X-RAY SPECTROSCOPY ON COOLED HEAVY IONS AT STORAGE RINGS

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X-RAY SPECTROSCOPY ON COOLED HEAVY IONS

- **Introduction**
- **Atomic Structure Studies at High-Z**
  - **Current Status of the 1s Lamb Shift Experiments**
  - **Two-Electron Contribution to Ionization Potential for He-Like Uranium**
- **Relativistic Quantum Dynamics**
  - **Angular Correlation and Polarization Studies**
  - **First Results for Polarization Studies of Radiative Capture Transitions**
- **Summary and Outlook**

Collaboration

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Mainz

Paris

Frankfurt

Grenoble

Jülich

Darmstadt

Caen

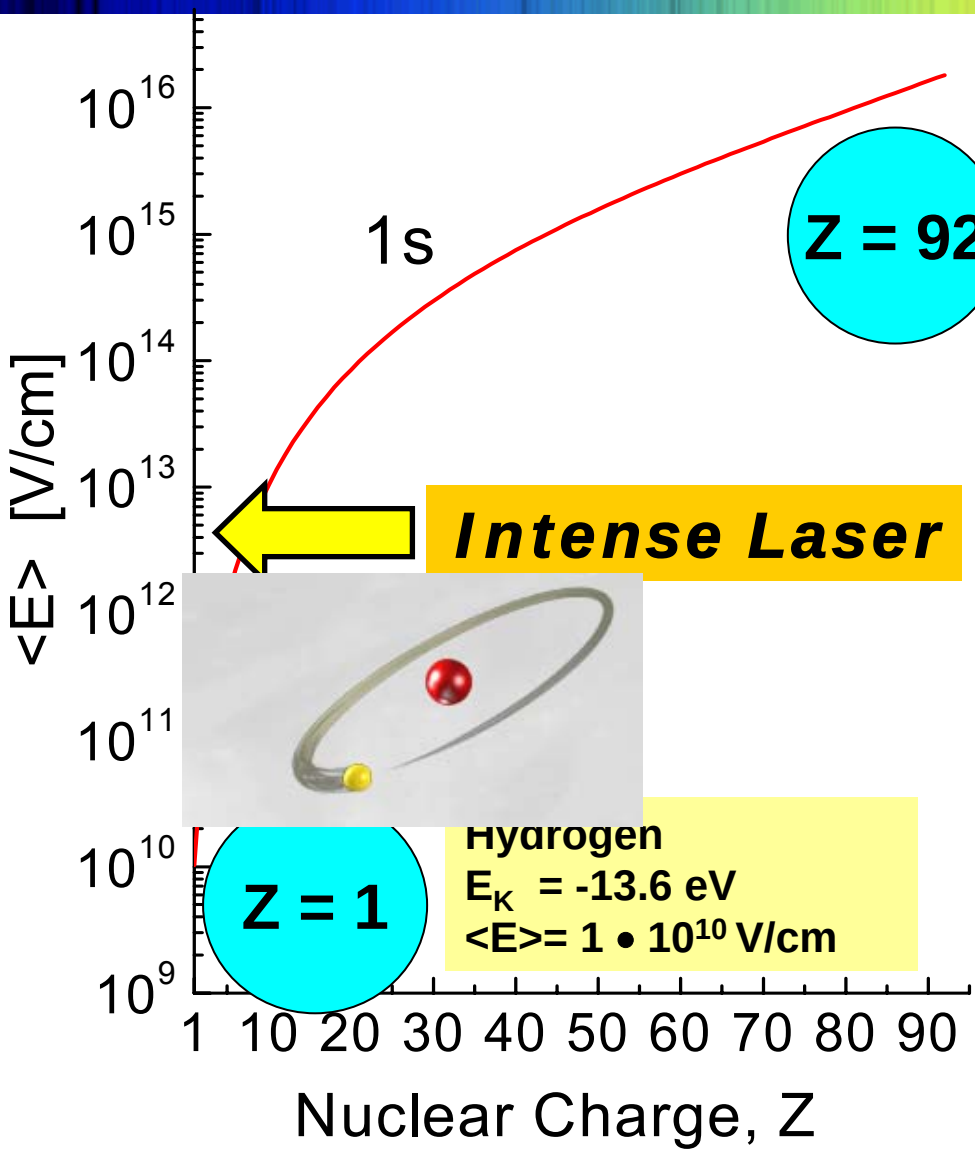
Cracow

Madison

Jena

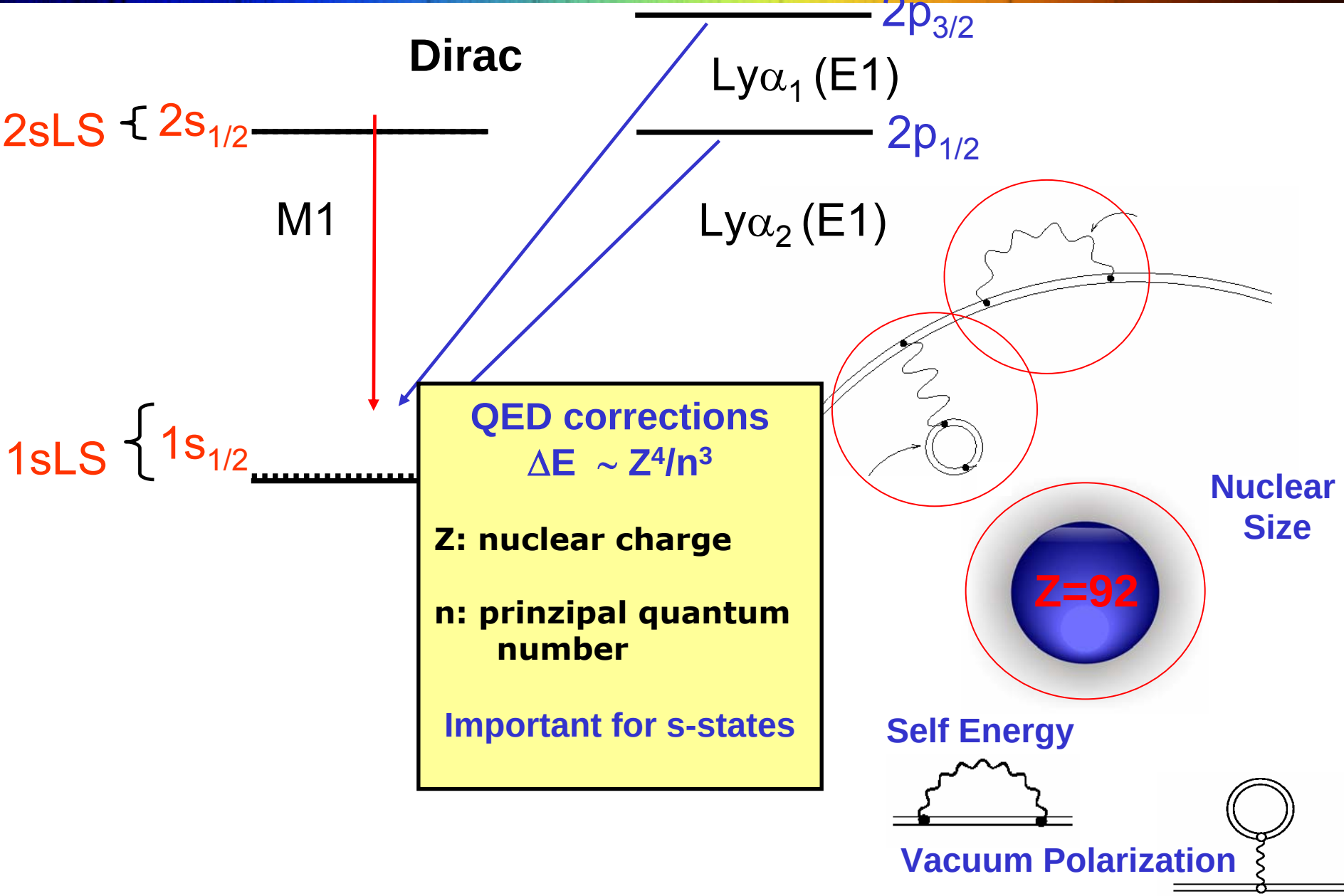
Greenbelt

Atomic Physics in Extremly Strong Coulomb Fields



Quantum
Electro-
Dynamics

The Structure of One-Electron Systems



Bound-State QED: 1s Lamb Shift

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

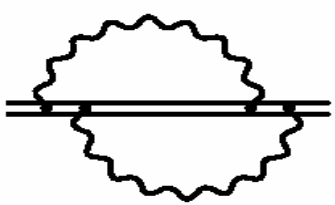
Self energy **Vacuum polarization**

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

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

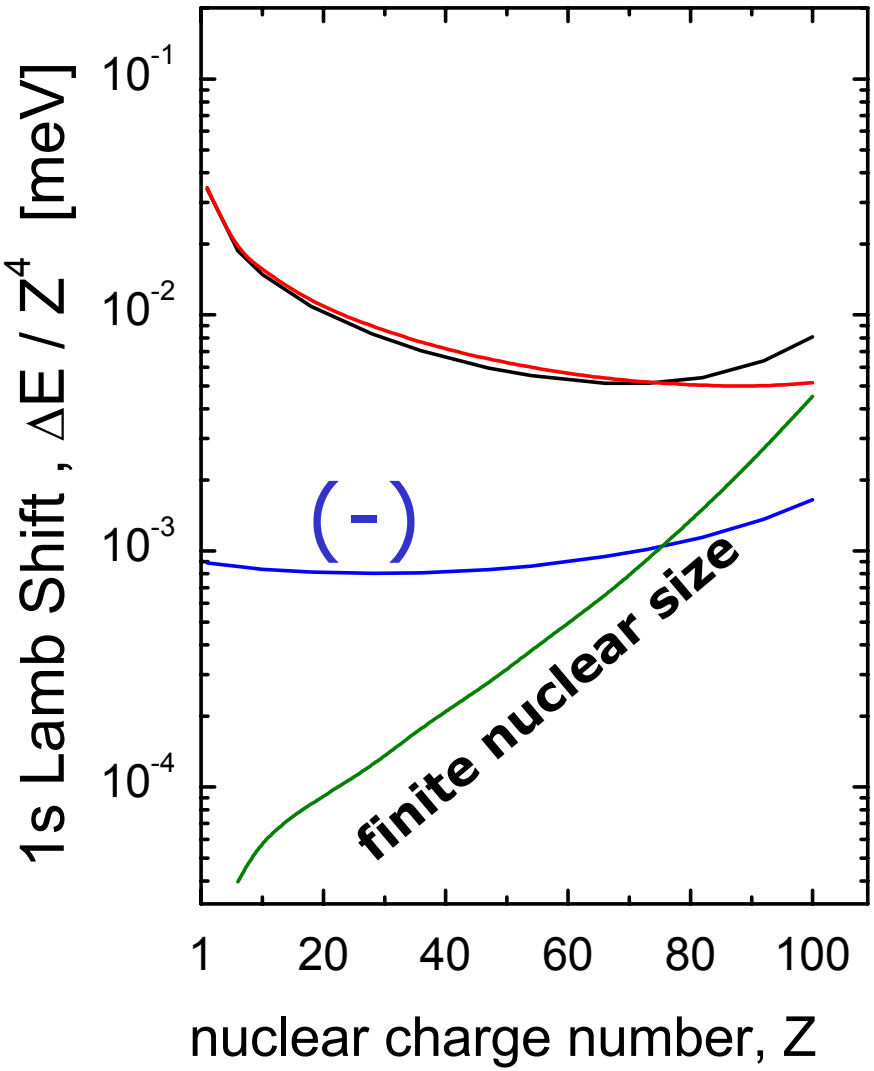
Low Z-Regime: $\alpha Z \ll 1$
$F(\alpha Z)$: series expansion in αZ

High Z-Regime: $\alpha Z \approx 1$
$F(\alpha Z)$: series expansion in αZ not appropriate

