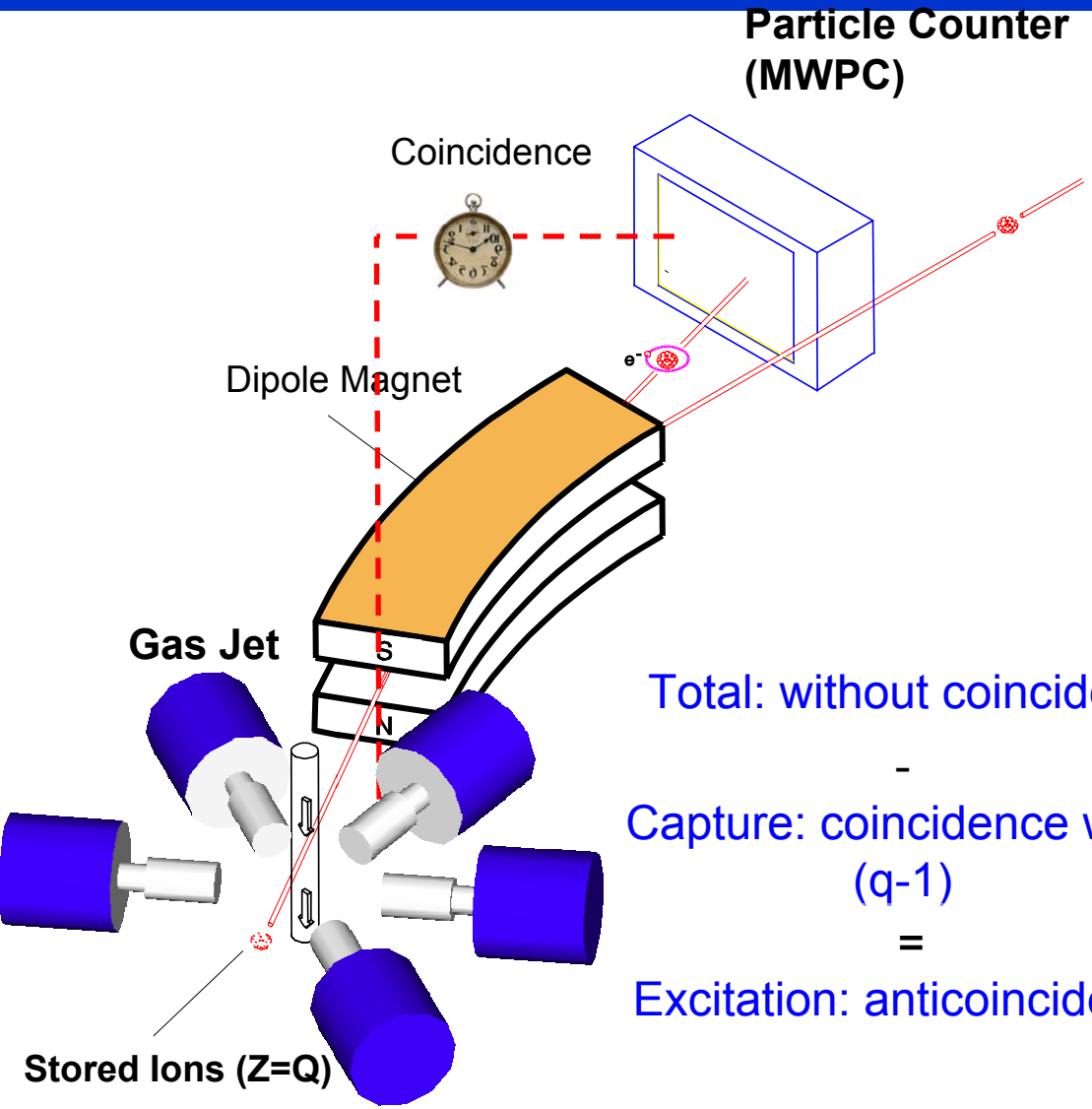
X-ray emission of hot plasmas produced by intense laser and ion beams

Atomic Dynamics at Strong Fields Explored With HCI at the Supersonic Gas Jet-Target of the ESR



Th. Stöhlker et al **Phys. Rev. A 57, 845 (1998)**
T. Ludziejewski et al **Phys. Rev. A 61, 052706 (2000)**

Excitation of H-like uranium in relativistic collisions with various targets



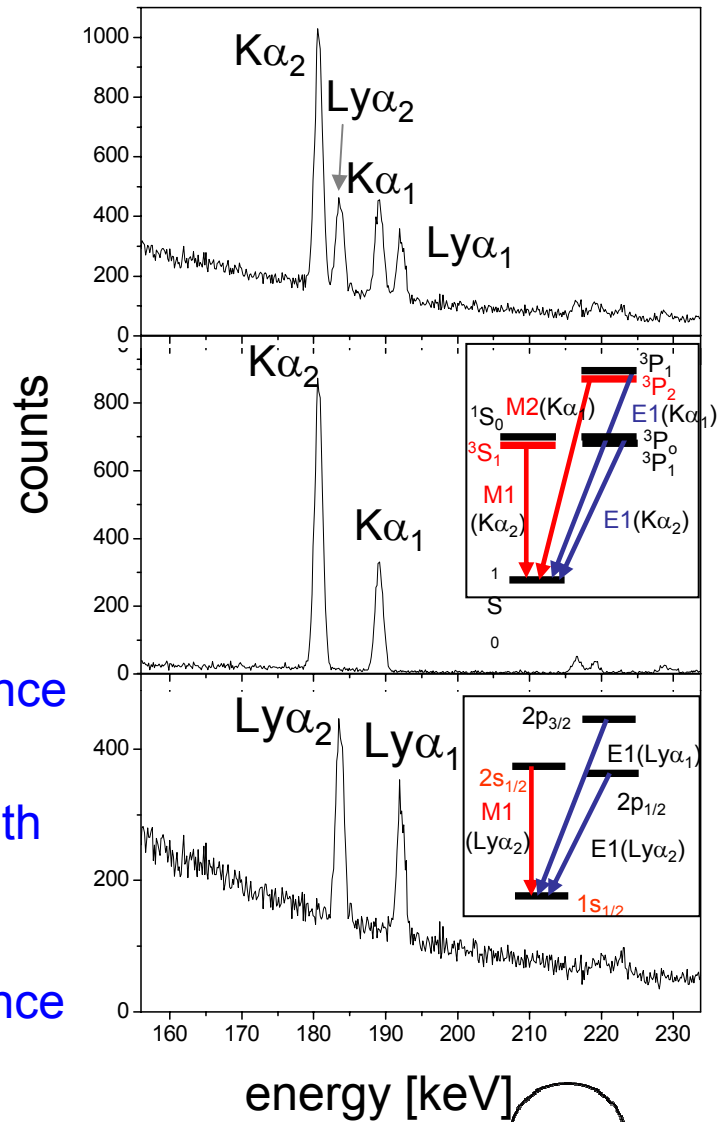
Total: without coincidence

-

Capture: coincidence with (q-1)

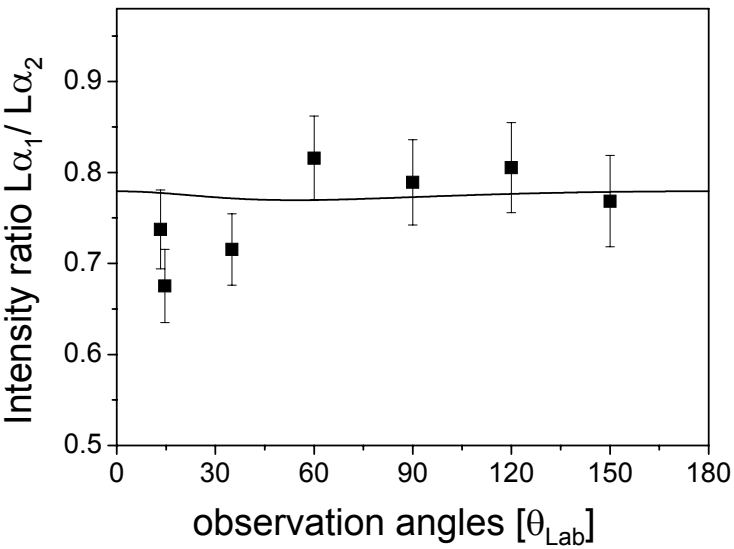
=

Excitation: anticoincidence



Magnetic sublevel population and alignment: angular differential measurements

$U^{91+} \rightarrow N_2$ @ 220 MeV/u
Excitation



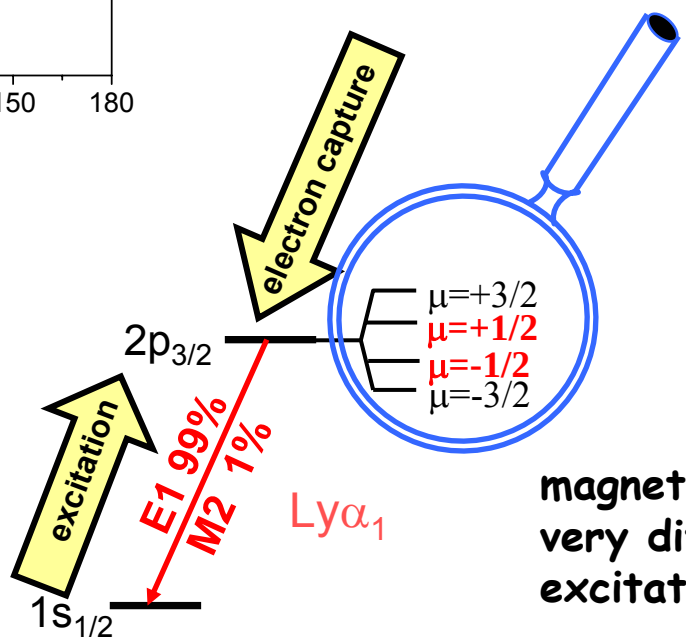
Alignment parameter
β_A is zero within
the experimental uncertainty

Alignment Parameter

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

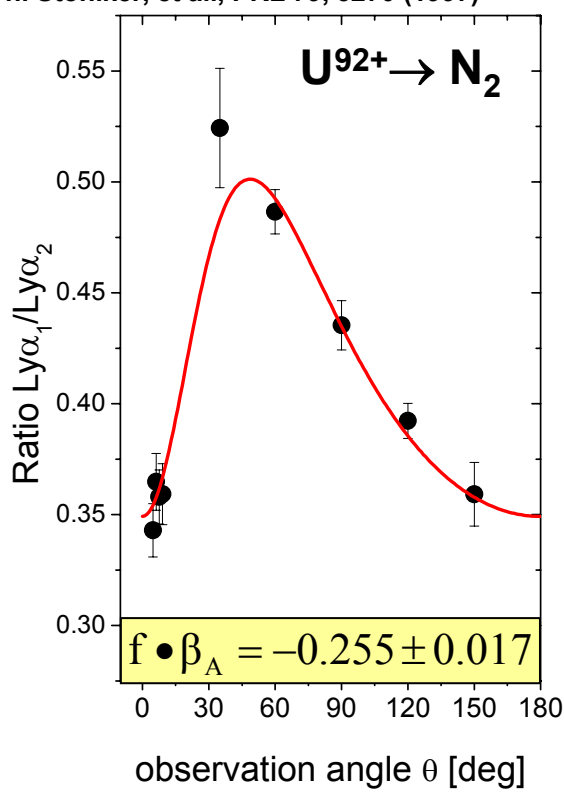
$Ly\alpha_2\,(2p_{1/2} - 2s_{1/2})$ is
Identically isotropic

$$W(\theta) \propto 1 + f\left(\frac{a_{M2}}{a_{E1}}\right) \bullet \beta_A \bullet \left[1 - \frac{3}{2}\sin^2\theta\right]$$



