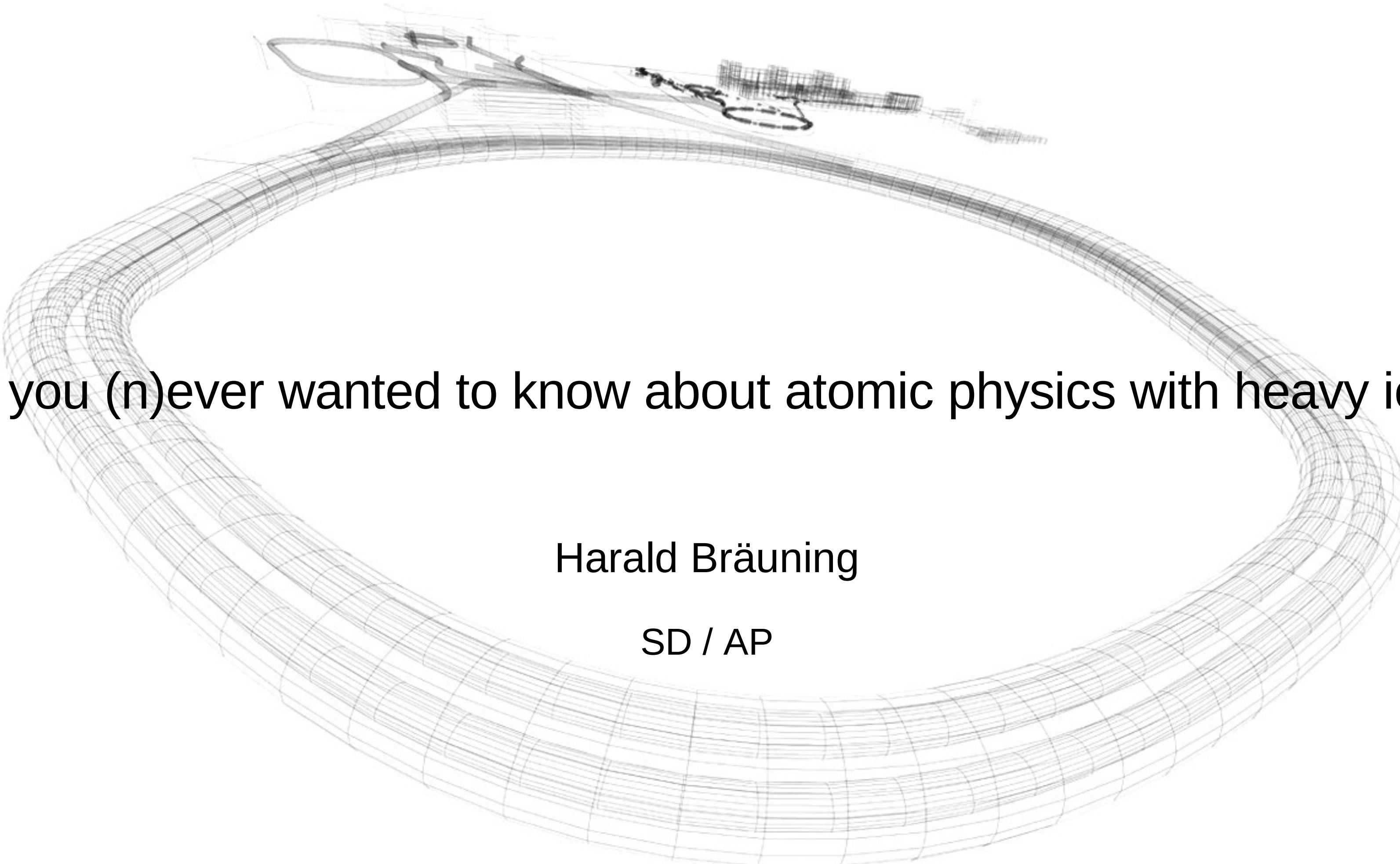
Atomic Physics @ GSI (and FAIR)

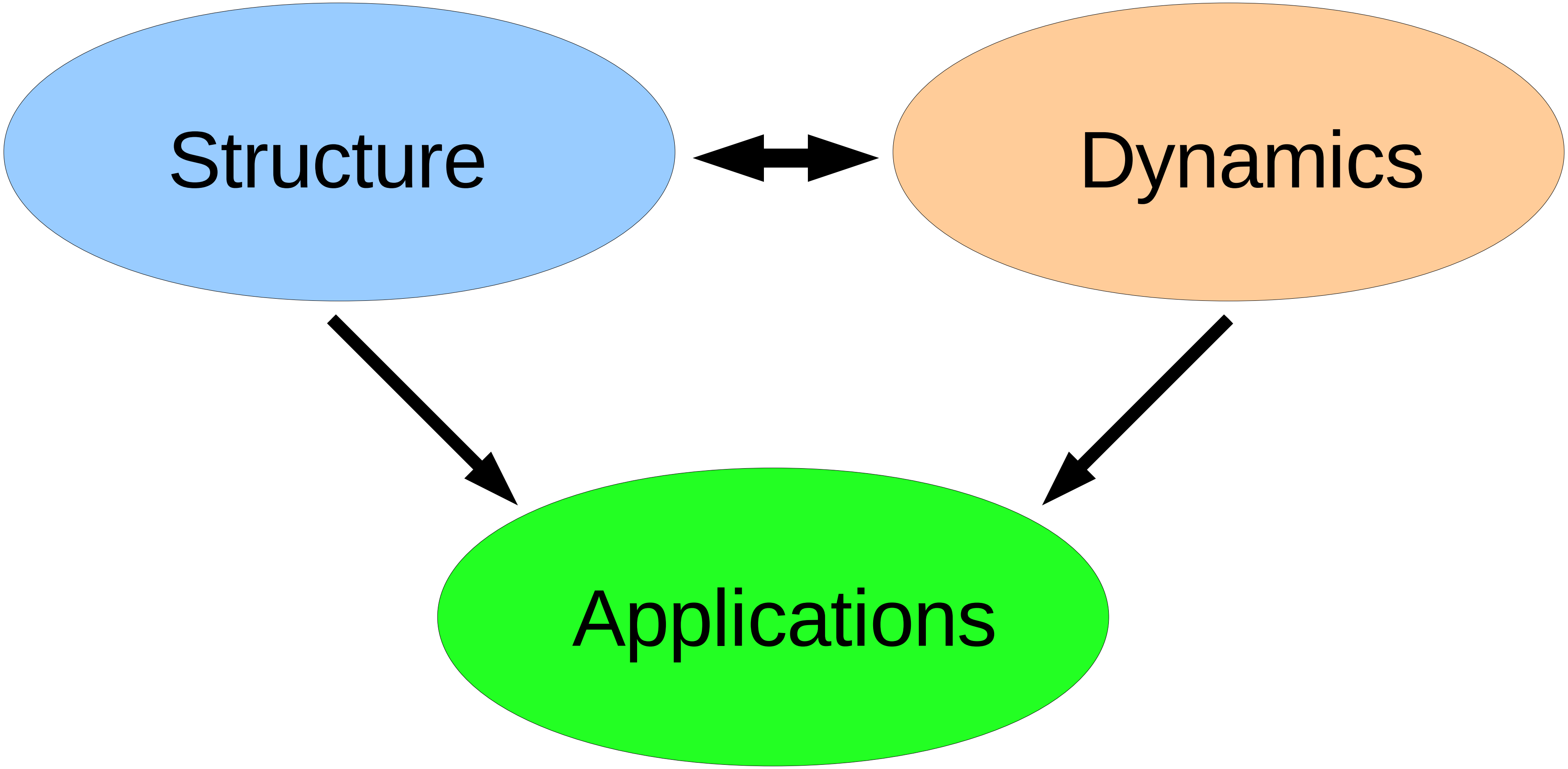


All you (n)ever wanted to know about atomic physics with heavy ions

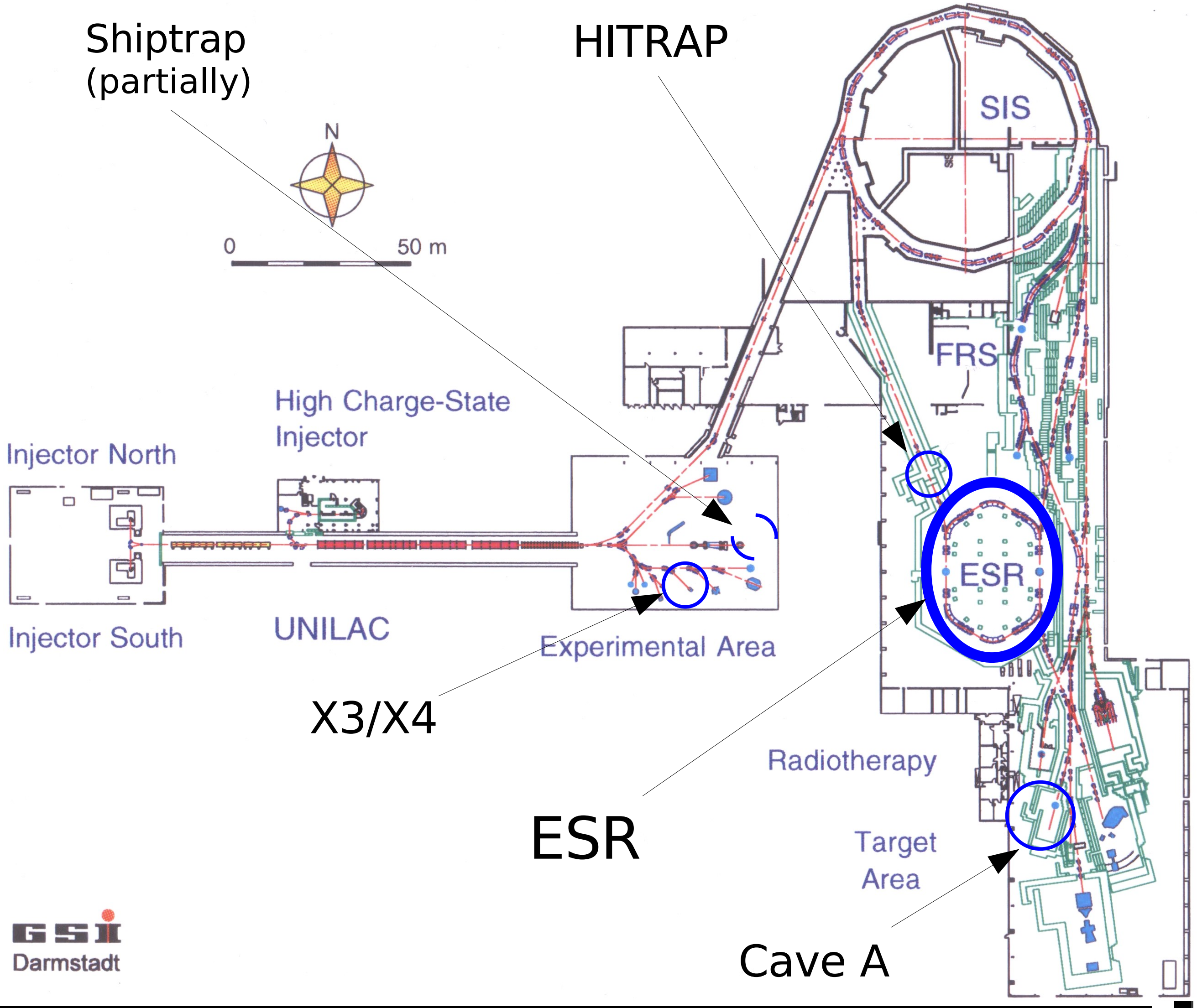
Harald Bräuning

SD / AP

Atomic Physics



AP @ GSI



Shiptrap
(partially)
HITRAP
SIS
N
0
50 m
FRS
High Charge-State
Injector
Injector North
ESR
UNILAC
Injector South
Experimental Area
X3/X4
Radiotherapy
ESR
Target
Area
Cave A
Darmstadt

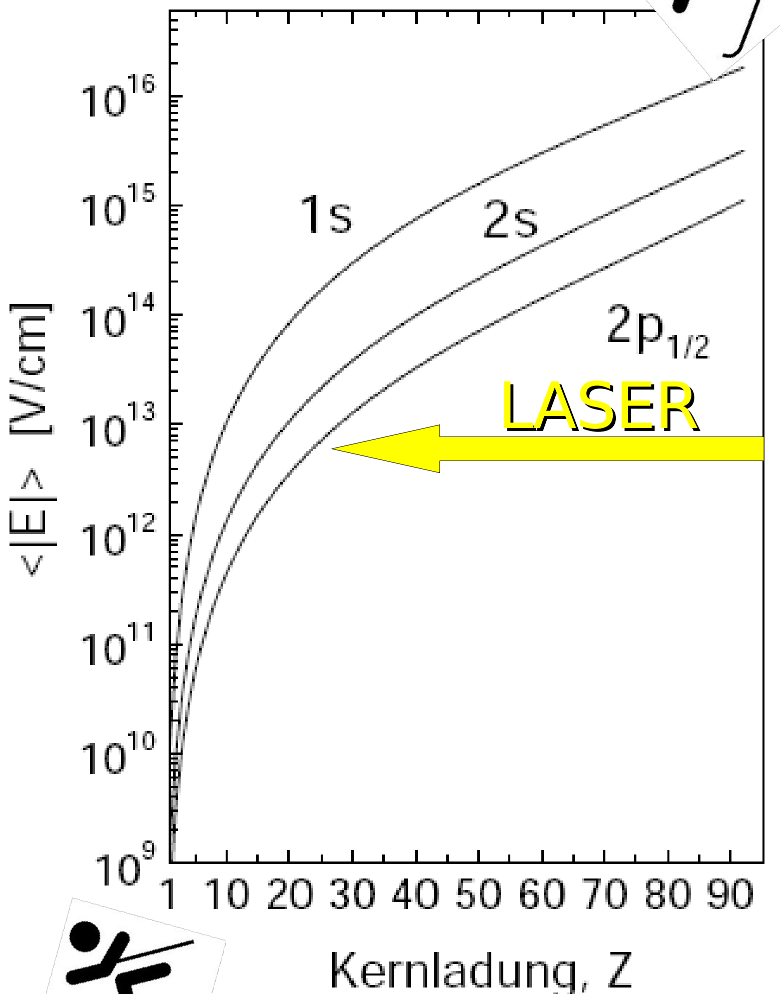
Highly Charged Heavy Ions

Hydrogen

- simplest atomic system
- best studied atomic system
- energy difference between the 1s and 2s measured with **10^{-14}** precision by Laser spectroscopy

Heavy Ions

- extremely strong electric fields
- relativistic effects become significant
- QED effect increase with Z^4
- QED becomes more difficult to calculate
- simple few electron systems



Quantum Electro-Dynamics

'...my physics students don't understand it either. That is because *I* do not understand it. Nobody does.'

'The theory ... describes Nature as absurd from the point of view of common sense. … So I hope you can accept Nature as She is – absurd.'