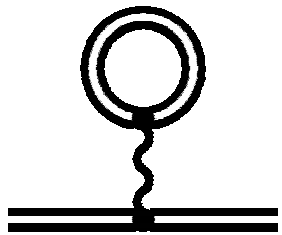
Goal:  **±1 eV**

Test of Bound-State QED at High-Z

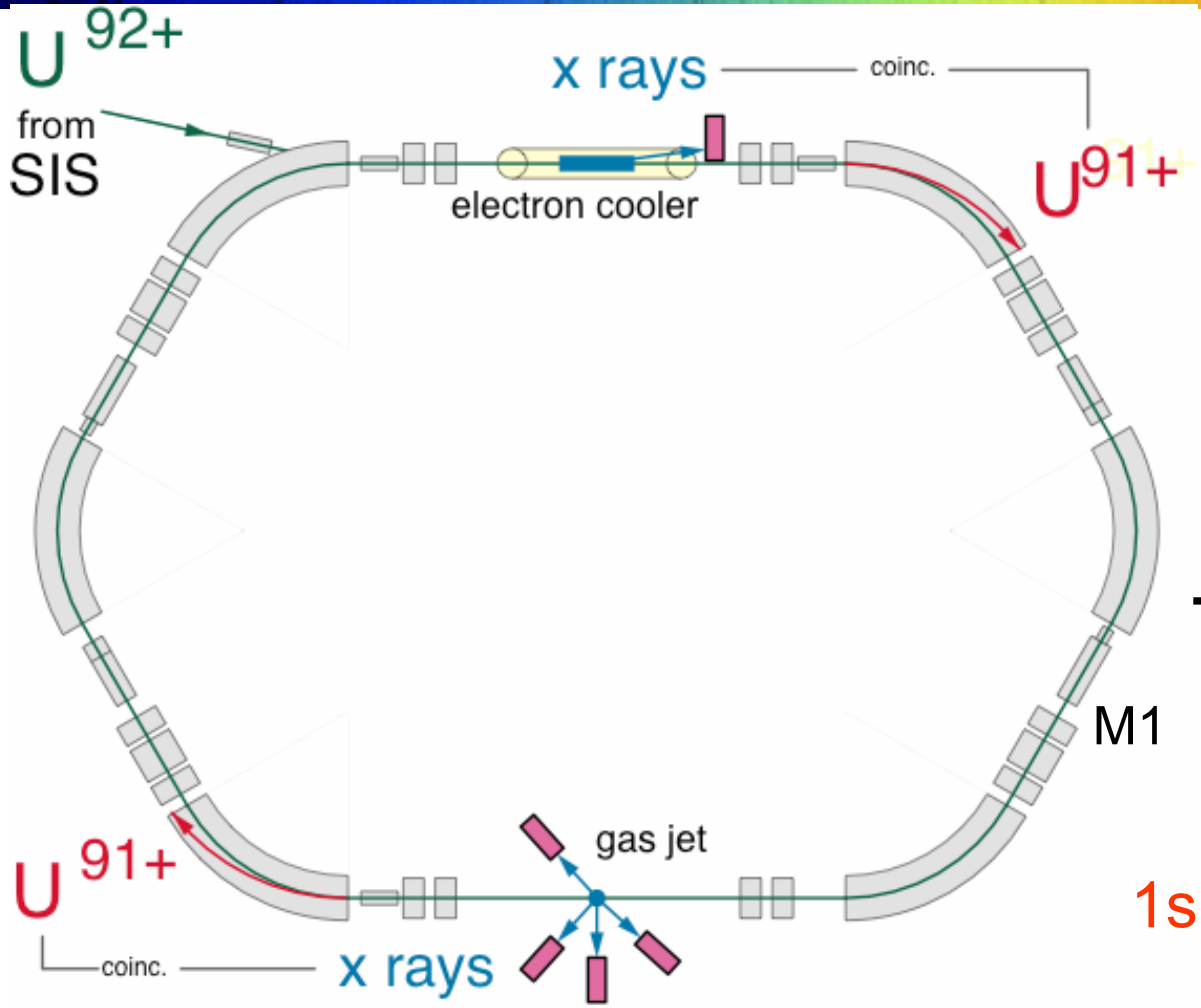
Self Energy



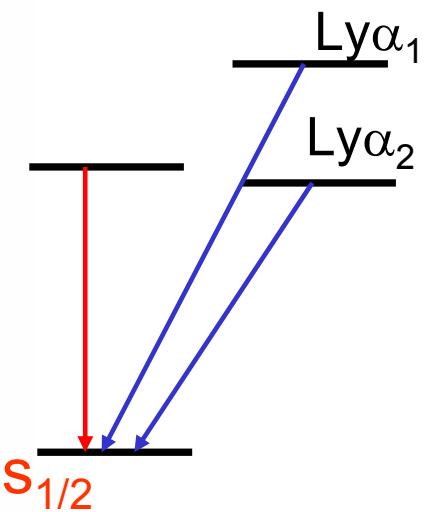
Vacuum Polarization



X-Ray Spectroscopy at the ESR Storage Ring



Injection Energy
300 - 400 MeV/U



circumference: 108 m
Number of Ions: 10^8
Frequency: 10^6 1/s

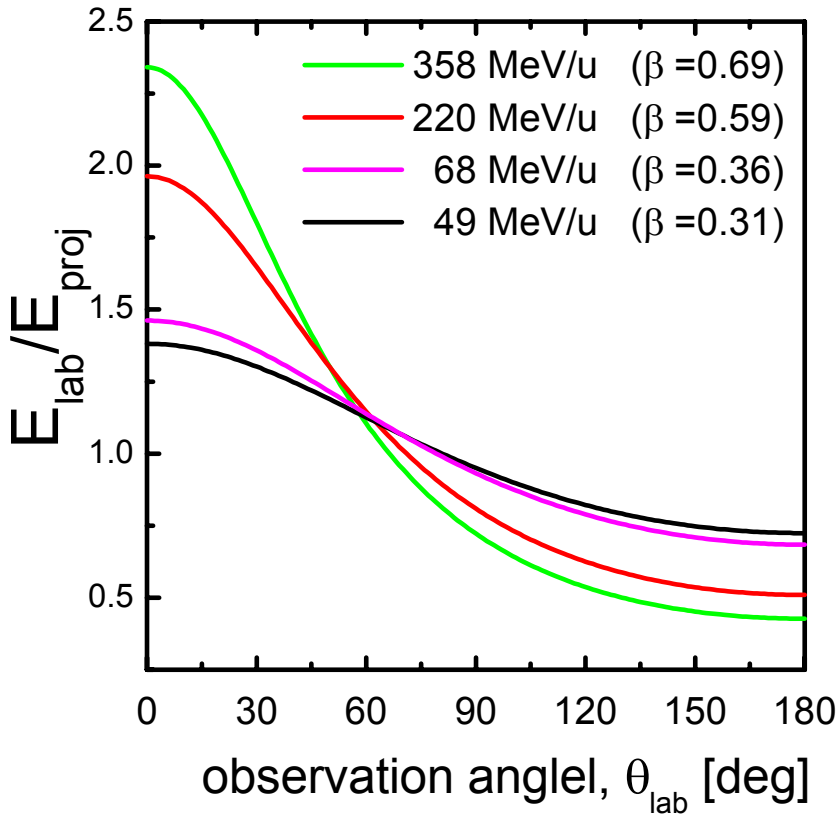
At the ESR, production of characteristic x-rays by electron capture into the bare ions (electron cooler or jet-target)

The Experimental Challenge

Relativistic Doppler-Transformation

$$E_{lab} = \frac{E_{proj}}{\gamma \cdot (1 - \beta \cdot \cos\theta_{lab})}$$

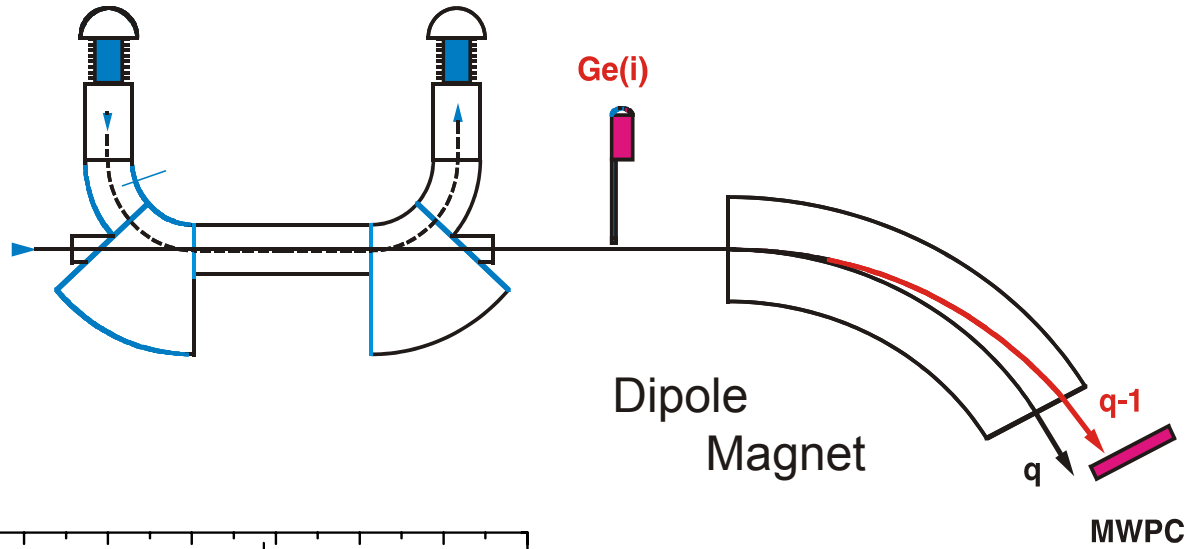
E_{lab}: Photon energy in the laboratory system
E_{proj}: Photon energy in the emitter system

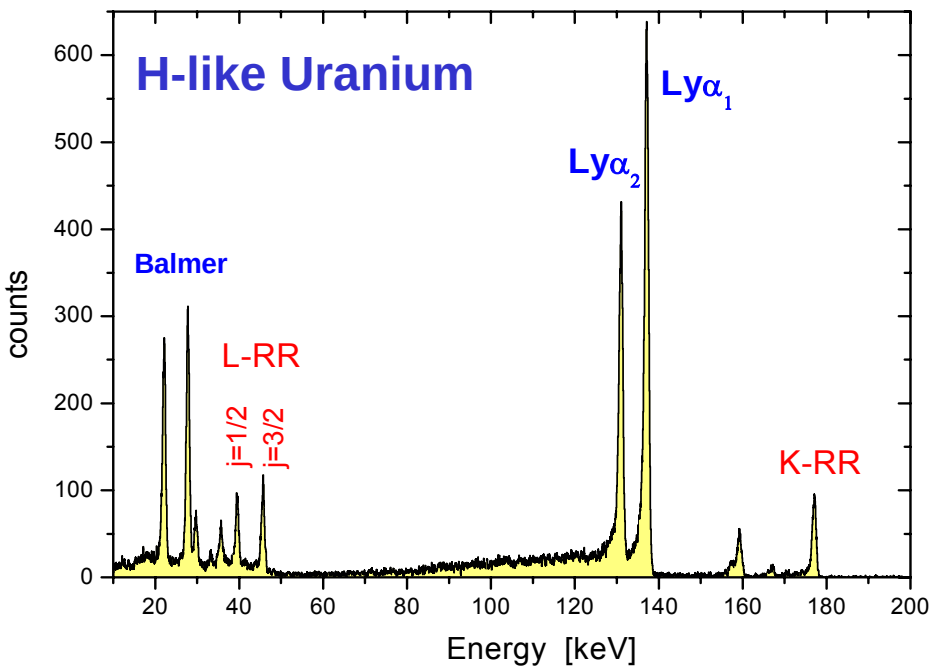


Doppler-Correction: *Strong dependence on velocity and the observation angle* θ_{LAB}

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

0º Spectroscopy at the Electron Cooler



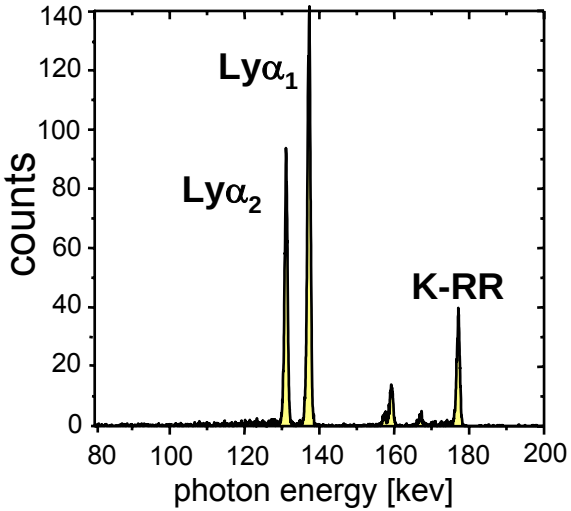


- **Blue shift has its maximum $\beta \approx 0.29 \Rightarrow E_{lab} \approx 1.43 \times E_{proj}$**
- **$\Delta\theta_{LAB}$ not critical, almost no Doppler width**
- **Uncertainty caused by $\Delta\beta$ has its maximum**

R. Reuschl et al., Poster: B7-21

Test of Quantum Electrodynamics (1s-LS)

