PRECISION TESTS OF QED IN STRONG FIELDS: EXPERIMENTS ON HYDROGEN- AND HELIUM-LIKE URANIUM

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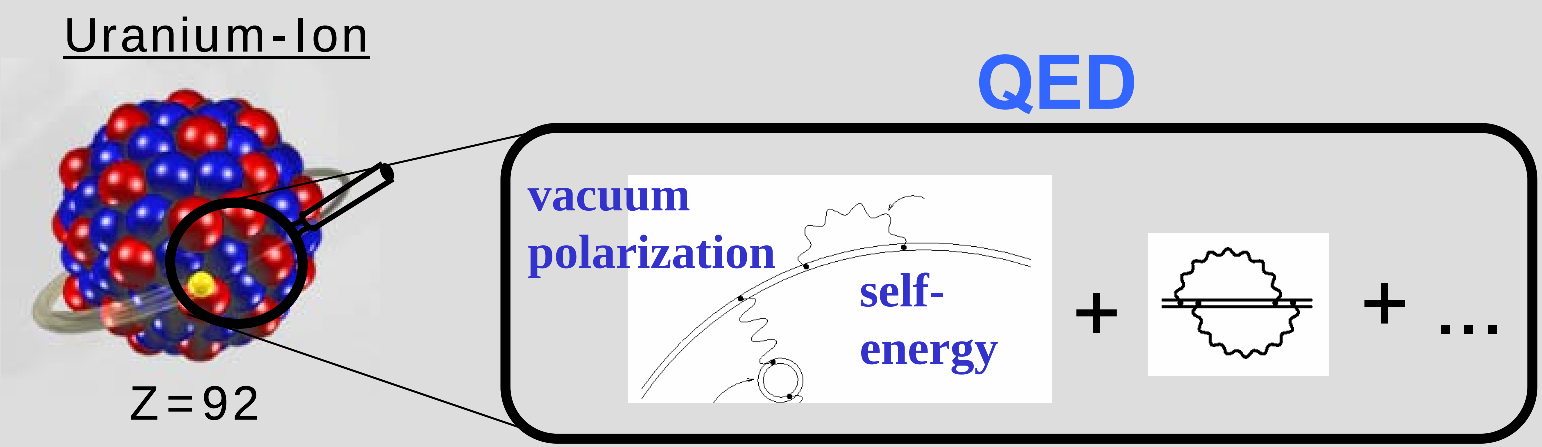


PRECISION TESTS OF QED IN STRONG FIELDS: EXPERIMENTS ON HYDROGEN- AND HELIUM-LIKE URANIUM

- ***Introduction:*** **QED, Lamb shift and the structure of one- and two-electron systems at high-Z**

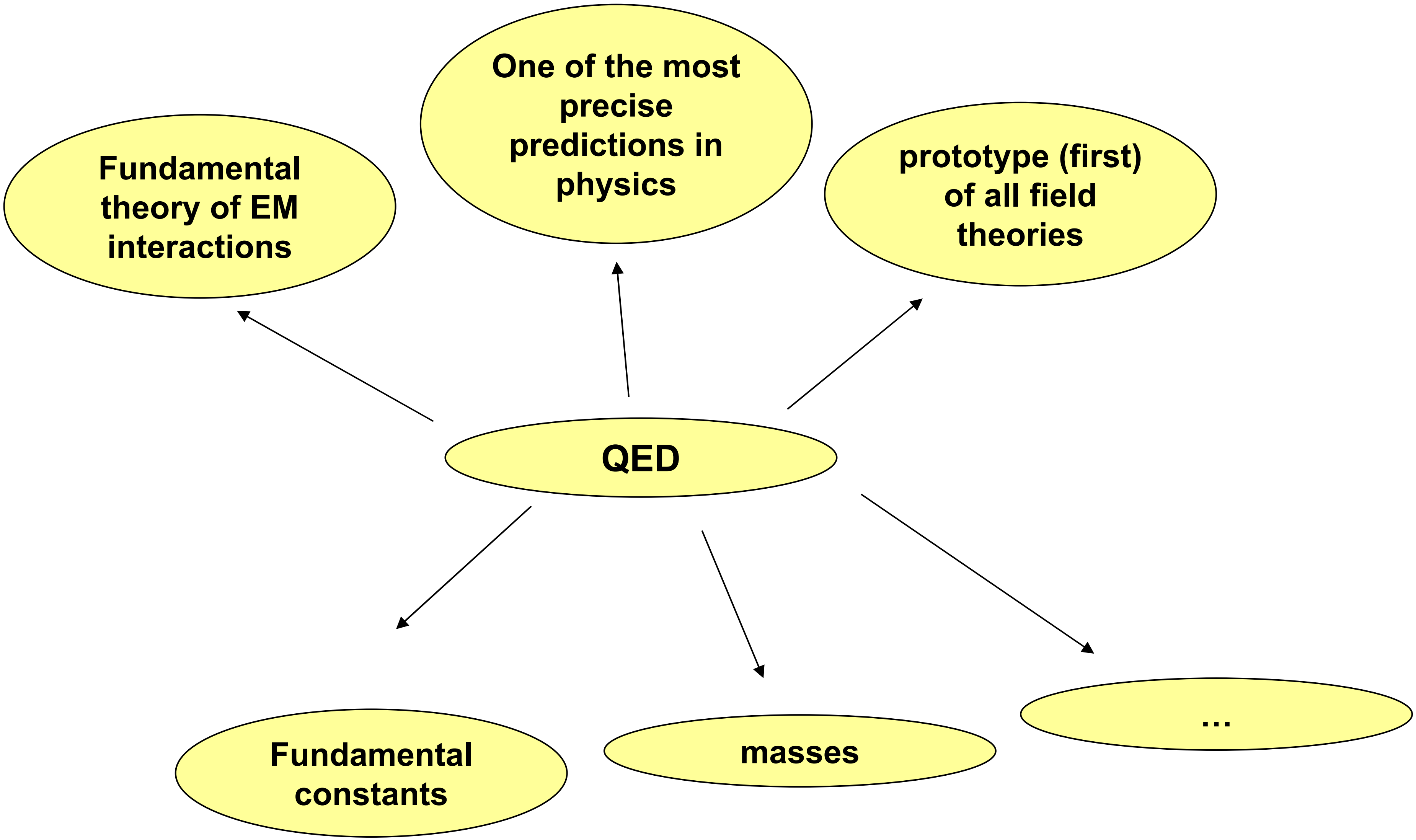
- ***Experiment at the storage ring ESR at GSI***
- **Production and storage of high-Z few-electron (or bare) ions**
- **X-ray spectroscopy at the ESR electron cooler, relativistic doppler effect**