REC

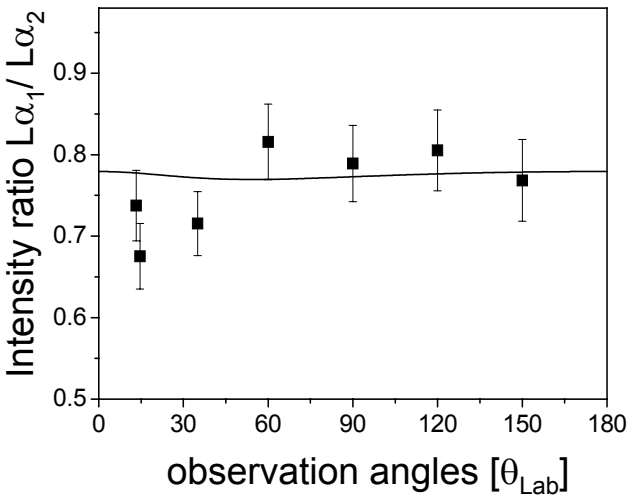
Th. Stöhlker, et al., PRL 79, 3270 (1997)



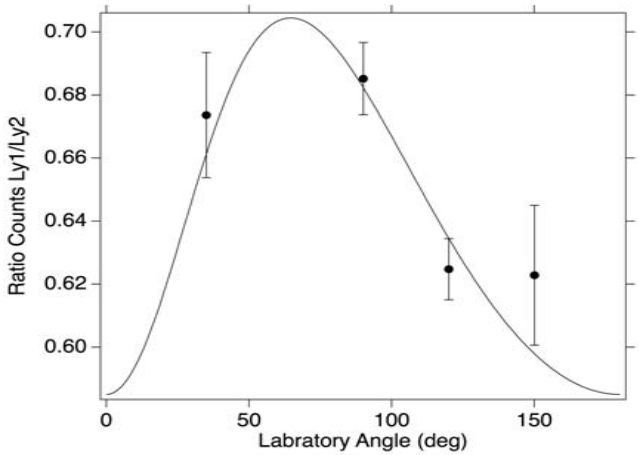
magnetic sublevels are populated very differently by Coulomb excitation and REC

Magnetic sublevel population and alignment produced by excitation for different targets and different energies

$U^{91+} \rightarrow N_2$ @ 220 MeV/u

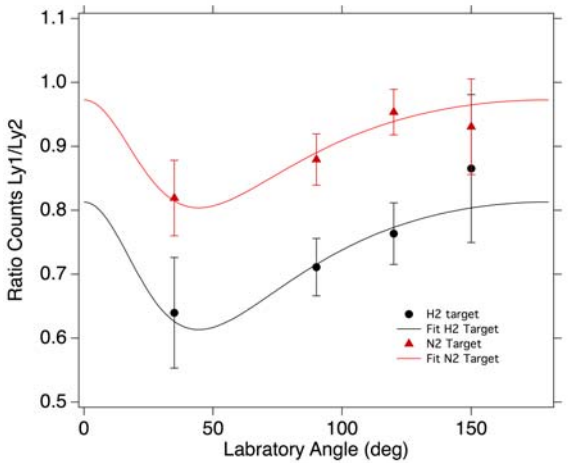


$U^{91+} \rightarrow N_2$ @ 100 MeV/u

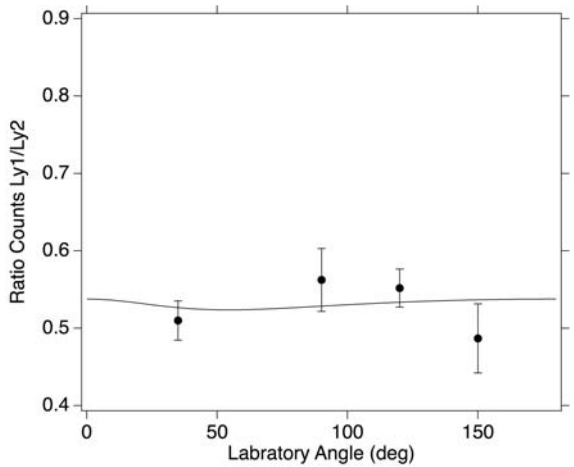


Magnetic sublevel population changes significantly with the collision energy

$U^{91+} \rightarrow H_2, N_2$ @ 400 MeV/u



$U^{91+} \rightarrow H_2$ @ 220 MeV/u

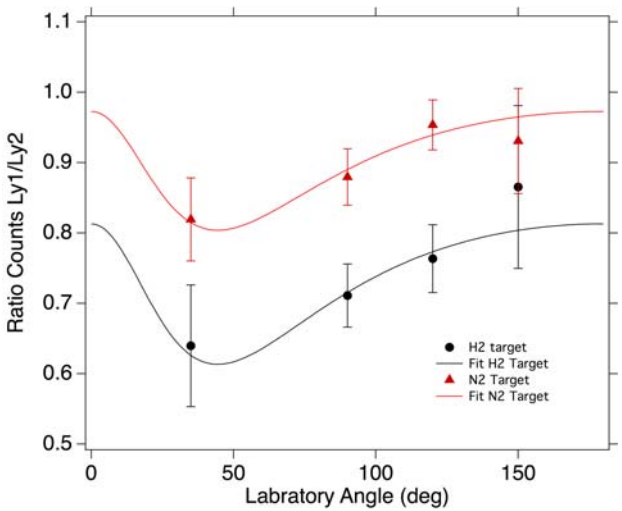


It seems not to be affected by change of the target. This is not the case for relative differential cross-section

Magnetic sublevel population and alignment produced by excitation for different targets and different energies

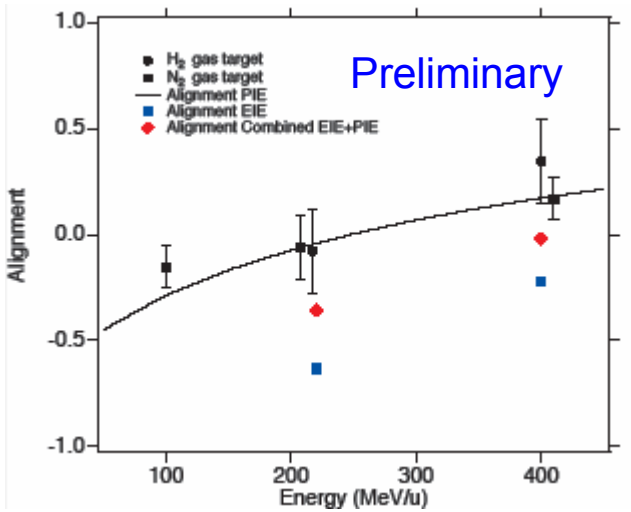
Excitation by the nuclear field scales as Z^2. EIE scales as Z.
changing the target -> change the relative contribution of the two processes

$U^{91+} \rightarrow H_2, N_2$ @ 400 MeV/u



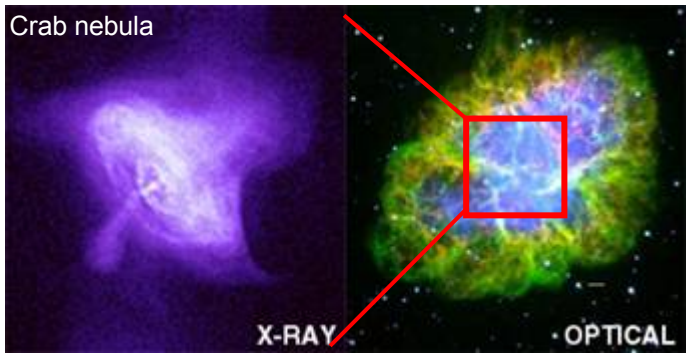
influence of EIE

$U^{91+} \rightarrow H_2$

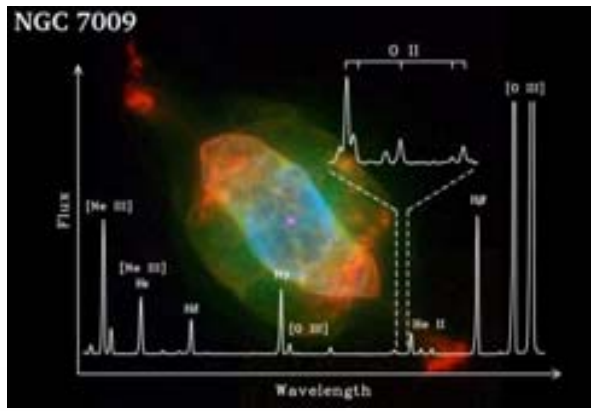


calculations by A. Surzhykov et al

EIE calculations by C. J. Fontes et al



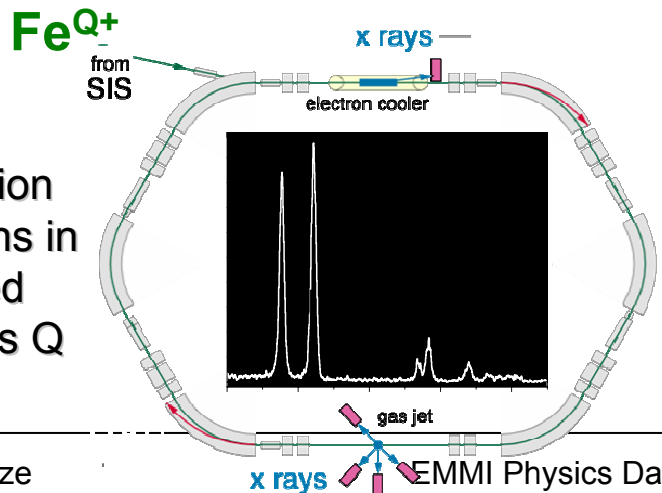
Direct insight into celestial plasmas

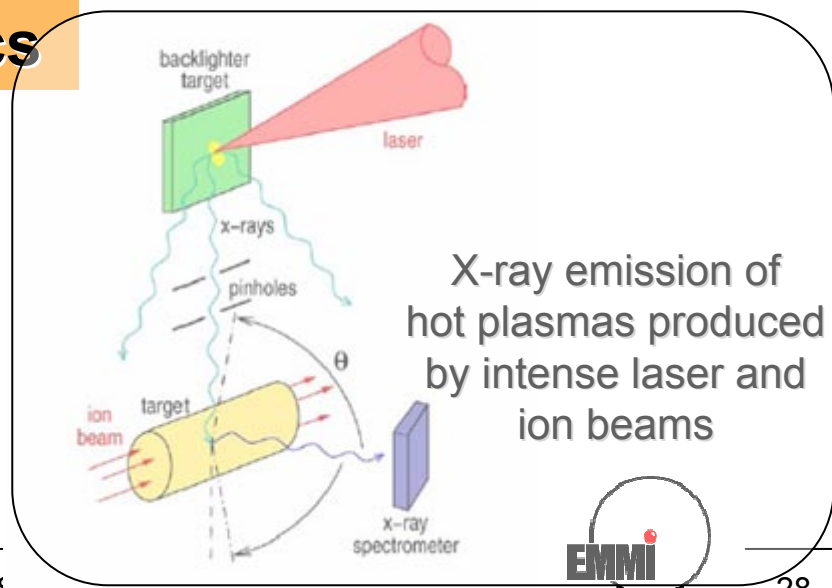


Spectra provide knowledge of temperature, density, element abundance, etc.