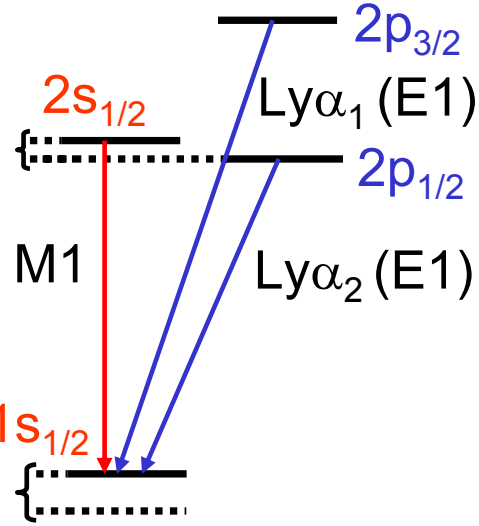
The 1s-LS in H-like Uranium

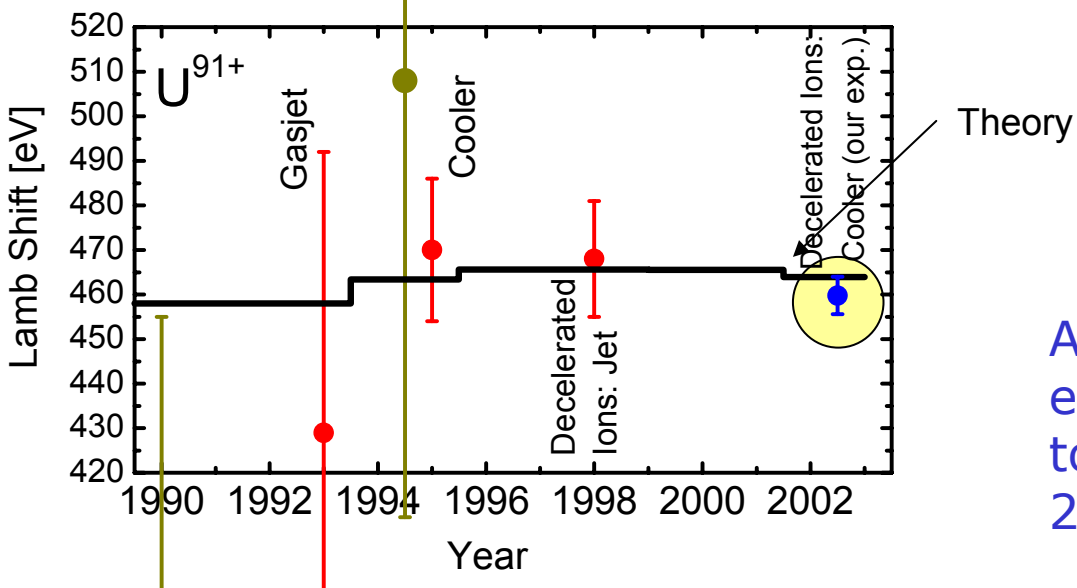


1s-Lamb Shift

Experiment: 459.8 eV ± 4.8 eV

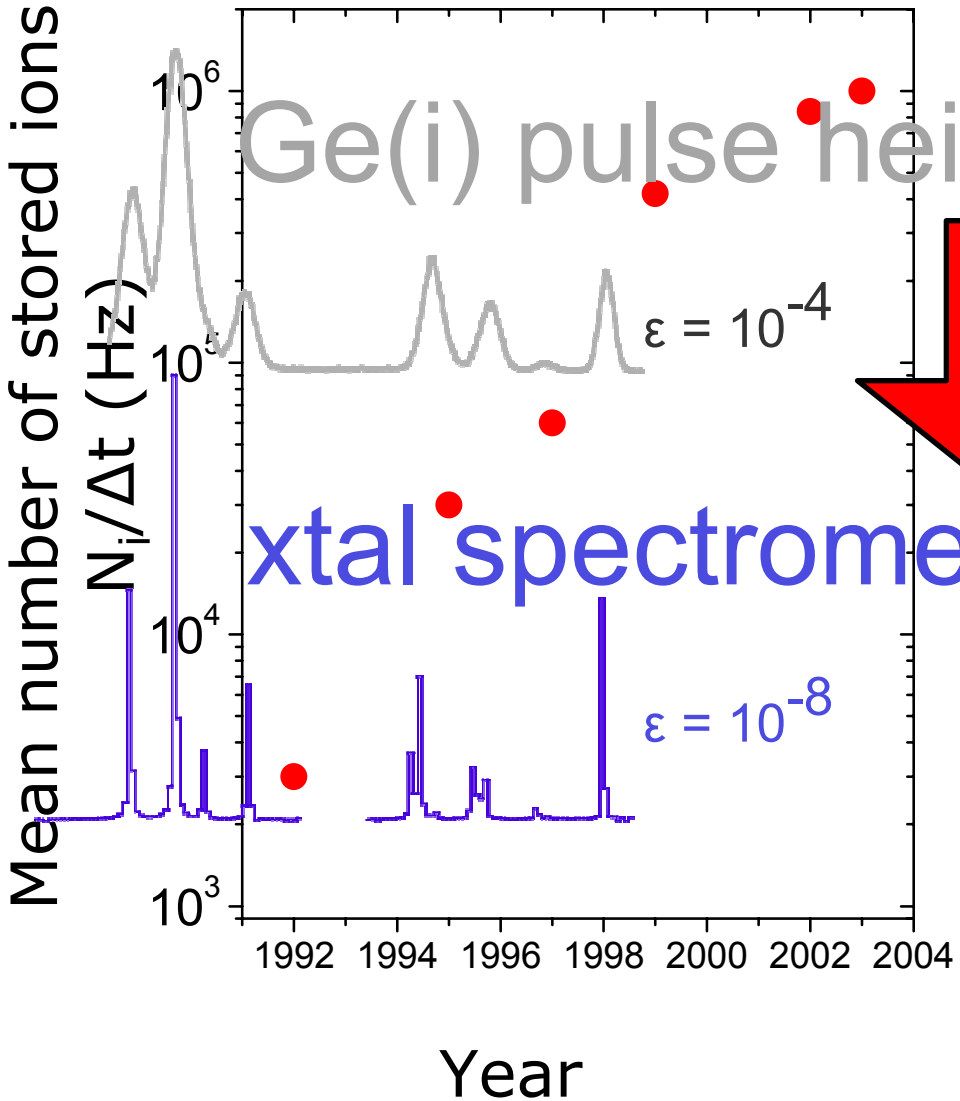
Theory: 463.95 eV





A. Gumberidze et al., to be published 2004

Towards an Accuracy of 1 eV



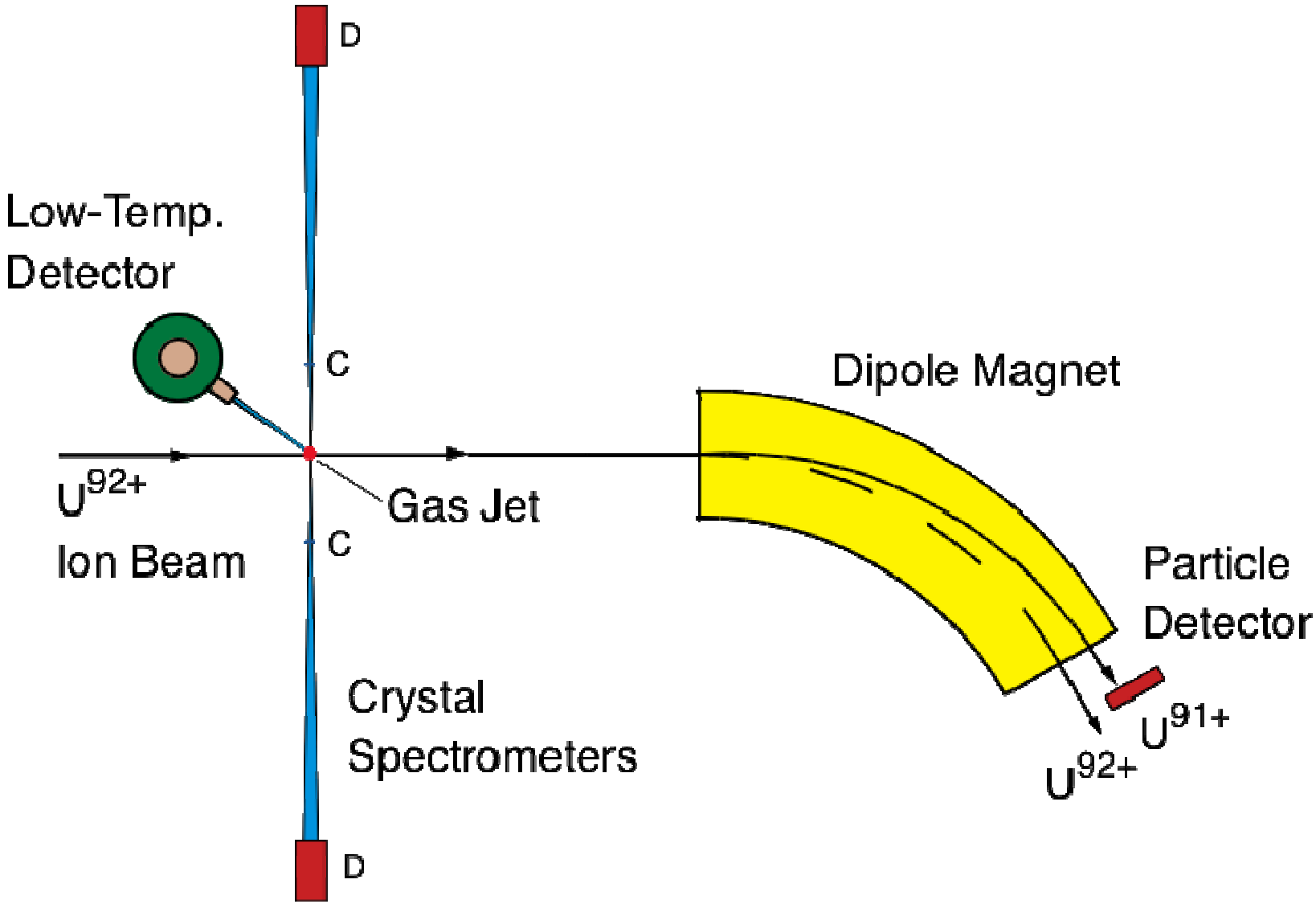
- **High Beam intensities**
  (10^8 Ions per Minute ⇒ 4.5×10^5 Photons in 4π)
- **Slow Ions or Ions in Rest**
  Deceleration of the Ions
  Small Doppler correction

Detector and Spectrometer Development

Crystal spectrometer
≤ 50 eV
(requires position sensitive solid state detectors)

mircocalorimeter ?

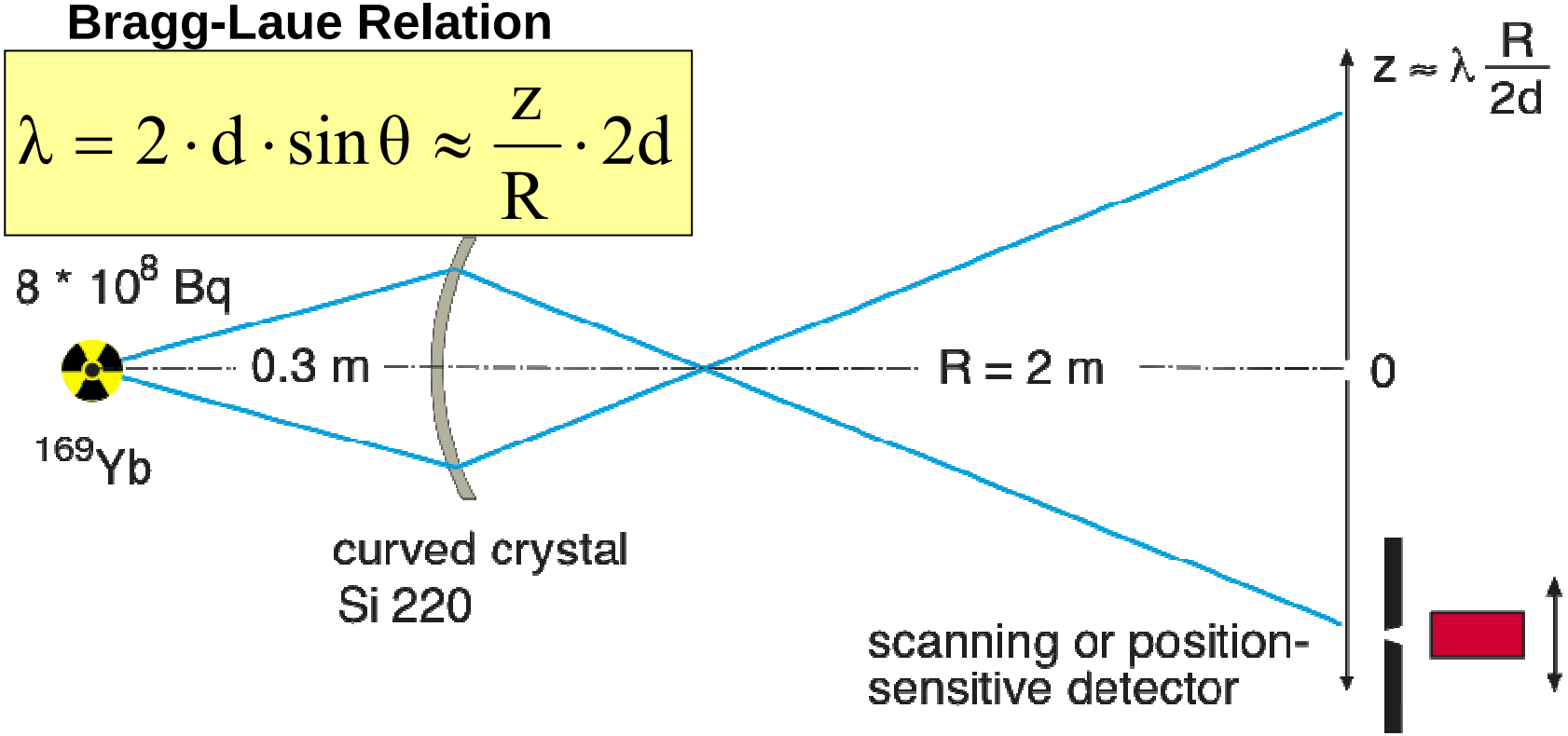
Transmission Crystal-Spectrometer
The Way Towards an Accuracy of 1 eV



FOCAL

Bragg-Laue Relation

$$\lambda = 2 \cdot d \cdot \sin\theta \approx \frac{z}{R} \cdot 2d$$



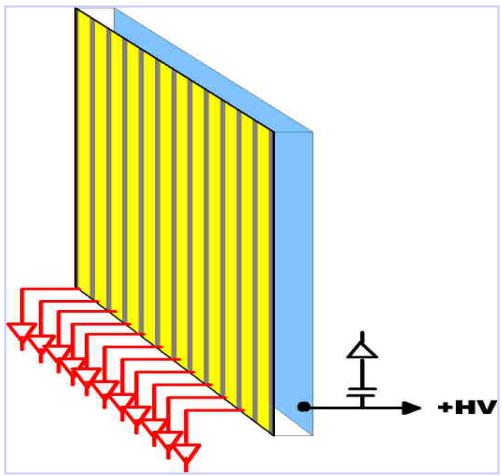
FOCAL Spectrometer: $\varepsilon \approx 10^{-8} \Rightarrow$ 3 Events per Hour