- **Results in comparison with theoretical predicitions**

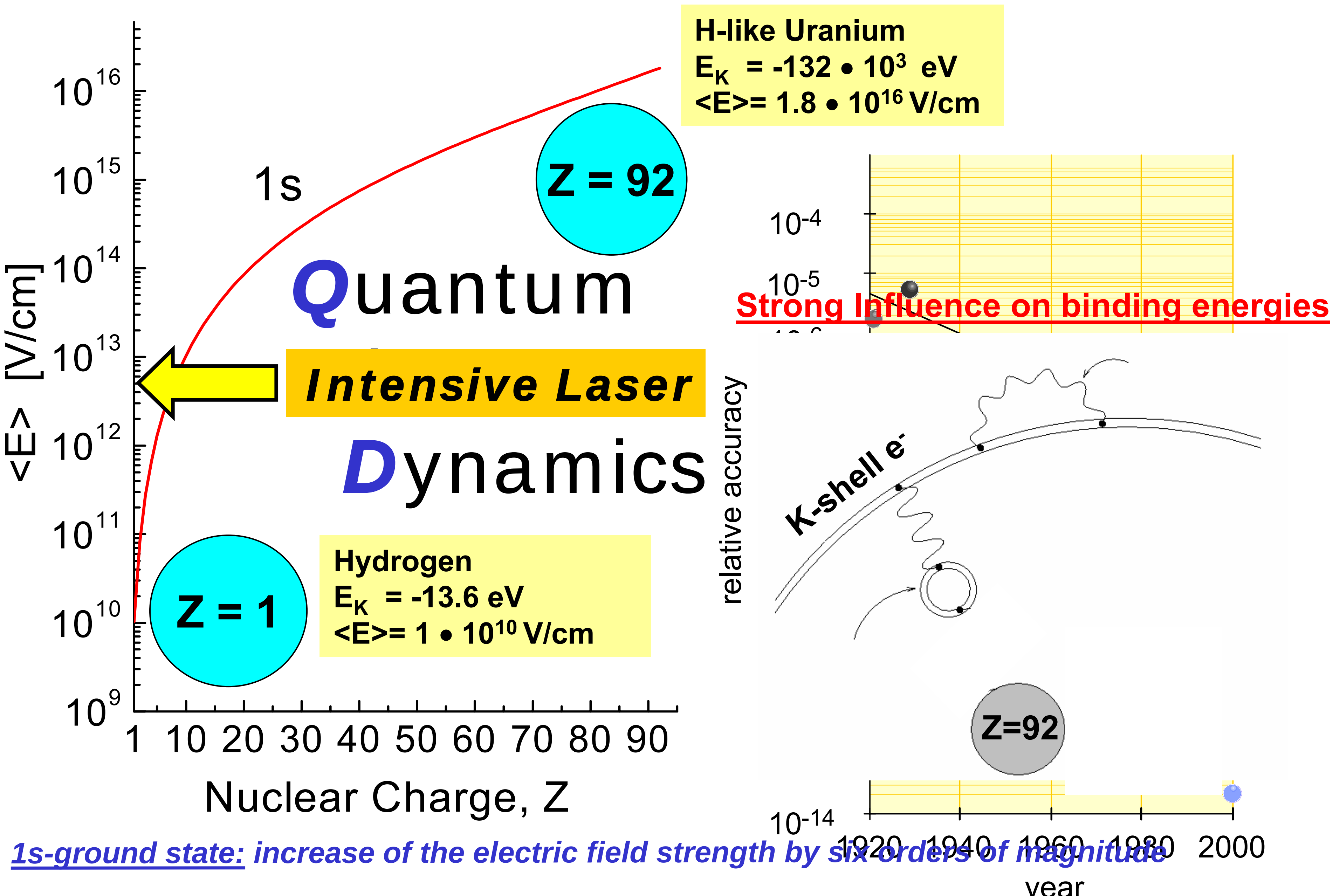
- ***Summary***

- ***Outlook***

  (towards ~1 eV precision)
- **Crystal spectrometer**
- **Detector development**

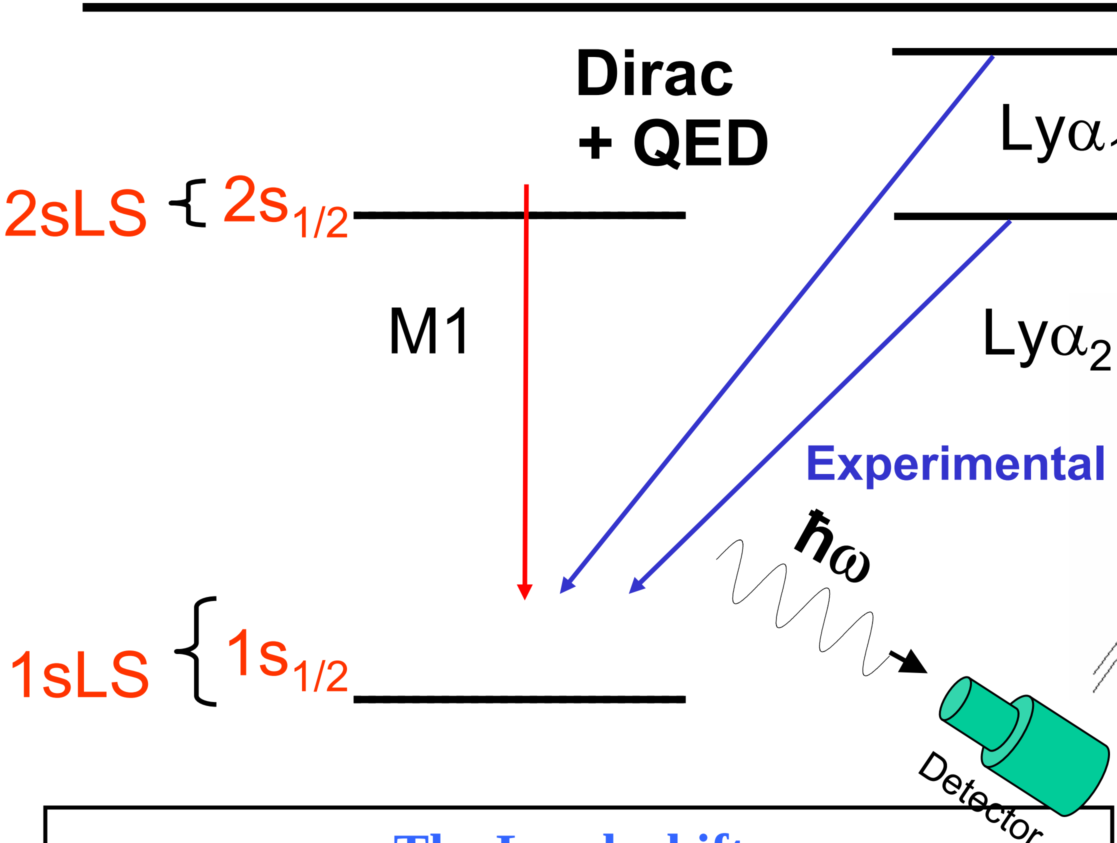

Fundamental theory of EM interactions
One of the most precise predictions in physics
prototype (first) of all field theories
QED
Fundamental constants
masses
...

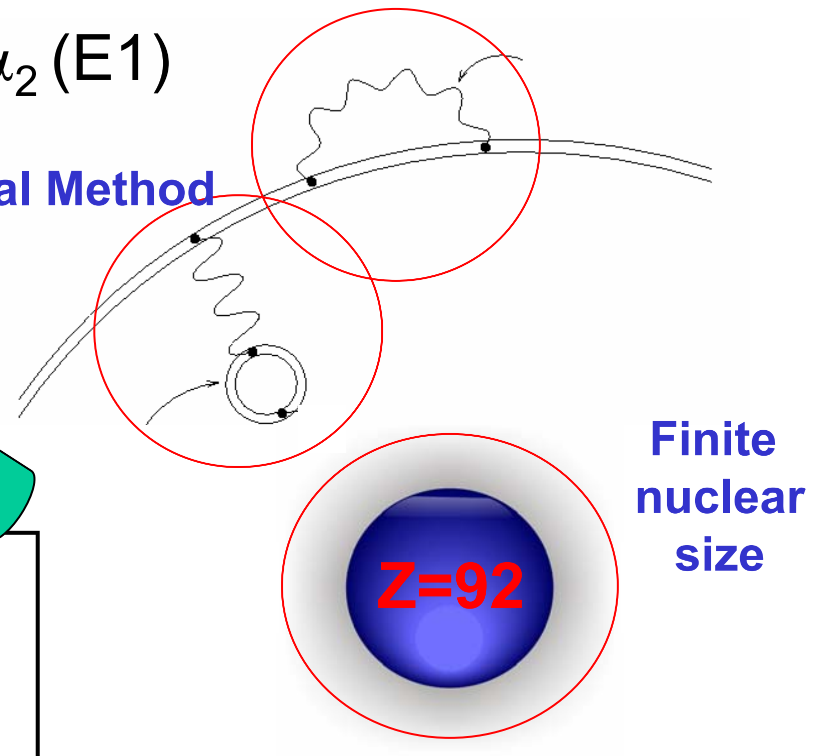
Atomic Physics in Extremly Strong Coulomb Fields



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

The Atomic Structure of One-electron System

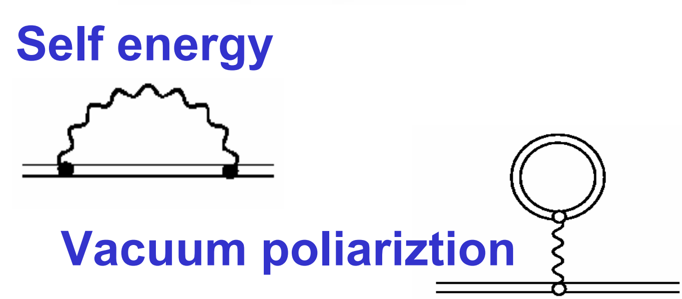




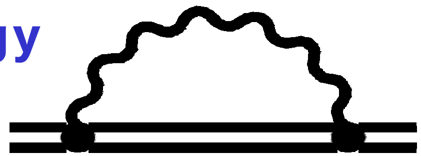
The Lamb shift:

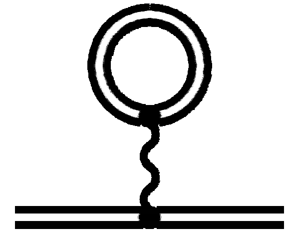
The sum of all corrections which lead to the discrepancy from the predictions of the Dirac-Theory for a point-like nucleus.

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



Self-energy





Vacuum-polarization

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

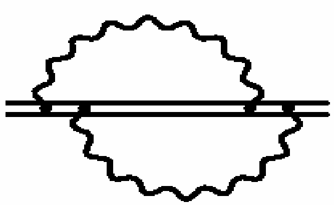
$$\Delta E = \alpha/\pi \, (\alpha Z)^4 \, F(\alpha Z) \, m_e c^2$$

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

$F(\alpha Z)$: expansion in αZ

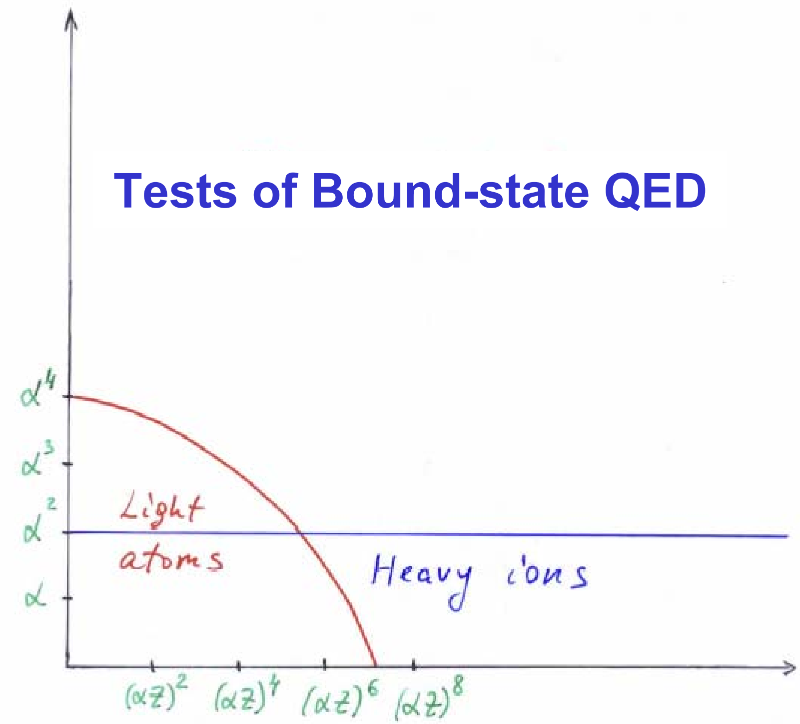
High Z-regime: $\alpha Z \approx 1$

$F(\alpha Z)$: expansion in αZ not applicable (calculation of all orders)