Laboratory Astrophysics

X-ray emission studies for ions in well defined charge-states Q





X-ray emission of hot plasmas produced by intense laser and ion beams

Hard X-Ray Inner-Shell Spectra Produced by Intense Picosecond Laser Pulses and Recorded by Cauchois Type Spectrometers

Exploiting Atomic Physics techniques for Exploring Plasmas Generated by High-power Laser

Goals and motivation

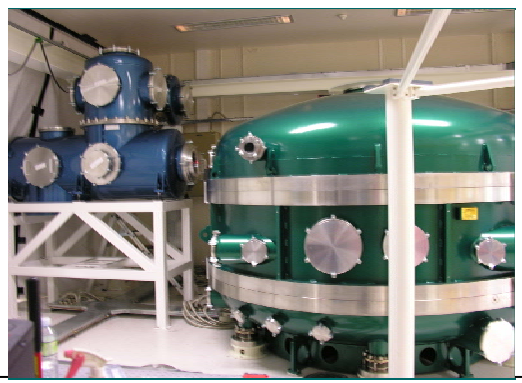
- **High-energy plasma diagnostics: temperature, density, ionization balance, opacity.**
- **Hot electron energy distribution, hard x-ray brightness optimization**
- **Conversion efficiency of Laser power to hard x-rays**

LULI pico2000 Facility

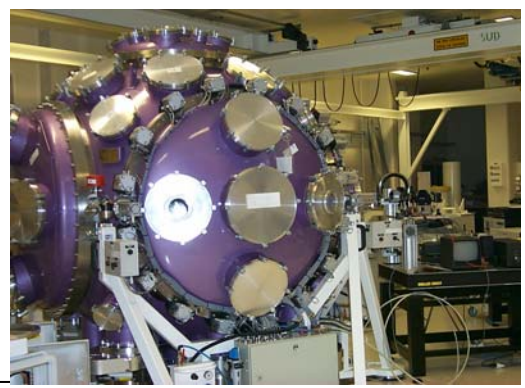
- Nd:glass laser, wave length: 1,053µm
- Long pulse beam: 1kJ, 1.5 ns
- Short pulse beam: 200 TW - 200 J in 1 ps

laser hall

capacitors bank

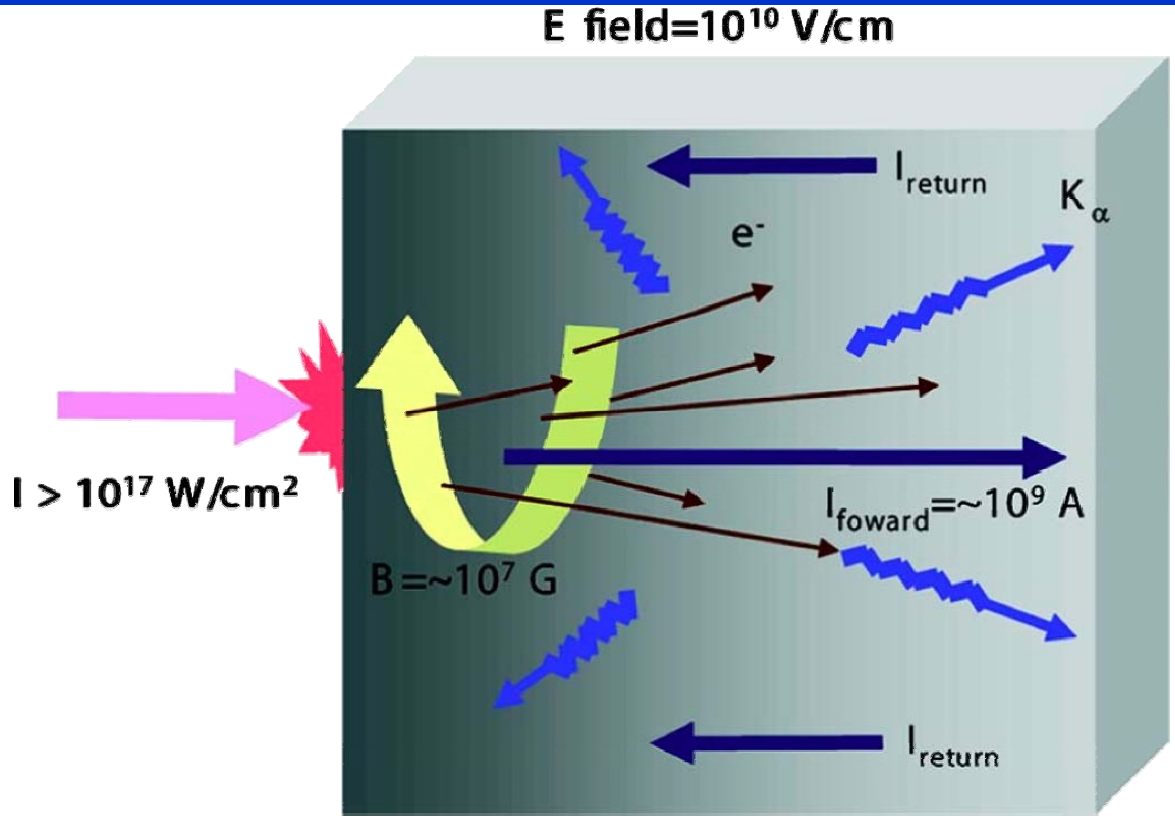


pico2000 compression chambers



MILKA target chamber

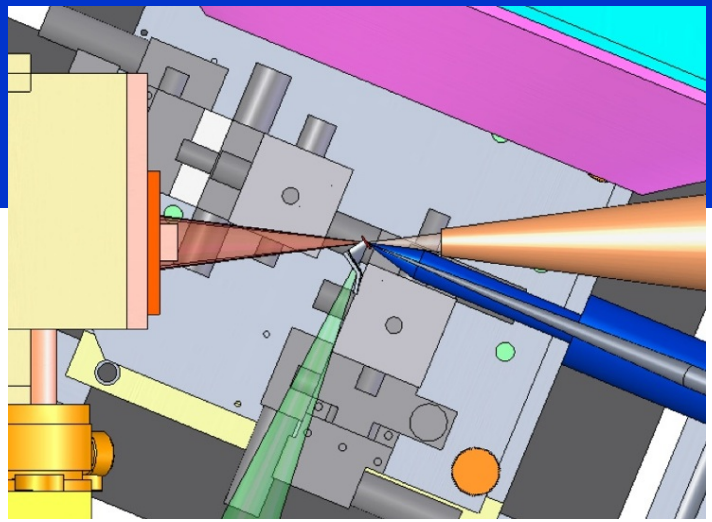
Schematic of Kα Production Mechanism



The high- intensity laser with $I \geq 10^{17}$ W/cm^2 creates superthermal to relativistic hot electrons. These hot electrons travel through the target material while producing Kα and Bremsstrahlung photons. Because of the self-generated electric fields from the ions, the hot electrons reflux at the material boundary, creating more photons. This mechanism is known to be a much more efficient way of generating high-energy photons >10 keV compared to thermally driven transitions.

Park H.-S. et al. Phys. Plasmas 15, 056309 (2008)

Experimental Setup



South beam (ps)

North beam (ns)

56.25°

56.25°

90°

triangular Bragg spectrometer

95 mm from window to target

target

BCS

22.5 ° from horizontal plane

LCS

600 mm stand-off

electron spectrometer

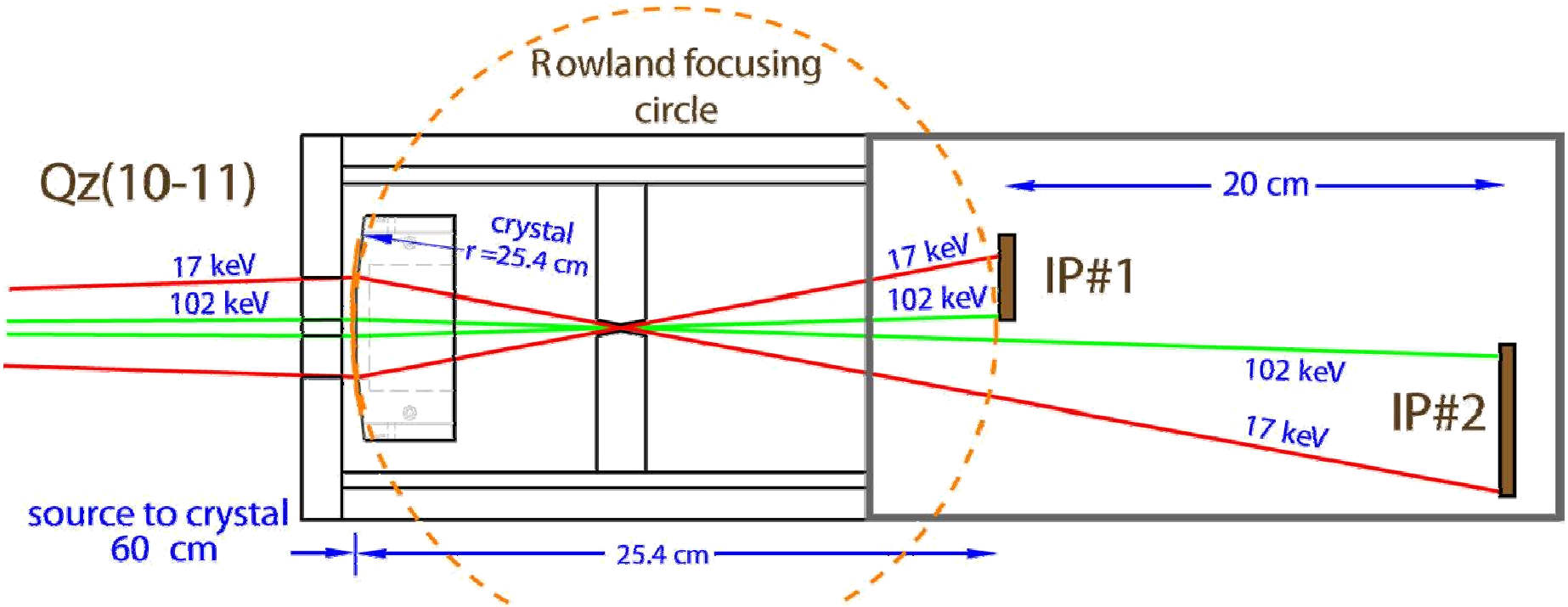
370 mm stand-off

Targets

- 100 µm **InSn** alloy foils with 50-50 % composition ratio,
- **Ag70Pd30**, 150 µm
  Pd70Ag30, 150 µm
- rare earth molybdate crystals: $Gd_2(MoO_4)_3$, ~214 µm or 444 µm
  $Tb_2(MoO_4)_3$, ~217 µm

LULI Crystal Spectrometer (LCS)

Built by a team from the Naval Research Laboratory (NRL) and the National Institute of Standards and Technology (NIST)



- 250 µm thick Qz(10-11) crystal bent to a cylinder with the radius of 254 mm
- Two detector positions:
  - 1) on the focusing Rowland circle
  - 2) 200 mm off the Rowland circle to increase resolution for point source Seely J. F. et al. Appl. Opt. 4 p.2767 (2008)
- Source to crystal stand off distance: 600 mm

