1s Lamb shift in high-Z H-like ions: recent results from the FOCAL collaboration

Alexandre Gumberidze

GSI Darmstadt, Germany

on behalf of the FOCAL collaboration

The FOCAL collaboration

H.F. Beyer[a], T. Gassner[a,h], M. Trassinelli[j], U. Spillmann[a], D. Banas[b], K.-H. Blumenhagen[a], F.Bosch[a], C.Brandau[d], W. Chen[a], E. Förster[c], A. Gumberidze[d], S. Hagmann[a,e], R. Hess[a,d], P.-M. Hillenbrand[a], P. Indelicato[f], P. Jagodzinski[b], T. Kämpfer[c], Ch. Kozhuharov[a], M. Lestinsky[a], D. Liesen[a], Y. Litvinov[a], R. Loetzsch[c], B. Manil[g], N.Petridis[d,e], S. Sanjari[a], M. Schwemlein[d], A. Simionovici[i], Th. Stöhlker[a,h,c], C. Szabo Foster[c], S. Trotsenko[h], G. Weber[h], O. Wehrhan[c], N. Winckler[a], D. Winters[a], N. Winters[a], E. Ziegler[k]

[a] GSI Helmholtzzentrum, Planckstrasse 1, 64291 Darmstadt, Germany

[b] Institute of Physics, Swietokrzyska Academy, 25-406 Kielce, Poland

[c] Inst. für Optik und Quantenelektronik, F. Schiller-Universität, D-07743 Jena, Germany

[d] Extreme Matter Institute, EMMI, GSI Helmholtzzentrum, Planckstrasse 1, 64291 Darmstadt, Germany

[e] Institut für Kernphysik, Goethe-Universität, D-60438 Frankfurt am Main

[f] Lab. Kastler Brossel, Université P. et M. Curie, F-75252 Paris Cédex 05, France

[g] Laboratoire de Physique des Lasers (LPL) UMR 7538 CNRS - Université Paris 13, F-93430, Villetaneuse, France

[h] Helmholtz-Institut Jena, Fröbelstieg 3, D-07743 Jena

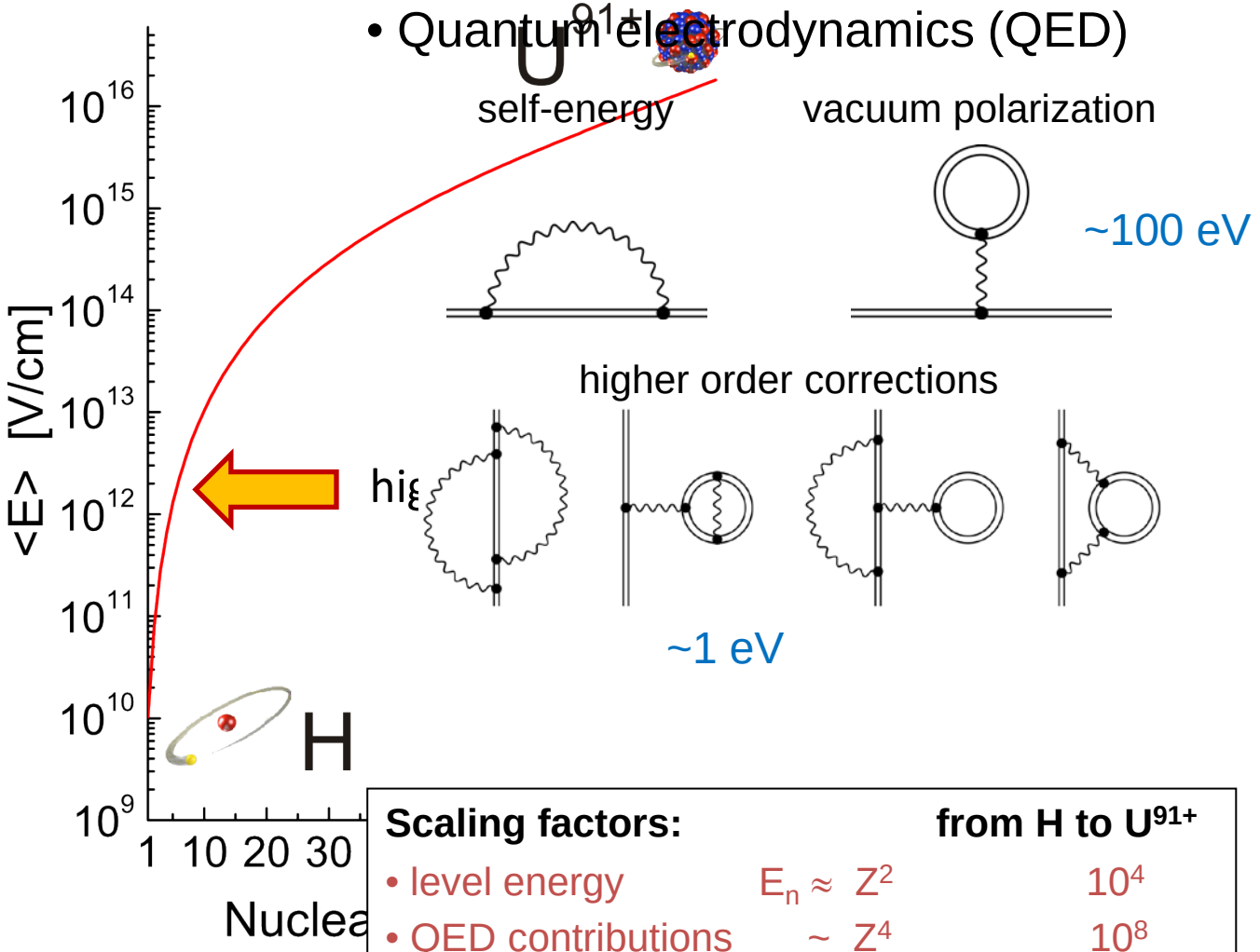
[i] LGIT, Observatoire des Sciences de l'Univers de Grenoble, F-38041 Grenoble Cedex 9, France

[j] Institut des Nanosciences de Paris, Université Pierre et Marie Curie-Paris 6 and CNRS-UMR 7588, 4 place Jussieu 75252 Paris, France

[k] ESRF, F-38043 Grenoble, France

Atomic Physics on Highly Charged Ions

- Quantum electrodynamics (QED)