~~Gas Counter~~

Position Sensitive Ge(i) Detectors

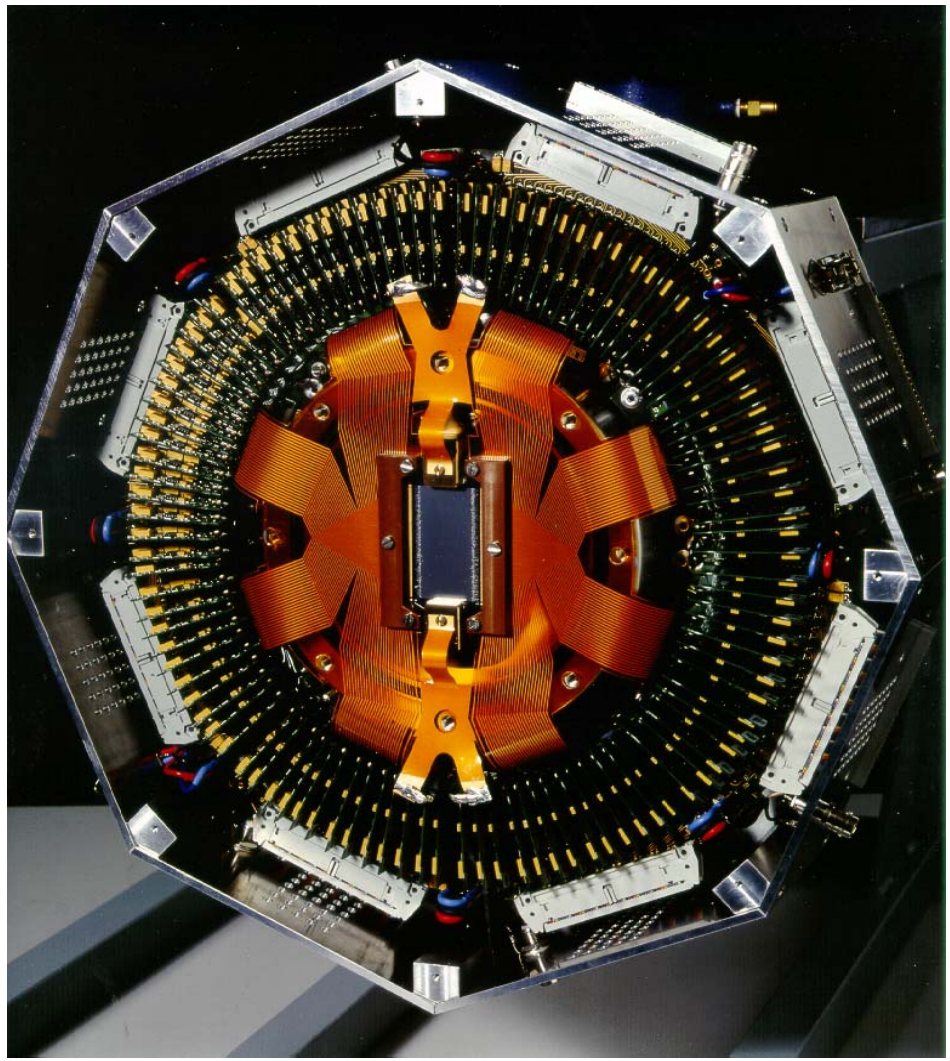
Micro-Strip Germanium: Detector Development

Energy Resolution **Position Resolution** **Timing**

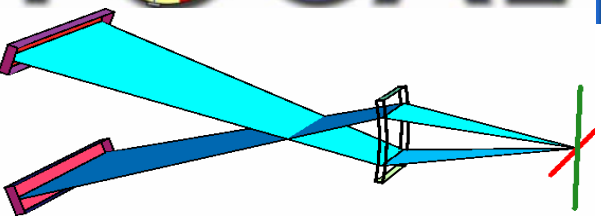


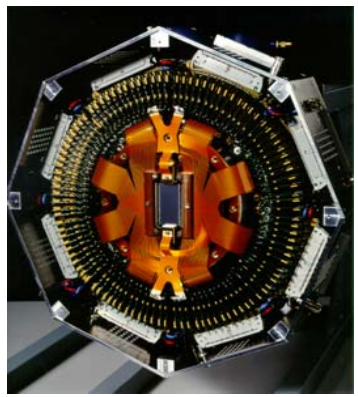
200 Strips

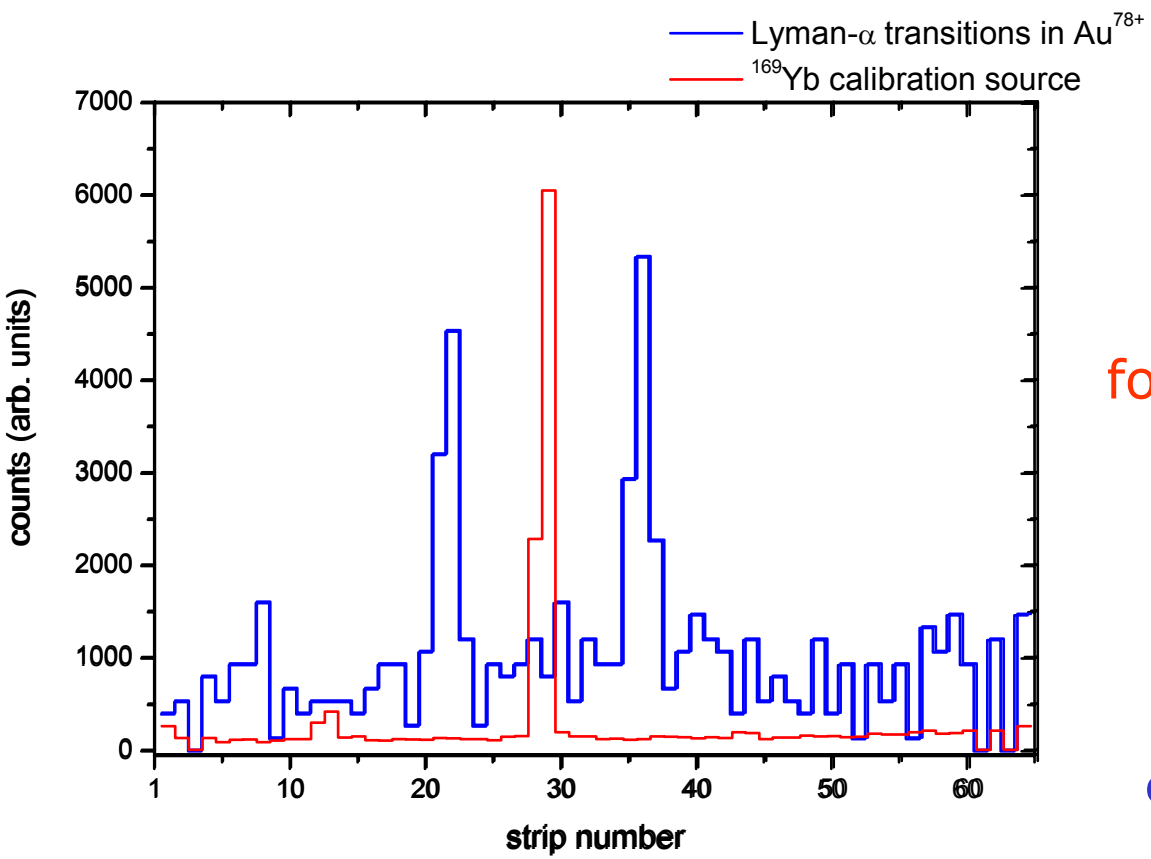
Δx ≈ 200 μm
ΔE ≈ 1.6 keV
Δτ ≈ 50 ns



Commissioning at the beam line







for data analysis
following conditions used

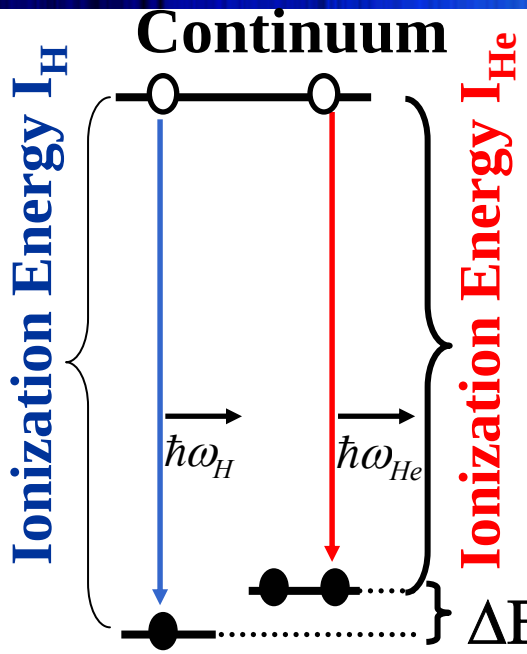
position

energy

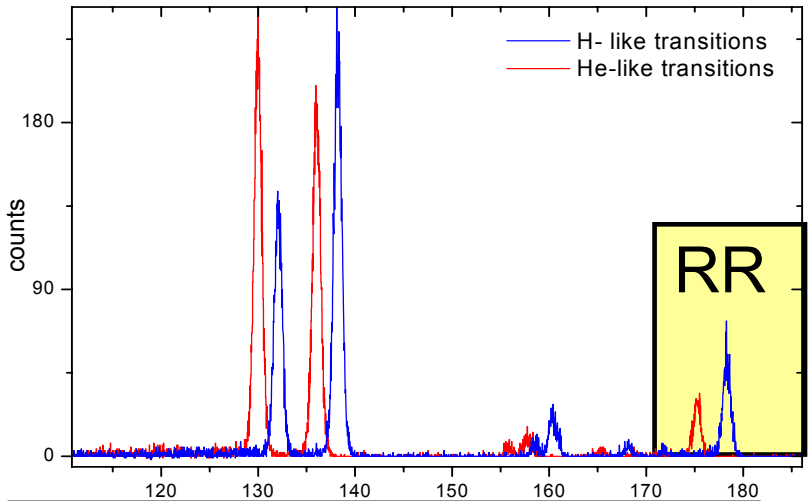
coincidence time

(3 events per hour)

Correlation and 2eQED Studies for He-like Uranium



$$I_H - I_{He} = \Delta E$$

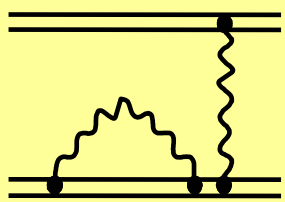


$\Delta E = 2.248\text{keV} \pm 9\text{ eV}$

- extension of former experiments at SuperEBIT to He-like uranium
- for the ground-state of high-Z He-like ions a sensitivity to 2eQED has been achieved

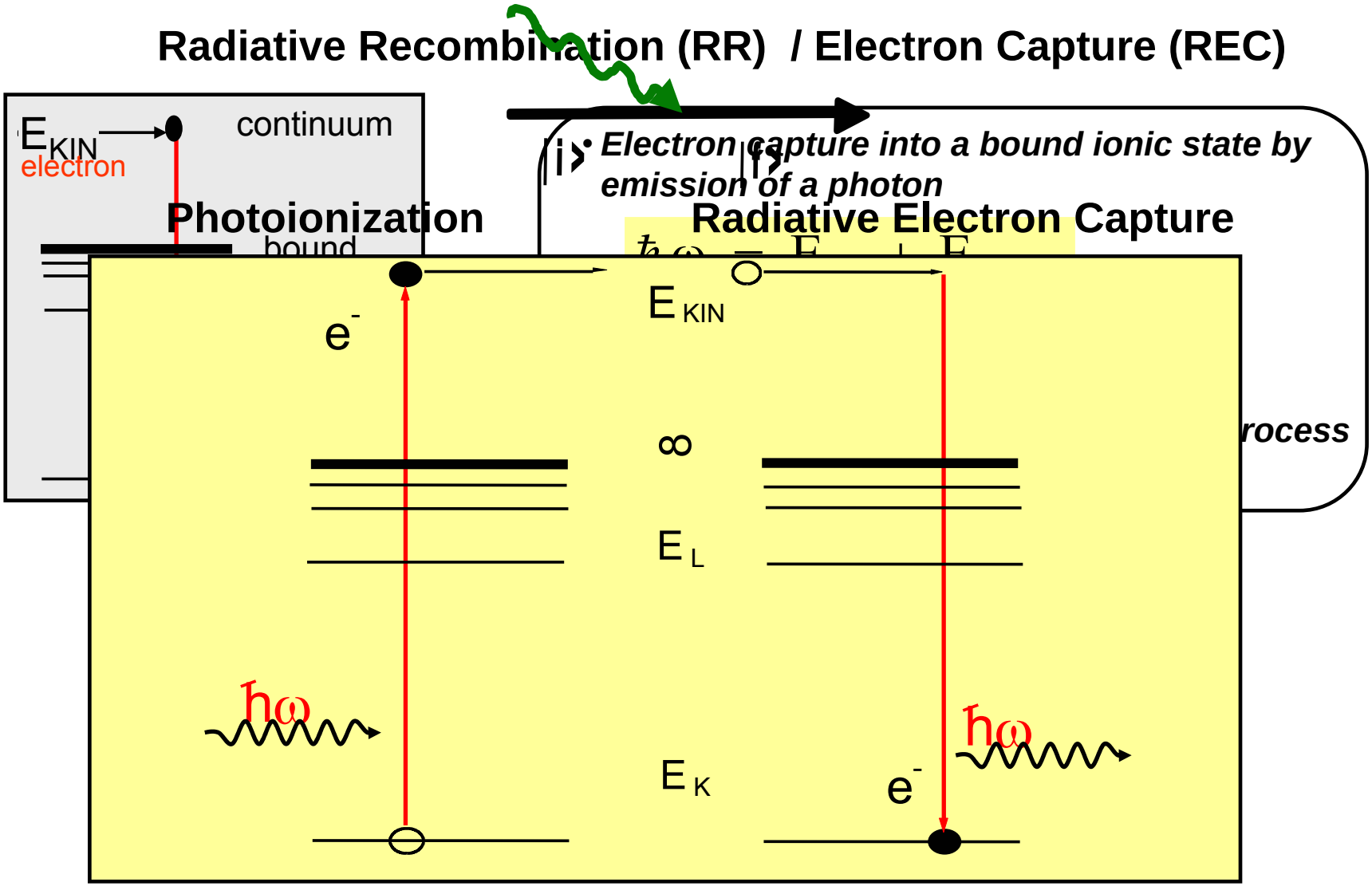
Two-Electron QED, e.g. 2nd order Self Energy