The FOCAL Crystal spectrometers together with Position-sensitive Ge Detectors

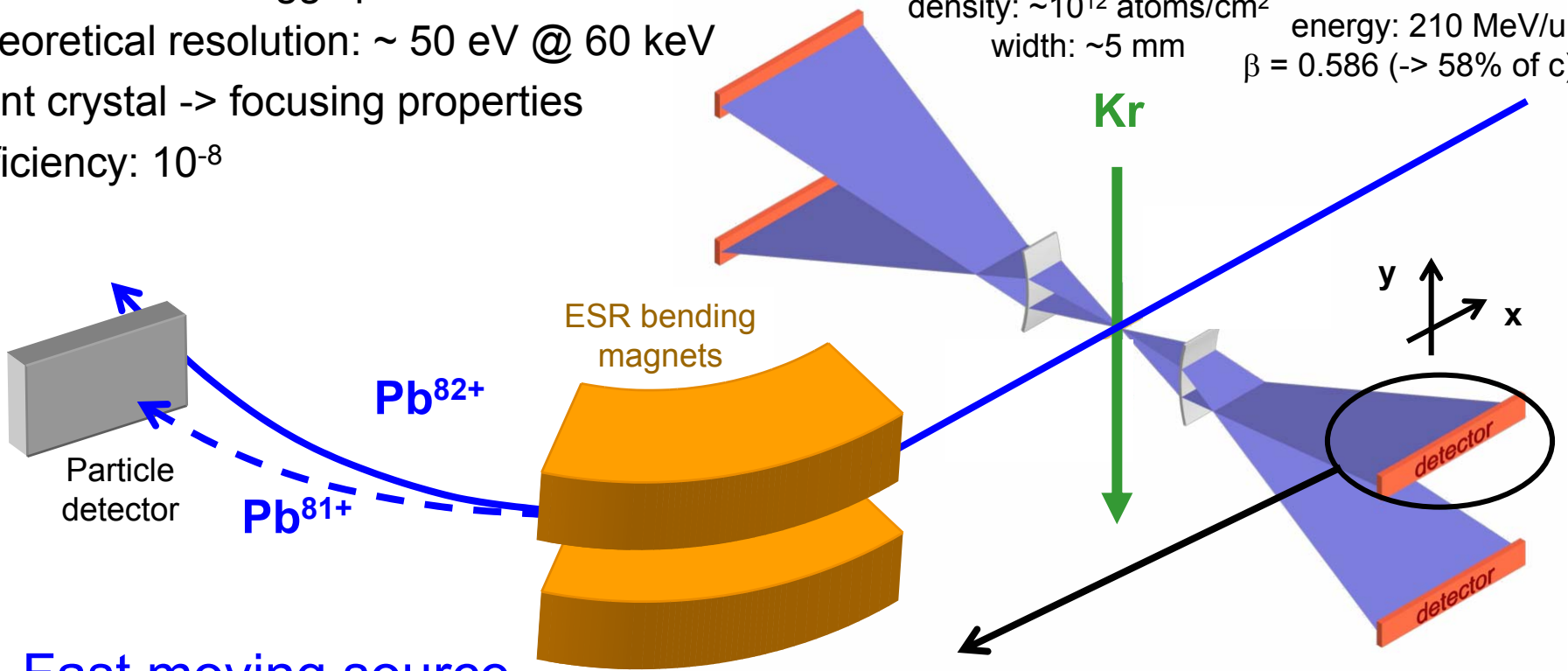
FOCAL Laue crystal spectroscopy [1]

- Transmission Bragg spectrometer
- Theoretical resolution: ~ 50 eV @ 60 keV
- Bent crystal -> focusing properties
- Efficiency: 10^{-8}

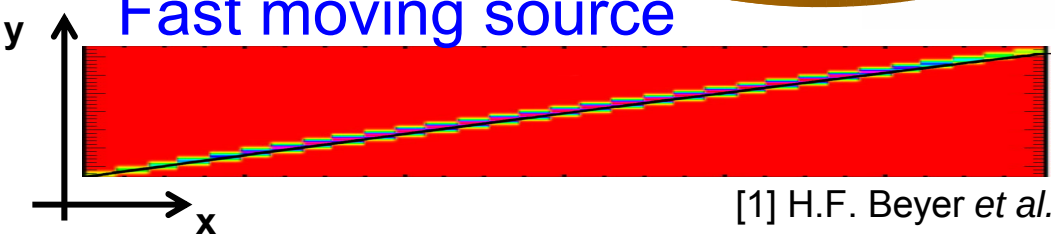
Lead 1s Lamb shift Experiment

Jet target
supersonic krypton jet
density: ~10^{12} atoms/cm^2
width: ~5 mm

Ion beam
$^{208}Pb^{82+}$ ion beam
energy: 210 MeV/u
β = 0.586 (-> 58% of c)



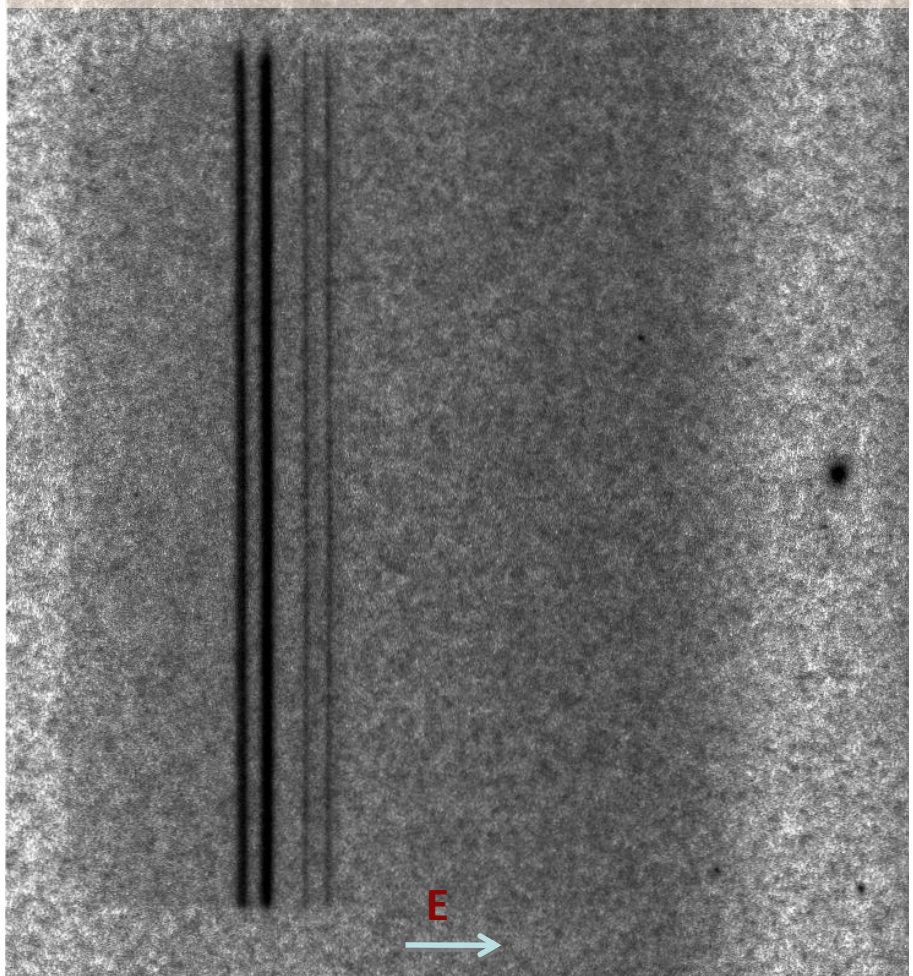
Fast moving source



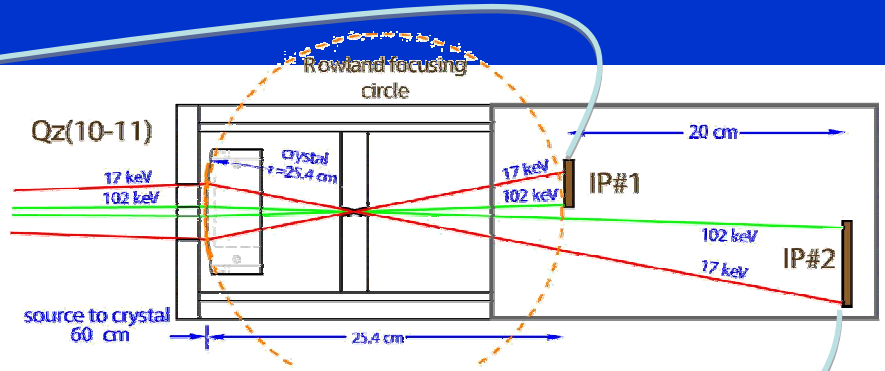
[1] H.F. Beyer *et al.*, Spectrochim. Acta, Part B **59**, 1535-1542 (2004).

Sample Spectral Image Registered with LCS

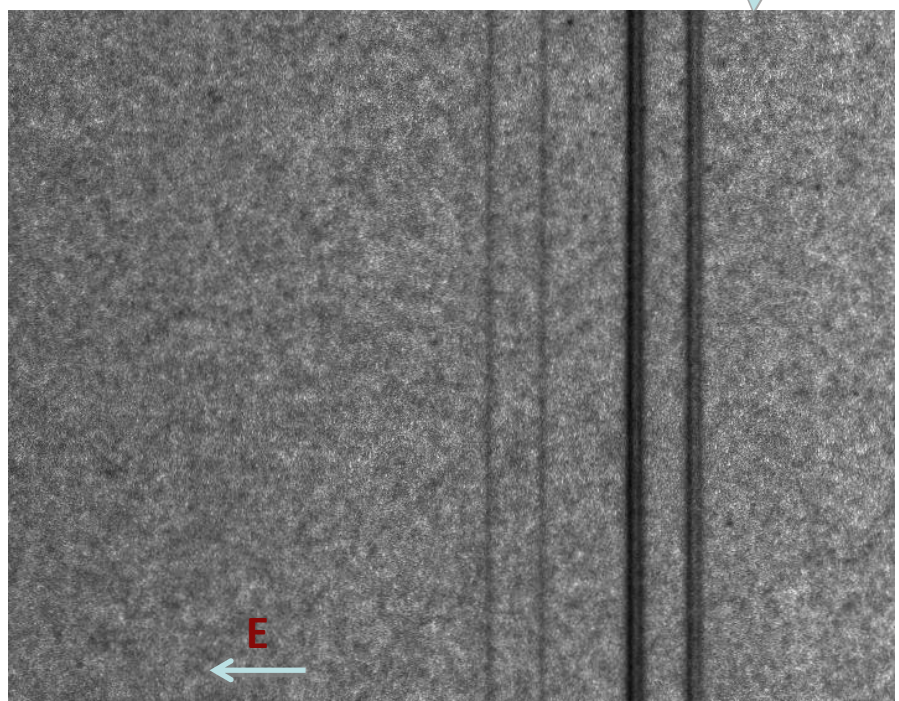
S03 LCS_A,
Target: Ag70Pd30 alloy foil, 150 µm