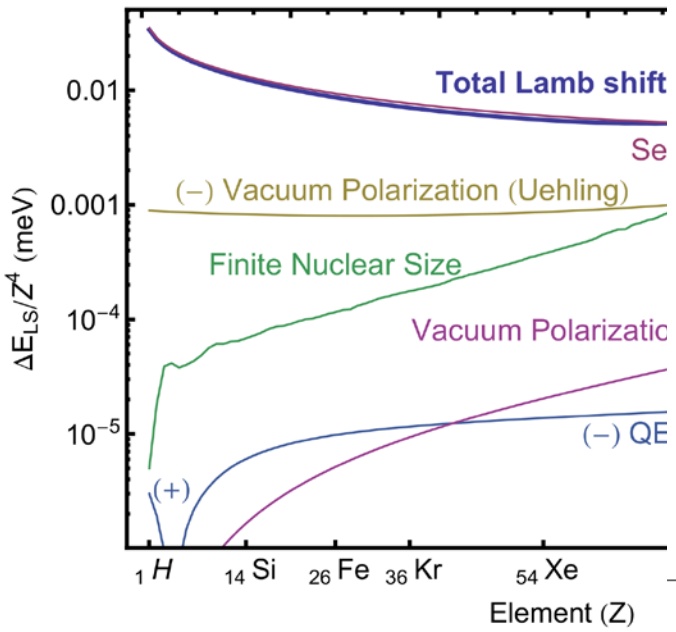


Scaling factors:		**from H to U^{91+}**
• level energy	$E_n \approx Z^2$	10^4
• QED contributions	$\sim Z^4$	10^8

T. Beier, Phys. Rep., **339** (2000) 79

The Lamb Shift (in H-like Gold Au^{78+})

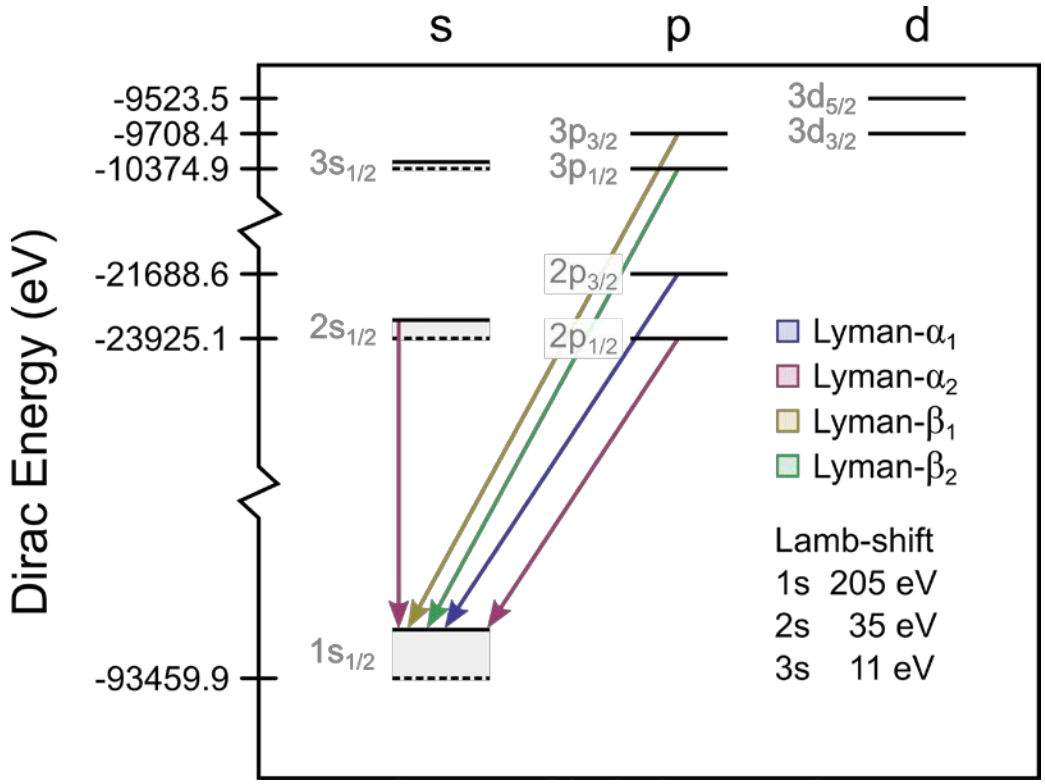
Lamb shift = Dirac value – Experiment $\Delta E_{\mathrm{LS}} = m_e c^2 \frac{\alpha}{\pi} \frac{(Z\alpha)^4}{n^3} F(Z\alpha)$



Effect	Contribution (eV)
Dirac Energy	−93 459.863
First-Order QED	
Self-Energy (SE)	+196.687(2)
Vacuum-Polarisation (VP)	
Uehling	−41.996(2)
Wichmann-Kroll	+1.7939(2)
Second-Order QED	
SESE	−0.6716(43)
SEVP	+0.41(13)
VPVP	−0.39(11)
Nuclear Contributions	
Finite Nuclear Size (FNS)	+49.14(11)
Nuclear Recoil	+0.3313(14)
Nuclear Polarisation	−0.049(49)
Total Lamb Shift	205.2(2)
Total Binding Energy	−93 254.6(2)

V.A. Yerokhin and V.M. Shabaev, J. Phys. Chem. Ref. Data **44** (2015) 033103

The Lamb Shift (in H-like Gold Au^{78+})

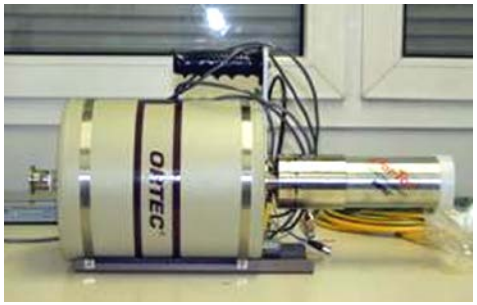


$$(E^{\text{theory}}_{2p_{3/2}} - E^{\text{experiment}}_{\text{Ly-}\alpha_1}) - E^{Dirac}_{1s_{1/2}} = \Delta E_{\text{LS}}$$

V.A. Yerokhin and V.M. Shabaev, J. Phys. Chem. Ref. Data **44** (2015) 033103

High Resolution X-Ray Detectors for HCI Spectroscopy

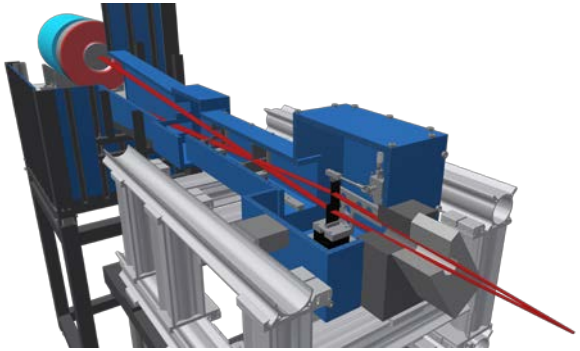
Semiconductor Detector



- relatively cheap
- easy to operate
- compact in size
- good efficiency

- moderate resolution (400 eV @ 60 keV)