-9.7 eV [U^{90+}]

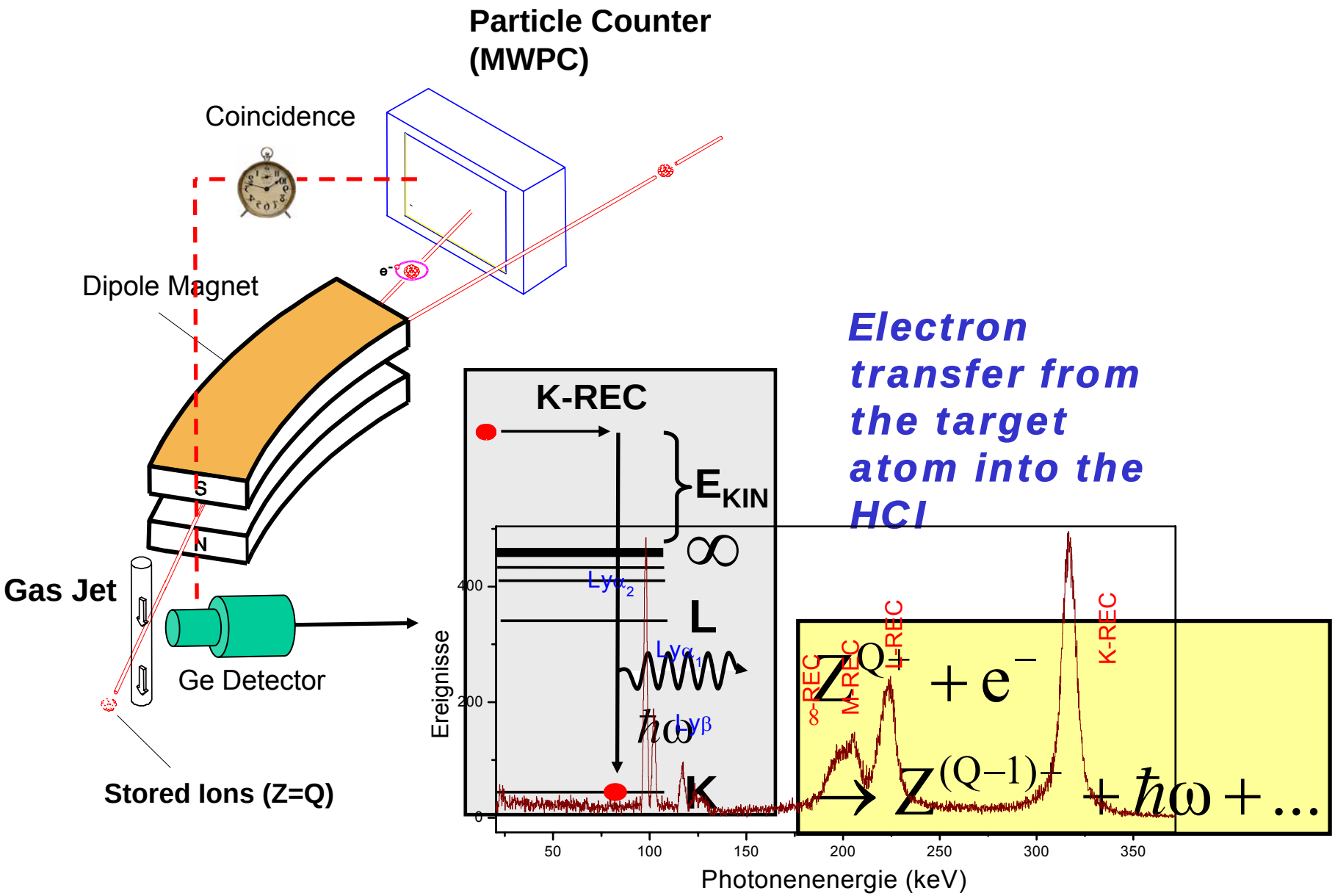


A. Gumberidze et al., PRL (2004); Poster: B2-20

Relativistic Quantum Dynamics

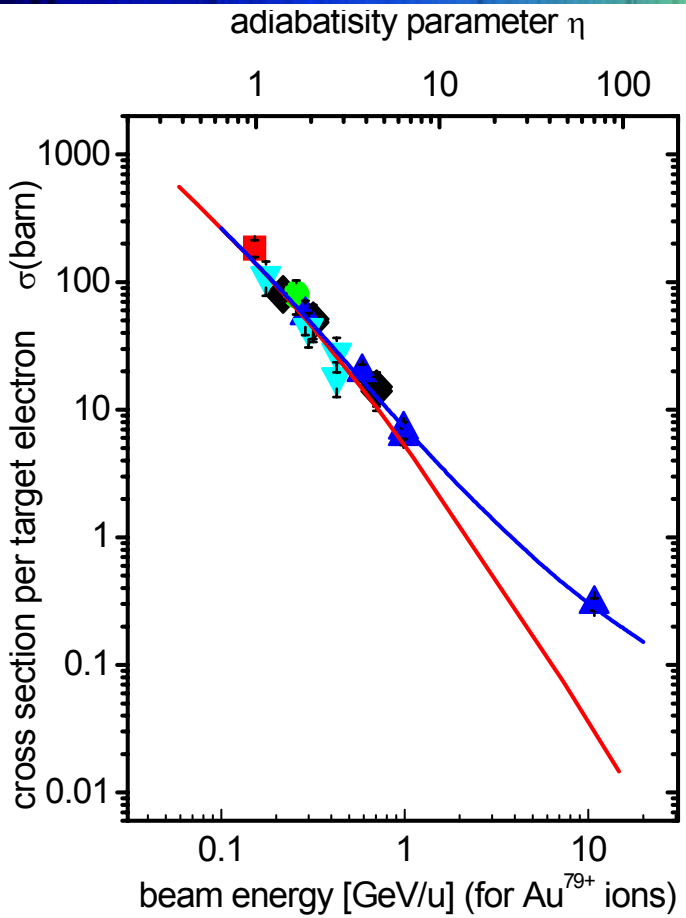


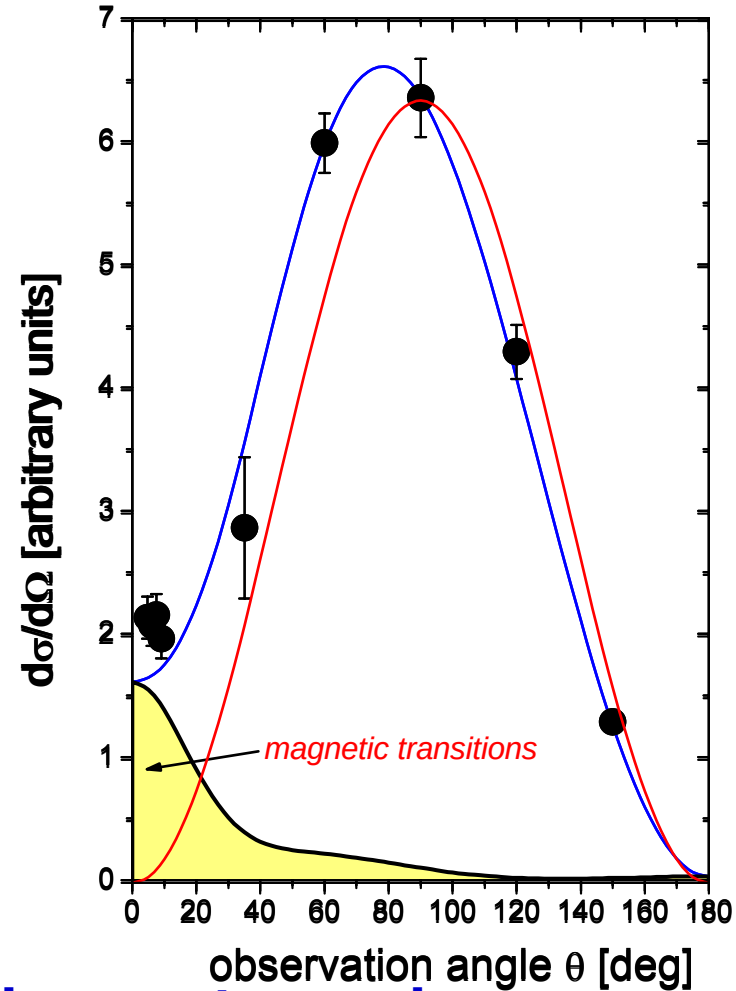
Experiments at the Jet-Target



Electron transfer from the target atom into the HCI

Experimental REC studies performed up to now





total REC cross sections for bare ions up to uranium (20 MeV/u – 170 GeV/u) ✓

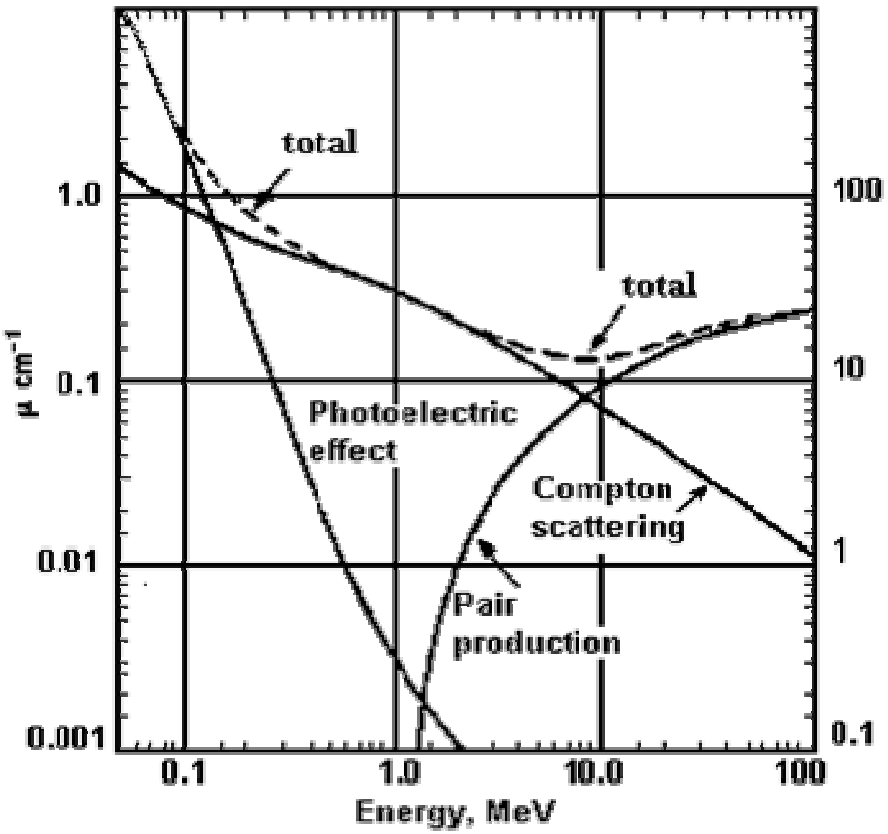
photon angular distribution studies for REC into the ground and excited states ✓

Open questions !

Angular distributions for few-electron ions close to the threshold (decelerated ions) ?

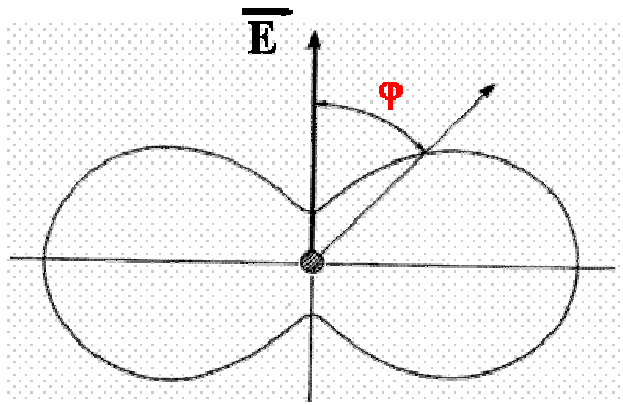
Polarization of the emitted photons (no experimental information available) ?