Laser Energy: 85 J
1 ps, focused

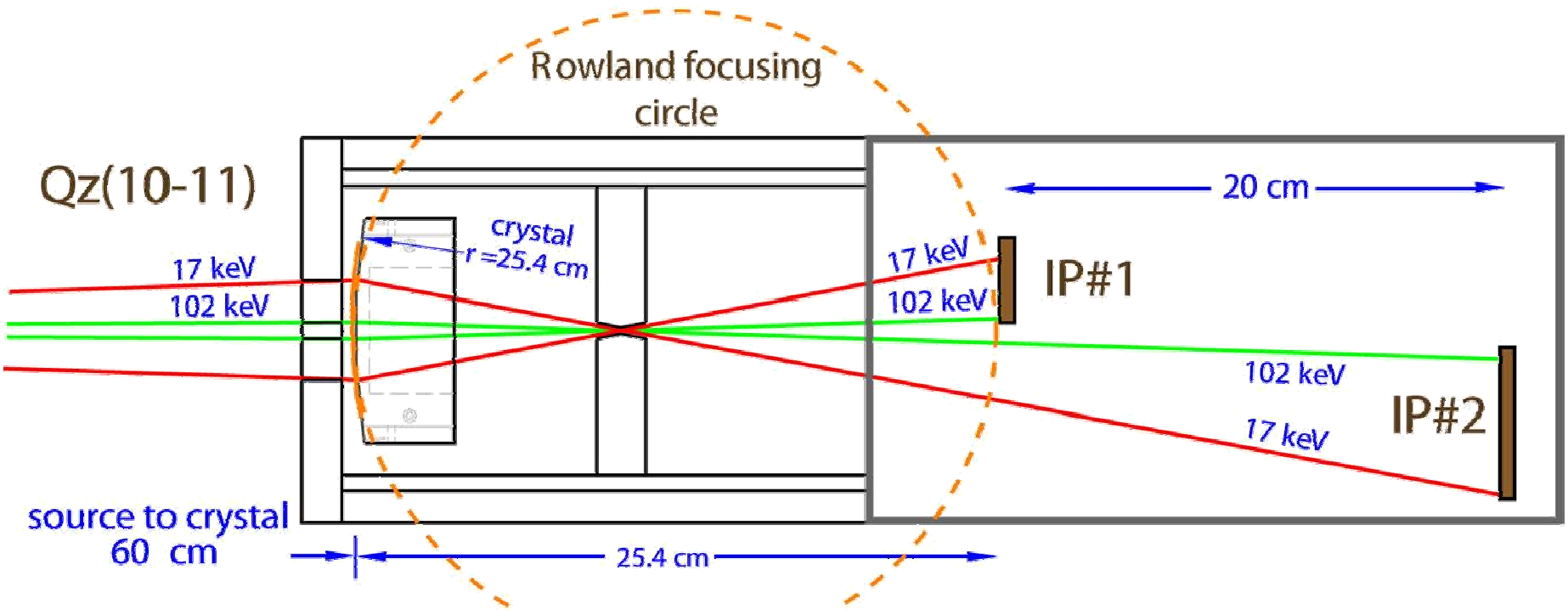


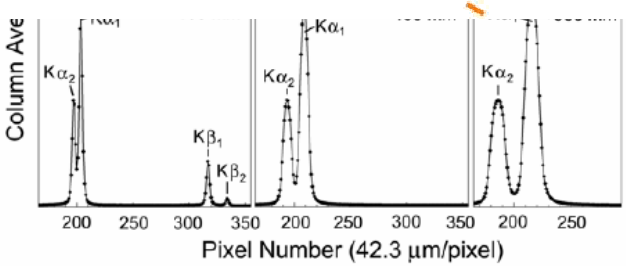
Fuji MS image plates



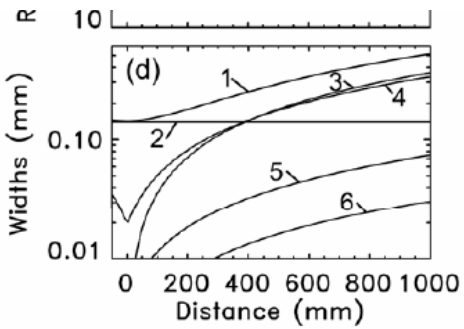
Ag Kß Pd Kß Ag Kα Pd

Energetic Electron Propagation Range: Source broadening of the spectral lines



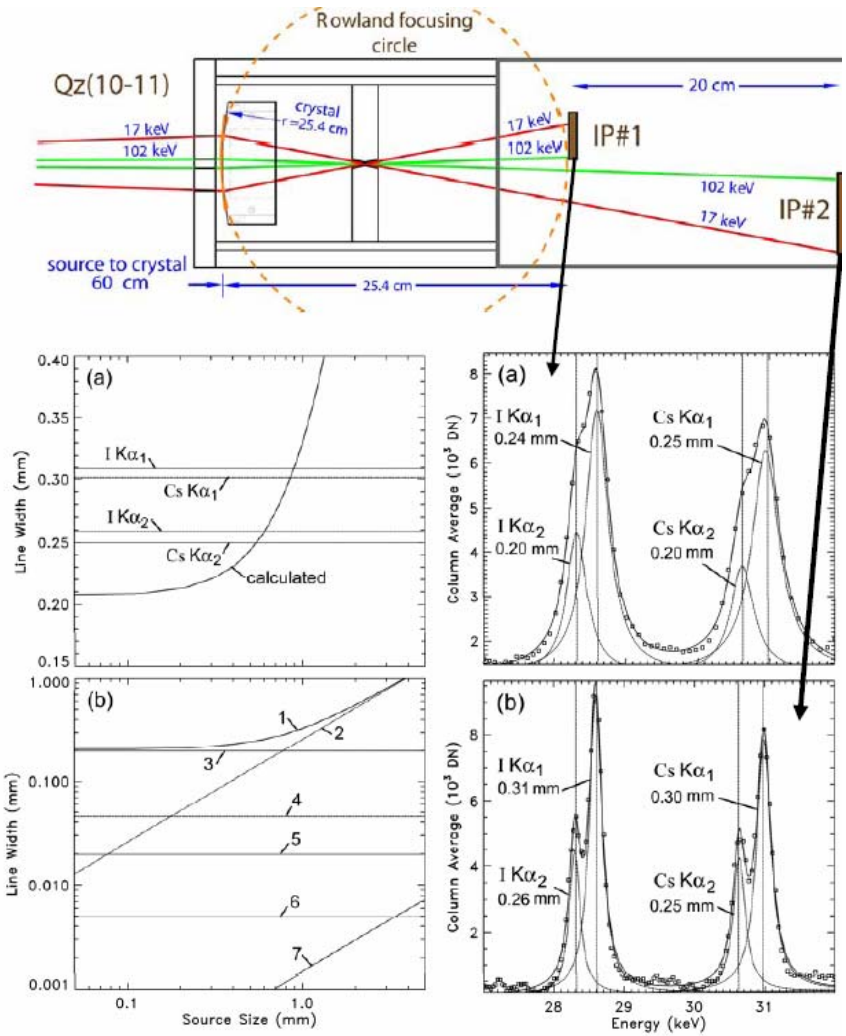


4 – Crystal thickness
5 – Natural width
6 – Crystal rocking curve
7 – Aberrations (very small)



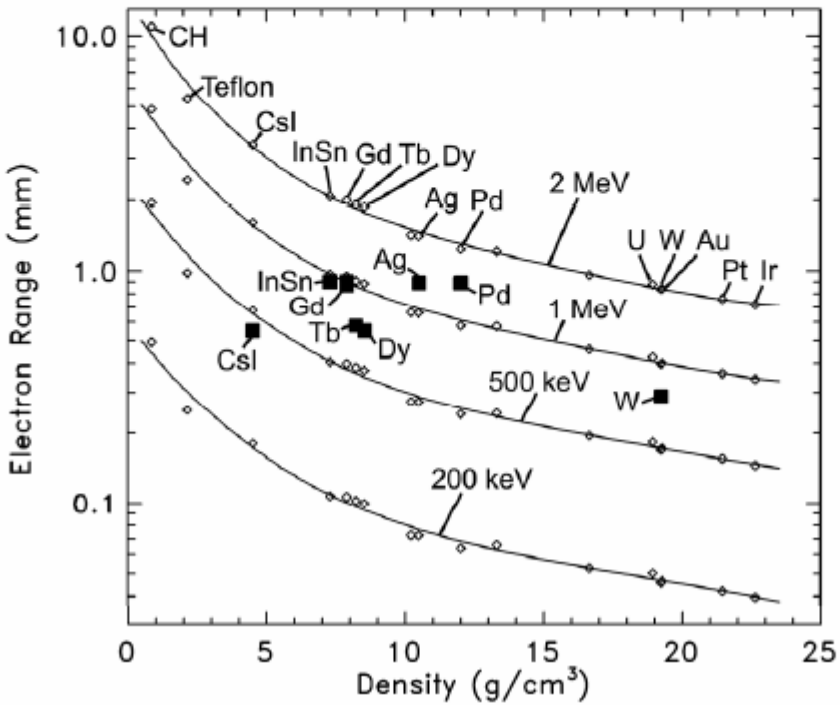
LULI ps Laser X-ray source size

- **LULI laser: 100 J, 1 ps, 10 μm focal spot, 10^{20} W/cm^2 focused intensity.**
- **Spectra were recorded by placing two MS image plates on the RC (detector broadening) and 20 cm behind the RC (source broadening).**
- **Comparisons with a geometrical model of the spectrometer indicate x-ray source size up to 1 mm.**
- **Energetic electrons generated in the focal spot propagate into the cold solid material beyond the focal spot and produce characteristic K-shell lines.**