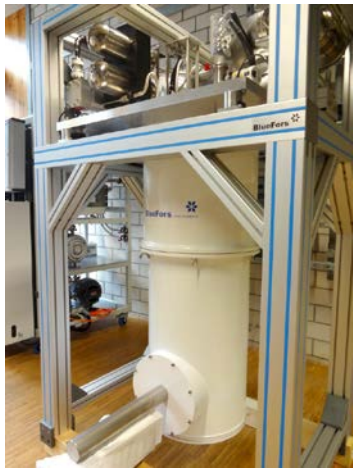
Crystal Spectrometer



- high resolution (< 60 eV @ 60 keV)

- low efficiency
- difficult to align
- large in size
- low dynamic range

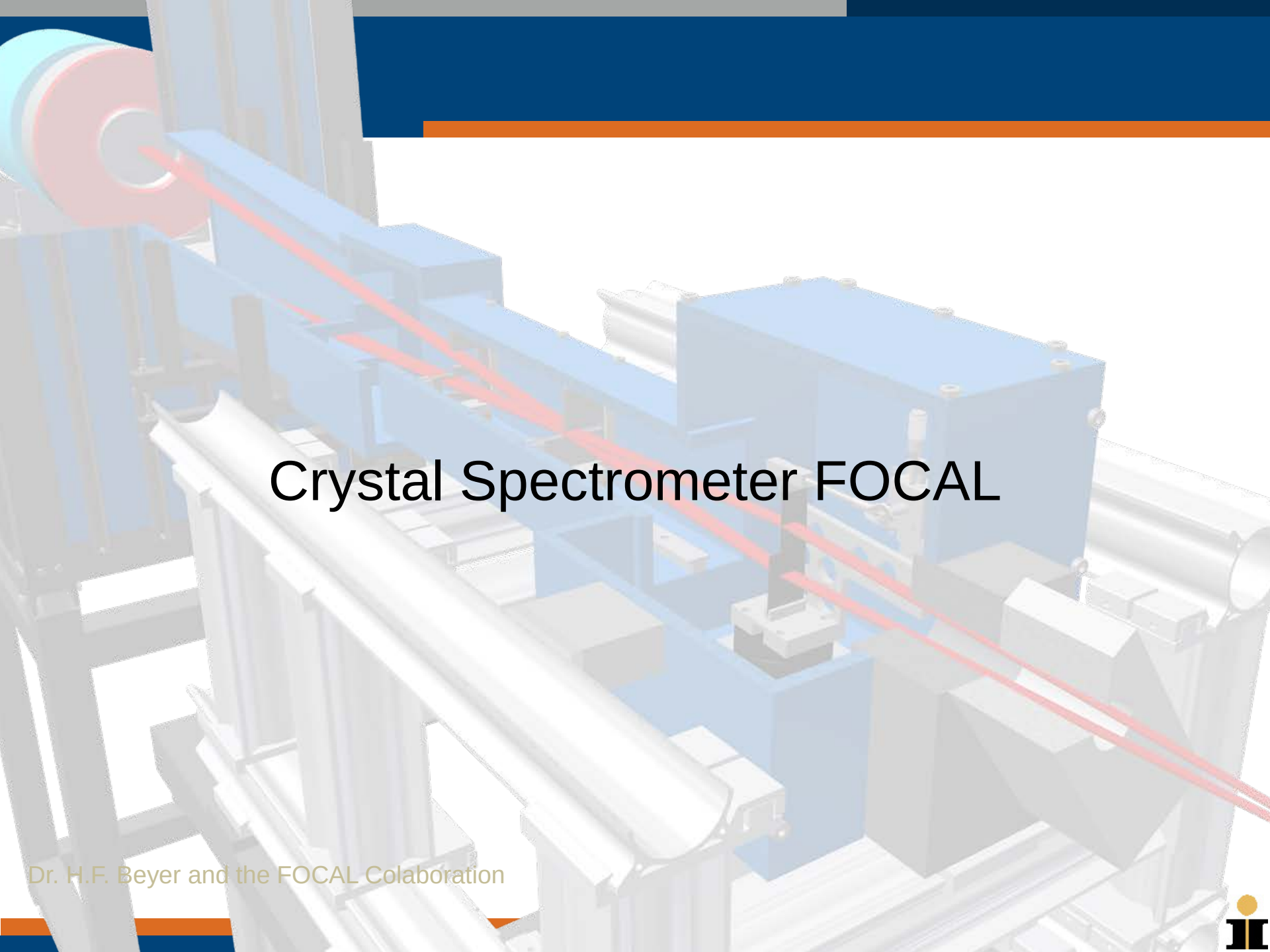
Microcalorimeter