Richard P. Feynman: QED - The Strange Theory of Light and Matter

Heisenberg's Uncertainty Principle

$$\Delta E \cdot \Delta t \geq \hbar$$

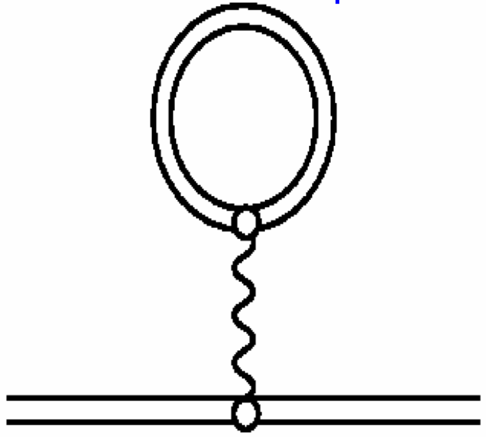
the law of energy conservation can be violated for a very short time

emission and absorption of virtual photons

QED

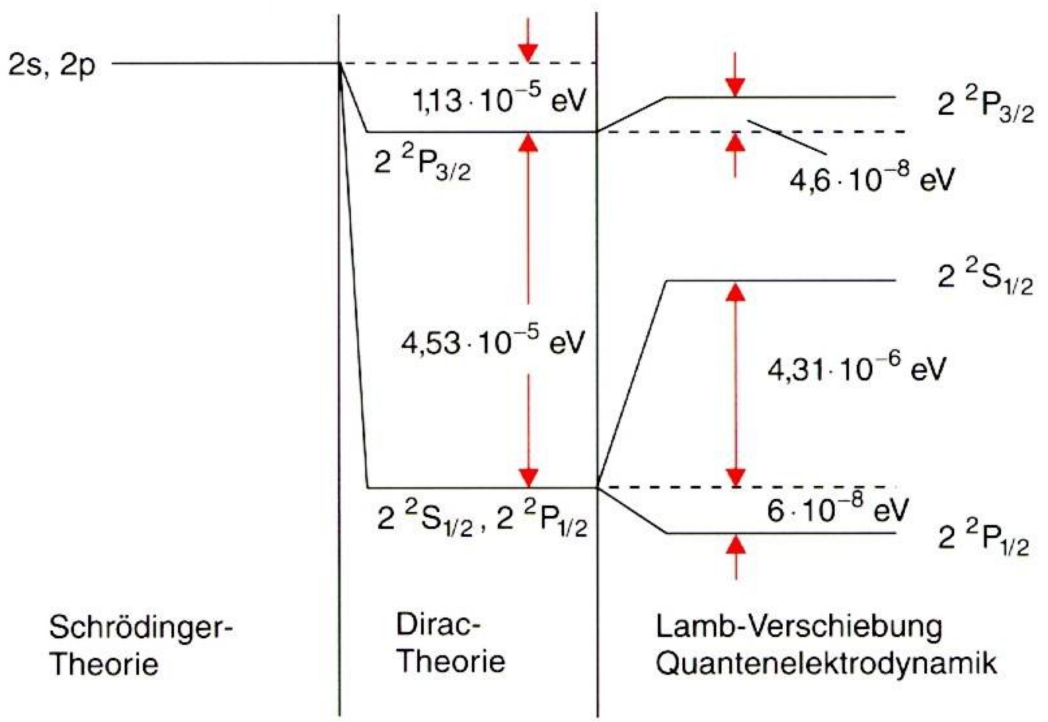
self energy

vacuum polarization



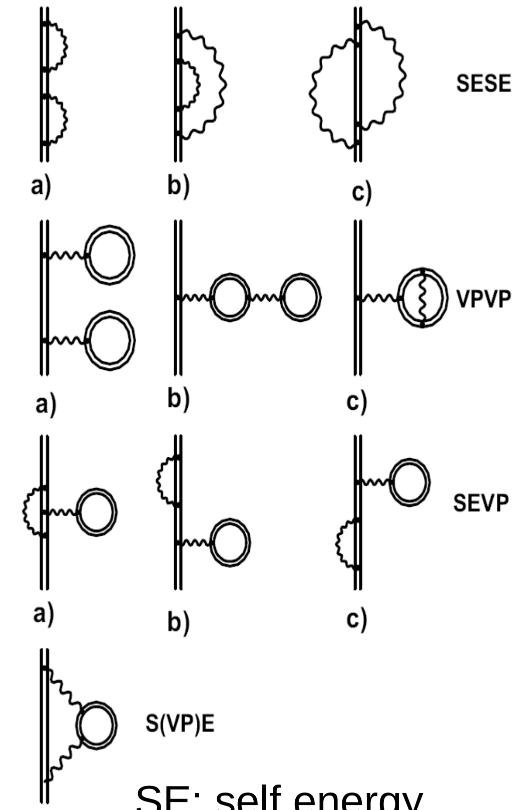
Quantum Electro-Dynamics

n=2 energy levels in hydrogen



QED contribution scales with Z^4/n^3

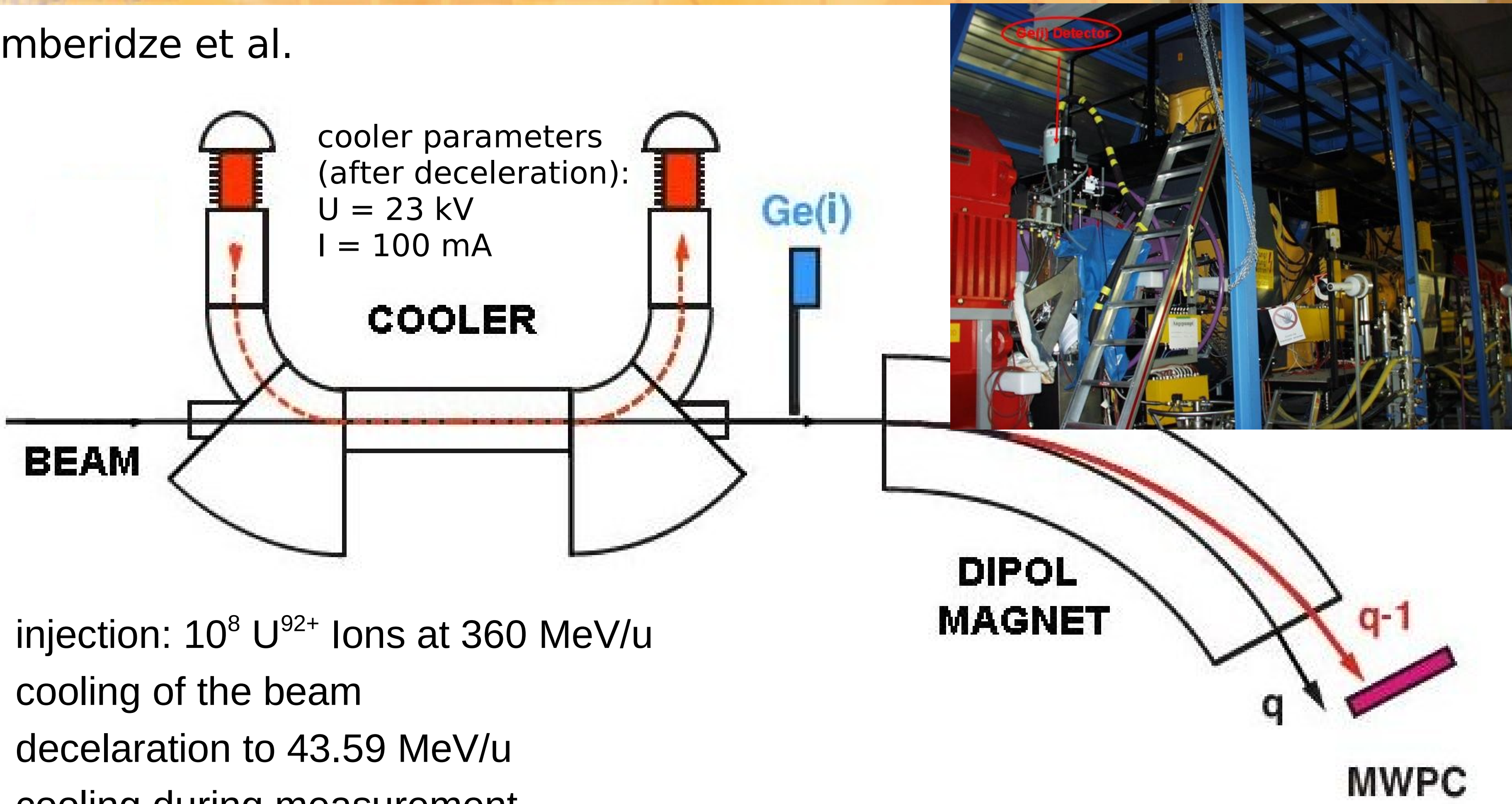
Higher Order QED Contributions



SE: self energy
VP: vacuum polarization

Measurements at the Electron Cooler

Gumberidze et al.



injection: 10^8 U^{92+} Ions at 360 MeV/u

cooling of the beam

decelaration to 43.59 MeV/u

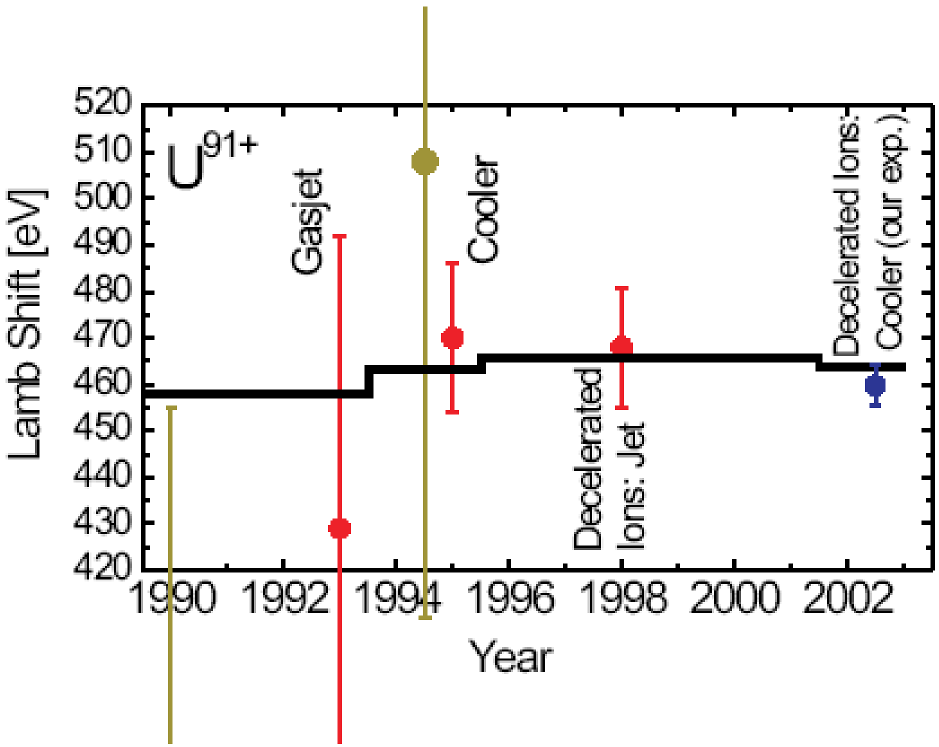
cooling during measurement

$$\Delta\beta/\beta \approx 10^{-4}$$

Measurements at the Electron Cooler

Gumberidze et al.: Phys. Rev. Lett. 94 (2005) 223001

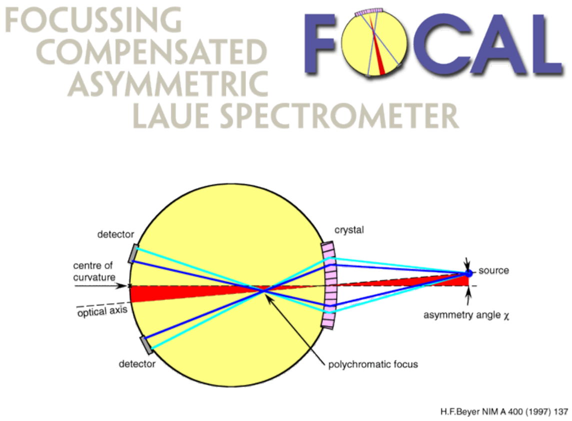
From the Lyα_1	From the K-RR	Mean value
460.9 ± 2.5	454.9 ± 5.4	459.8 ± 2.3
The final result for the 1s Lamb shift	459.8 ± 4.2	

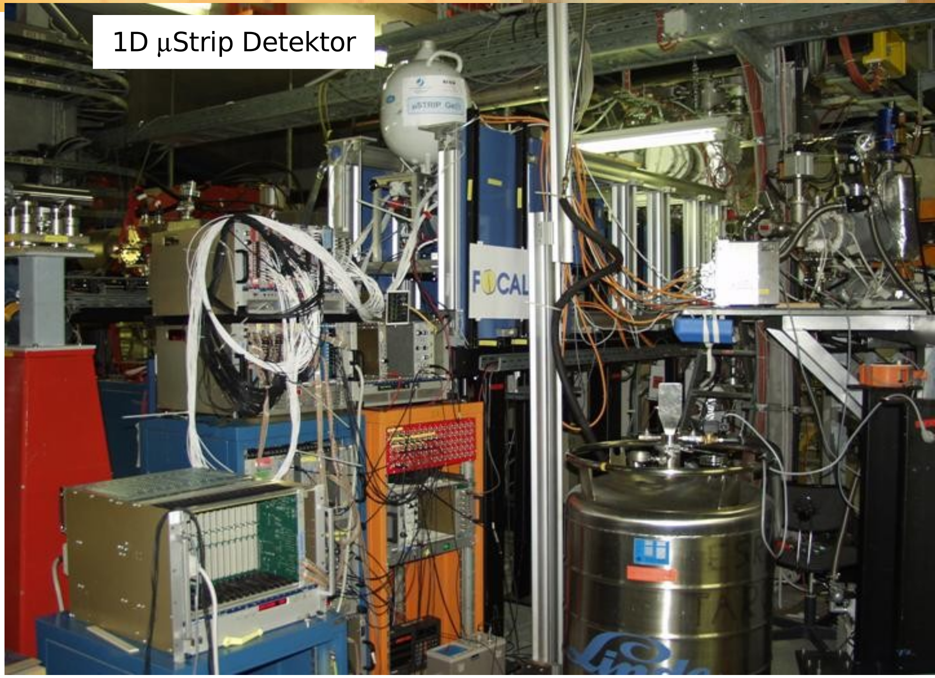


Finite nuclear size	198.81
Nuclear Recoil	0.46
Nuclear Polarization	-0.19
VP (see Fig 2.1)	-88.60
SE (see Fig 2.1)	355.05
SESE (see Fig 2.2)	-1.87
VPVP (see Fig 2.2)	-0.97
SEVP (see Fig 2.2)	1.14
S(VP)E (see Fig 2.2)	0.13
Total Lamb shift	463.95±0.5
Experiment	459.8±4.2