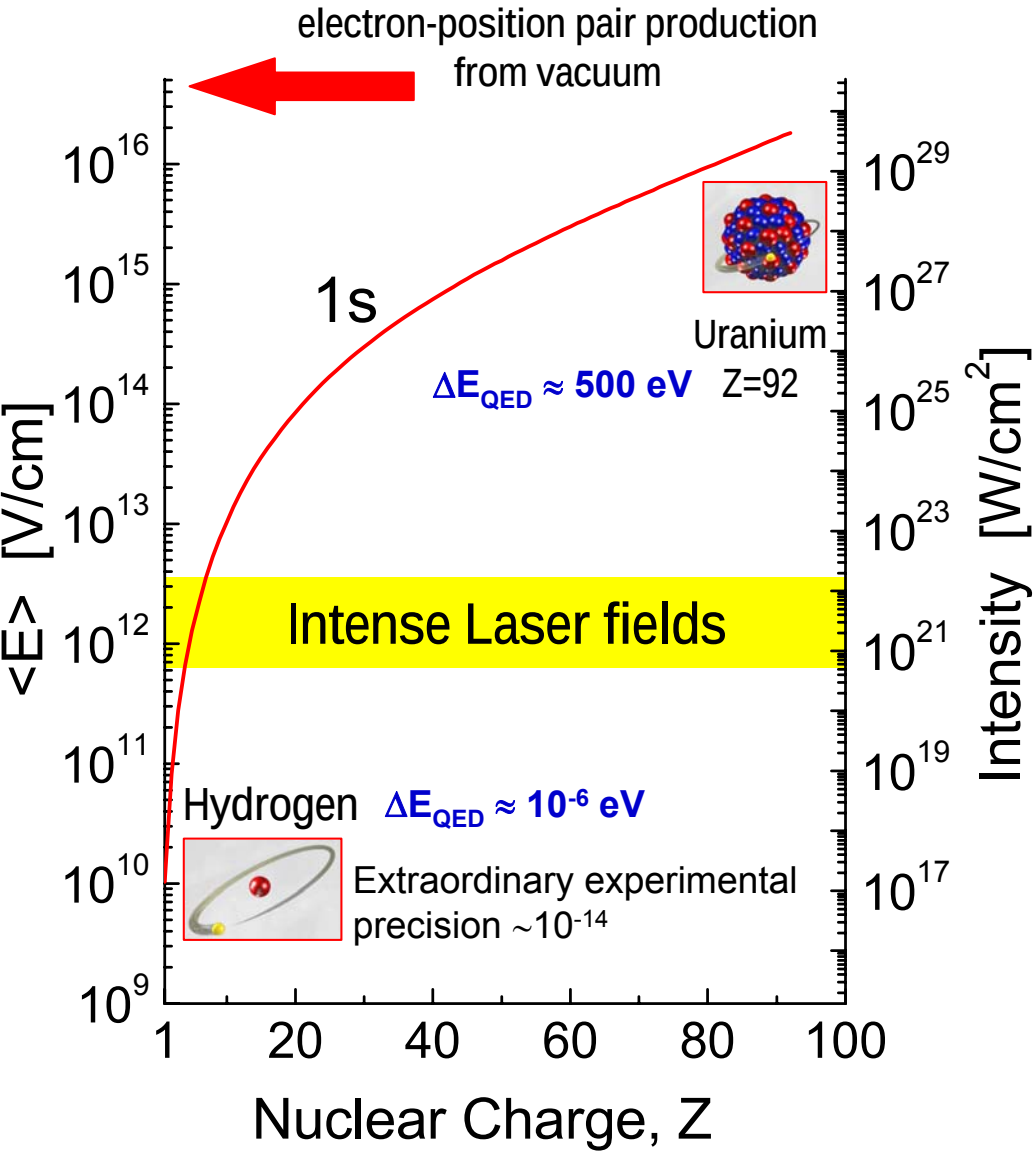


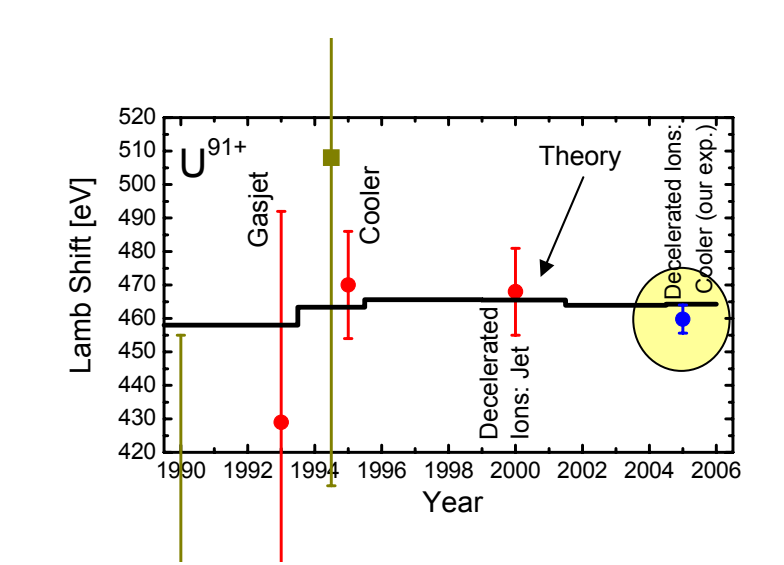
Electron Ranges Measured from Line Broadening

- The range in electrically resistive CsI is relatively smaller than in highly conducting Ag and Pd.
- This suggests that energetic electron propagation in the resistive material is inhibited by the resistive electric force (lower return current).



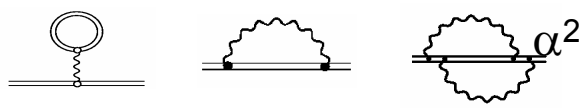
Atomic Physics in Extremely Strong Fields





Experiment (Gumberidze et al.,PRL 2005): **460.2 ± 4.6 eV**

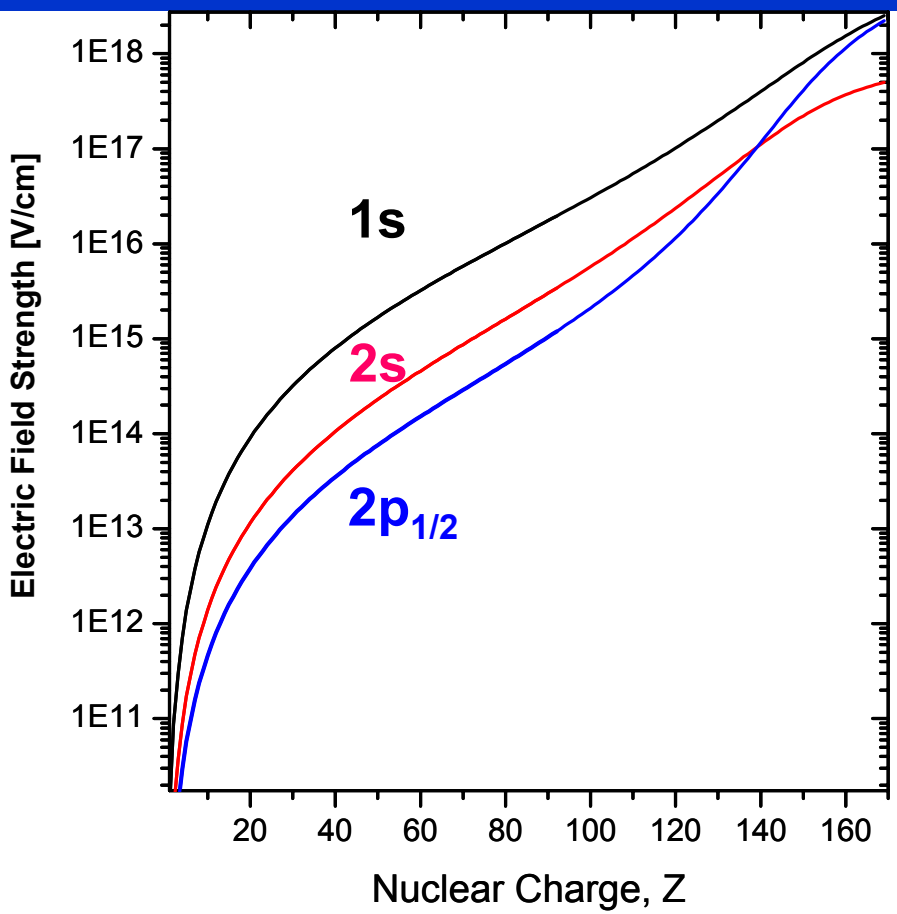
Theory (Yerokhin et al., PRL 2003): 464.26 ± 0.5 eV



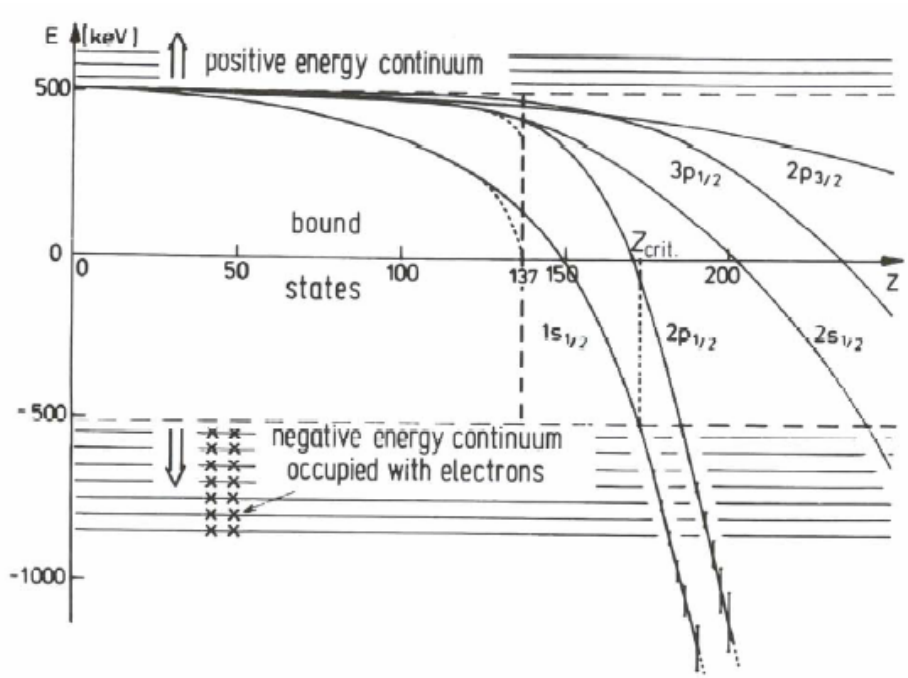
→ **1% sensitivity to the 1s Lamb shift**

→ **stringent test of bound-state QED for one-electron high-Z systems**

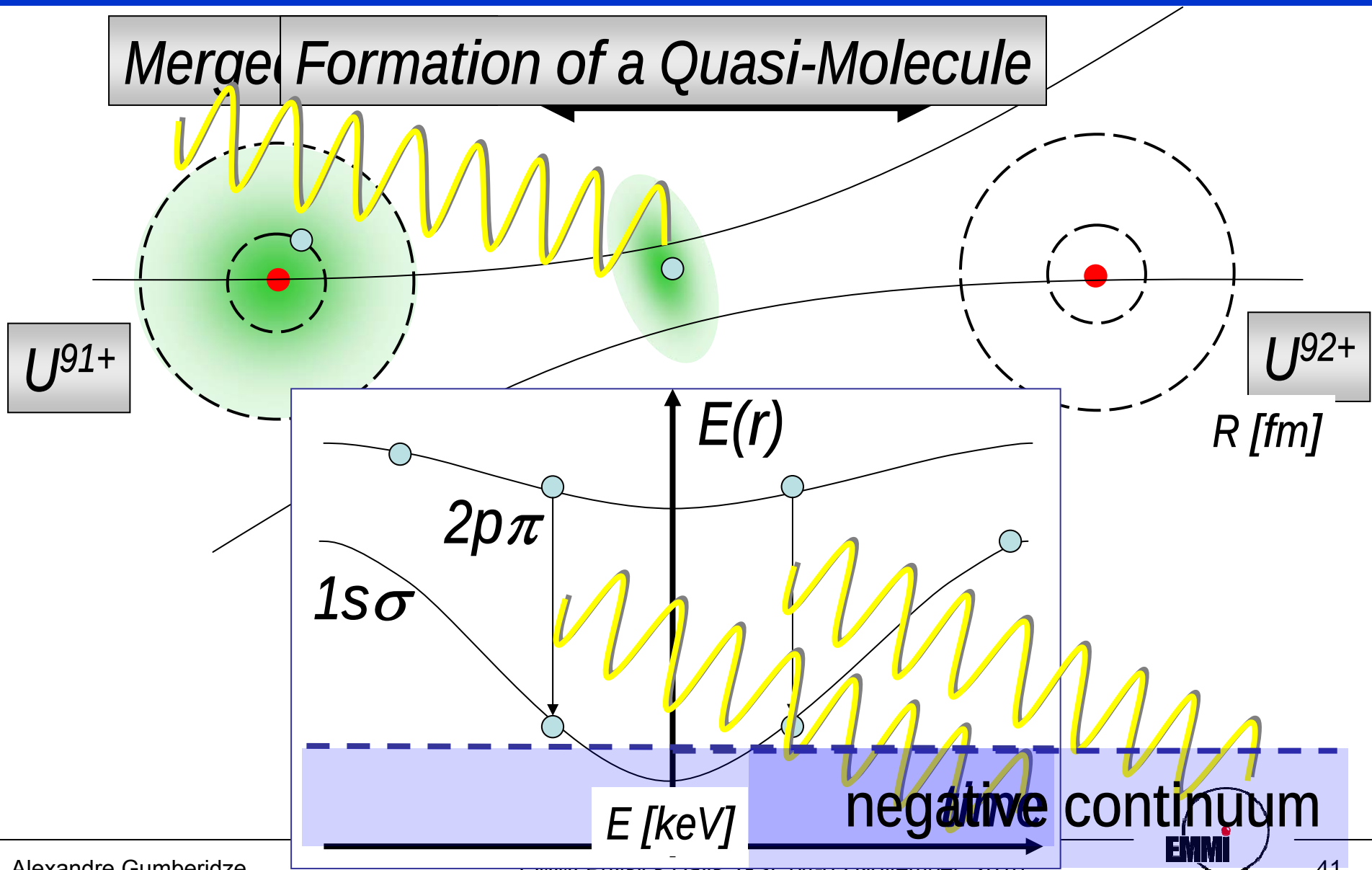
Critical- and Super-Critical Fields



spectroscopy of the inner shells in superheavy quasimolecule systems with energy eigenvalues in the vicinity of the negative continuum

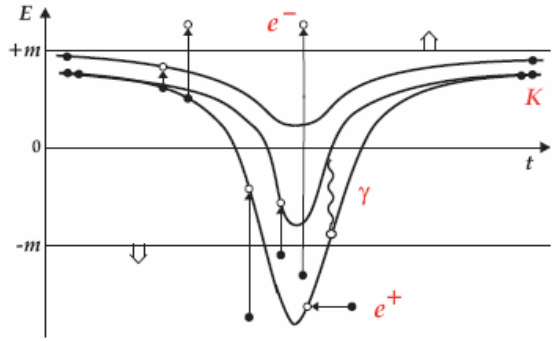


Quasimolecules



Various Processes and Experimental Observables

In systems with $(Z_1 + Z_2) > 137$:
"Collapse" of wave functions leads to strong $\partial/\partial R$ couplings (between $\kappa = \pm 1$ states). *Multi-step processes* become important.