- high resolution (< 60 eV @ 60 keV)
- large dynamic range

- medium efficiency

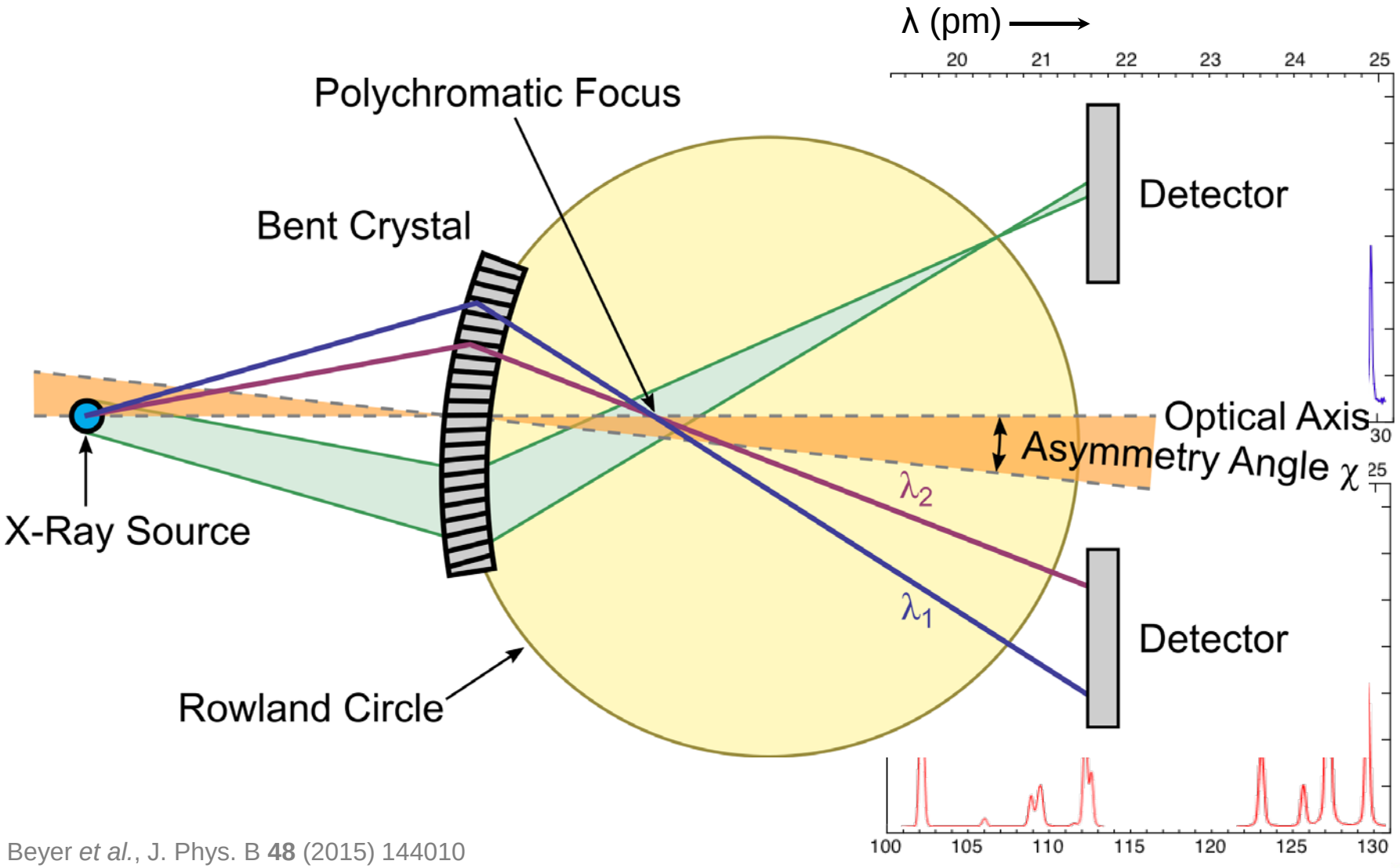
- expensive
- complex device



Crystal Spectrometer FOCAL

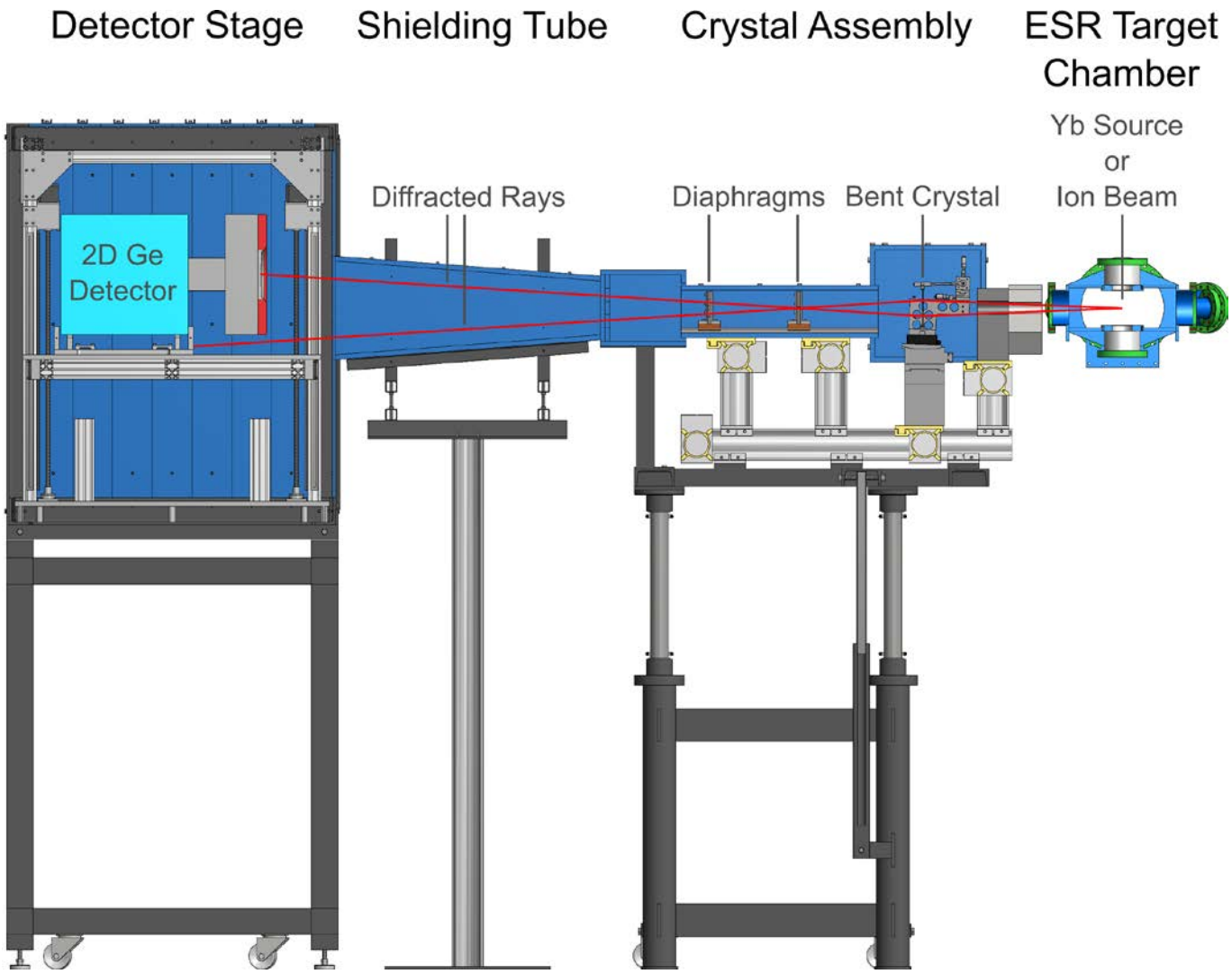
Dr. H.F. Beyer and the FOCAL Colaboration