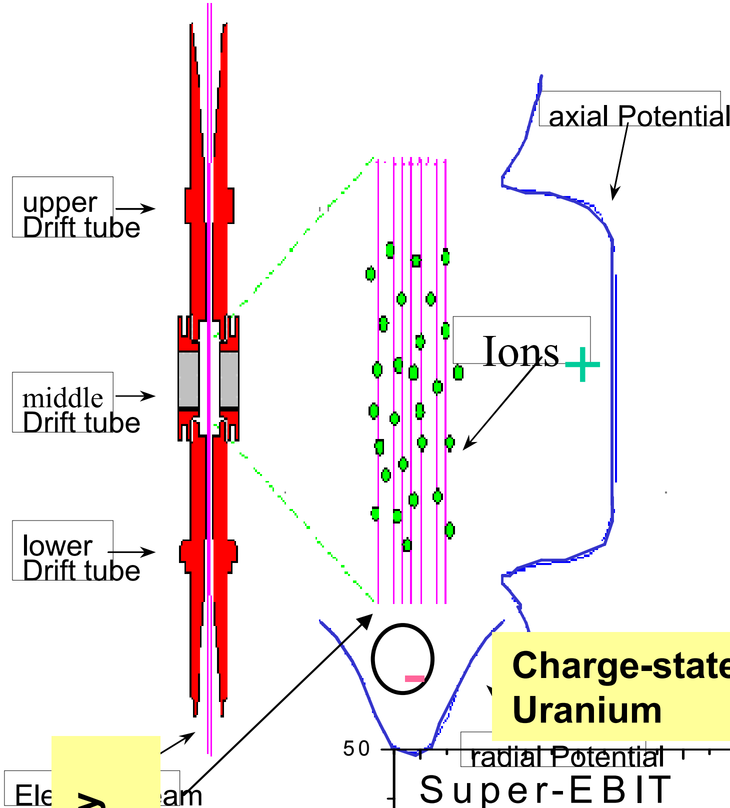


±1 eV

Tests of Bound-state QED



Production of highly charged heavy ions

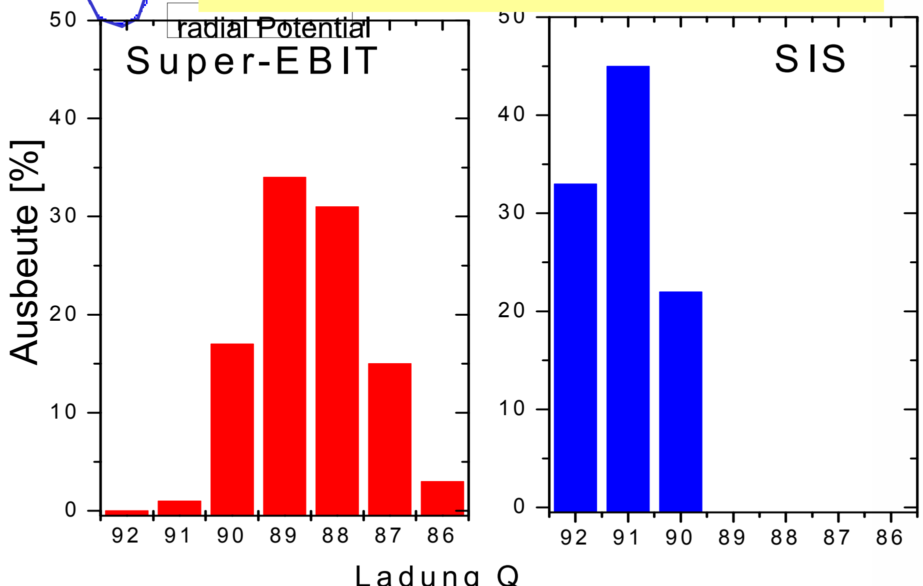


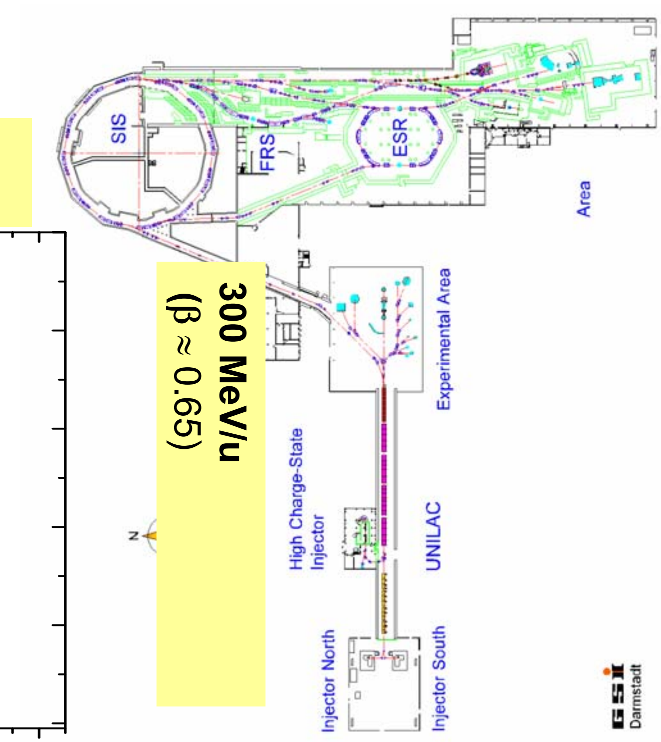
200 keV electron energy (ions at rest)

Traps (EBIT): production of highly charged ions by collisions with high energy electron beams

Accelerator: production of highly-charged ions by fast collisions with target atoms.