Interaction of radiation with matter



Klein-Nishina formula

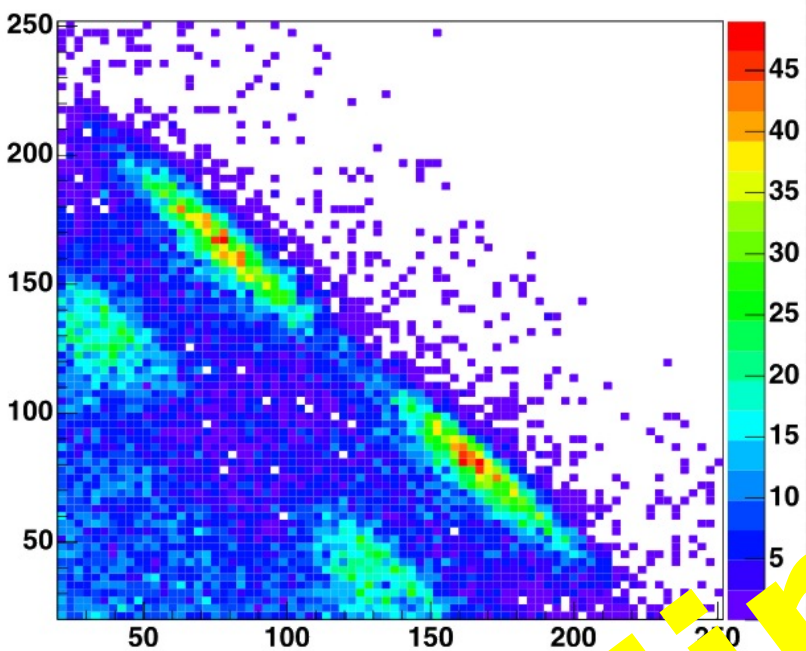
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\sin^2\theta_c \cos^2\varphi\right)$$

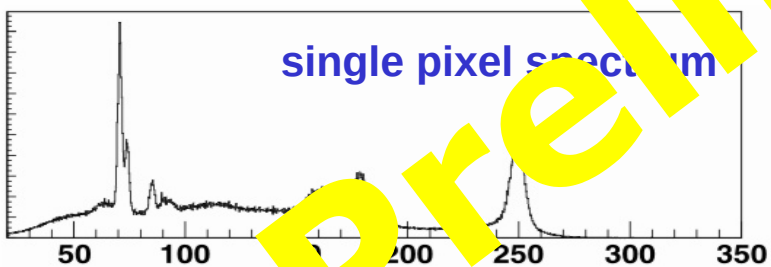


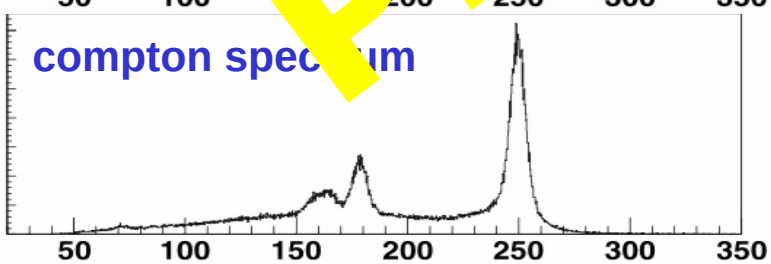
angular distribution of scattered photons

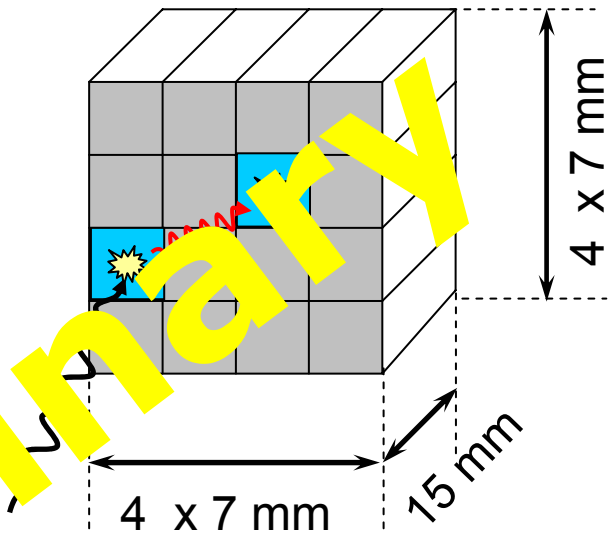
- photoelectric effect
- *Compton scattering*
- pair production

Compton Polarimetry: Application of segmented solid state detectors









Preliminary

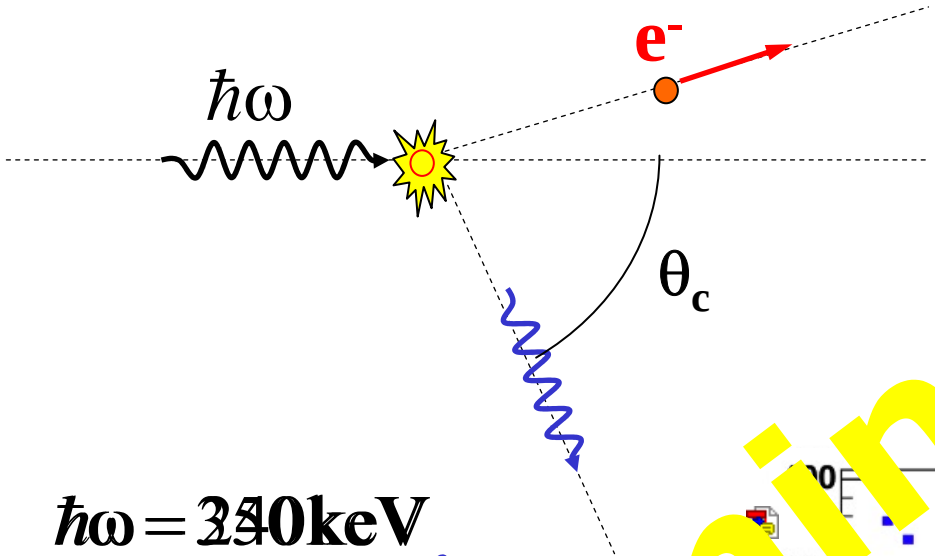
Pixel matrix 4x4

Pixel size 7x7 mm

Energy resolution: 2 KeV

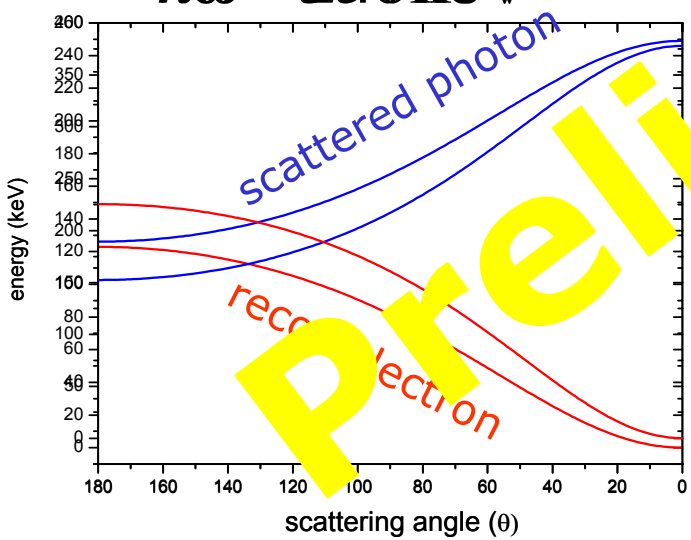
(Detector: D. Protic, FZ-Jülich)