Crystal Spectrometer

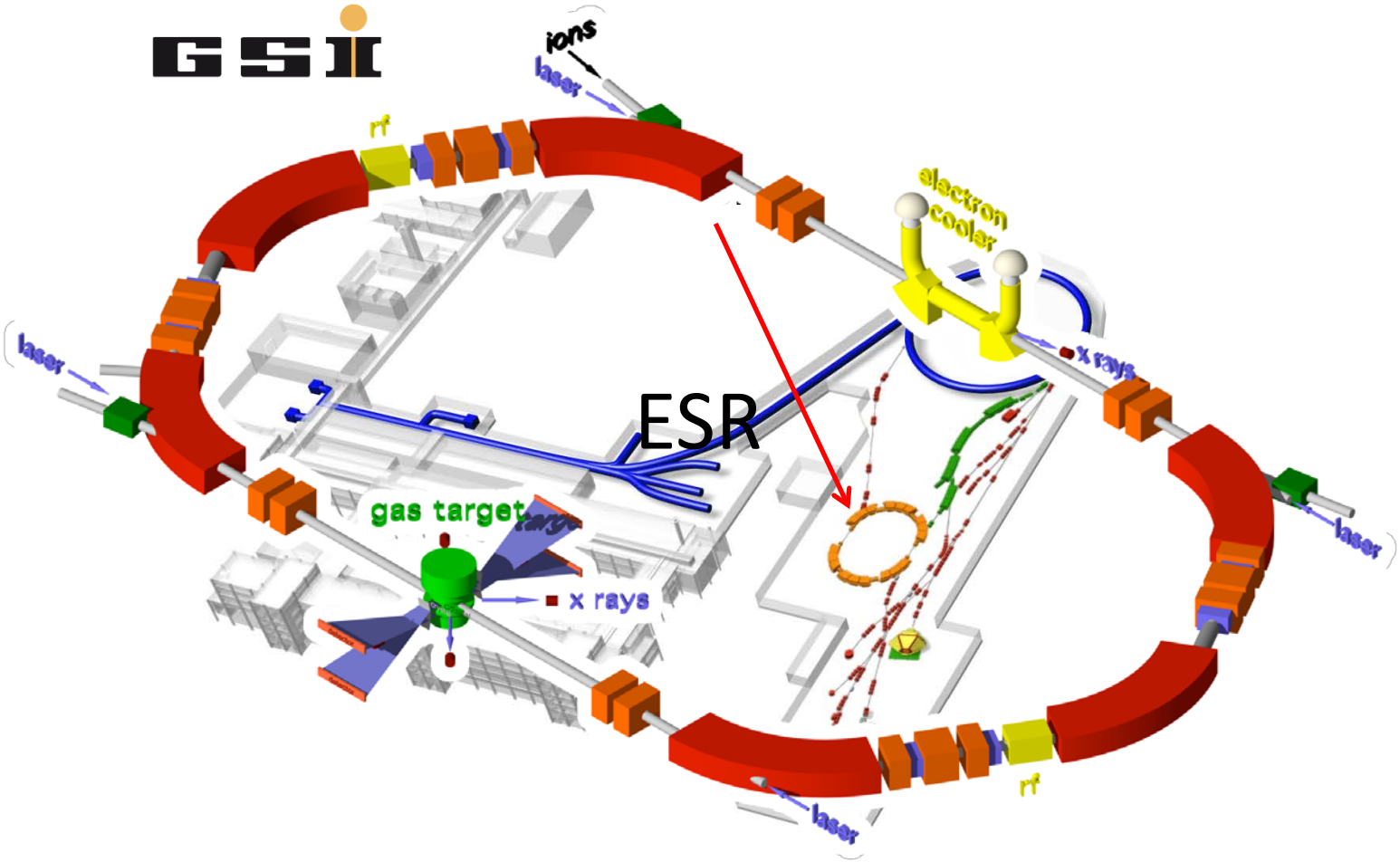


H.F. Beyer *et al.*, J. Phys. B **48** (2015) 144010

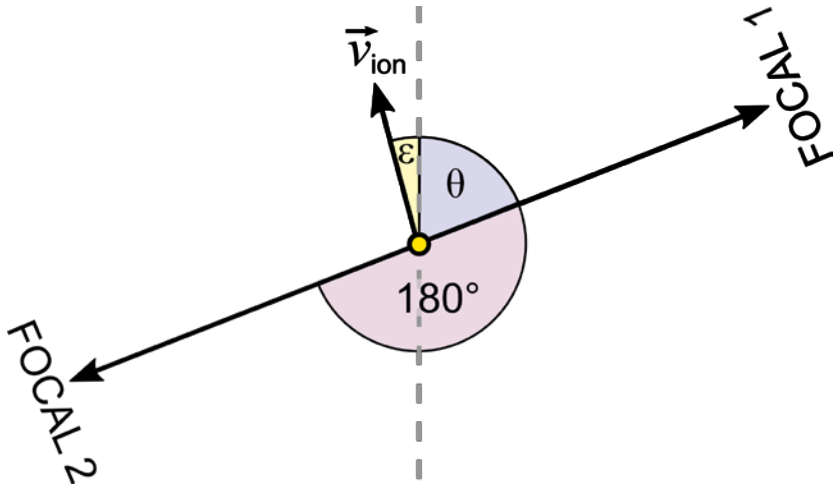
Crystal Spectrometer



The GSI Accelerator Complex in Darmstadt



Doppler Effect



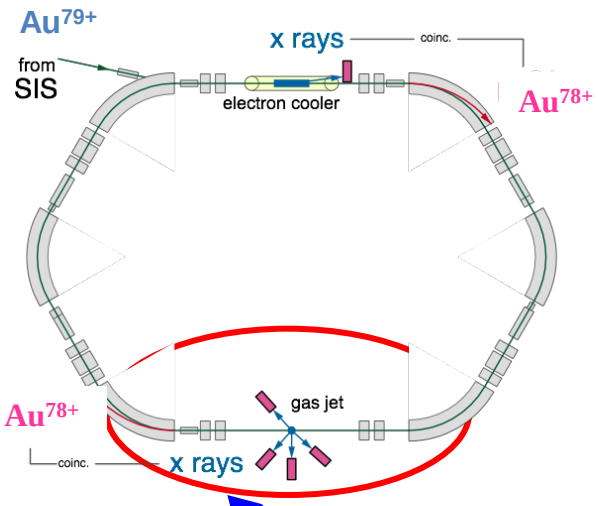
Doppler correction:

$$\lambda_1 = \lambda_0 \gamma \cdot (1 - \beta \cdot \cos\theta)$$

Cancellation of alignment errors:

$$\lambda_1 + \lambda_2 = 2\gamma\lambda_0$$

The FOCAL setup



gasjet target
supersonic Argon-jet
density: ~10^{12} atoms/cm^2
width: ~5 mm

ion-beam
Au^{79+} ion beam
energy:125 MeV/u

Ar

Au^{79+}

dipole magnet

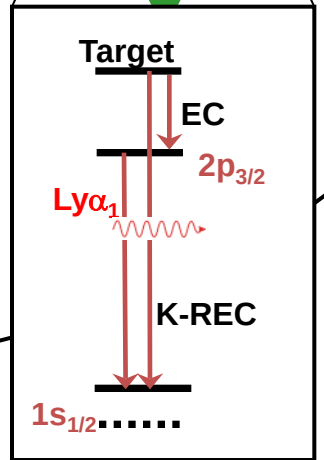
Au^{79+}

Au^{78+}

particle-detector

detector

detector

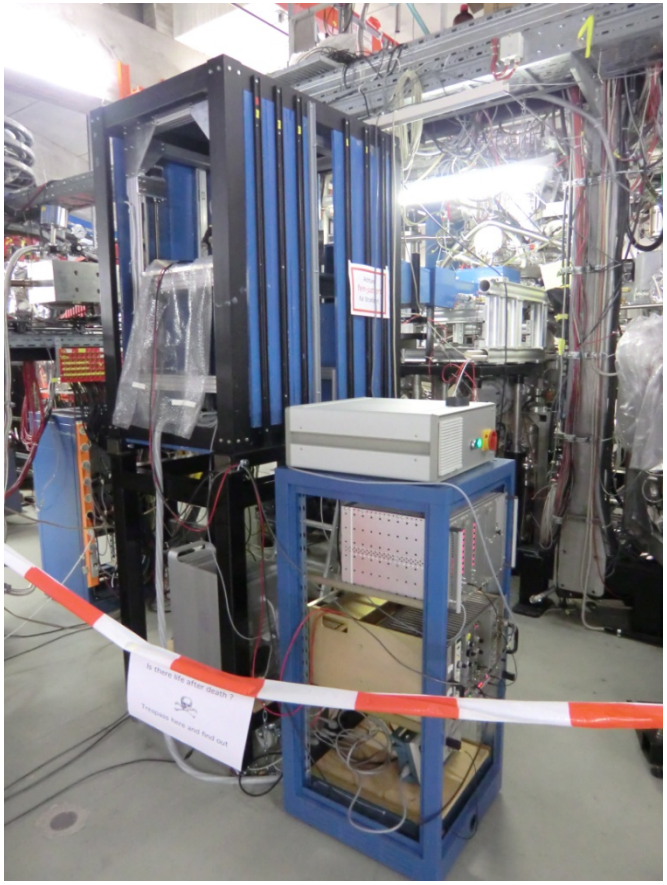


coincidence between particle- and x-ray detector