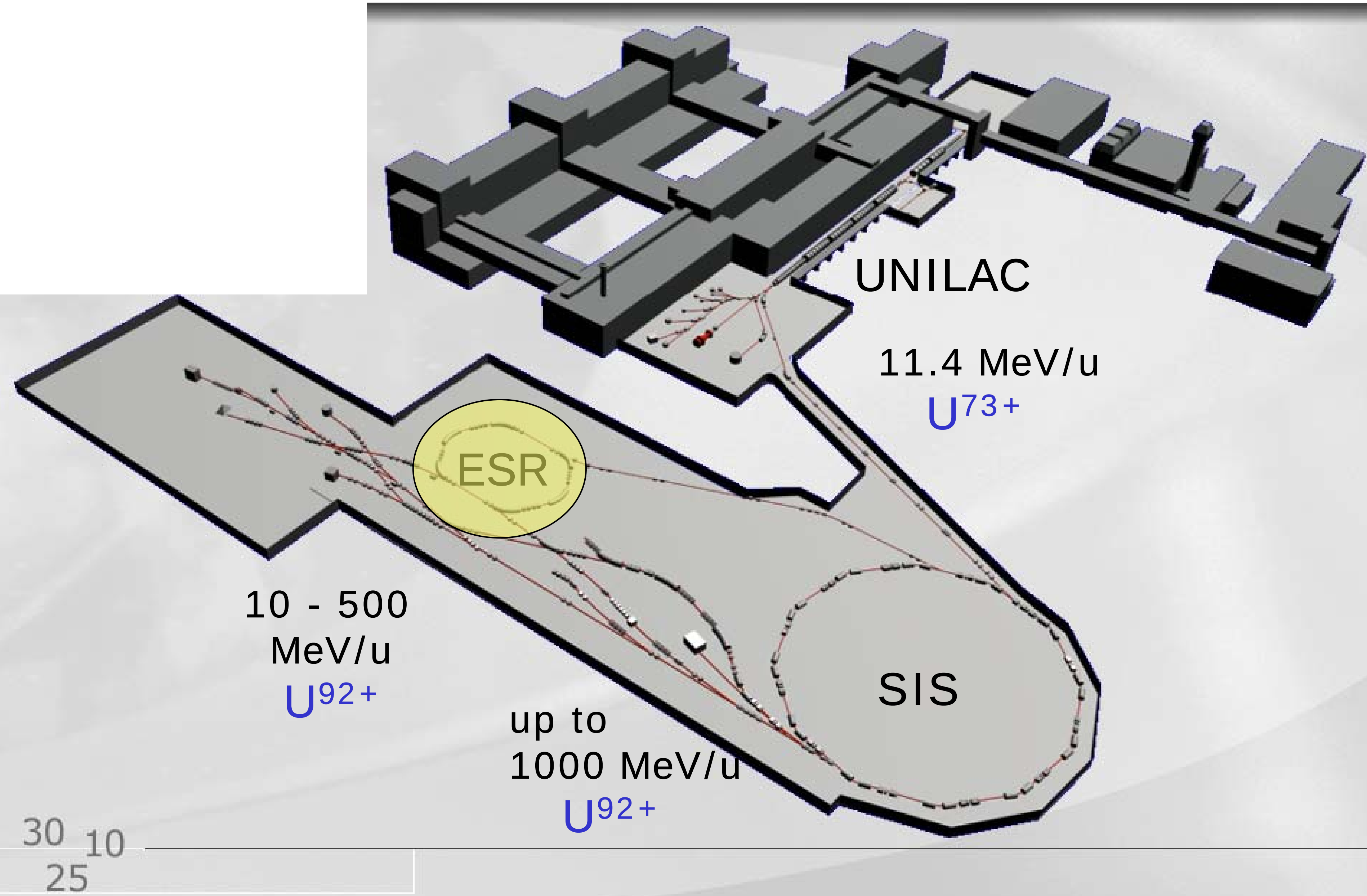
Charge-state distribution for Uranium



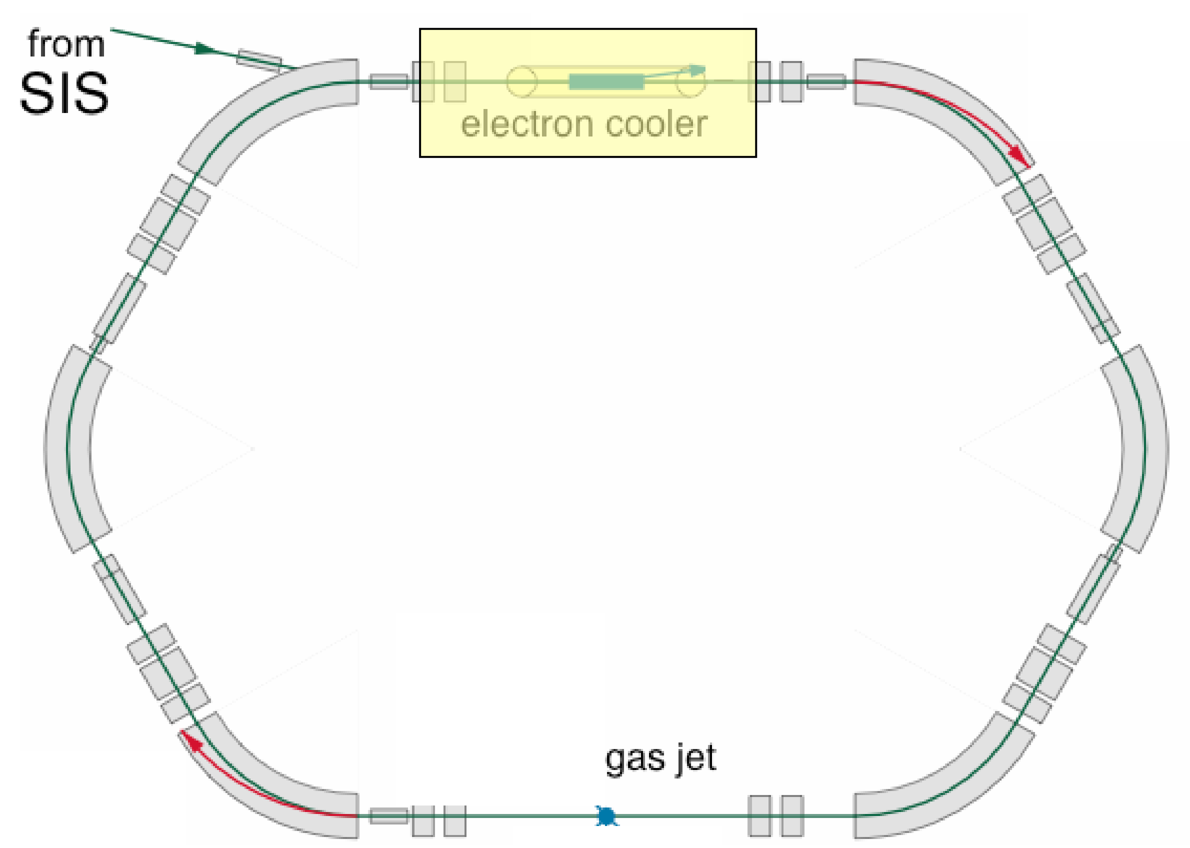


300 MeV/u ($\beta \approx 0.65$)

GSI-ACCELERATOR FACILITY



Experiments at the ESR



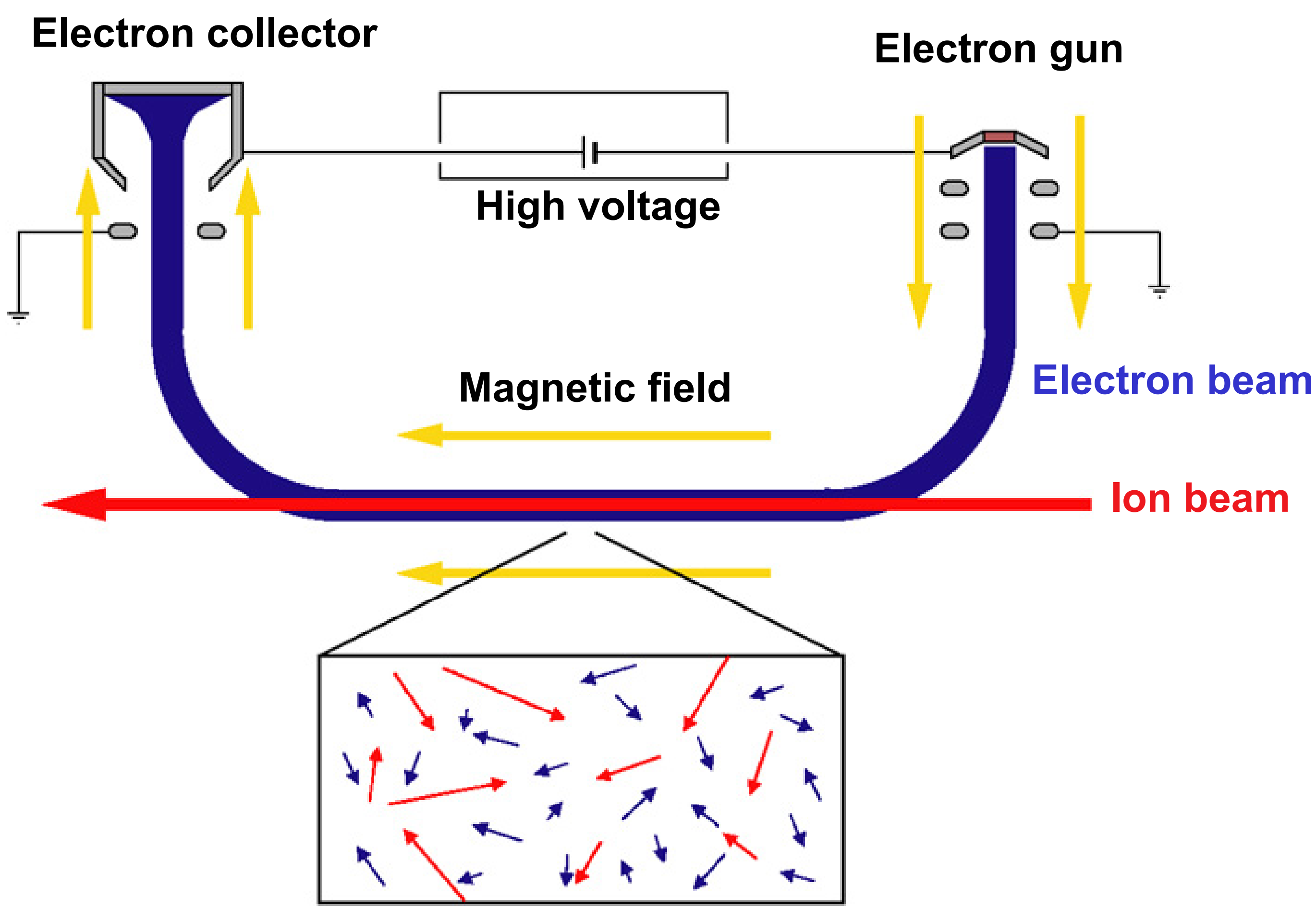
$\beta \approx 0.65$

$E \approx 300$ MeV/u

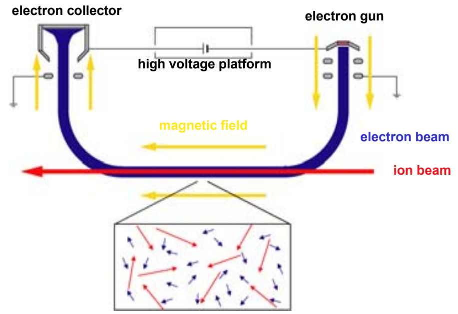
Revolution Frequency
f: $\approx 10^6$ 1/s

ESR
circumference: 108 m
number of Ions: 10^8

COOLED HEAVY-ION BEAMS



COOLED HEAVY-ION BEAMS



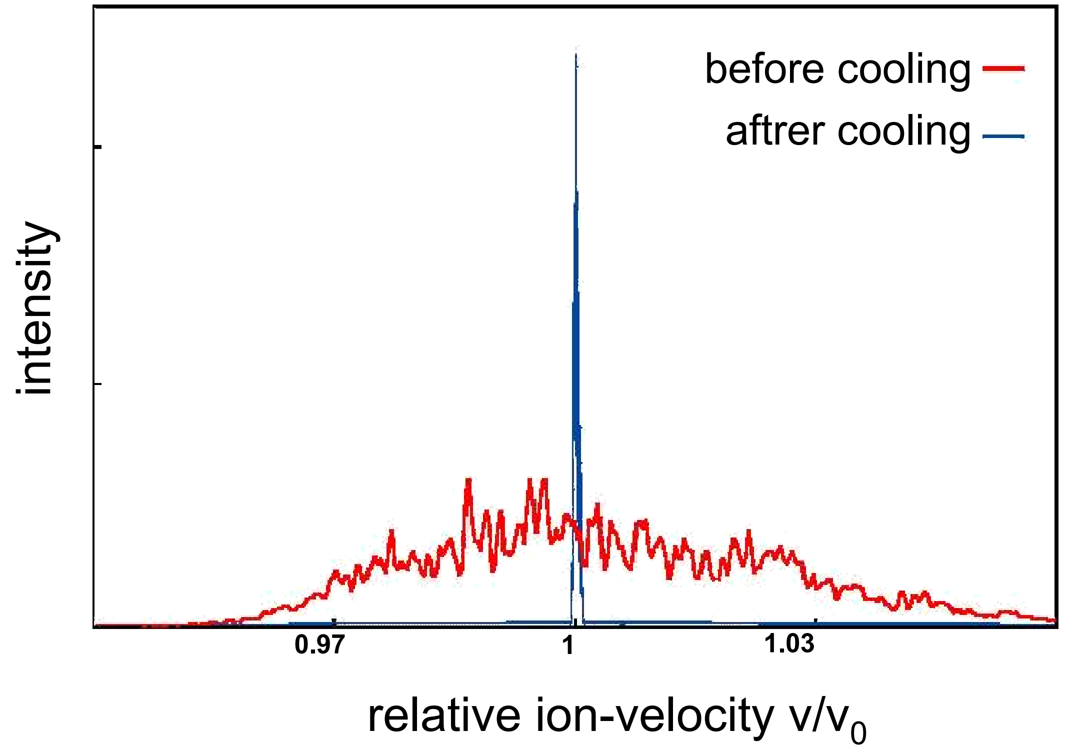
Electron cooler

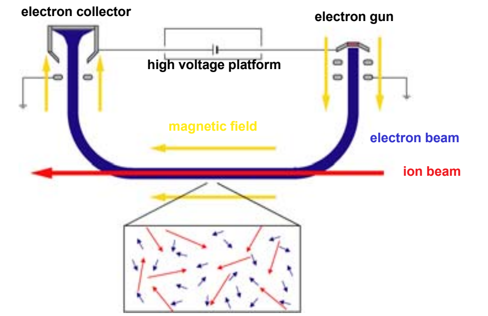
Voltage: 5 to 200 kV

Current: 10 to 1000 mA

2.5 m interaction zone

COOLED HEAVY-ION BEAMS





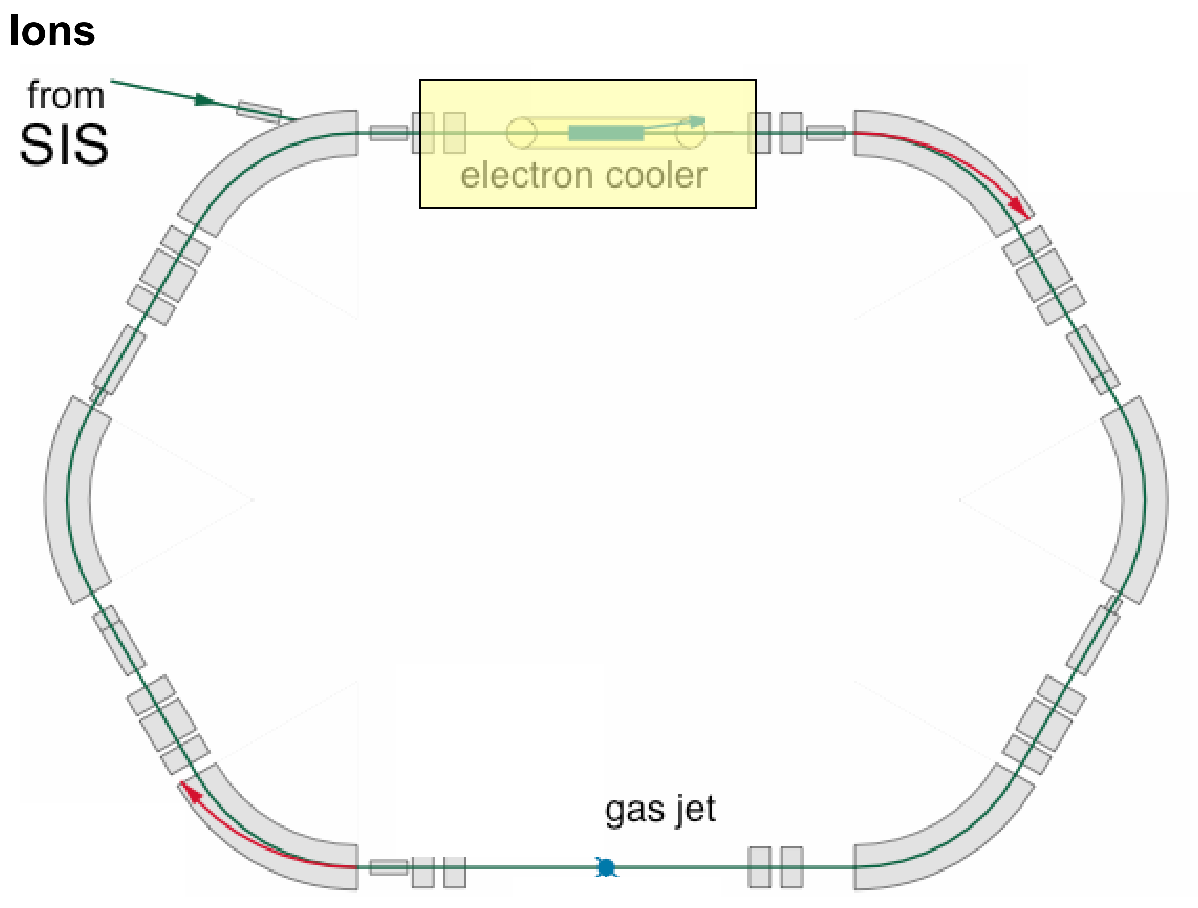
ions interact 10^6 1/s with the collinear cold electron beam