Experiment not sensitive to higher order contributions

FOCAL





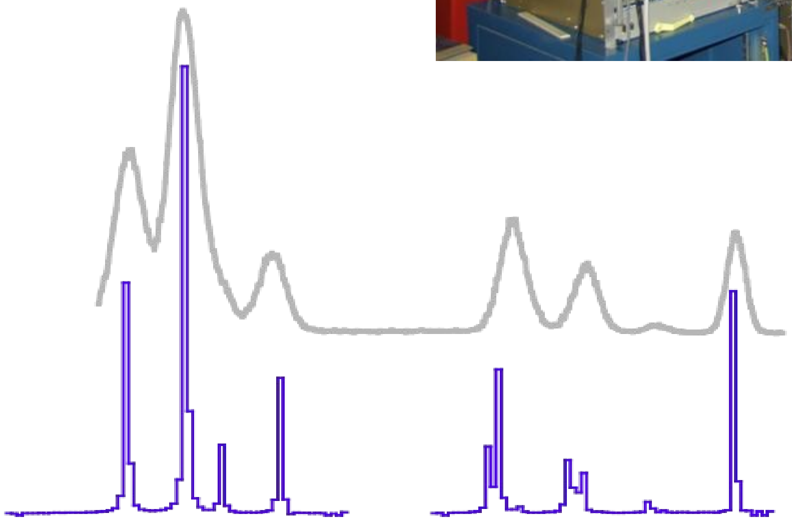
Comparison:
Ge(i) detector - crystal-spectrometer

Ge(i) pulse height

$\varepsilon = 10^{-4}$

crystal spectrometer

$\varepsilon = 10^{-8}$



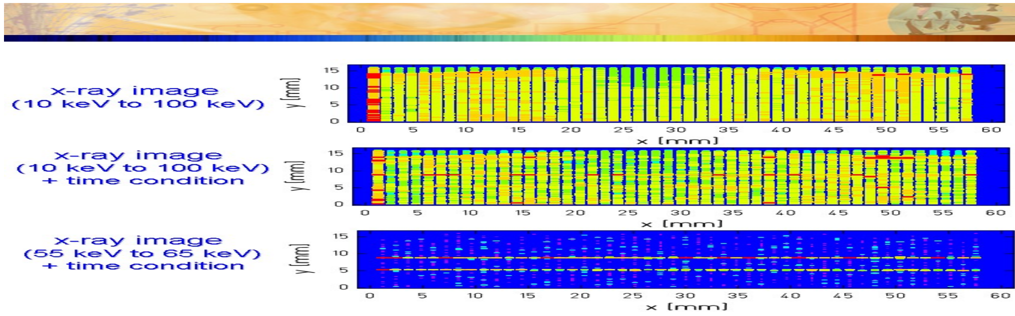
3 - 5 events / h

FOCAL

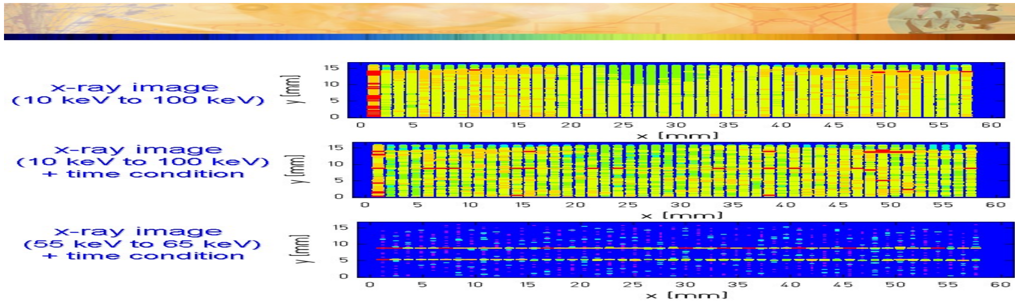
1. Beamtime with a 2d µ-strip detector: March 2006

H. Beyer, R. Reuschl, et al.

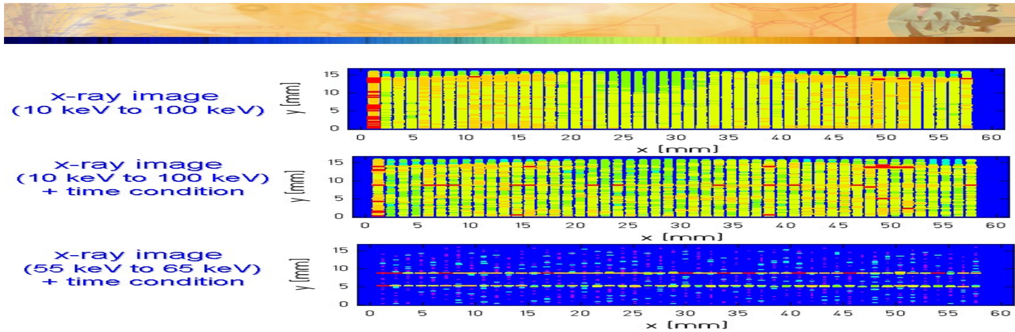
raw x-ray image



x-ray image in coincidence with down-charged ion (electron capture)



x-ray in image in coincidence with down-charged ion and with pre-selected x-ray energies (58-65 keV)

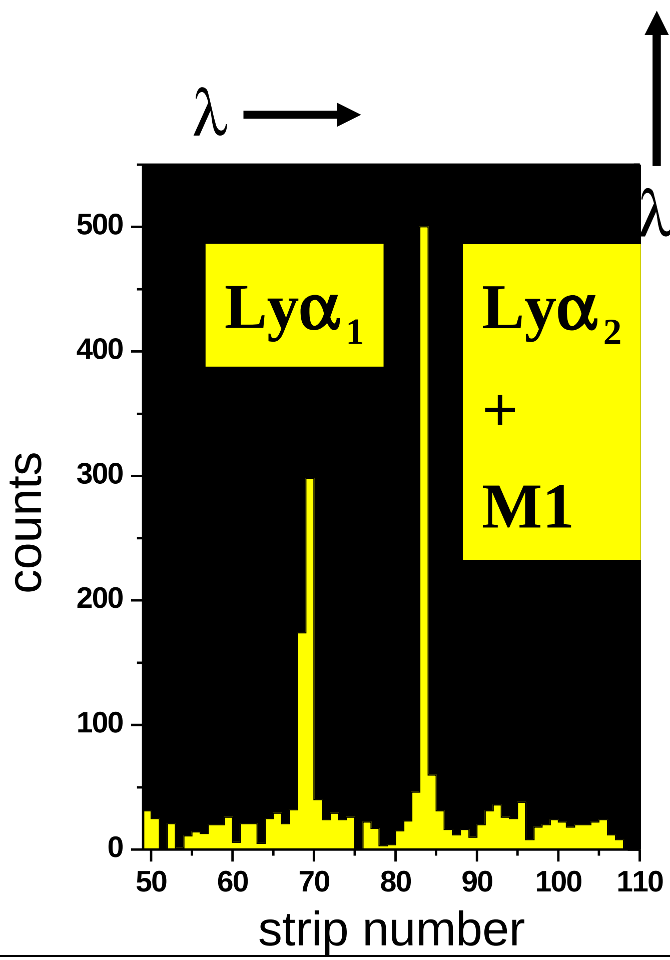


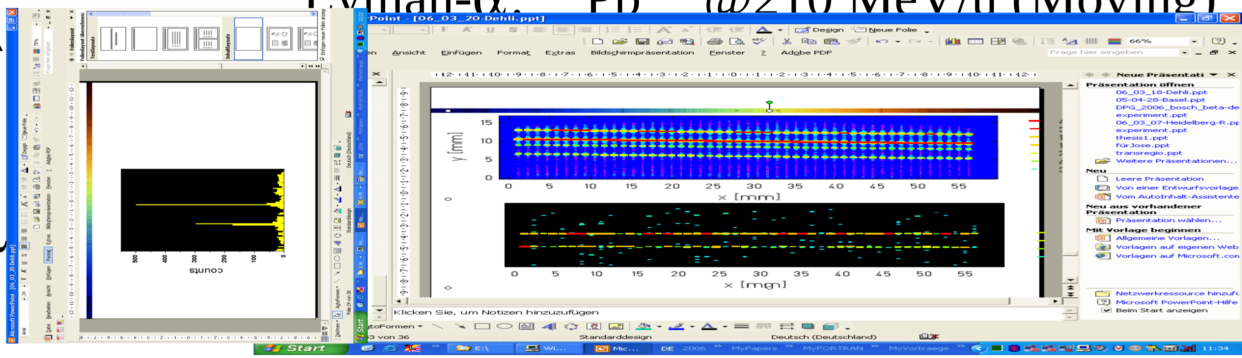
FOCAL

1. Beamtime with a 2d μ-strip detector: March 2006

H. Beyer, R. Reuschl, et al.

Lyman-α: $^{208}Pb^{81+}$ @210 MeV/u (Moving)





Problems:

resolution determined by width of detector strips

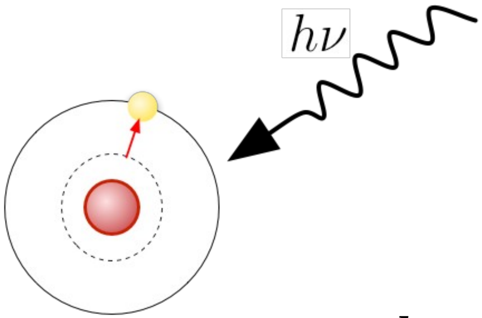
detectors with smaller strips not realistic

Current Development:

sub-pixel resolution via pulse shape analysis

Resonant Coherent Excitation

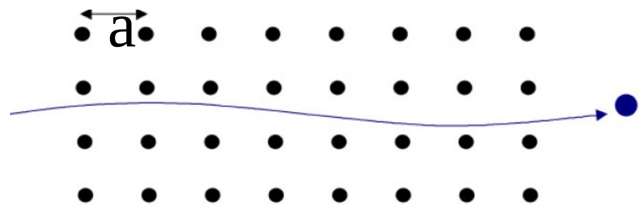
Photoabsorption

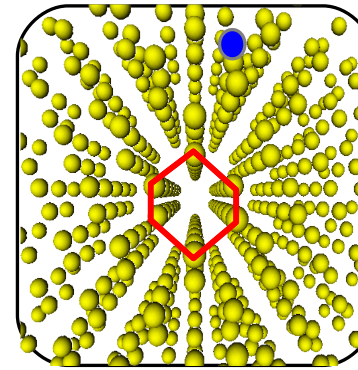


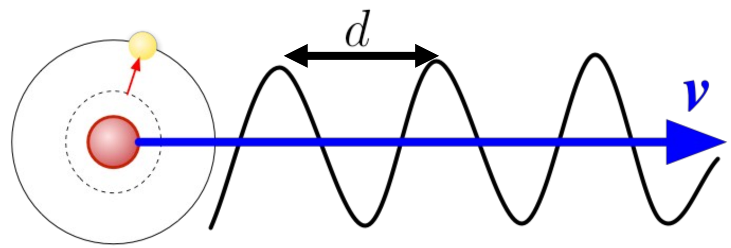
$$E = h\nu$$

photon energy → excitation energy

Periodic Potential







$$E = h\nu = h\frac{v}{d}$$ (non relativistic)

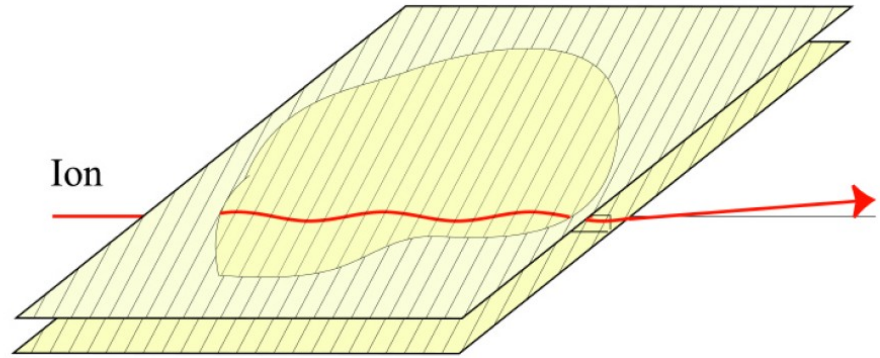
kinetic energy → excitation energy

Resonant Coherent Excitation

planar channeling

$$E_{trans} = \frac{h v \gamma}{a}\left(\sqrt{2}\,k\cos\theta + l\sin\theta\right)$$

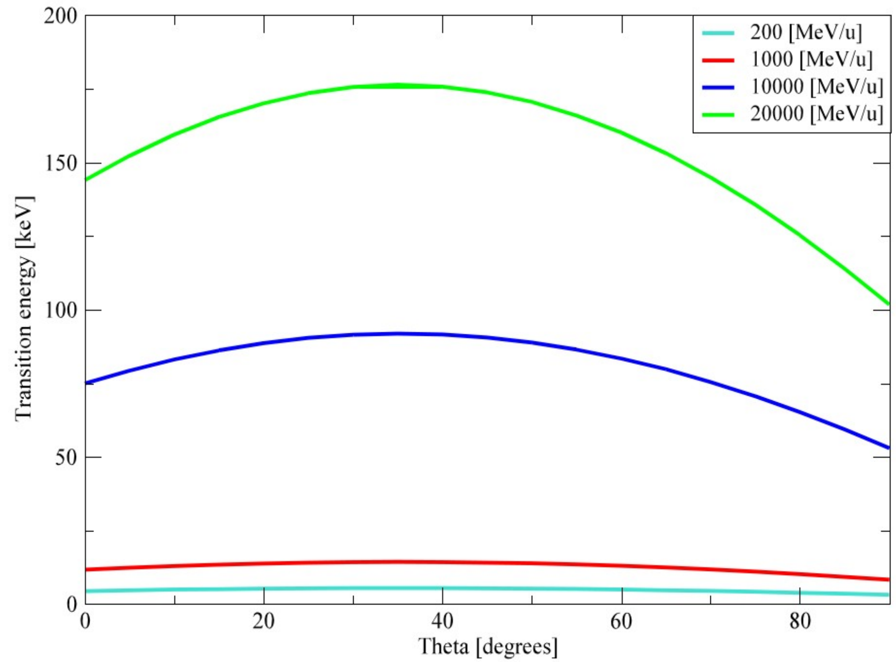
a: lattice constant; k,l,m: Miller-Indices