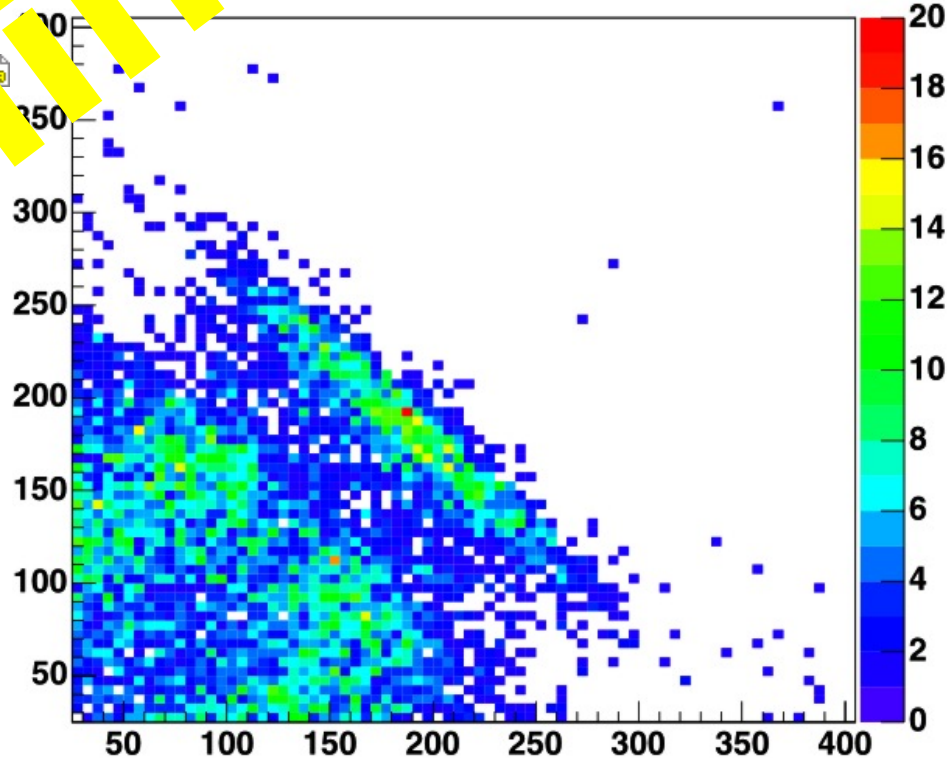
Compton Kinematics



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

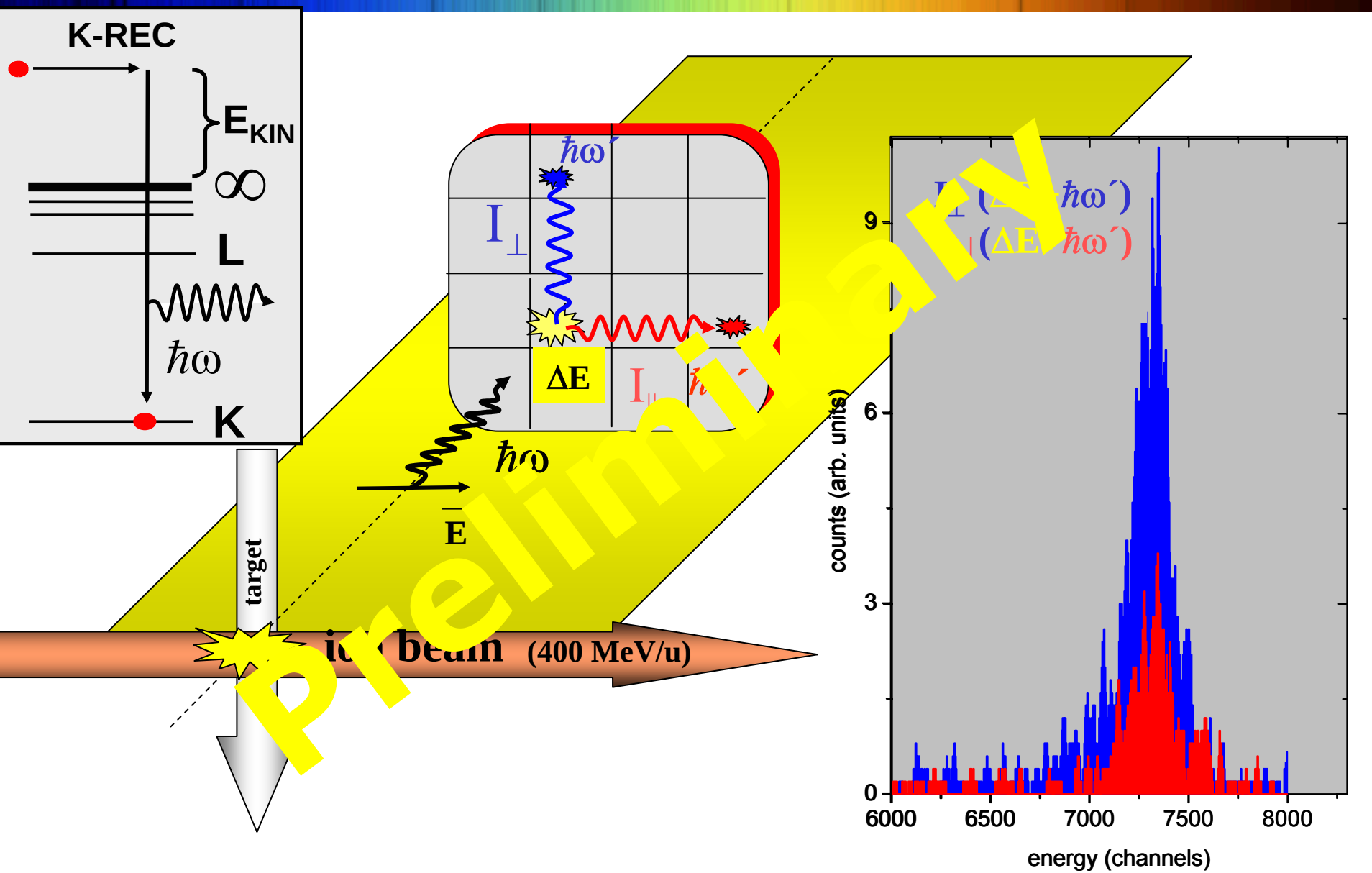
$\hbar\omega = 340\text{keV}$



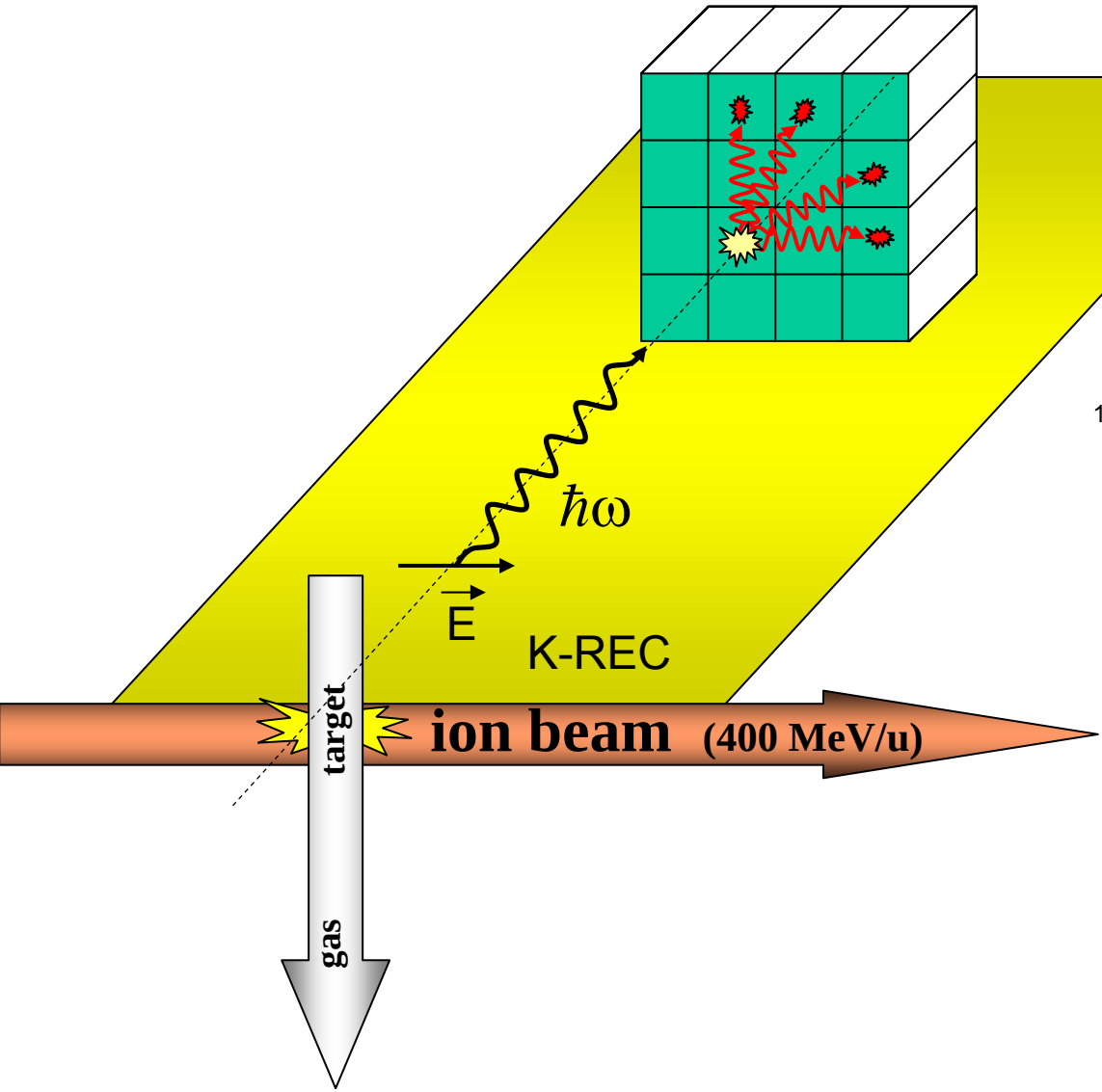


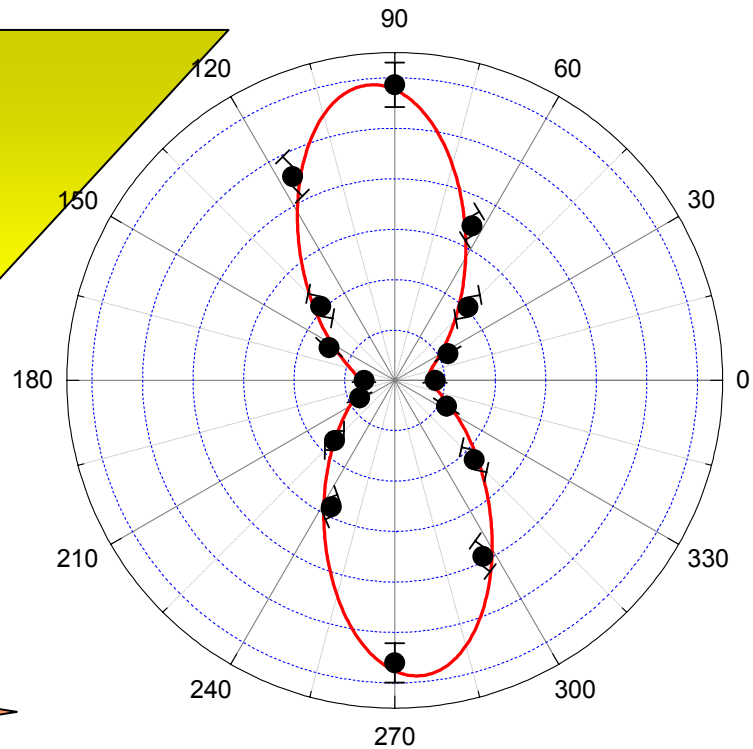
Preliminary

Polarization Measurement for Radiative Recombination Transitions ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)



Polarization Measurement for Radiative Recombination Transitions ($U^{92+} + e^- \Rightarrow U^{91+} + \hbar\omega$)

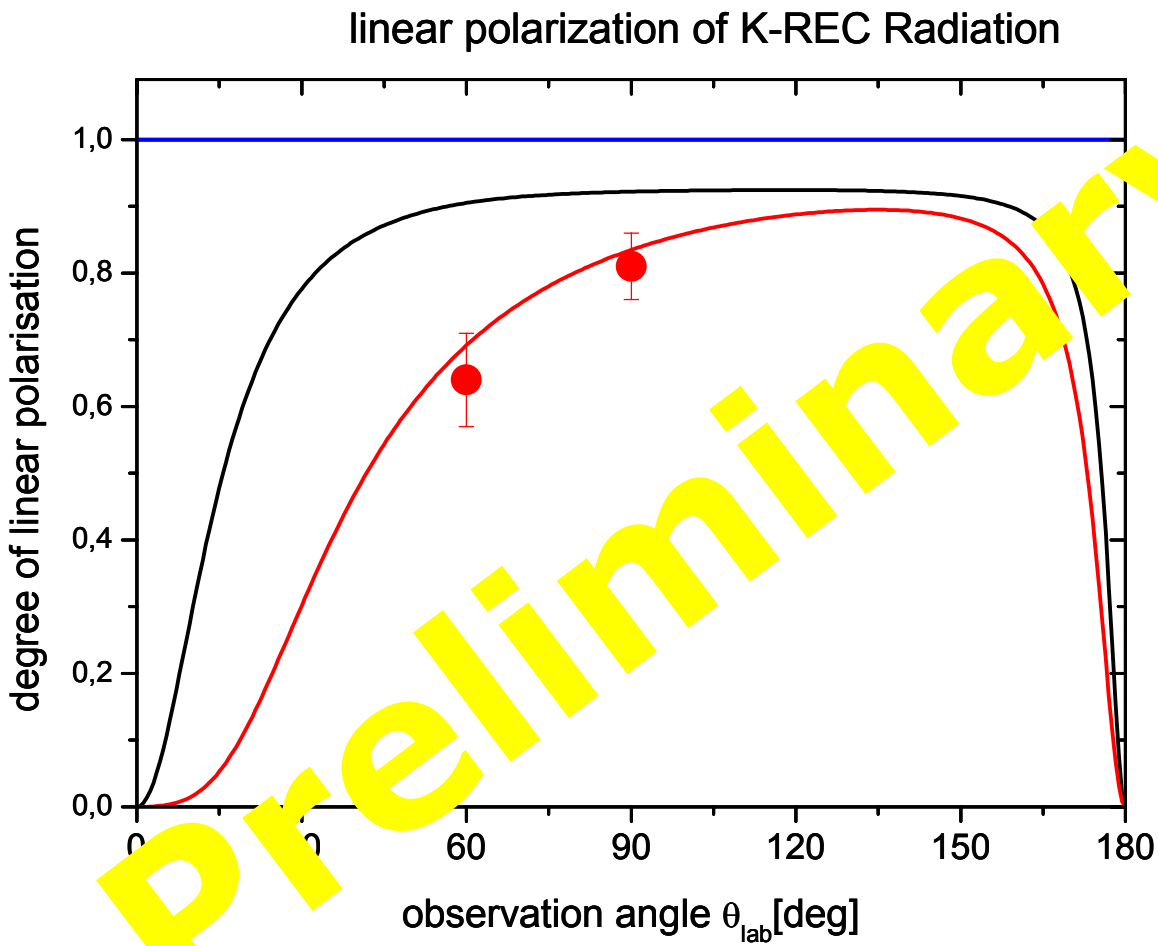




- ✓ K-REC radiation is strongly polarized
- ✓ polarization is in the scattering plane

Unique: By using 2D strip or pixel detectors, the plane of polarisation can be measured