properties of cold ion beams

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

size 2 mm

Experiments at the ESR



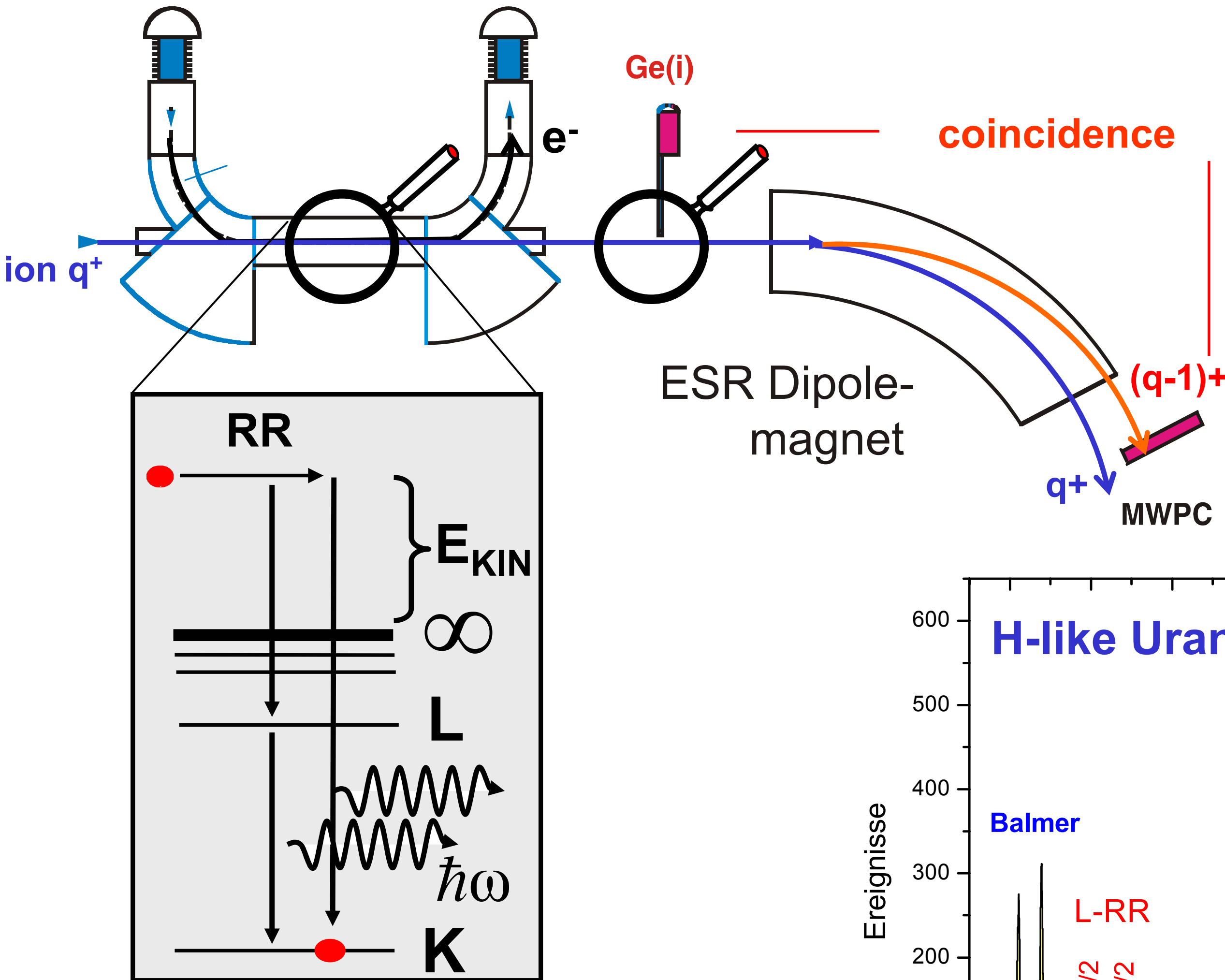
ESR
circumference: 108 m
number of Ions: 10^8

$\beta \approx 0.65$

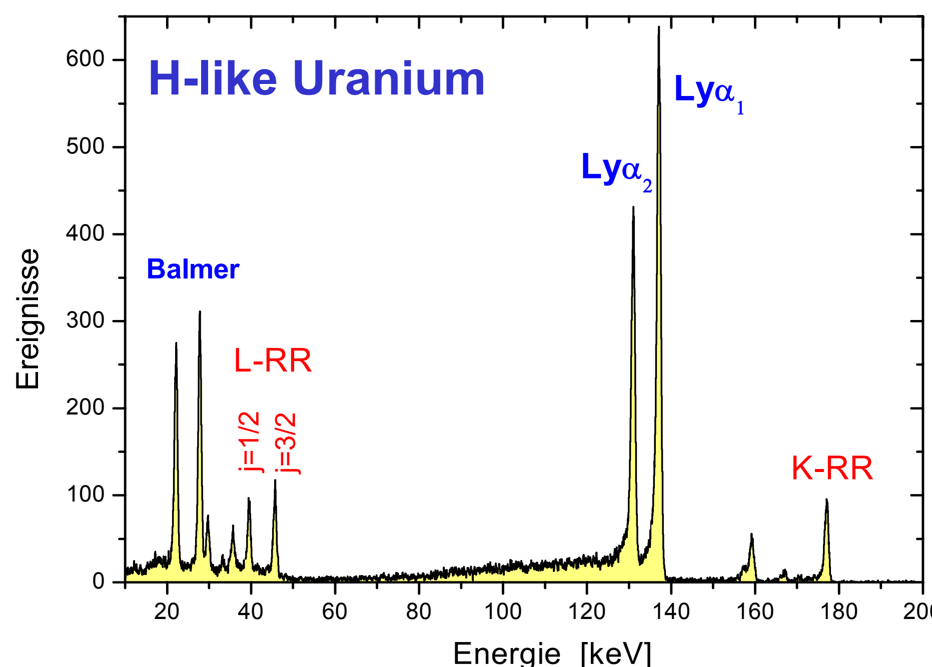
E≈300 MeV/u

Revolution Frequency
f: $\approx 10^6$ 1/s

0º Spectroscopy at the Electron Cooler



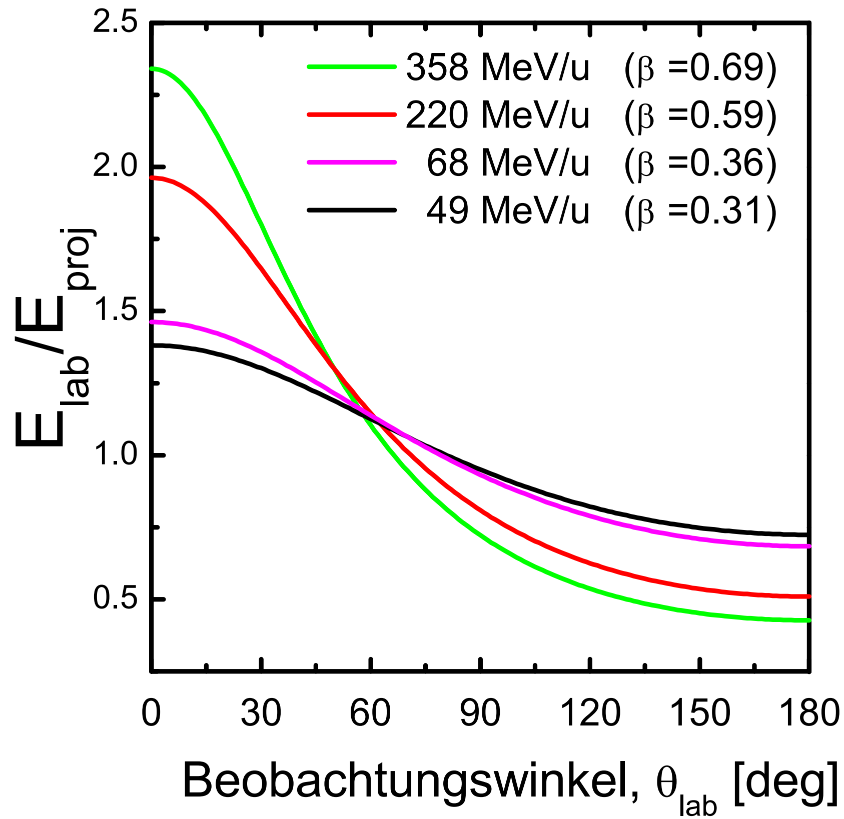
- maximum blueshift
  $\beta \approx 0.29 \Rightarrow E_{lab} \approx 1.43 \times E_{proj}$
- $\Delta\theta_{LAB}$ not critical, minimum Doppler broadening
- uncertainty due to $\Delta\beta$ maximum



Relativistic Doppler-Transformation

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

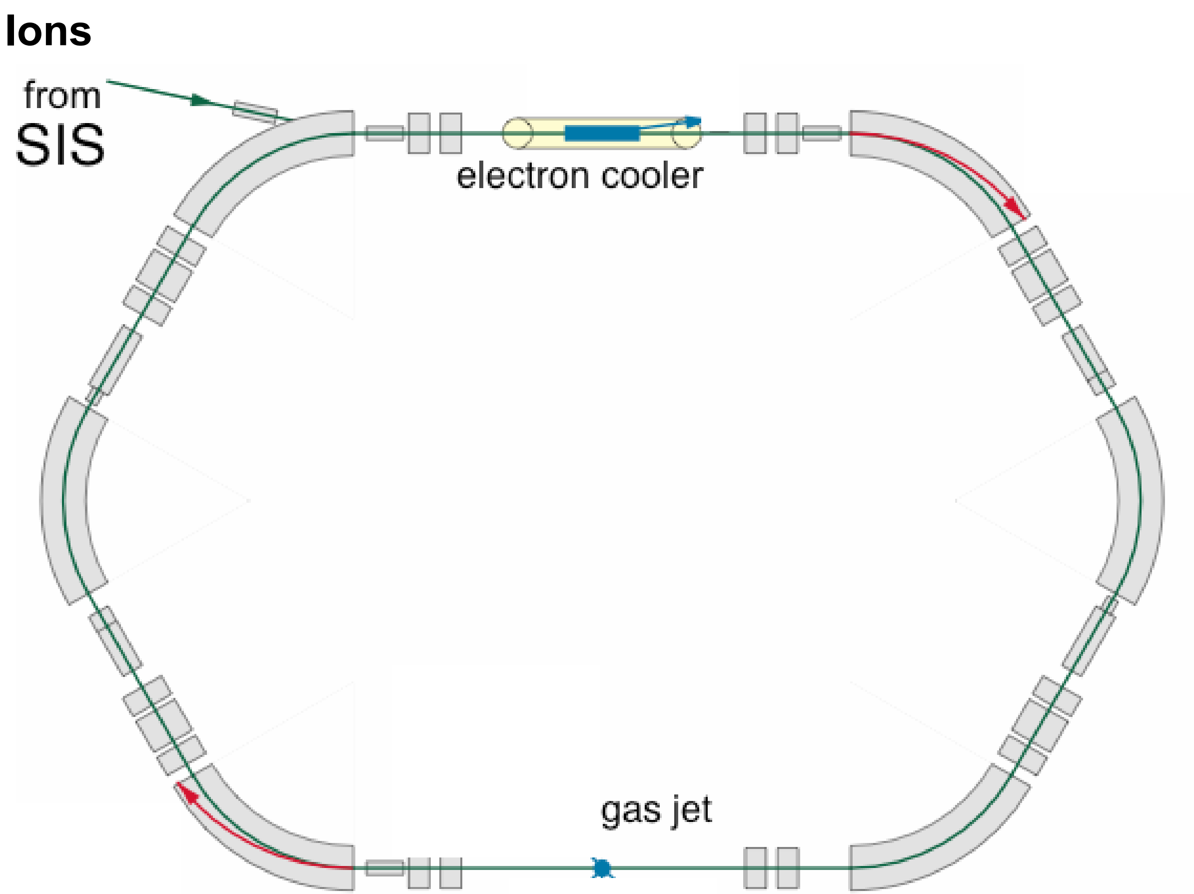
E_{lab}: Photon energy in the laboratory frame
E_{proj}: Photon energy in the Emitter frame



Doppler correction
Strong dependence on velocity v
and on observation angle θ_{LAB}