Tunable source of virtual photons:

coarse tuning: beam energy

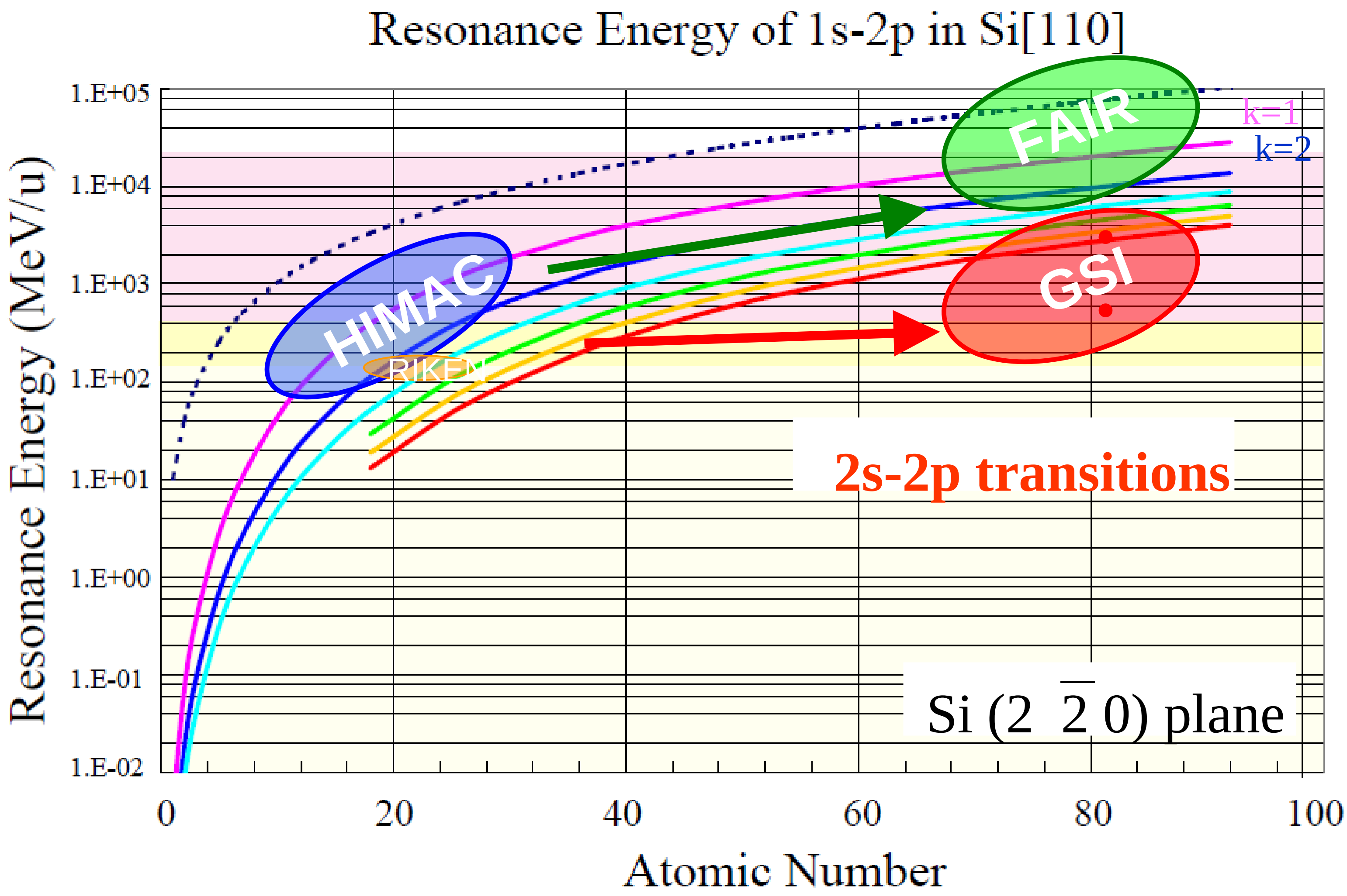
fine tuning: crystal orientation



Simulations: Klimova, Bräuning, Bräuning-Demian

Resonant Coherent Excitation

Condition for 1s - 2p Transitions

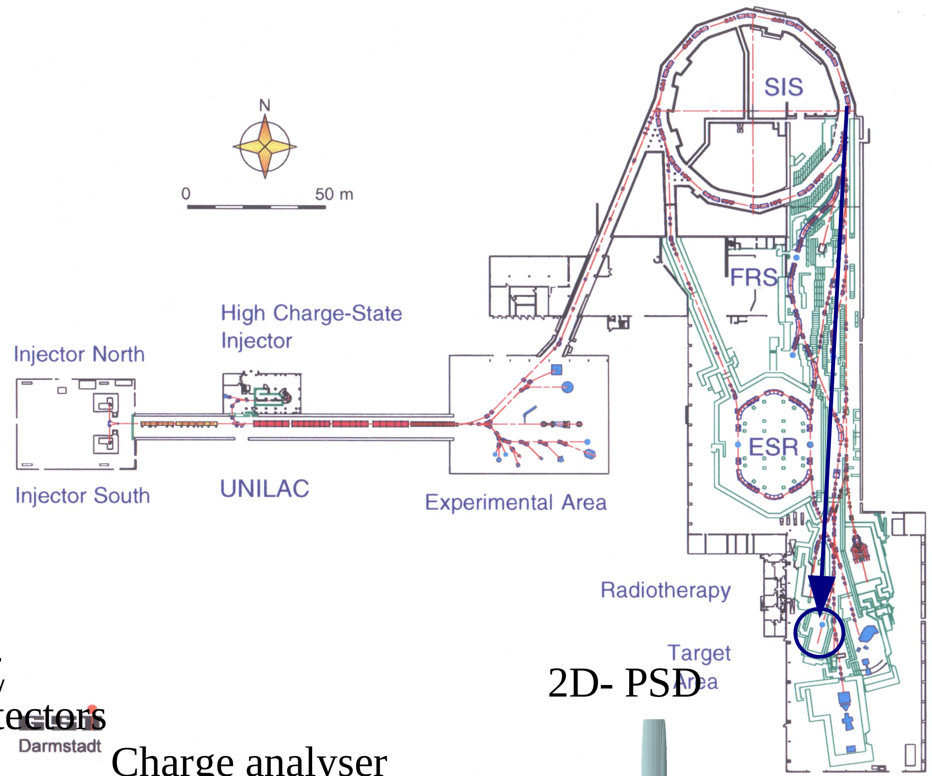


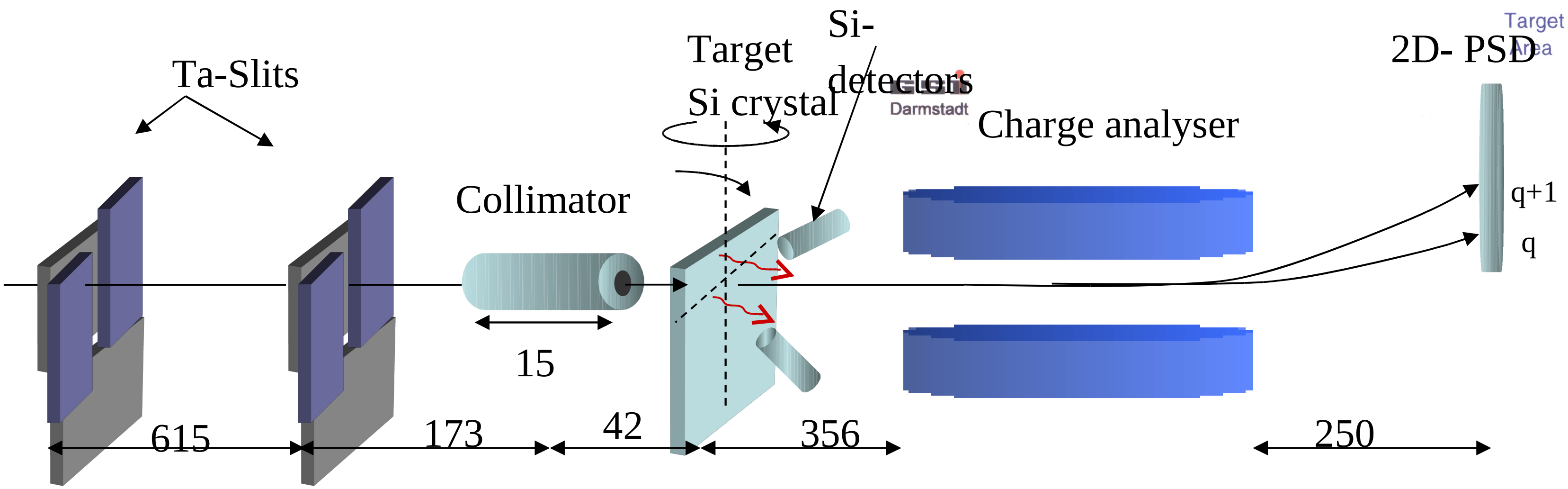
Resonant Coherent Excitation

First Beamtime: Sep. 2009 in Cave A

Li-like U^{89+}

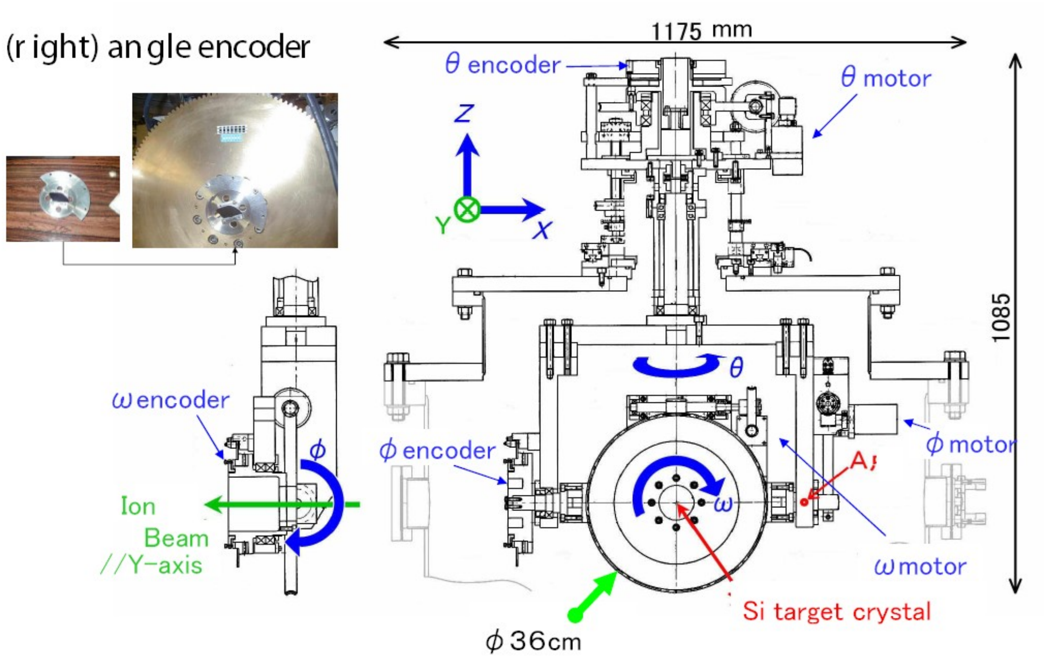
direct SIS beam

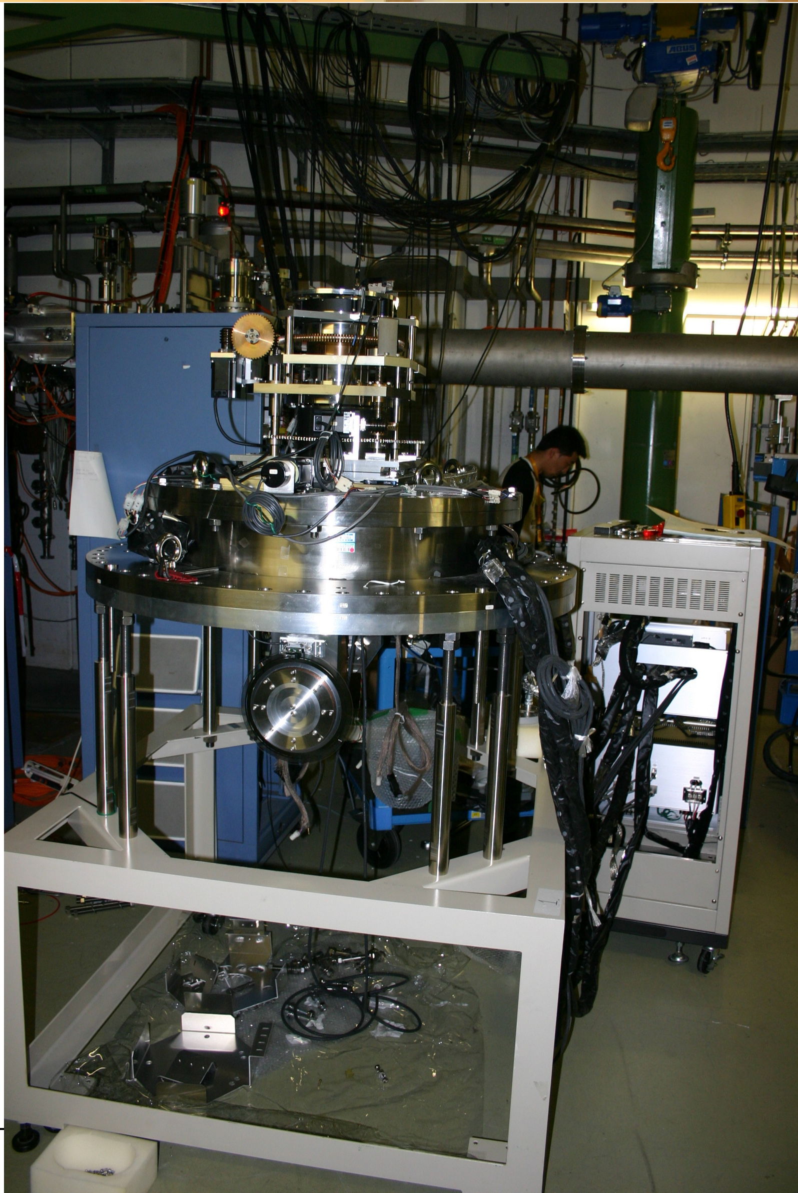




Resonant Coherent Excitation

5 axis goniometer

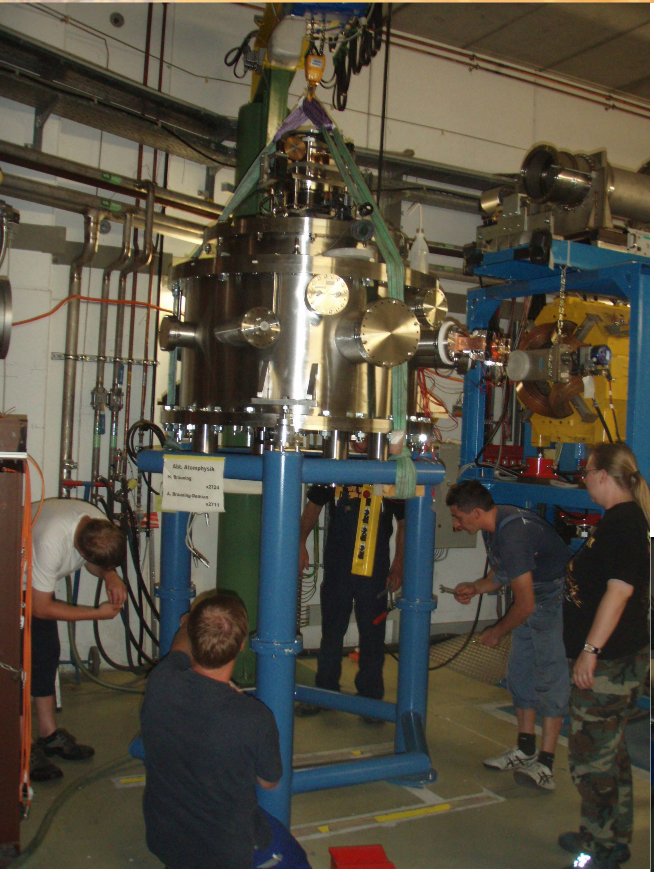




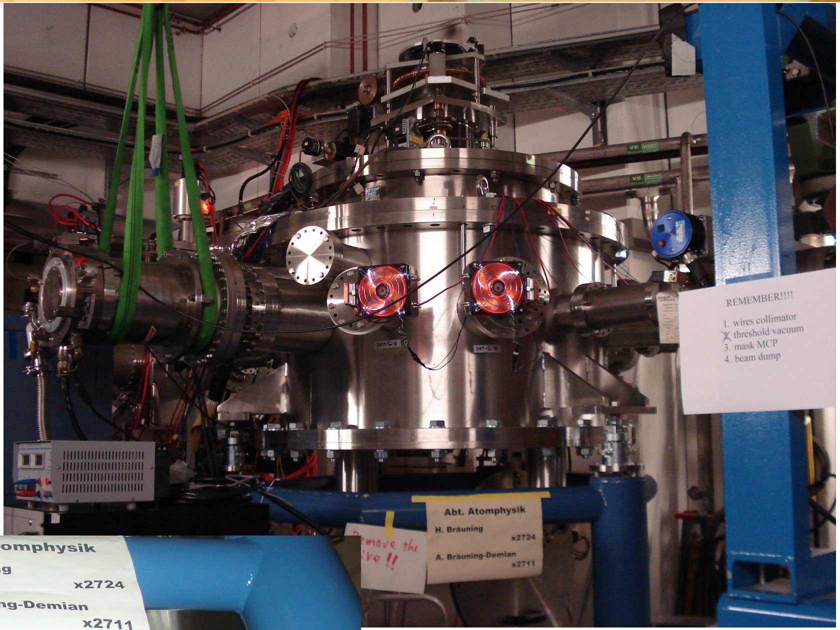
0.4 μrad angular resolution

Made in Japan

Resonant Coherent Excitation

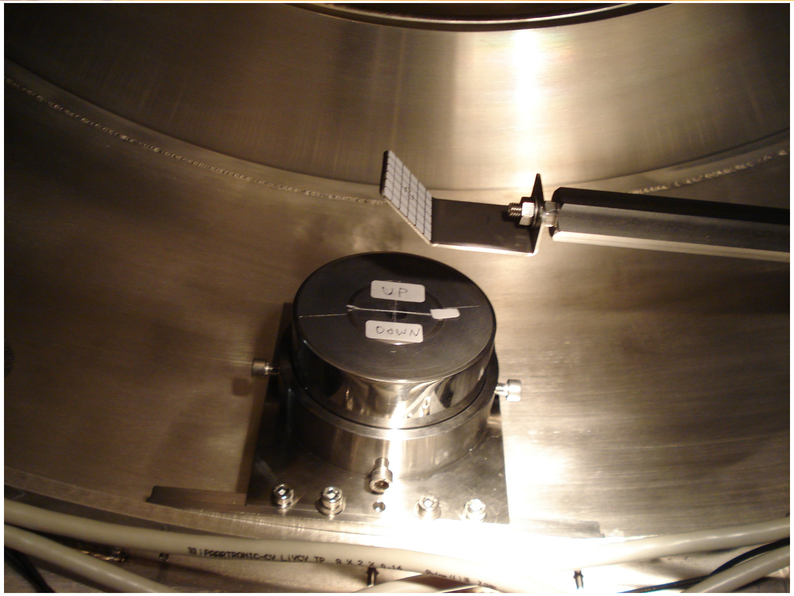


Target Chamber

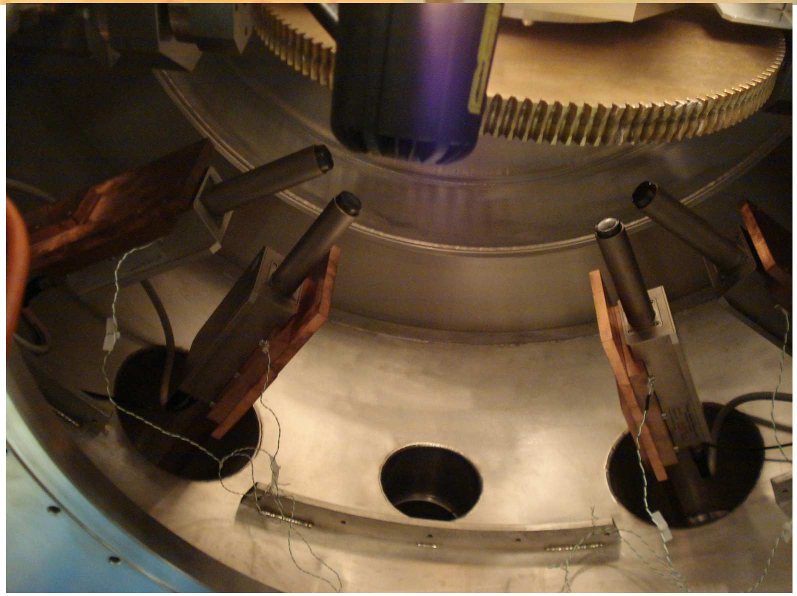


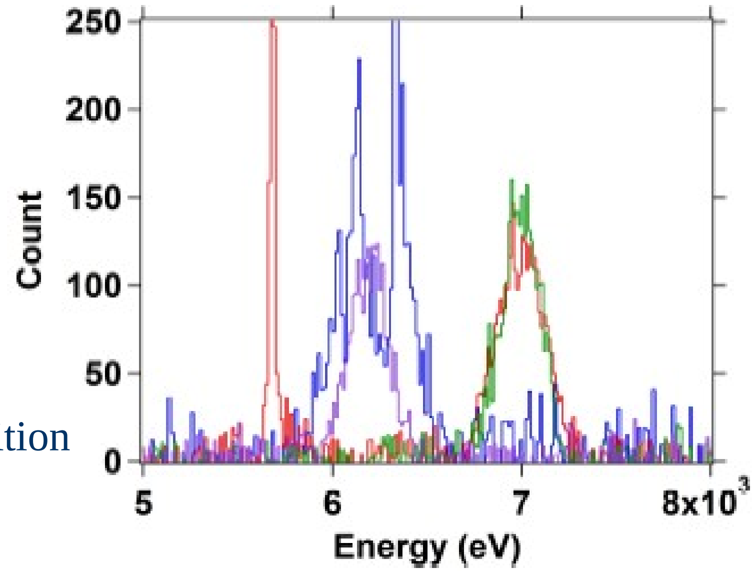
Made in Germany

Resonant Coherent Excitation



Beam Diagnostics



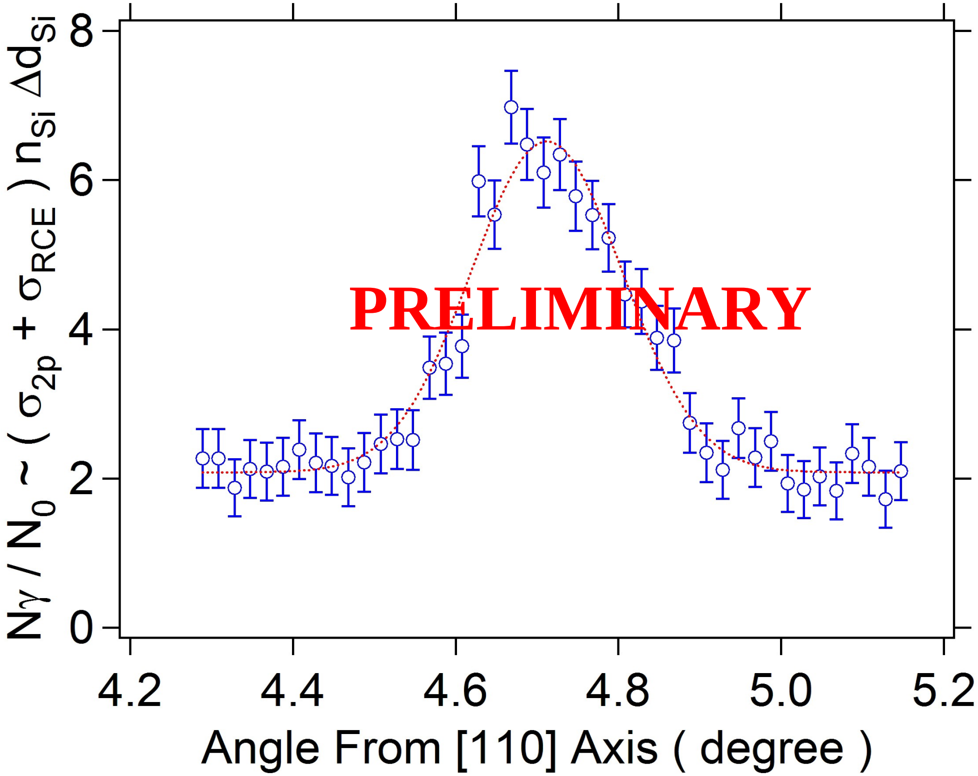