Polarization Studies



Preliminary

non-relativistic dipole approximation

Exact relativistic Treatment

Eichler et al., PRA, 2001
Surzykov et al., PRA, 2001

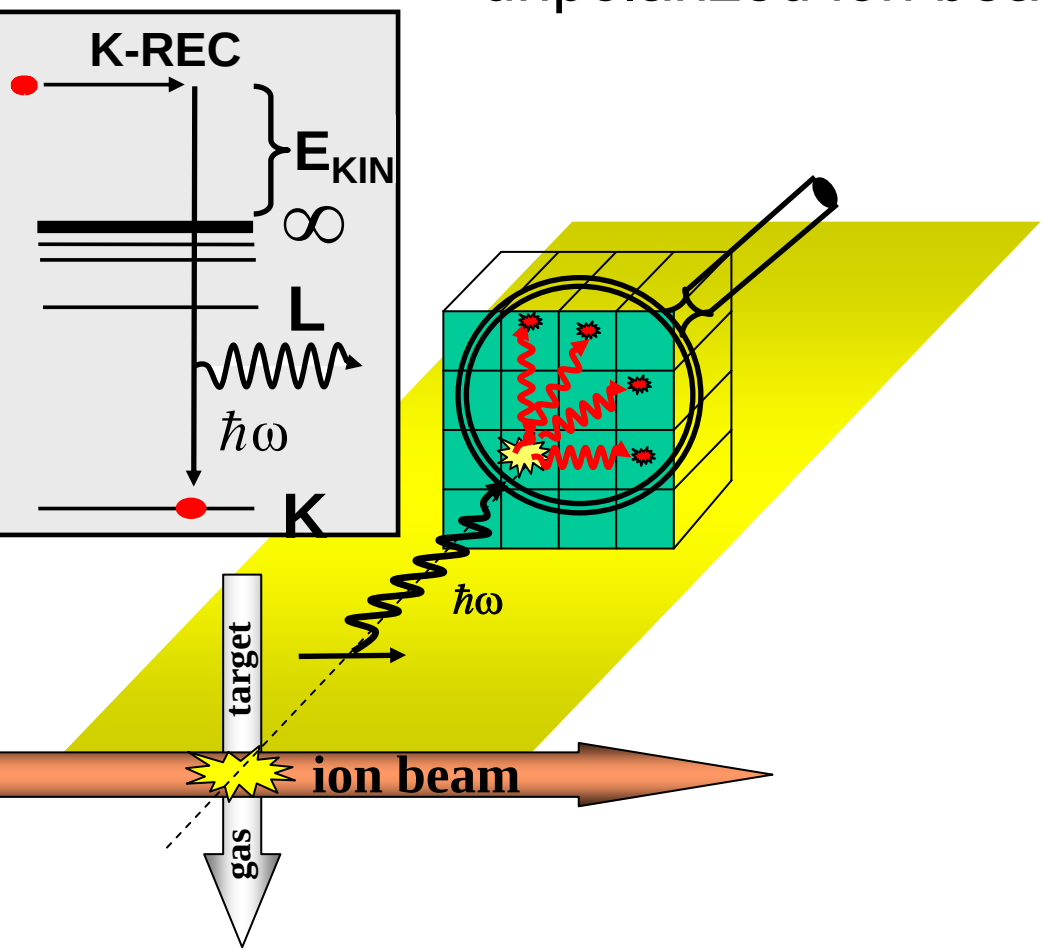
Experiment:
Tachenov et al., 2003

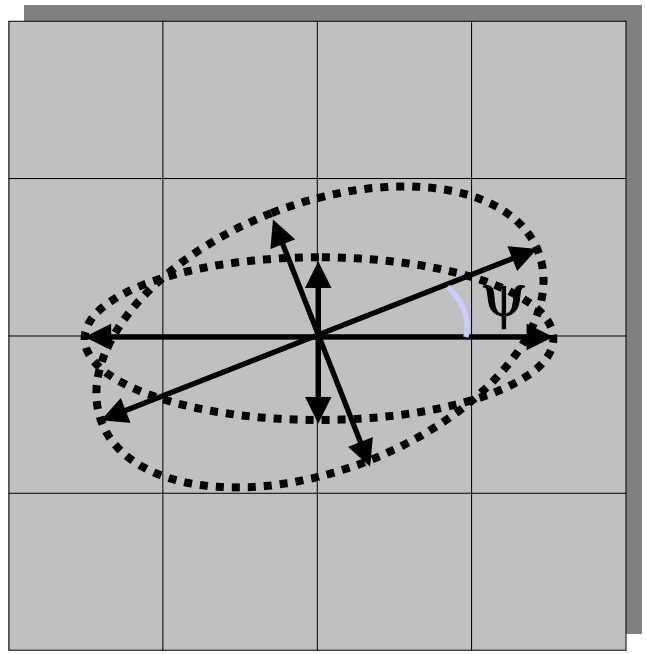
20 MeV/u

400 MeV/u

Detection of spin polarized ion beams

spin polarized ion beams
unpolarized ion beams

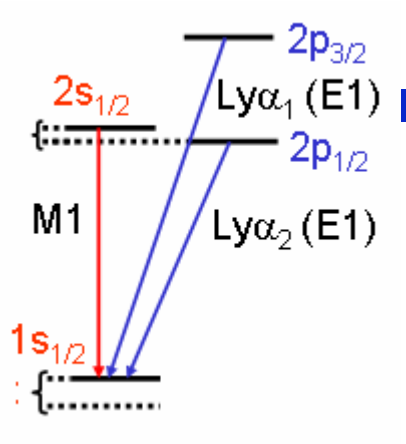


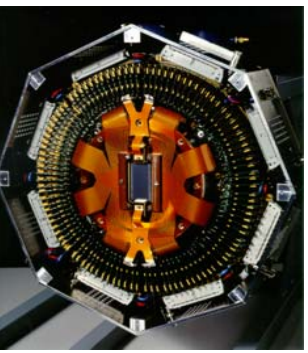


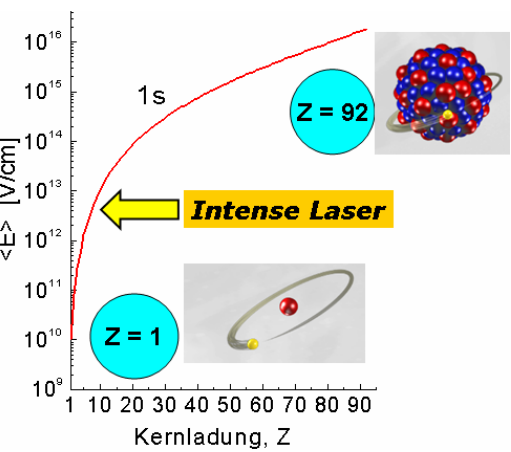
$\psi \Rightarrow$ degree of ion beam polarization

A.Surzhykov et al., Poster: B7-24

Summary





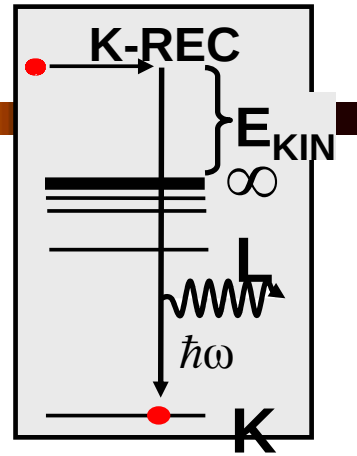


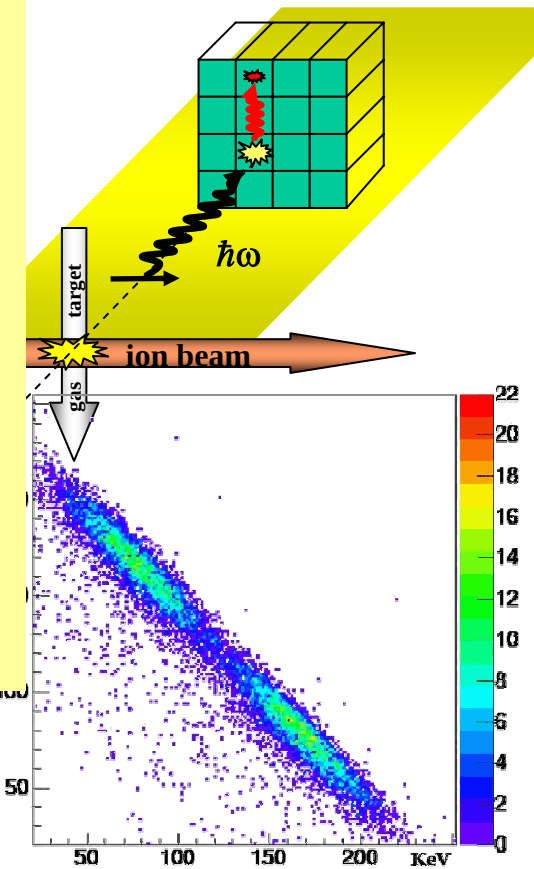
Atomic Structure at High-Z

- 1s LS in H-like uranium confirmed on a level of 1%
- further progress towards an absolute accuracy of 1 eV can be expect from high-resolution spectroscopy techniques

Quantum Dynamics

- segmented solid state detectors, an excellent tool for polarization studies in the hard X-Ray regime
- first polarization studies for hard x-rays
- unique tool for the diagnostic for spin polarized ion beams





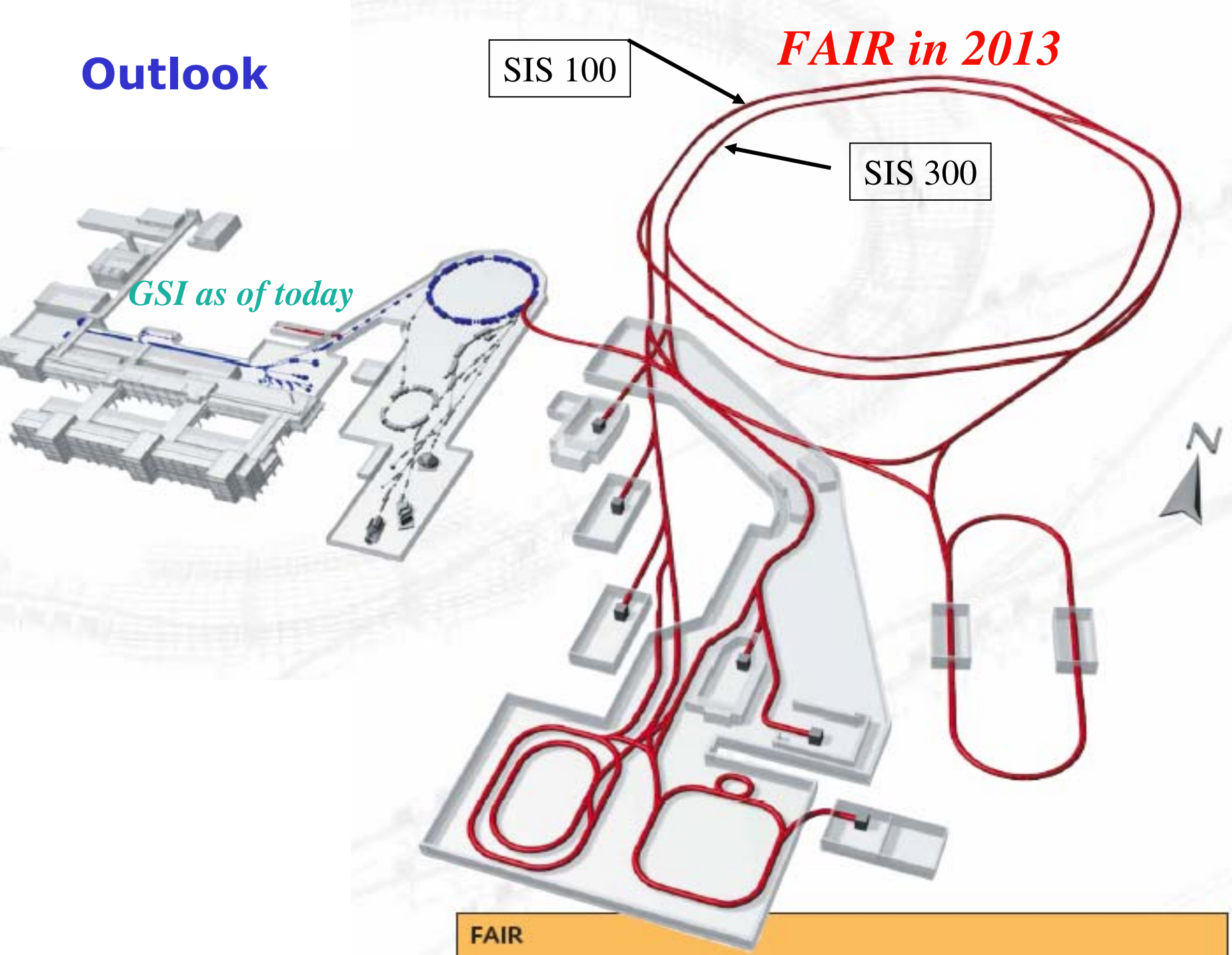
Challenges and Opportunities

For Atomic Physics at

The Future GSI-Facility

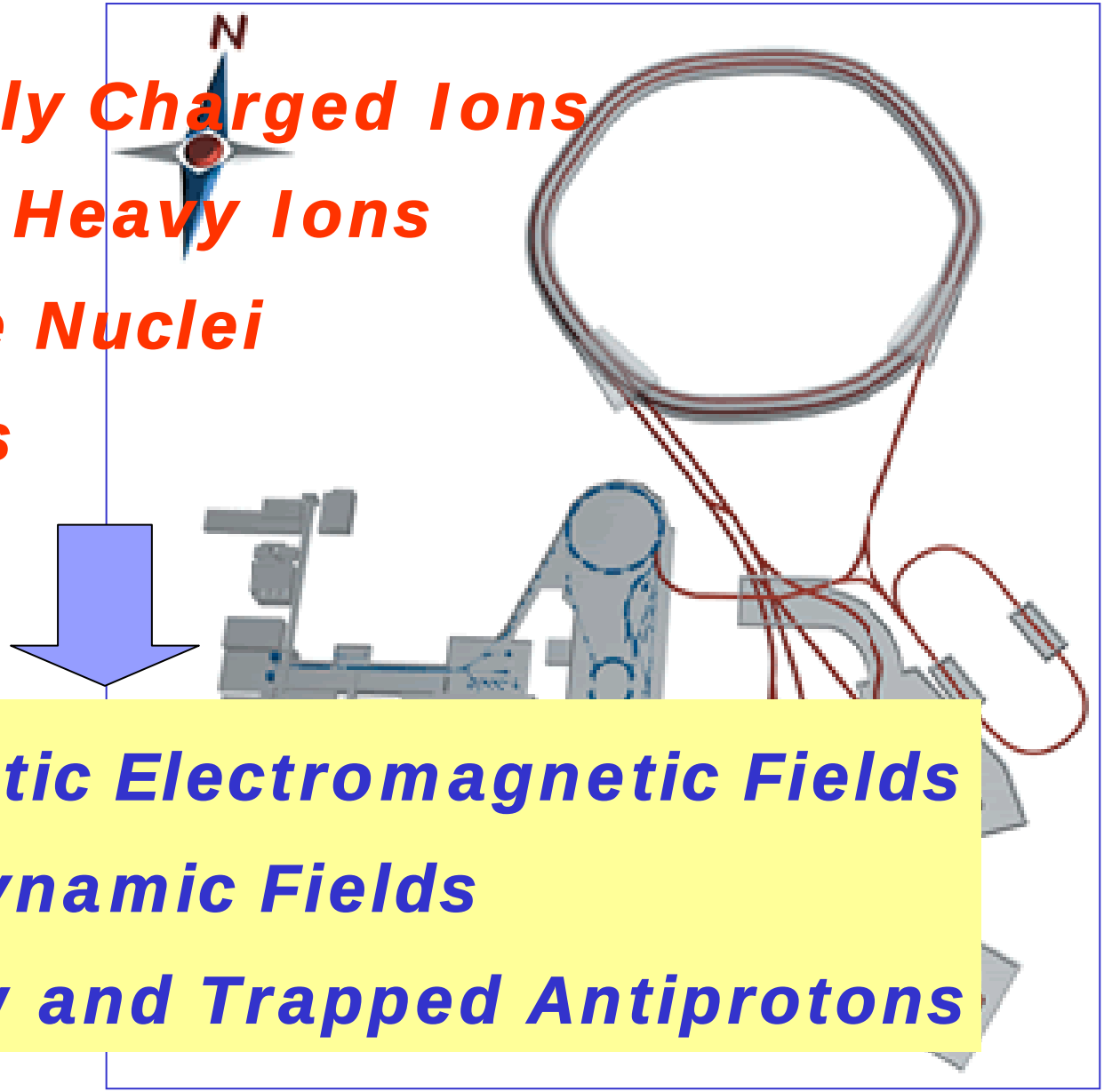
FAIR

Outlook



Unique Challenges and Opportunities

- *Heavy Highly Charged Ions*
- *Relativistic Heavy Ions*
- *Radioactive Nuclei*
- *Antiprotons*



I. Extreme Static Electromagnetic Fields

II. Extreme Dynamic Fields

III. Ultra-Slow and Trapped Antiprotons

Atomic Physics Experiments at the International Accelerator Facility for Beams of Antiprotons and Ion Research (FAIR)

The SPARC-Collaboration:

Atomic Physics with Heavy Stable and Radioactive Ions

Poster: B7-23

SPARC

Stored **P**article **A**tomic **R**esearch **C**ollaboration

The FLAIR-Collaboration:

Atomic Physics with Slow Antiprotons

Poster: B5-11

FLAIR

Facility for **L**ow-Energy **A**nti-Protons and **I**on **R**esearch