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

Experiments at the ESR



ESR
circumference: 108 m
number of Ions: 10^8

$\beta \approx 0.65$

$E \approx 300$ MeV/u

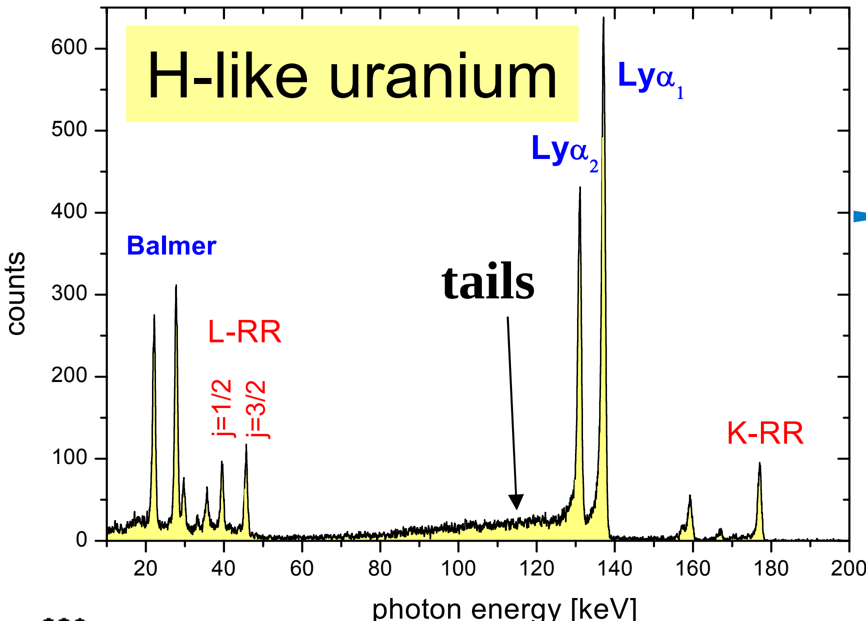
Revolution Frequency
f: $\approx 10^6$ 1/s