detection of the 2p → 2s transition

Observation angles: ±43.4 deg and ±32.8 deg

E_{lab}= 6.97 KeV and 6.25 keV for the 4.4 6 keV Uranium transition

Resonant Coherent Excitation



Detected x-rays as function of crystal orientation

Peak position (fit): 4.712(4) deg; width: 0.093(4) → E_{ion} = 191.5 (4) MeV/u

E_{acc} = 191.6 MeV/u

Resolution 10^{-3} is compatible with beam ΔE/E and estimated divergence

Resonant Coherent Excitation

Tokyo University & RIKEN
Y. Takano
Y. Nakano
Y. Kanai
R. Yoshida
T. Azuma
Y. Yamazaki
T. Ikeda

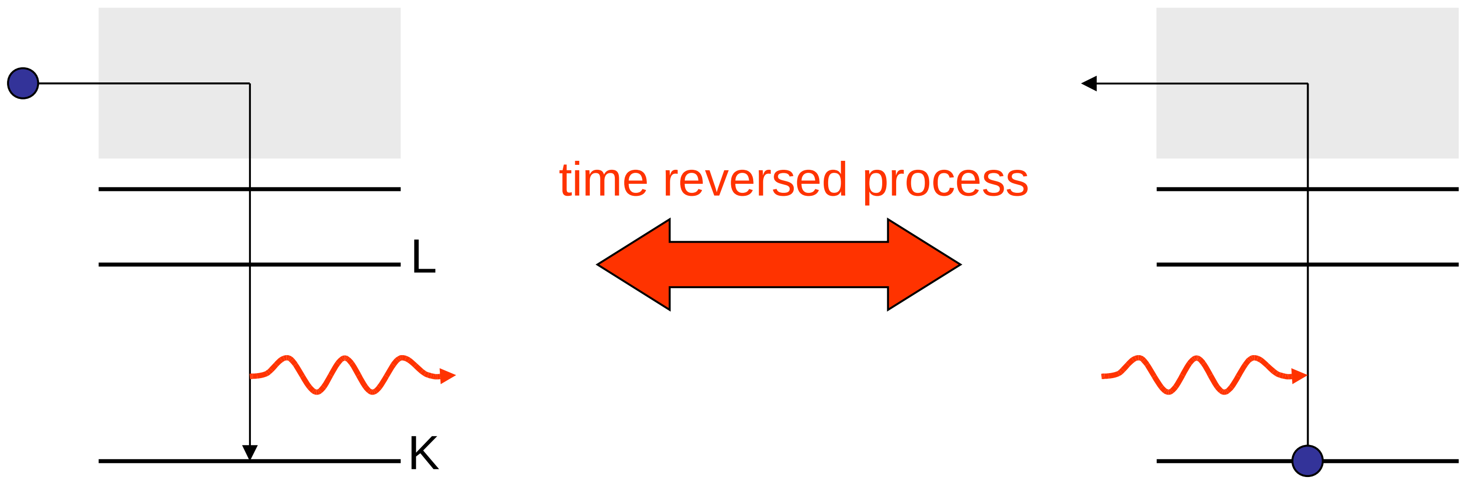
IPN Lyon
D. Dauvergne

GSI
H. Braeuning
A. Braeuning-Demian
D. Racano
A, Bardonner

Tomsk University
K. Klimova
Y. Pivovarov

Radiative Electron Capture

REC | Photoionization

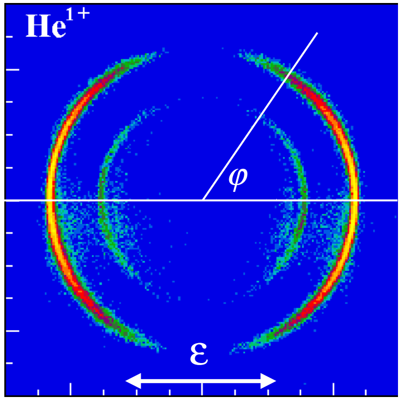


Polarization

photoelectron angular distribution

$$I_e \sim \sin^2\theta \cos^2\varphi$$

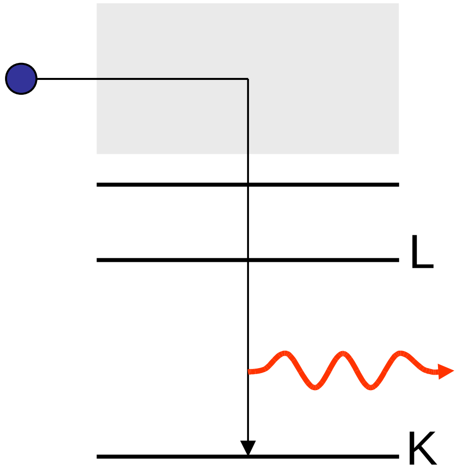
emission predominantly within the plane of the electric field