- **K-hole production**

High ionisation rates: $P_{1s\sigma} \simeq 10\%$.
Approximate scaling behaviour:

$$P_{1s\sigma}(b) \simeq D(Z)\, \mathrm{e}^{-2R_{\min}q_{\min}}$$ where $$q_{\min} = \frac{E^B_{1s\sigma}(R_{\min})}{\hbar v_{\mathrm{ion}}}$$ (minimum momentum transfer)

➔ "Spectroscopy" of superheavy quasimolecules.

- **δ-electron production**

The high-energy tail (up to $E_e > 2\ \mathrm{MeV}$) probes the high-momentum components of the the quasimolecular wave functions.

- **Quasimolecular X rays (MOX)**

Broad photon spectra. No "end point", quasistatic picture not applicable.

- **Positron creation**
  - Drastic increase of positron yield with nuclear charge Z : $P_{e^+} \propto Z^{20}$
  - *No qualitative signal* for level diving expected. (*Collisional broadening*)
  - Good quantitative agreement with experiments: $P(b), P(Z), dP/dE_{e^+}$.

Early MO Studies Using Solid Targets
Single-pass experiments

1972: Mokler, Stein and Armbruster, **X Rays from Superheavy Quasiatoms Transiently Formed during Heavy Ion-atom Collisions** PRL 29.

1974: Kraft, Mokler and Stein, **Anisotropic Emission of Noncharacteristic X Rays from Low-Energy I-Au Collisions**, PRL 33**.**

1978: Liesen, Armbruster, Behncke, and Hagmann, **4.7 MeV/u Xe-Au impact parameter measurements of K-shell vacancy production**, Z. Physik A 288.

1979: Kozhuharov et al., **1.4 GeV U-Pb and Pb-Pb positron production, impact parameter measurements for b<40fm**, PRL 42.

1983: Maor, Liesen, Mokler, Rosner, Schmidt-Böcking and Schuch, **impact parameter measurements for 1.4 MeV/u Ni-Zr,Ag,Te,Au collisions**, PRA 27.

1983: L. Tserruya et al. **Interference Effects in the Quasimolecular *K* X-Ray Production Probability for 10-MeV Cl^{16+}-Ar Collisions** Phys. Rev. Lett. **50, 30**

1983: P. Armbruster, **Heavy ion collision induced characteristic x-ray production – cross section experiments**, in W. Greiner (ed.) Quantum electrodynamics of strong fields, Plenum Press, New York,, p. 135.

F. Bosch, **Experiments on the excitation of the innermost electrons in extremely strong fields,** ibidem, p.155

1984: P. H. Mokler and D. Liesen, **X-rays from superheavy collision systems**, in H. J. Beyer and H. Kleinpoppen (eds.) Progress in atomic spectroscopy, Part C, Plenum Press, New York and London,, p.321

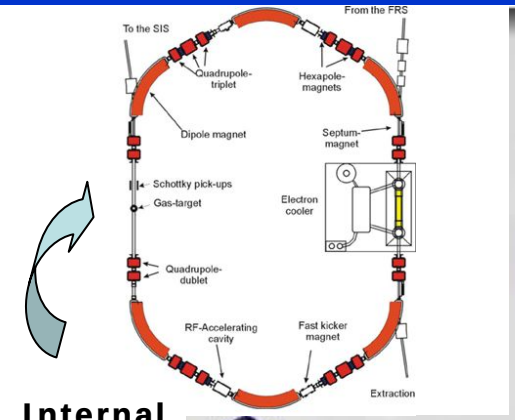
H. Backe and Ch. Kozhuharov, **Investigations of superheavy quasiatoms via spectroscopy of δ rays and positrons** ibidem, p.459

1985: R. Anholt, **X-rays from quasimolecules** Rev. Mod. Phys. 57, 995.

1988: R. Schuch et al., **Quasimolecular x-ray spectroscopy for slow Cl16+-Ar collisions** Phys. Rev. A **37, 3313**

1994: U. Müller-Hehler and G. Soff, **Electron excitations in superheavy quasimolecules** Phys. Reports **246,** 101.

HCI Production at GSI-ACCELERATOR FACILITY



Internal Gas-jet Target

UNILAC
11.4 MeV/u
U^{73+}

ESR

10 - 500
MeV/u
U^{92+}

up to
1000 MeV/u
U^{92+}

SIS

30 10

First Step in ESR Studies of K-Shell Excitation and Ionization at Small Impact Parameters and in Symmetric Heavy Systems

Overall Goals

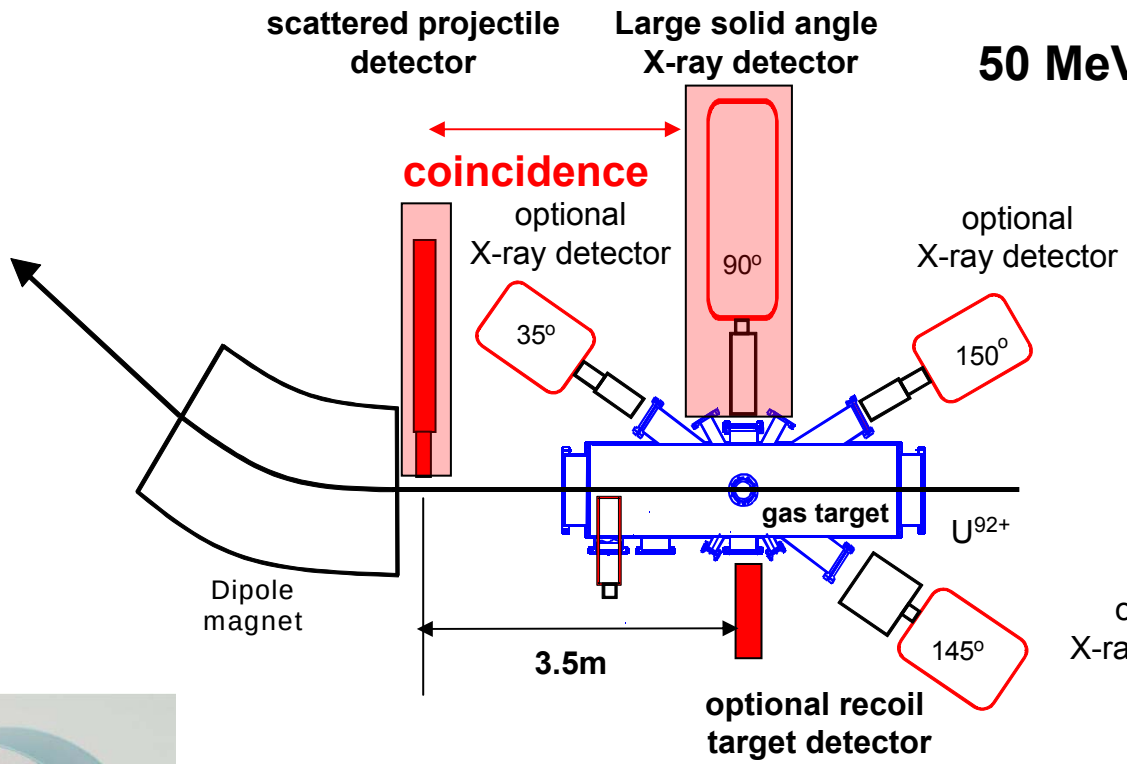
Extend ESR studies to new regimes, e.g., to study

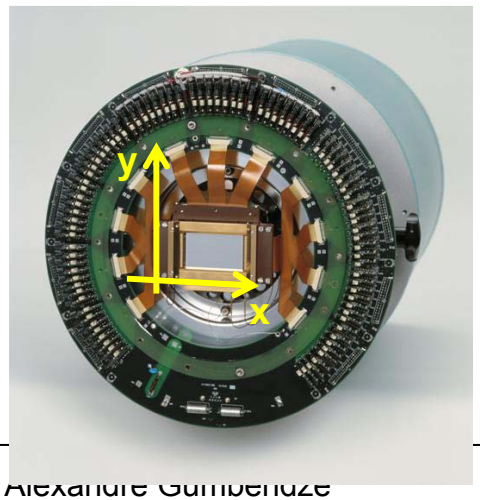
- symmetric heavy particle interactions where the combined nuclear charge is >100
- K-shell excitation and ionization processes at small impact parameters
  (much less than K-shell radius, e.g. < 200 fm)
- excitation and ionization of quasi-molecules produced in slow collisions

First Step

- Measure K-shell excitation at small impact parameters for "symmetric" heavy particle system, e.g., **50 MeV/u He-like Xe- Xe or 100 MeV/u He-like Au - Xe.**
- Investigate signal rates and backgrounds and use present study as a stepping stone for future impact parameter studies of K-shell ionization, excitation, and radiative electron capture.
- Test possibility of using the ESR and internal gas target to measure MO radiation produced in very heavy quasi-molecules.