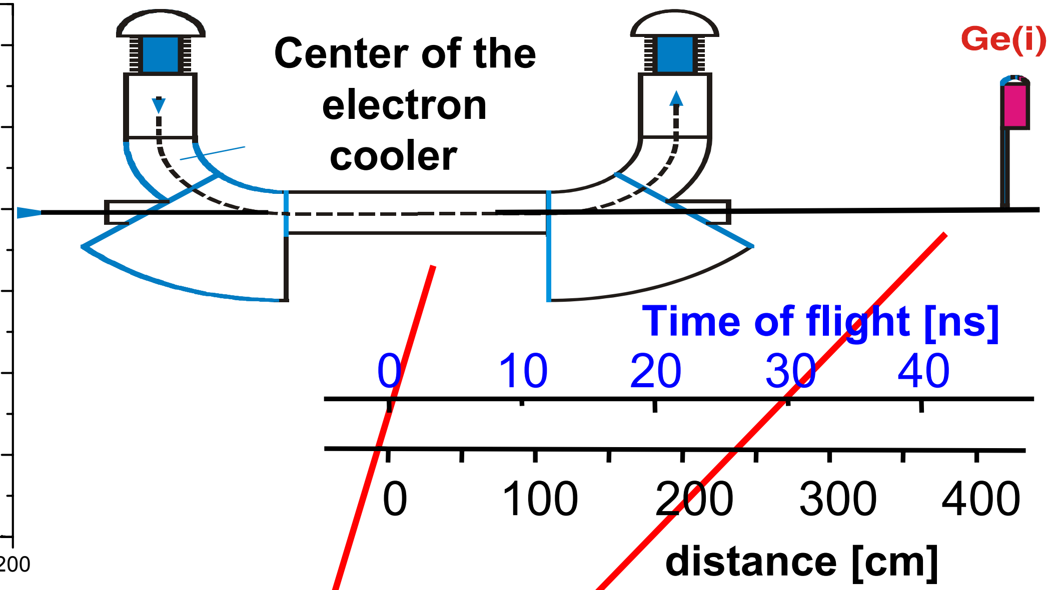
300 MeV/u

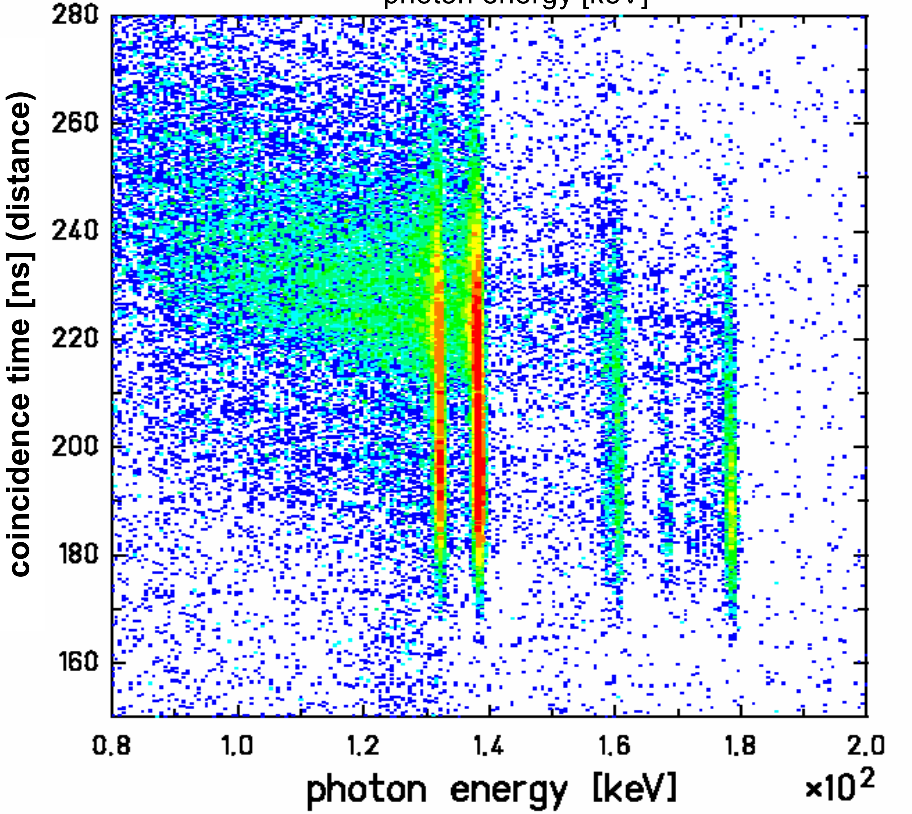
deceleration

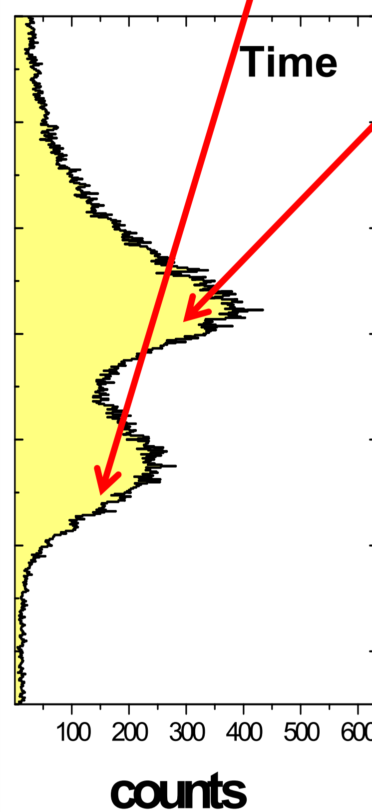
4 MeV/u

Ge(i) Detector

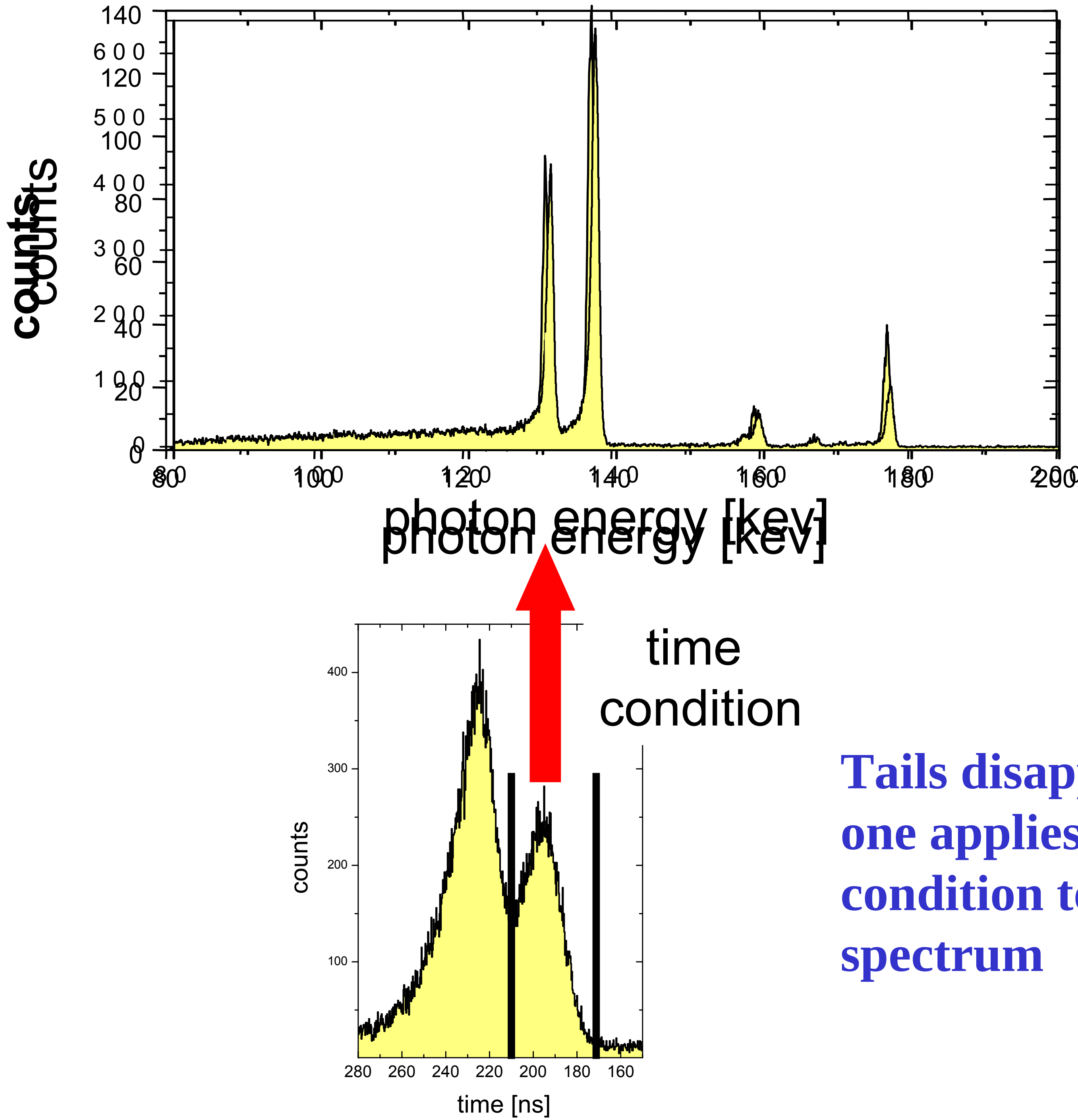






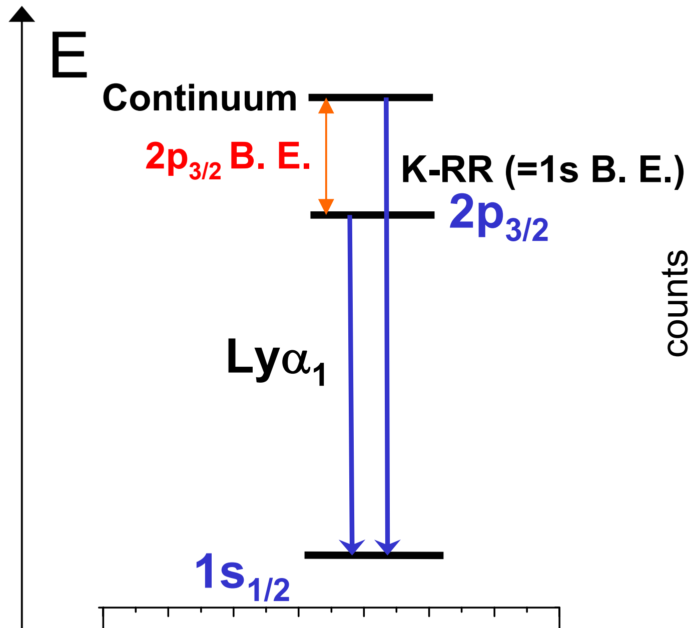


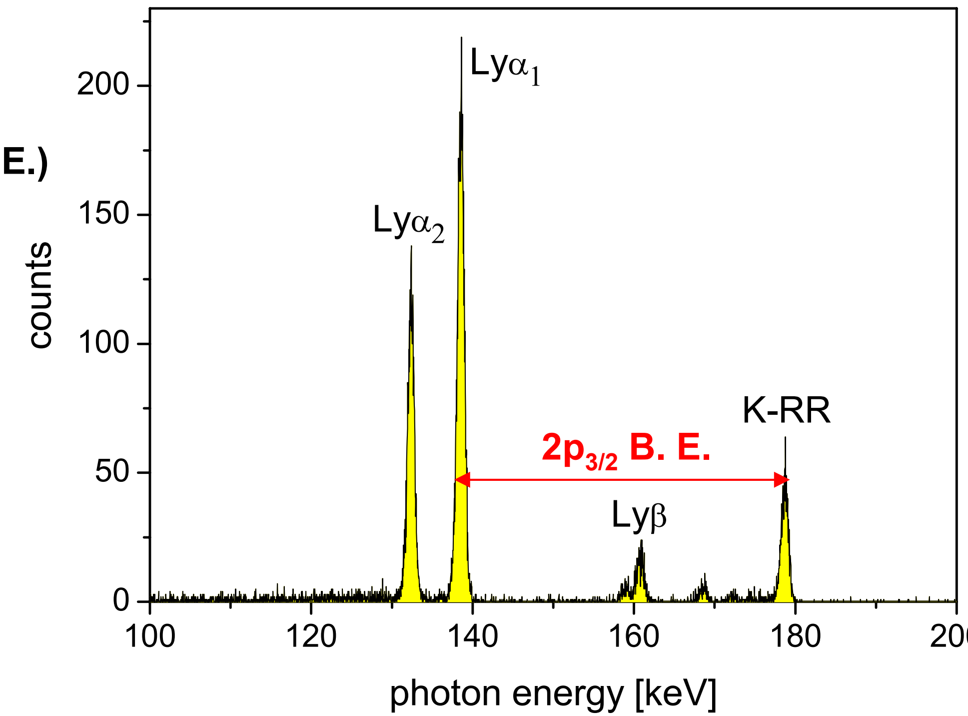
Recombination into Rydberg states leads to the delayed Lyman emission, by up to microsecond.