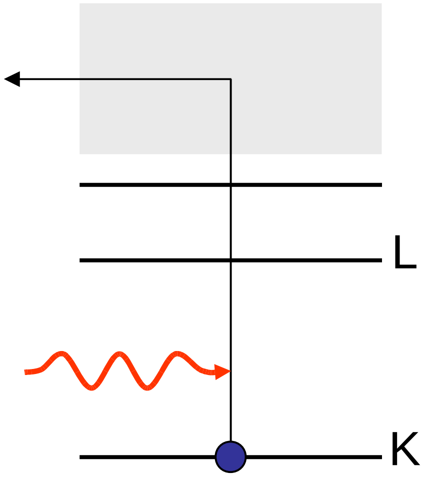
H. Stobbe, Ann. Phys. 7 (1931) 661

Radiative Electron Capture

REC

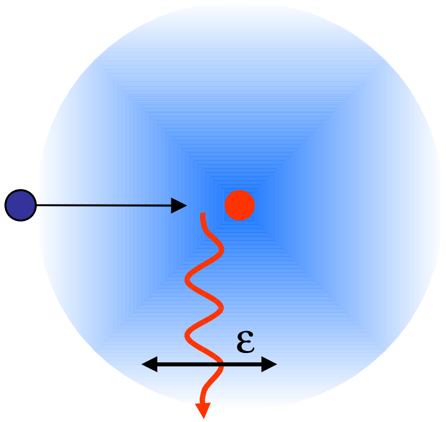


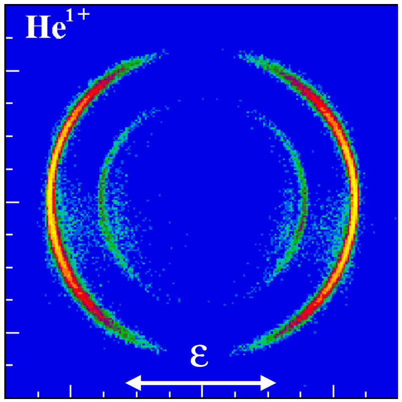
Photoionization



time reversed process

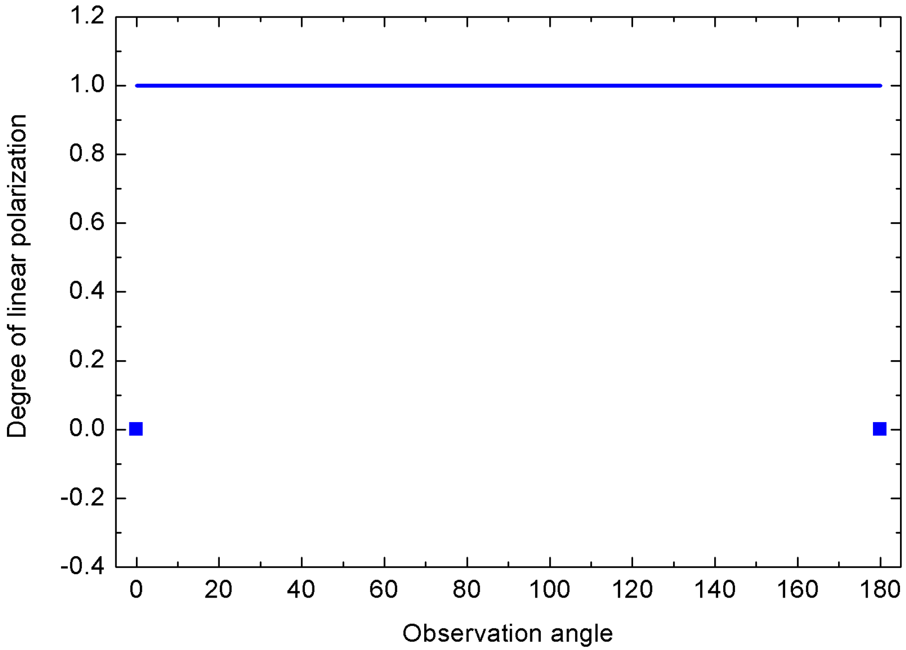
Polarization



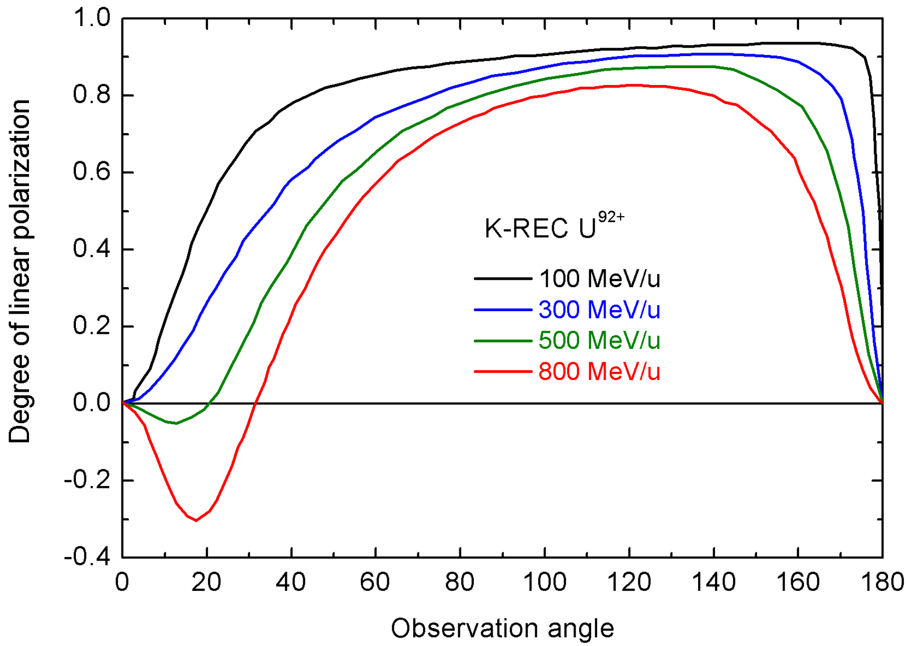


Radiative Electron Capture

non-relativistic



relativistic



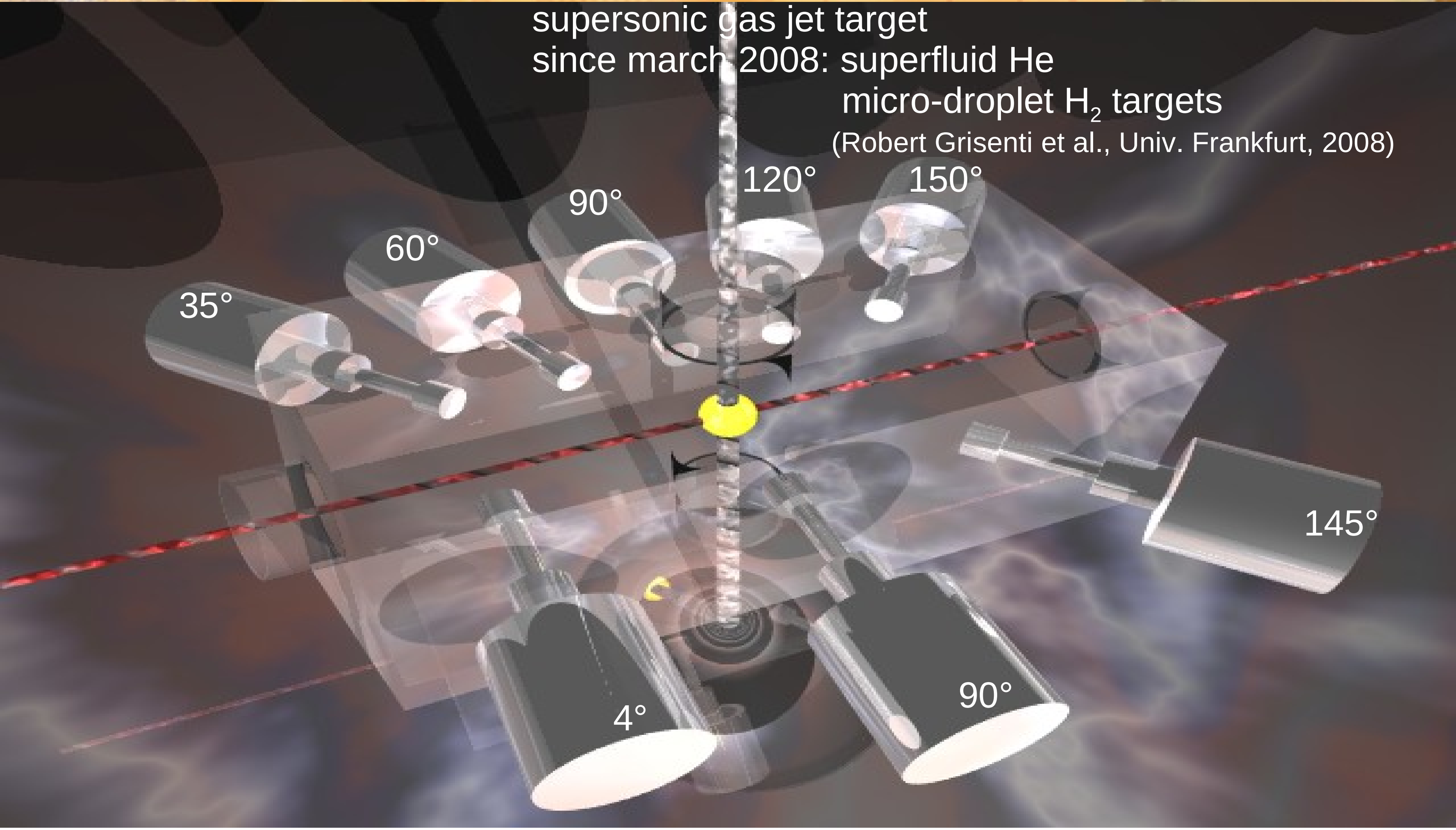
Relativistic effects decrease the linear polarization

For high energies a "cross-over" effect can be observed

F. Sauter, Ann. Phys. 9 (1931) 21

A.Surzhykov et al., Phys. Lett. A 289 (2001) 213; J. Eichler et al., Phys. Rev. A 65 (2002) 052716