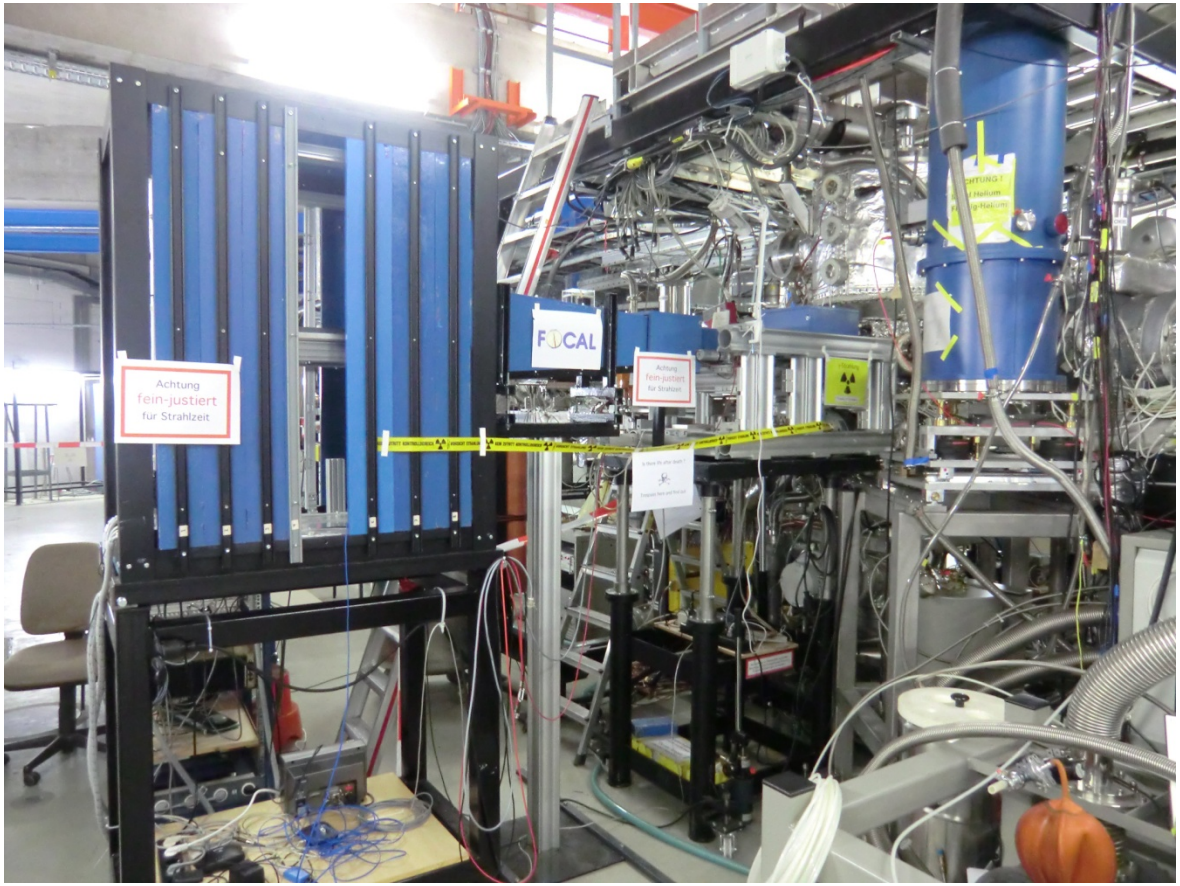
3 – 5 counts/h

Experiment Impressions

FOCAL 1

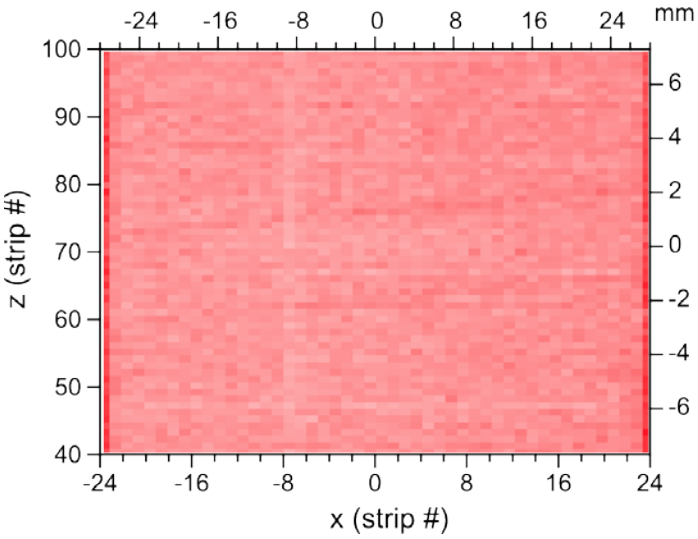


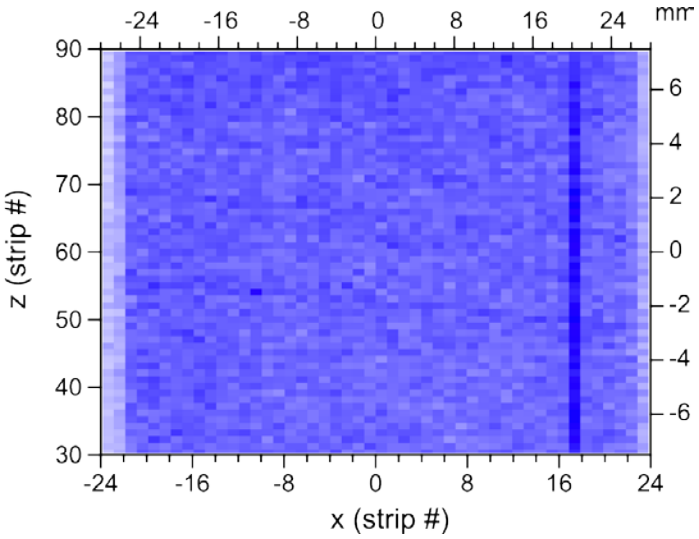
FOCAL 2



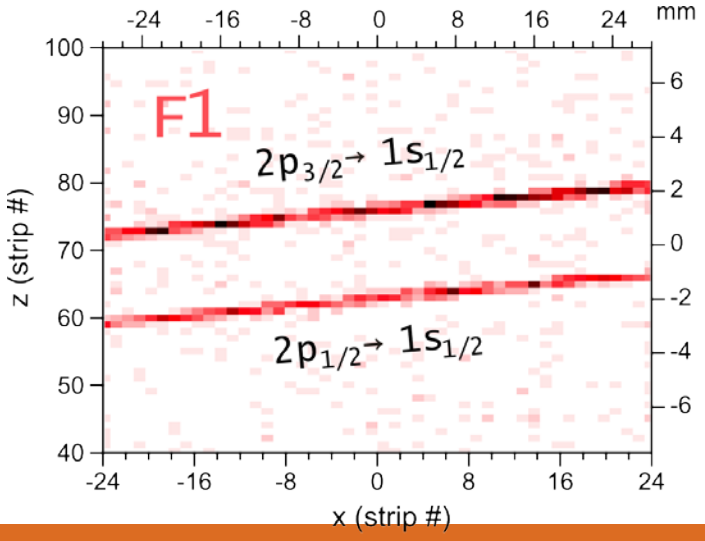
Preliminary results

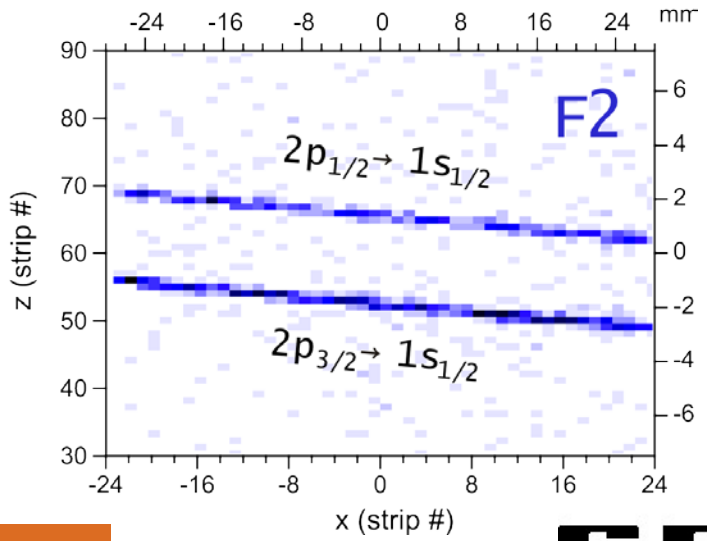
Raw 2D spectrum



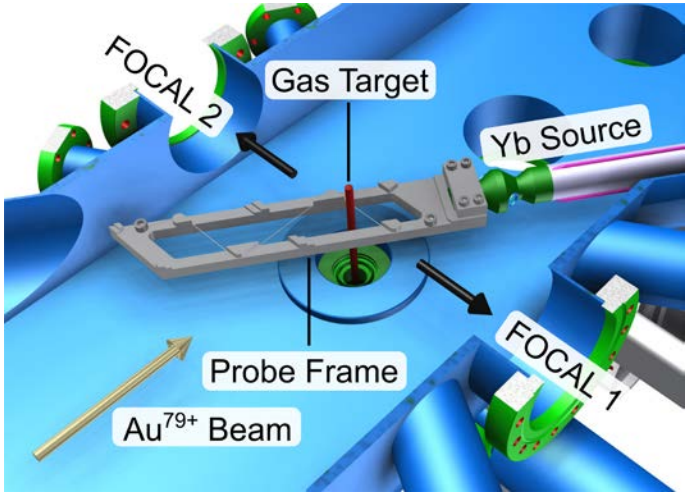


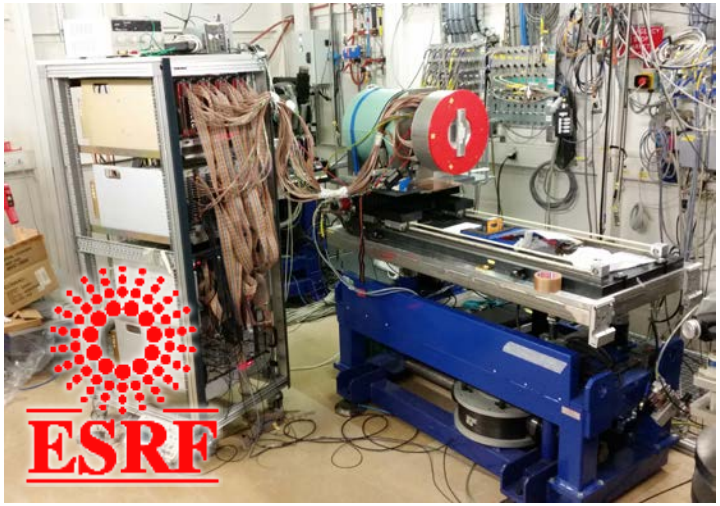
2D spectrum with energy and time condition