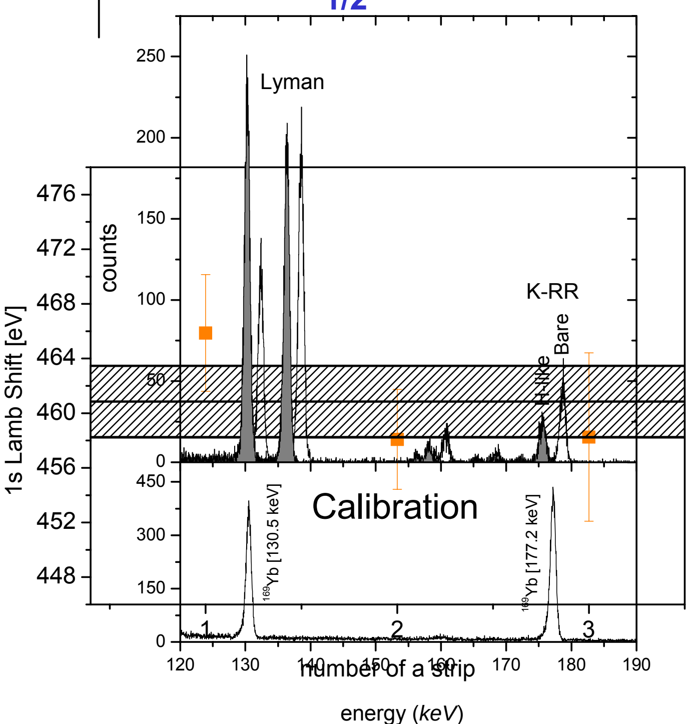


Tails disappear when one applies a proper condition to the time spectrum

The Ground State Lamb Shift in H-like Uranium







1s Lamb shift in U^{91+}

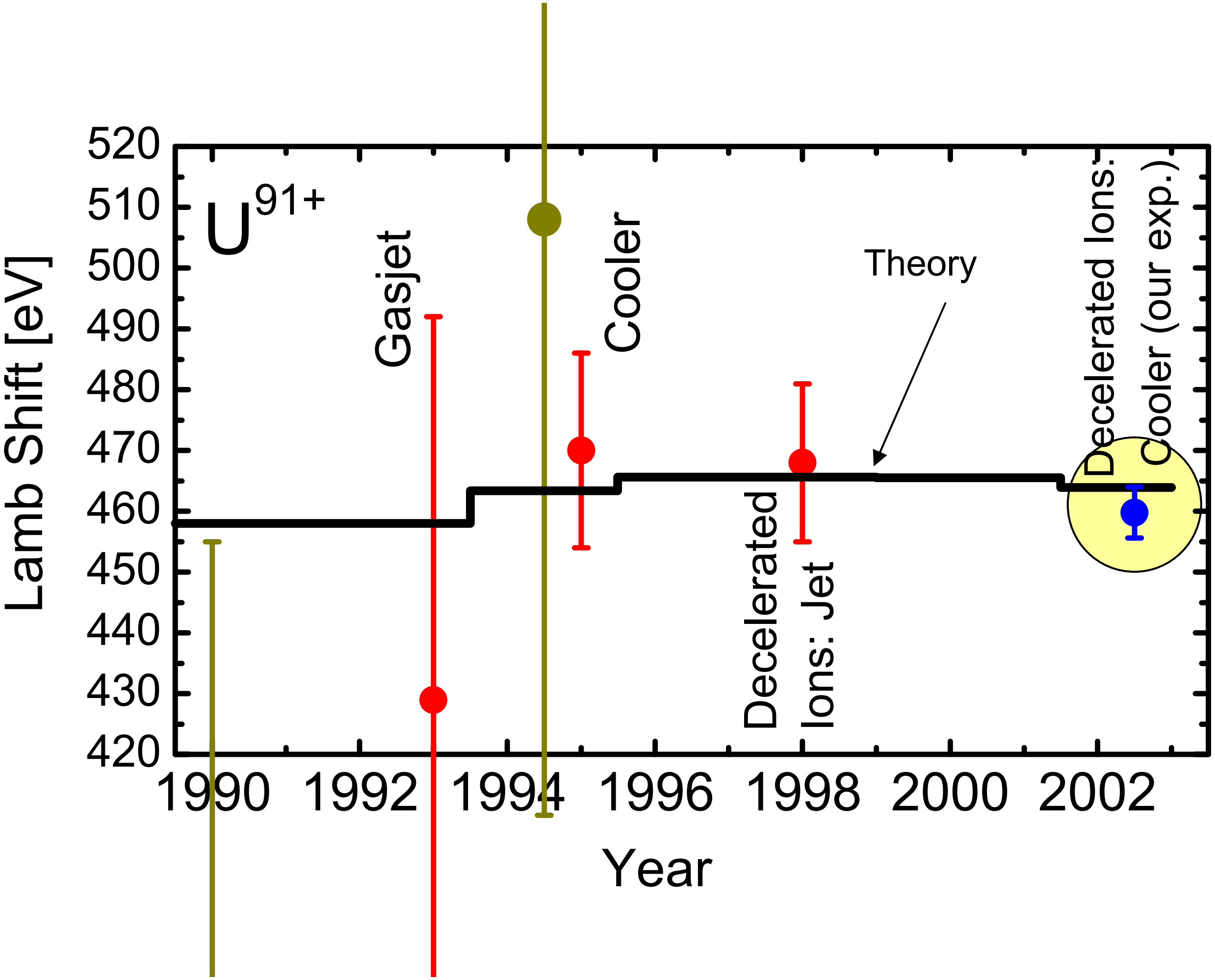
460.2±2.3±3.5 eV

4.6 eV

statistical

uncertainty in the β

Experimental Results in Comparison with Theory



Experiment: **460.2±4.6 eV**

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

SE = 355.0 eV, VP = -88.6 eV

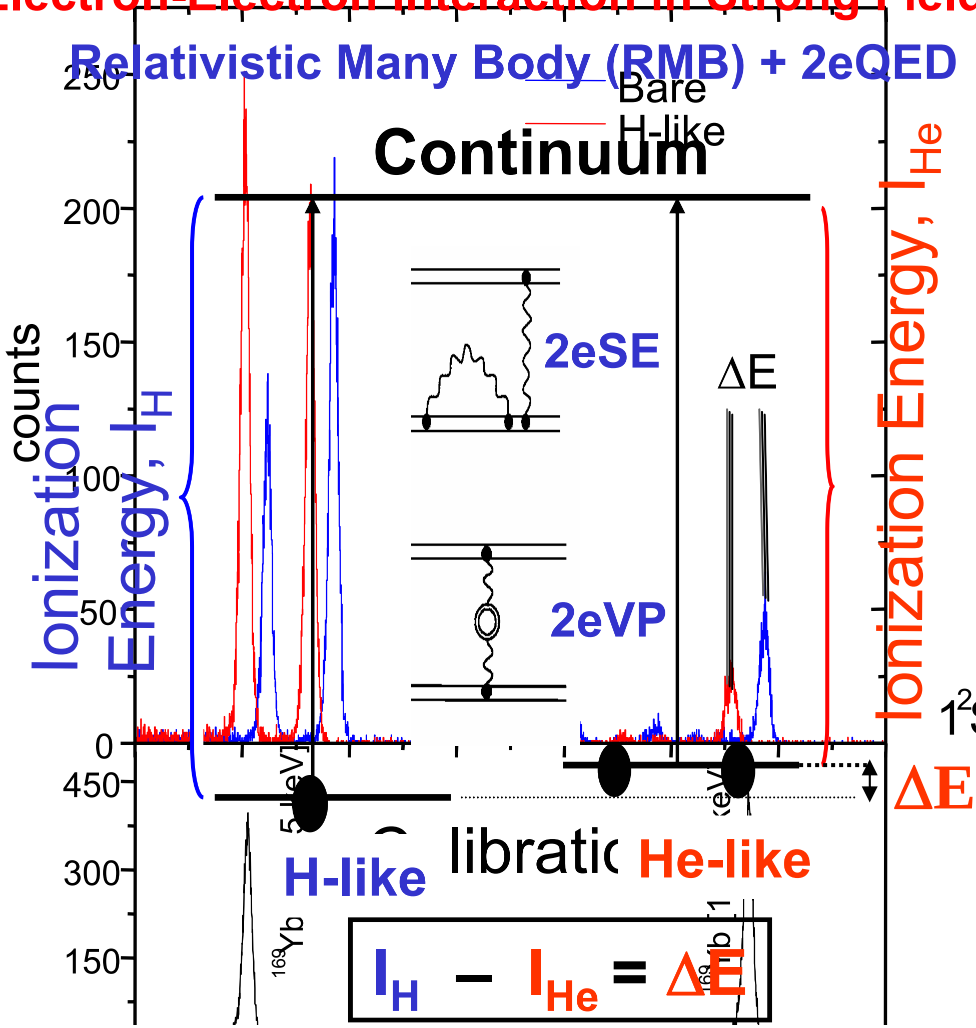
NS= 198.7 eV, HO ~ 1.8 eV

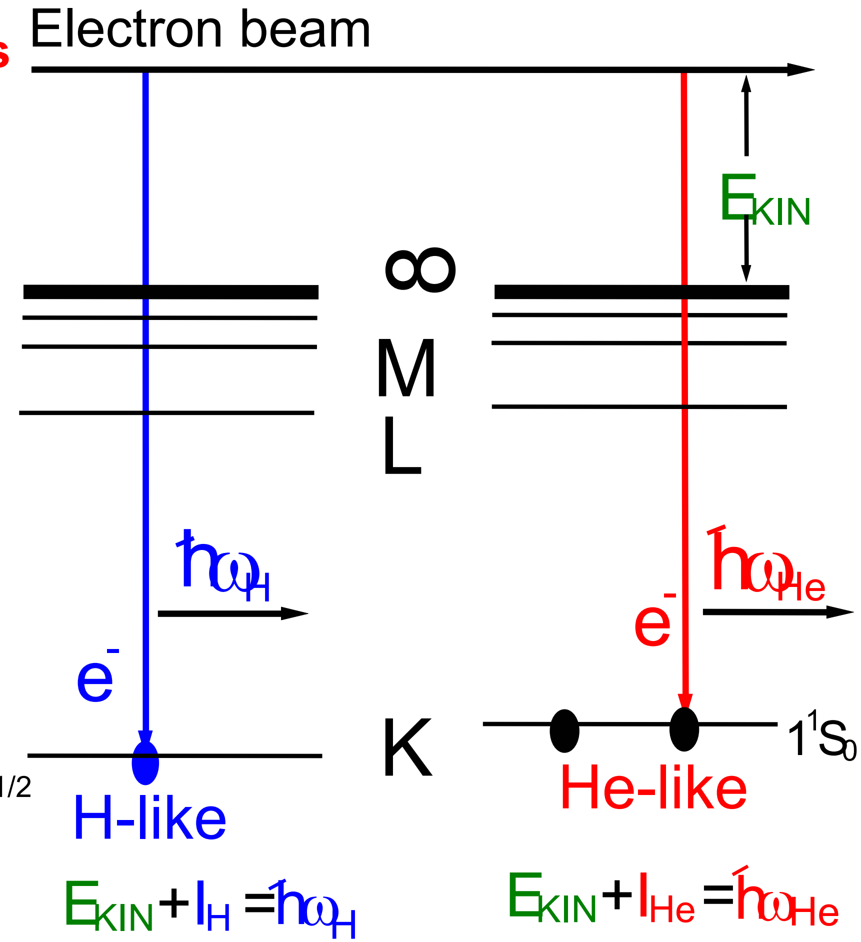
→ **1% sensitivity to the 1s Lamb shift**
4% Sensitivity to the self energy
15% Sensitivity to the vacuum polarization

Relative Measurement of the Two-electron Contribution to the Ground State Binding Energy in He-like Uranium

Electron-Electron Interaction in Strong Fields

Relativistic Many Body (RMB) + 2eQED





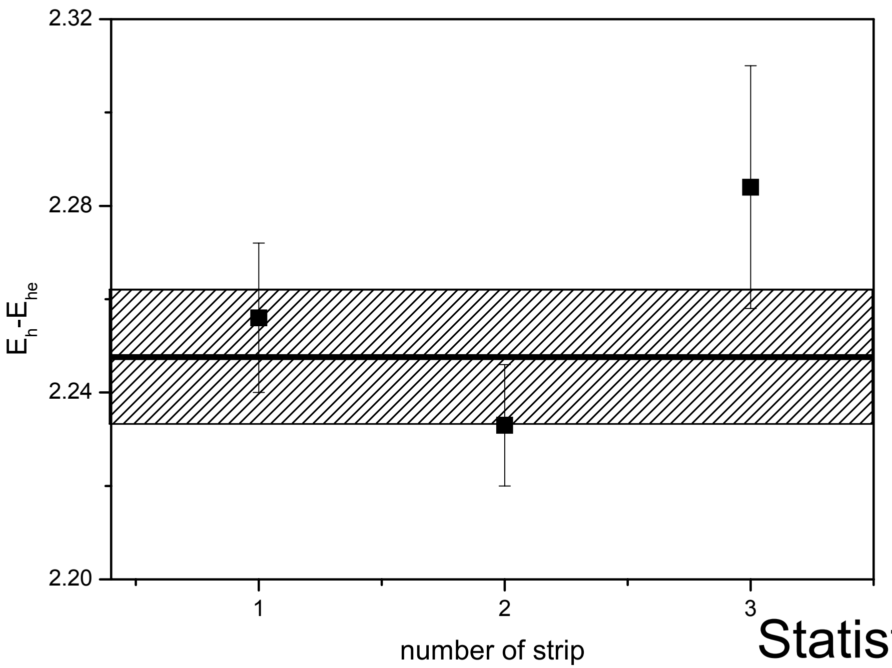
$$\Delta E(\hbar\omega_H - \hbar\omega_{He}) = I_H - I_{He}$$

ΔE: *Two-Electron Contribution to the Ionization potential in the He-like System*

Relative measurement

All one electron contributions cancel out (e.g. finite nuclear size)

- Data subdivided into several groups
- Checked for consistency



2248 ± 9 eV

Statistical uncertainty for ΔE: 9 eV

~~Uncertainty caused by doppler shift:~~

The result for the splitting ΔE is 2248 ± 9 eV

Experimental Results in Comparison with Theory

ESR (First experiment for the two-contribution U^{90+}): 2248(9) eV
Theory (Yerokhin et al. 1997): 2246 eV

2 photon exchange ~14 eV 2eSE ~ 9.7 eV

Super-EBIT (First measurement of the 2e contribution)

(Marrs et al, 1995)

But!! Results limited by counting statistics (Z<83)

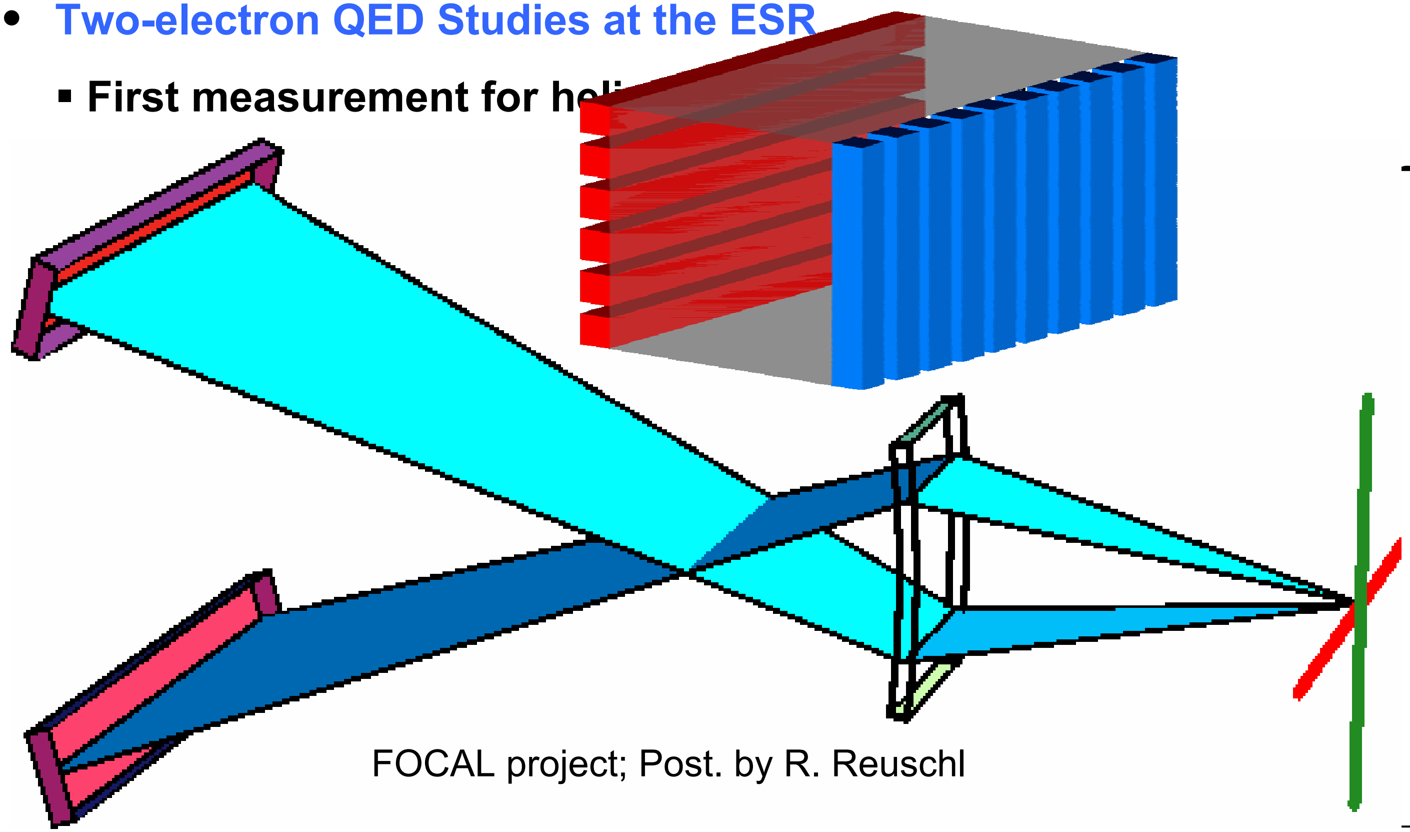
As an example; for Bismuth an uncertainty of 14 eV has been achieved for the value of 1876 eV. 2eQED ~ 6.7 eV

- Our result agrees well with the most recent theoretical value.
- The experimental uncertainty is of the order of two-electron QED contributions.
- Compared to the former studies at Super-EBIT in Livermore, we could substantially improve the statistical accuracy and extend studies to the higher-Z regime.

SUMMARY AND OUTLOOK

- **Two-electron QED Studies at the ESR**
  - **First measurement for heli**

…d to former exp.,



FOCAL project; Post. by R. Reuschl

of three,

Simultaneous measurement at 0 and 180 deg.

High resolution detection devices; spectrometer + PSG, calorimeter

Excellent agreement between experimental results and theory for both cases

'No test can prove a theory but any single test can disprove it.'

Karl Popper