ESR Internal Target Section



Compton - Polarimetry

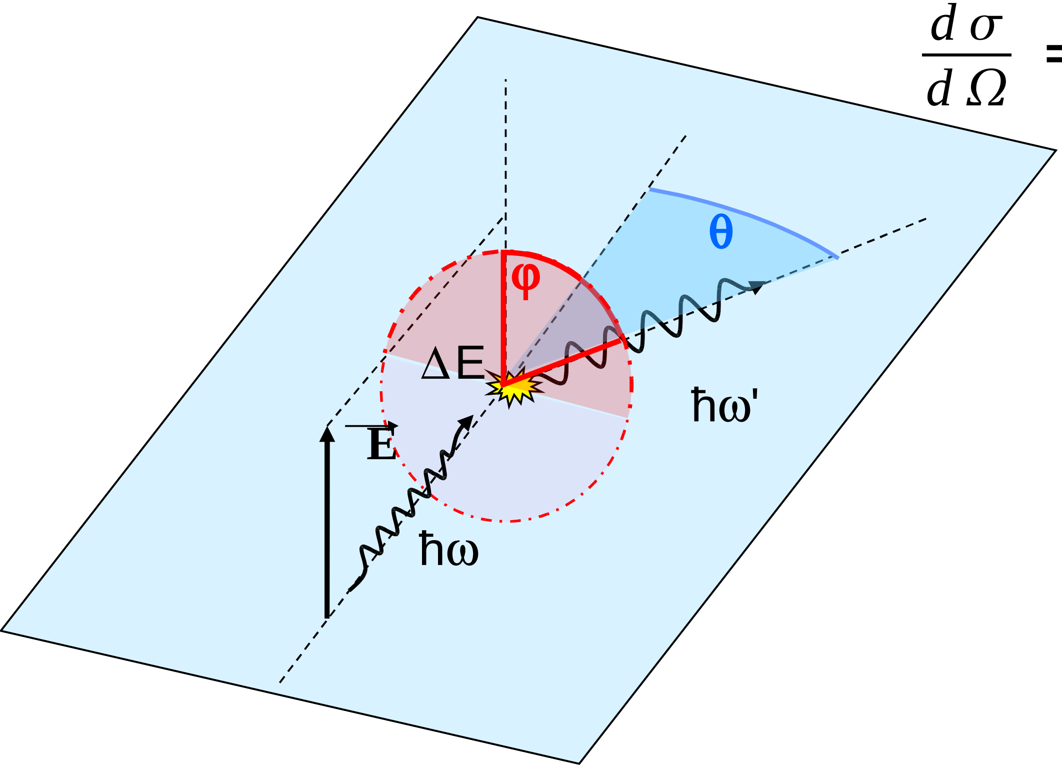
Compton - Scattering

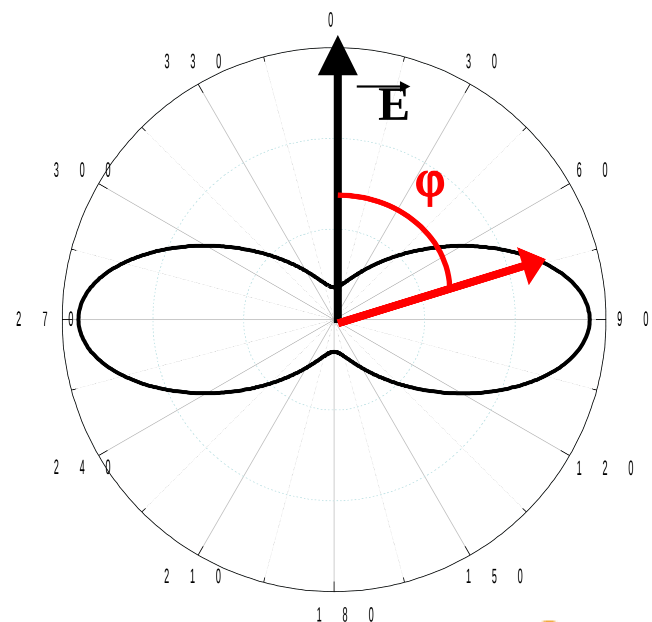
Linearly Polarized

Radiation

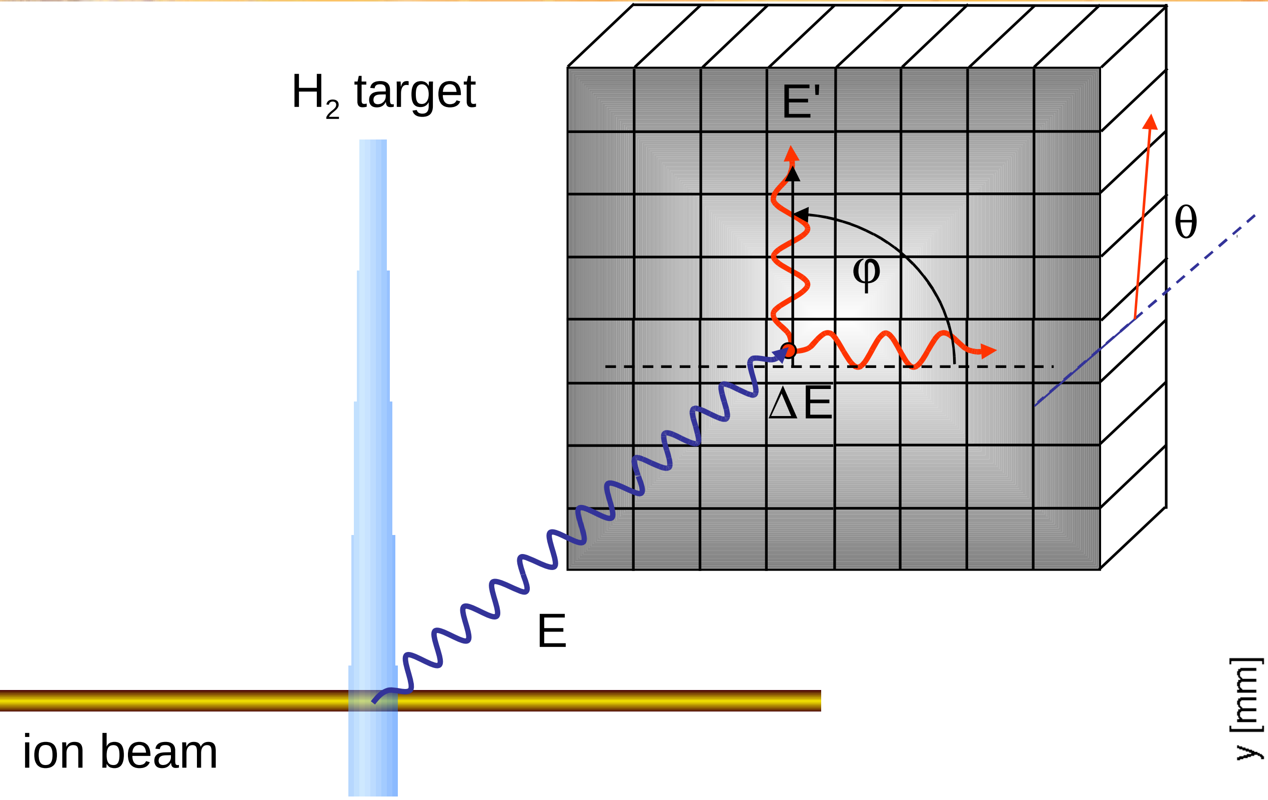
Klein-Nishina equation

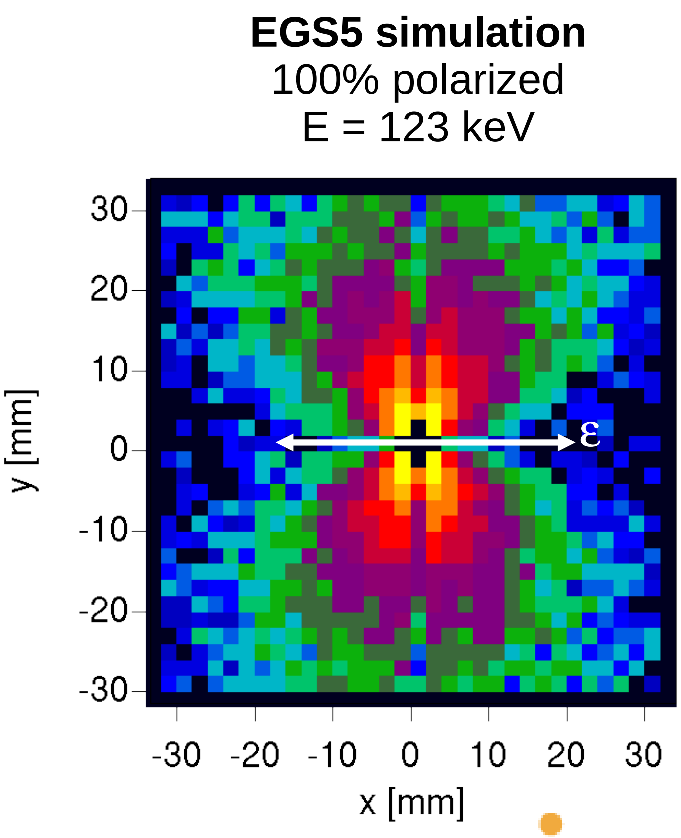
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'}{E}\right)^2 \left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right)$$





Compton - Polarimetry

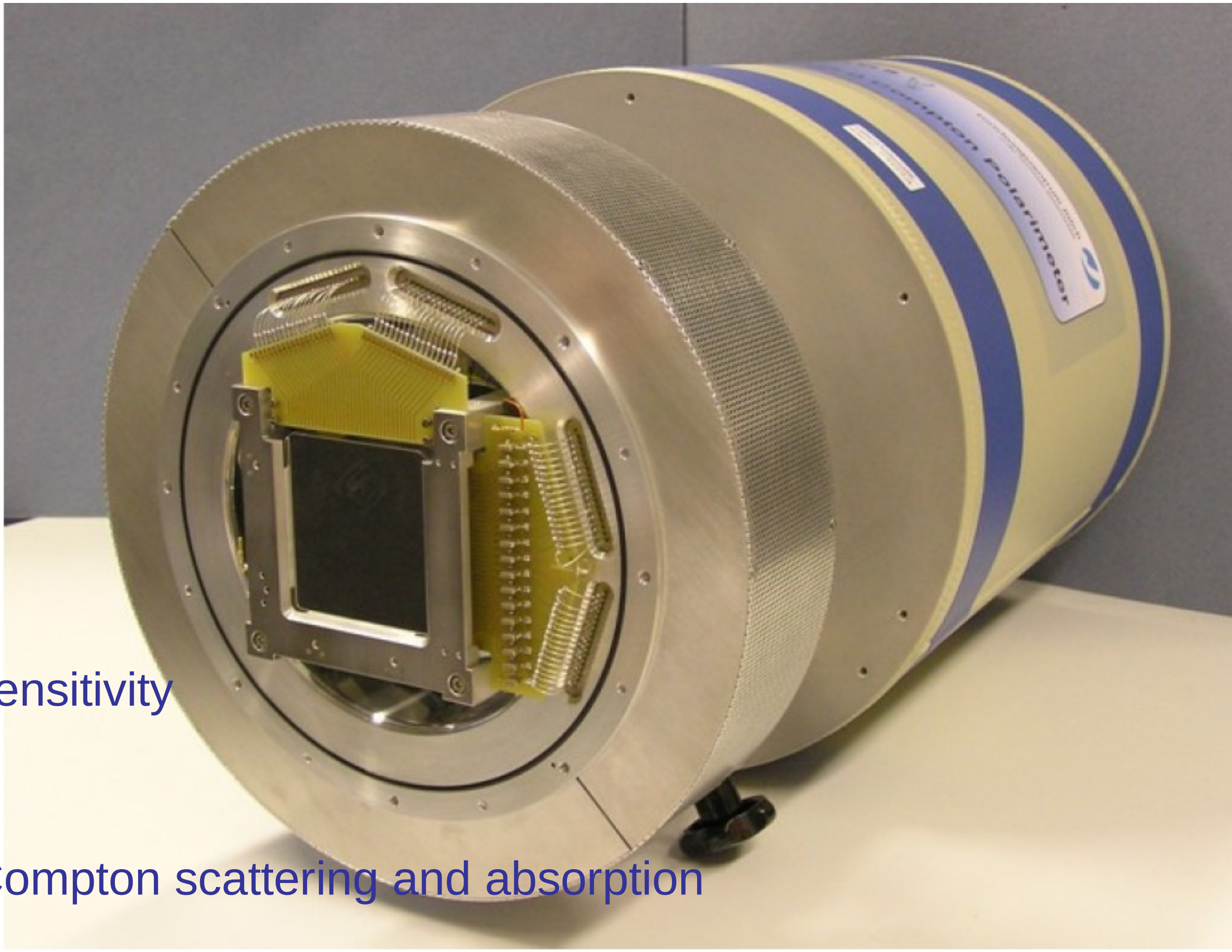




$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'}{E}\right)^2 \left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\varphi\right)$$

Micro – Strip Detectors

New micro-strip semiconductor detectors

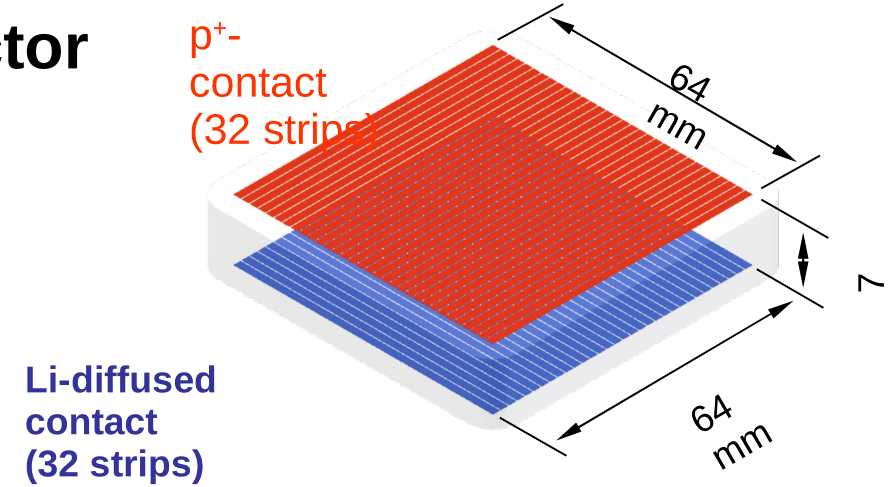


- Si(Li) or Ge(i)
- energy resolution
- timing
- 2D (3D) position sensitivity
- multi-hit capability
- single crystal for Compton scattering and absorption

Micro – Strip Detectors

2D position sensitive Si(Li) detector

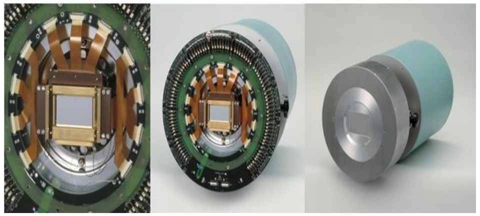
active area: 64 x 64 mm²
crystal thickness: 7 mm
number of strips: 32 + 32
pitch: 2mm



2D position sensitive Ge(i) detector

active area: 64 x 64 mm²
crystal thickness: 11 mm
number of strips: 48 + 128
pitch: 1167µm and 250µm

2D µSTRIP germanium detector
J-GSI

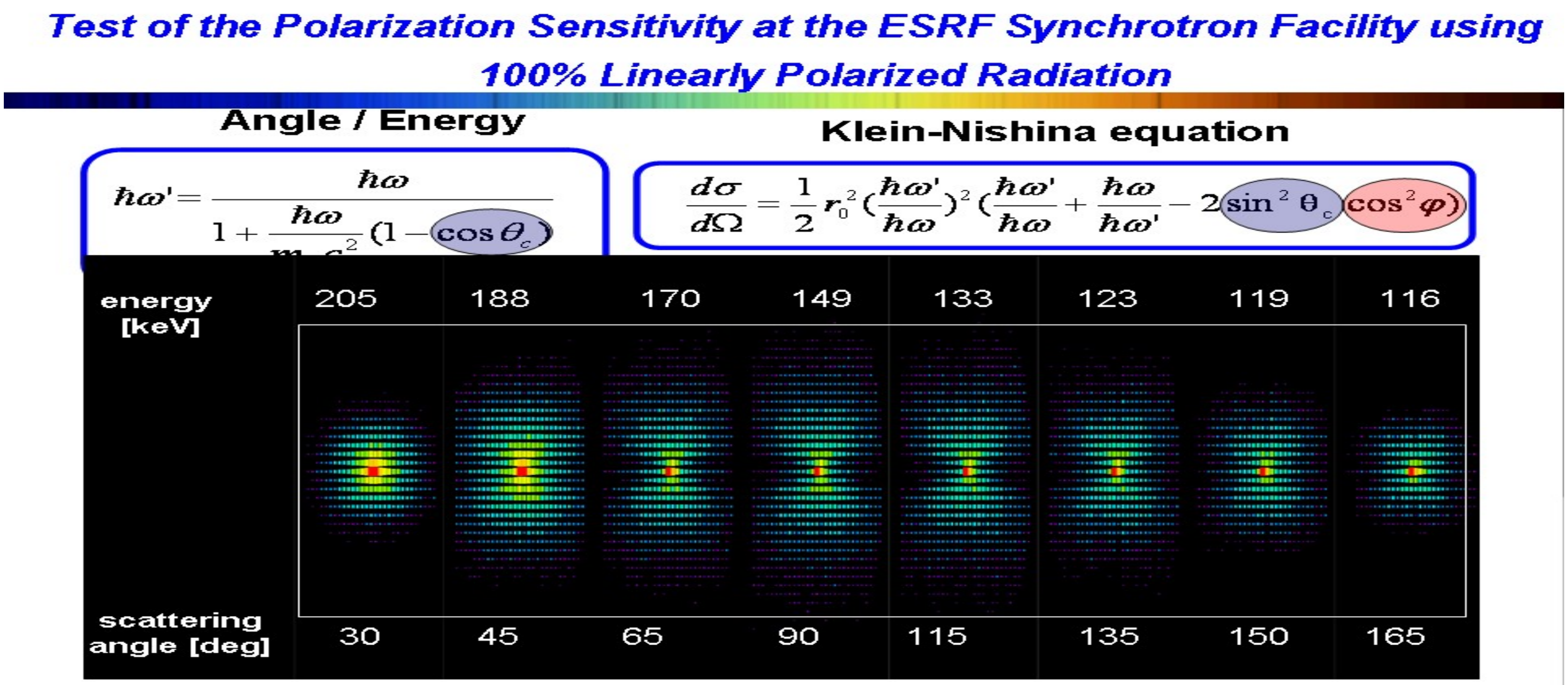


Compton - Polarimetry

Images of Compton scattering distributions for well defined scattering angles

Energy ↔ Angle

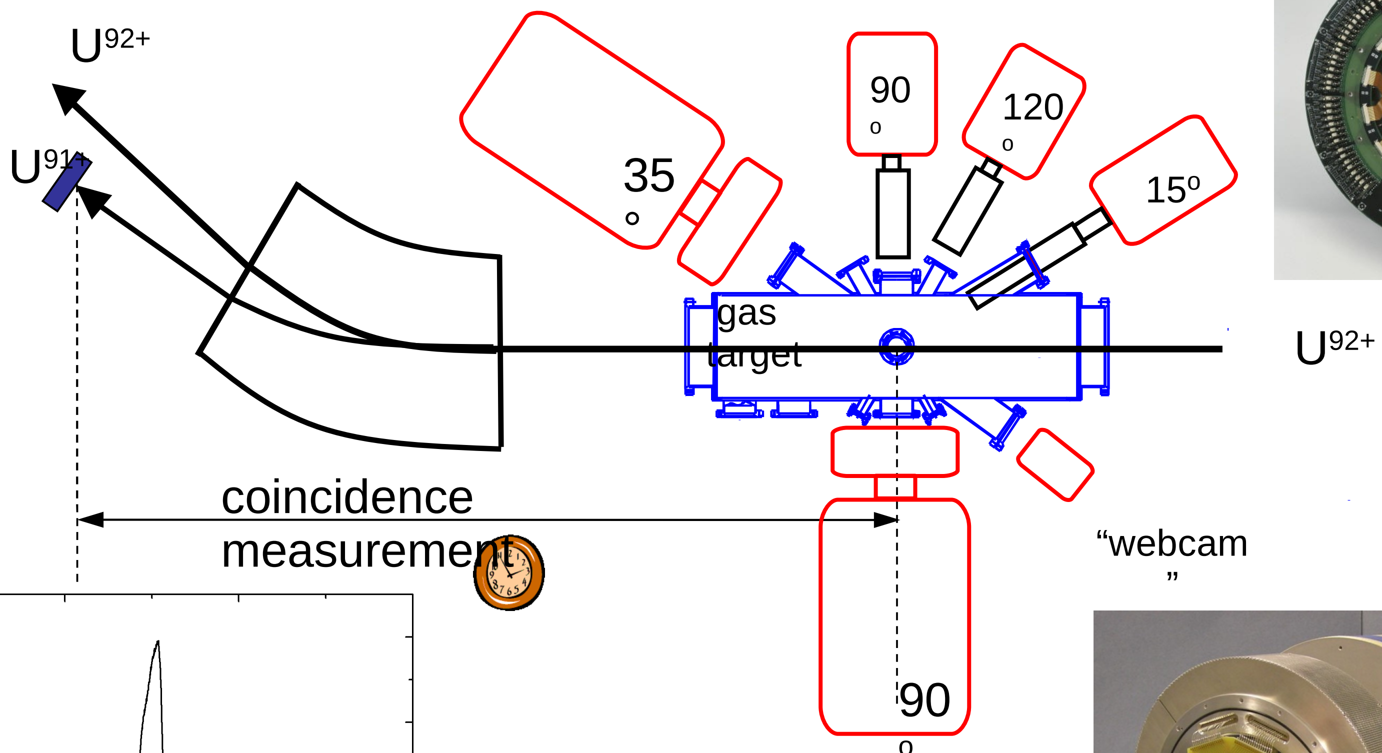
$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta_c)}$$