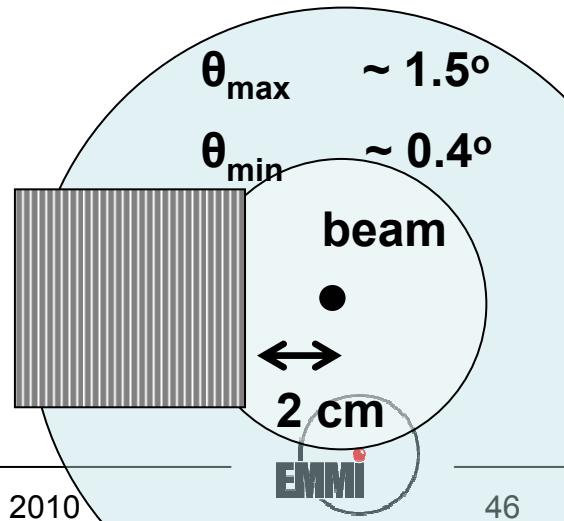
Proposed Study: Experimental Method





2D μSTRIP germanium detector – GSI

5 x 5 cm particle detector ~ 3 m downstream

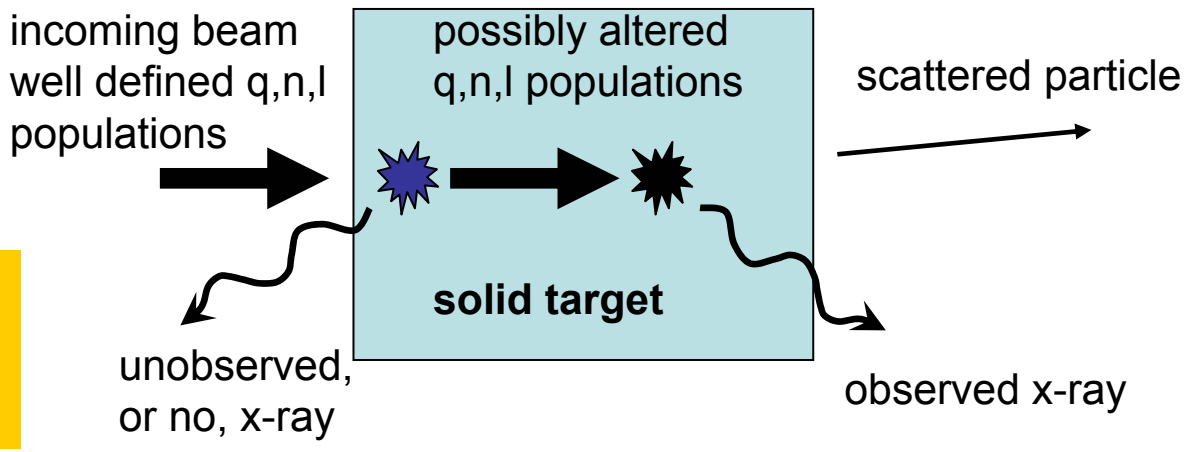


Advantages and improvements as compared to the previous studies

- incoming ion in a well defined and desirable charge-state
- gas-target: single collision conditions
- outgoing ion charge-state undisturbed

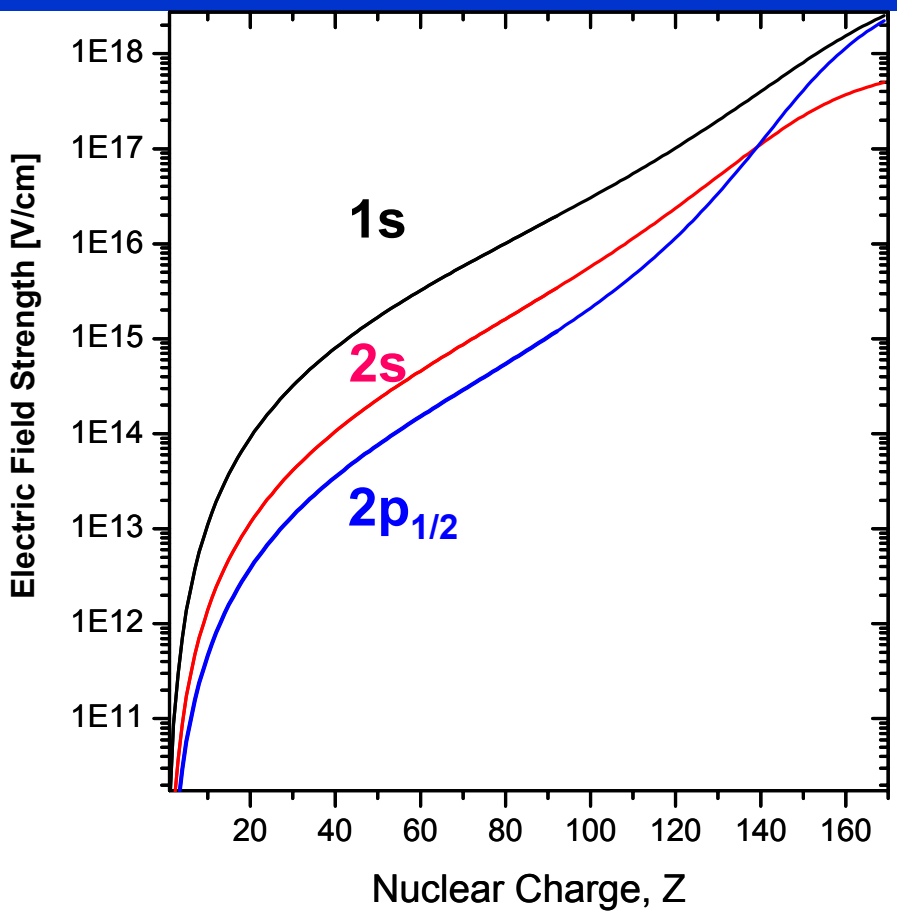
Advantage:
high signal rates,
very high Z_{targ} possible

Dissadvantage:
data must account for possible alterations in initial and final q,n,l populations.



- possibility to conduct experiments in a wide collision energy range (Deceleration capability of the ESR)
- novel segmented solid-state detectors: position, energy and time resolution

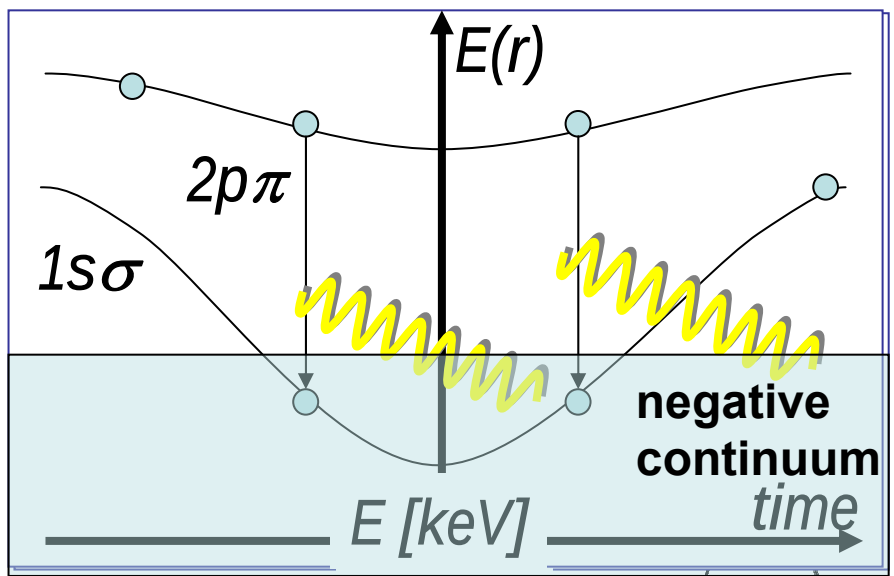
Critical- and Super-Critical Fields



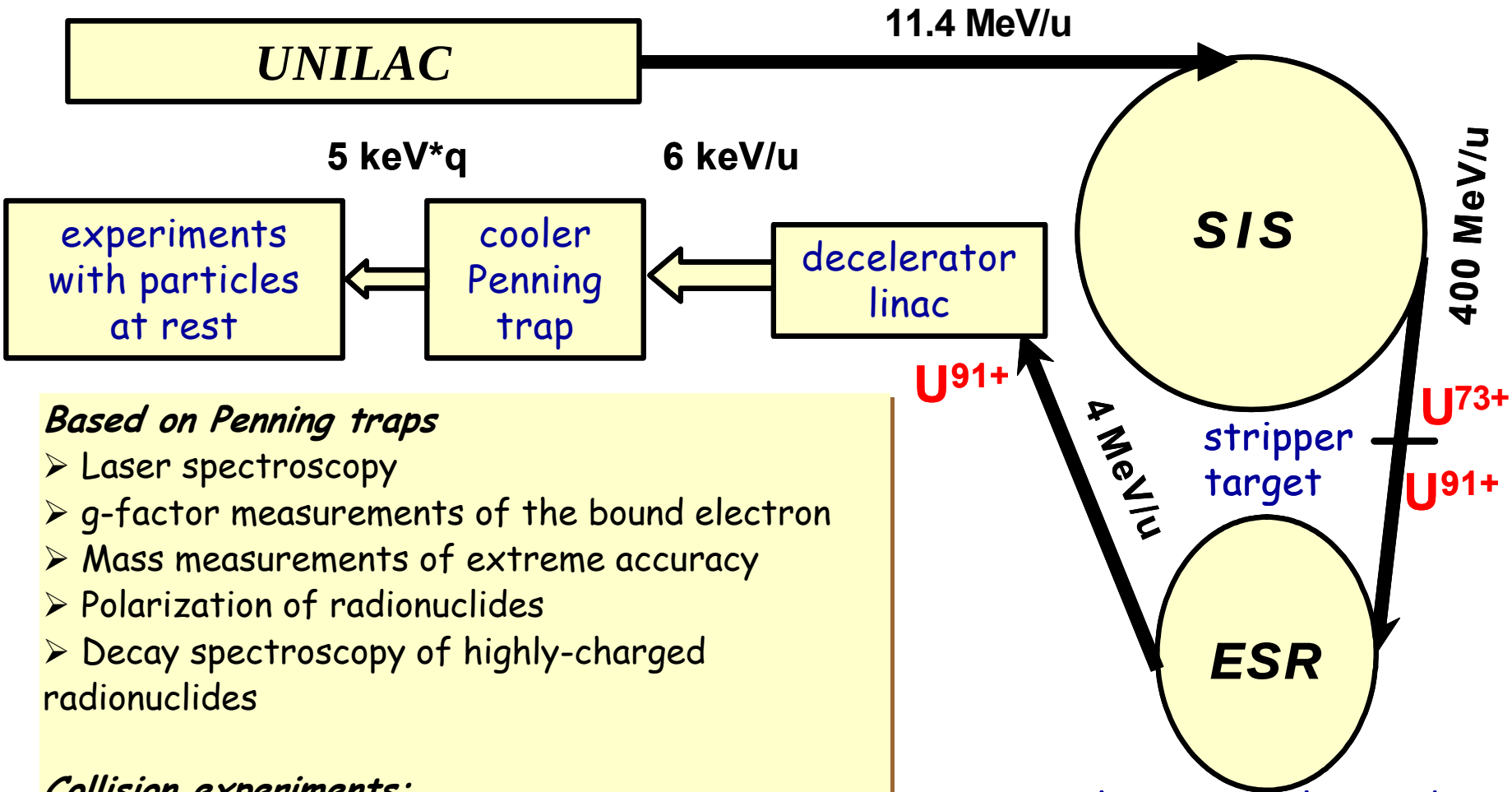
spectroscopy of the inner shells in superheavy quasimolecule systems with energy eigenvalues in the vicinity of the negative continuum

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

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



HITRAP overview



Based on Penning traps

- Laser spectroscopy
- g-factor measurements of the bound electron
- Mass measurements of extreme accuracy
- Polarization of radionuclides
- Decay spectroscopy of highly-charged radionuclides

Collision experiments:

- Collisions at very low velocities
- Surface studies and hollow-atom spectroscopy
- X-ray spectroscopy

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Summary

Precision Studies of Atomic Structure at High-Z

- 1s LS in H-like uranium confirmed on a level of 1%
- Further progress towards an absolute accuracy of 1 eV is expected from high-resolution spectroscopy techniques (Beamtime beginning of next year)

Atomic Collision Dynamics and Photon-matter Interaction in Strong Perturbative Regime

First experimental studies of excitation for the Heaviest H-like Ion in Relativistic Collisions

Exploiting Atomic Physics techniques for Exploring Plasmas Generated by High-power Laser

Hot electron energy distribution

Various precision experimental tools developed and available in fundamental atomic physics research with heavy ions can be successfully utilized for exploring extreme states of matter.

Outlook

Atomic Physics at Extreme Fields at GSI Darmstadt and at the FAIR Facility

Critical- and Super-Critical Fields

spectroscopy of the inner shells in superheavy quasimolecule systems with energy eigenvalues in the vicinity of the negative continuum

Outlined a new experimental ESR program based upon a new observable, the impact parameter. This will allow us to study K-shell ionization, excitation, and radiative electron capture in more detail than previously possible.

Described an upcoming experiment which will establish techniques, signal rates, and backgrounds for planning future studies.

Collaboration

EMMI / GSI

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