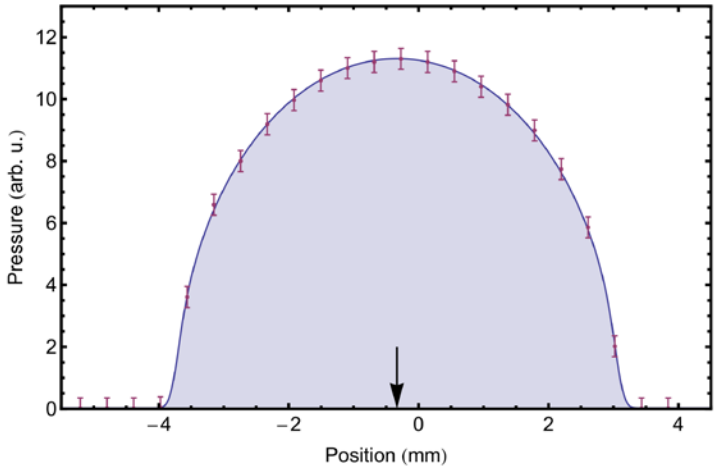


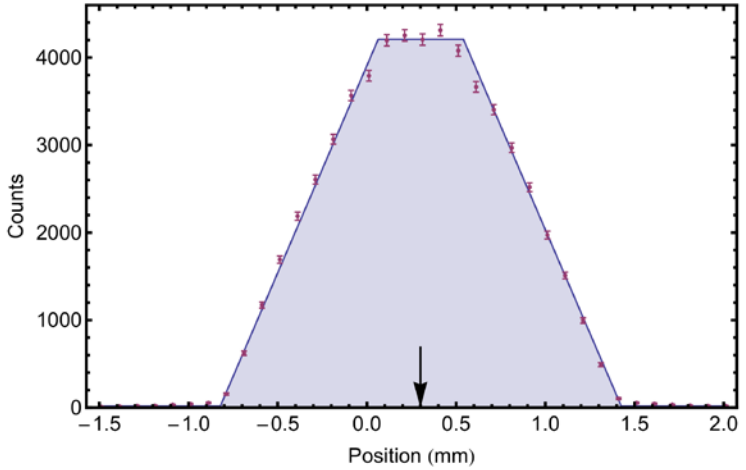


Accompanying Experiments: Gas-Jet & Detector Crystal Position







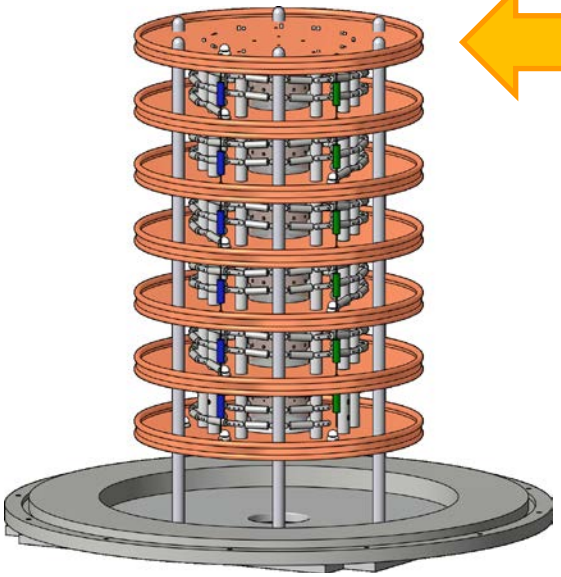


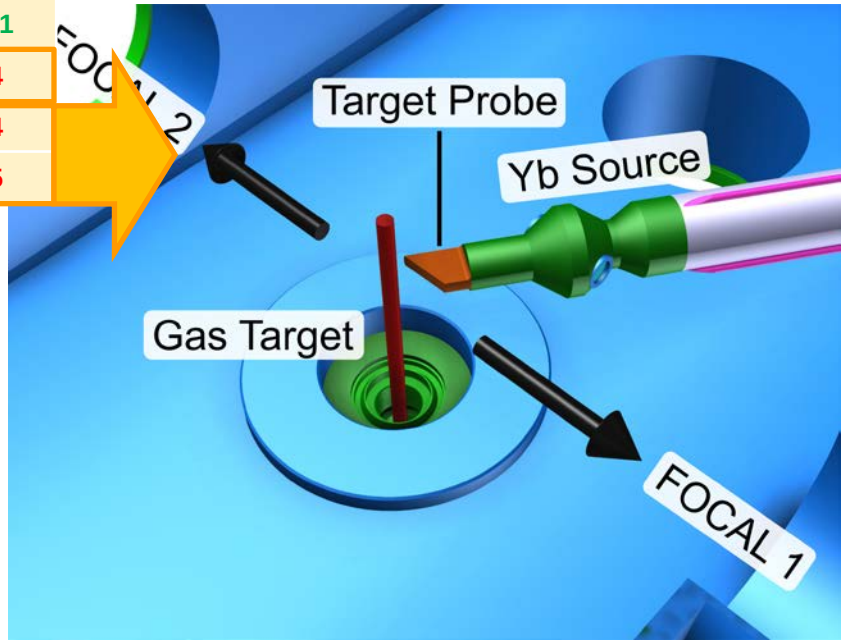
T. Gassner and H.F. Beyer, Phys. Scr. T166, 014052 (2015)

T. Gassner *et al.*, GSI annual report 2015

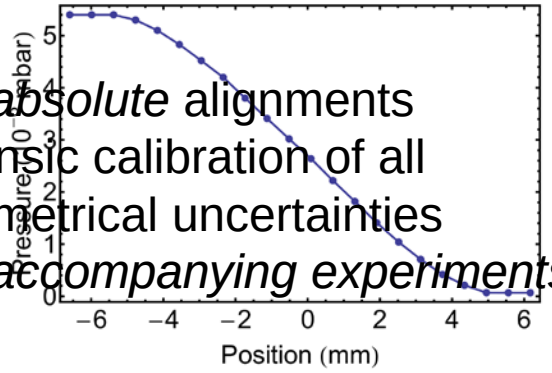
Outlook: Future Improvements

Quantity	Unc.
Line Position	2
Temporal Drift	2.8
Calibration	0.1
Beam Velocity	4
Gas Target Position	4
Detector Position	5





- High voltage divider
- Precision ≤ 10^{-4} (@70kV)
- PTB calibrated
- Permanent voltage monitoring



- No *absolute* alignments
- Intrinsic calibration of all geometrical uncertainties
- No *accompanying experiments*

J. Ullmann *et al.*, Journal of Physics B **48**, p. 144022 (2015)

Summary

• The ESR storage ring at GSI has proven to provide very favorable conditions for precision x-ray spectroscopic studies of atomic structure for heaviest one- (and few-electron) ions

• Next generation experiments aiming at testing higher-order QED effects in the heaviest H-like ions are underway utilizing dedicated high-resolution devices, e.g. crystal spectrometers in combination with micro-strip germanium detectors and microcalorimeters

• The FOCAL experiment has successfully proven a feasibility for the usage of high-resolution / low-efficiency crystal spectrometers at a storage ring

• Systematic effects still need to addressed in detail

Thank you very much for your attention !