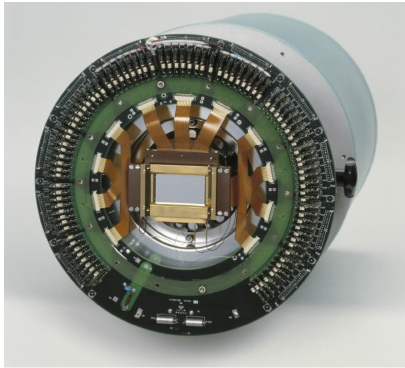


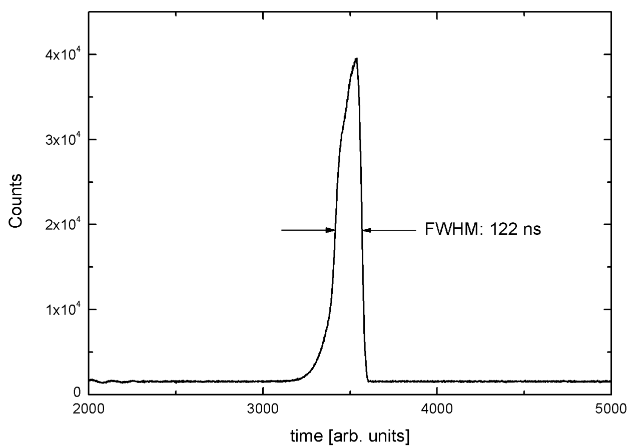
Results of a test beamtime at the ESRF with 98% linearly polarized x-rays

Experimental Set-Up

Ge(i) polarimeter

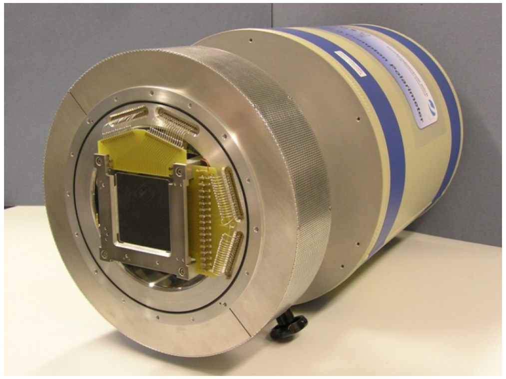






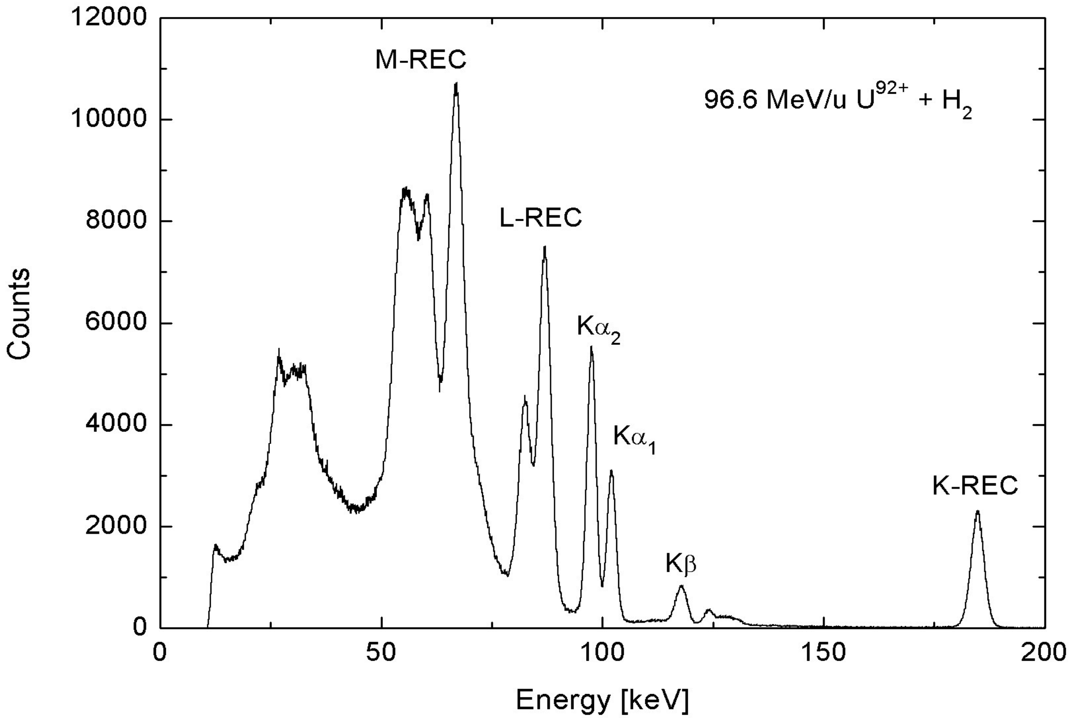
Si(Li) polarimeter

“webcam”



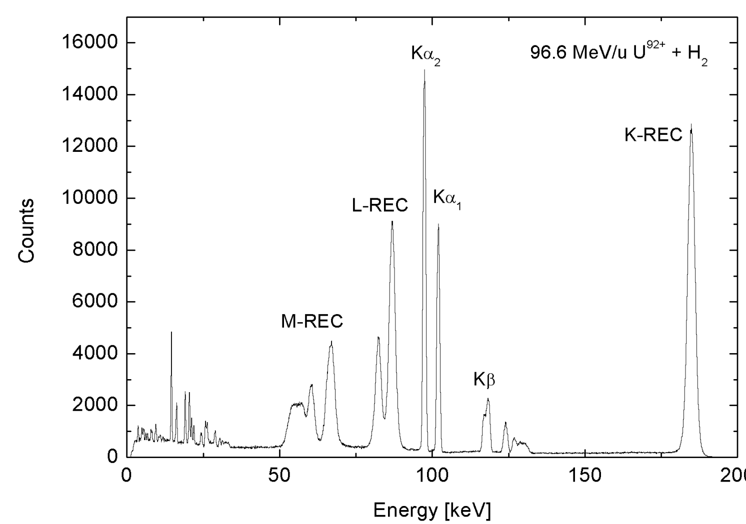
96.6 MeV/u U^{92+} + H_2

X-ray spectrum after electron capture



Si(Li) polarimeter

conventional Ge(i) detector

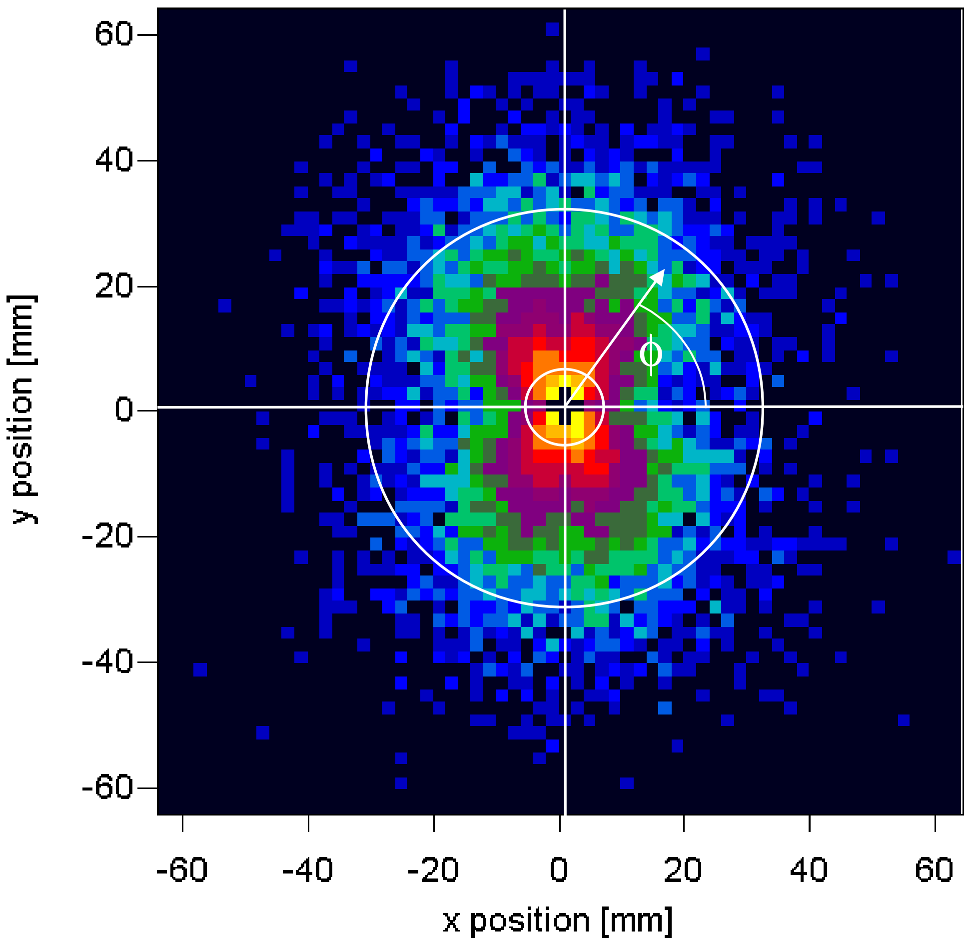


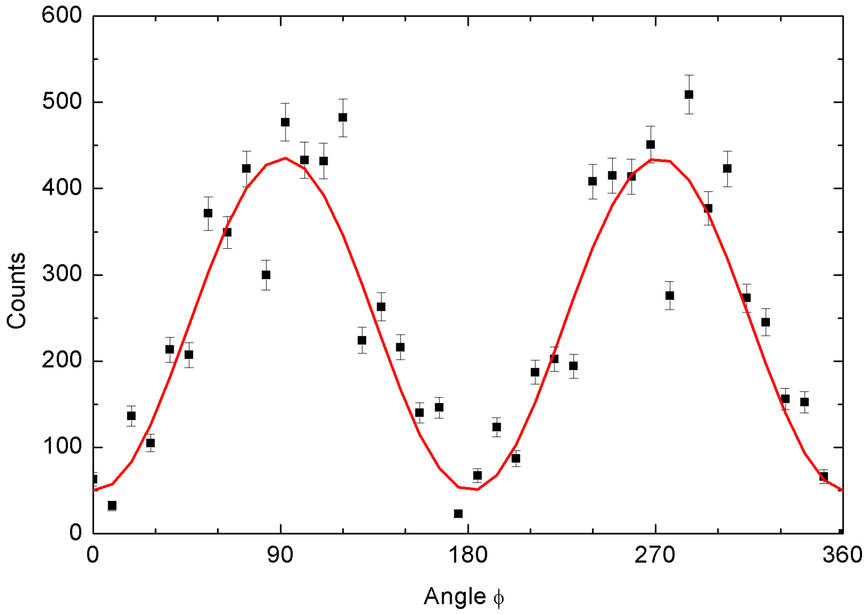
energy resolution: 2.2 keV at 98 keV (Kα_2 line)

total acquisition time: 82h

96.6 MeV/u U^{92+} + H_2

K-REC

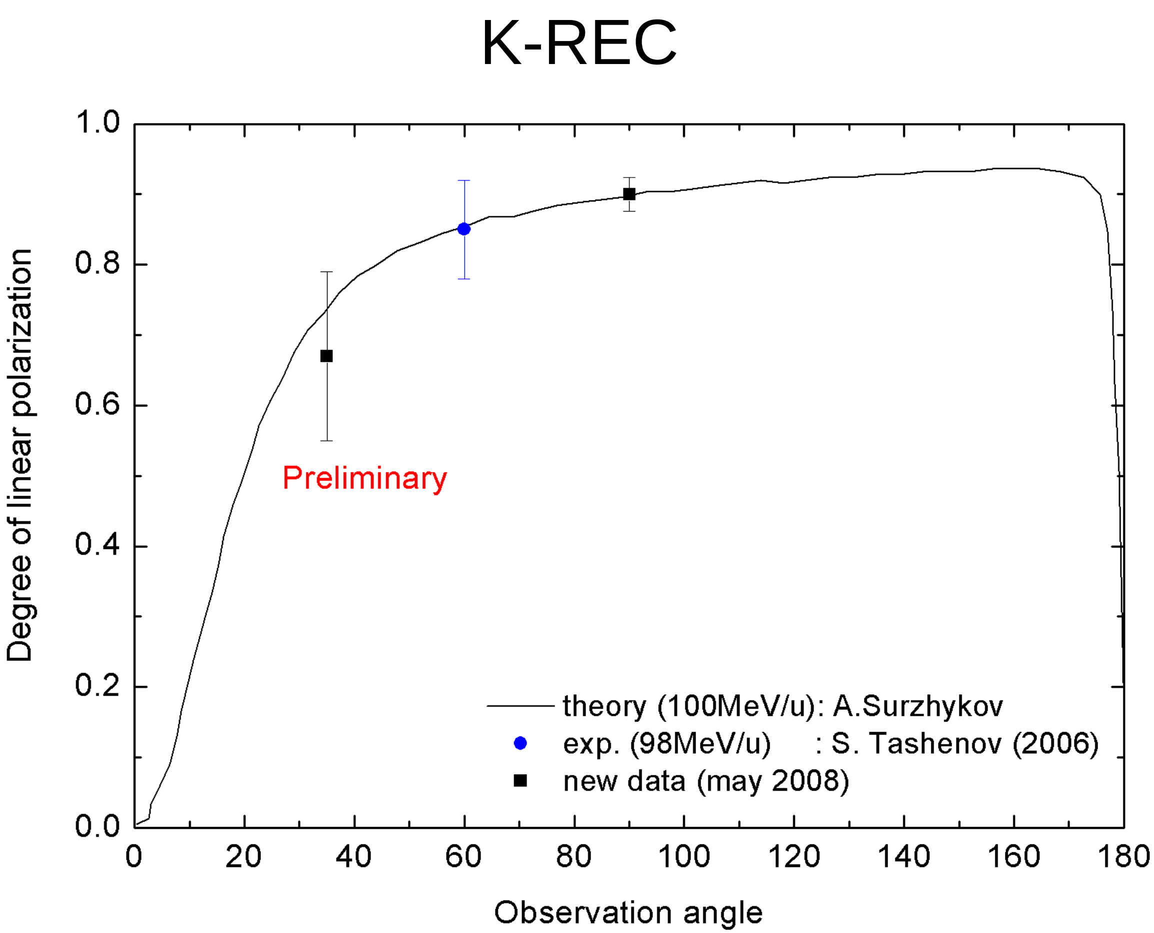




Compton scattering angle:

$\theta = 90° \pm 10°$

96.6 MeV/u U^{92+} + H_2



Doktorarbeit: S. Hess

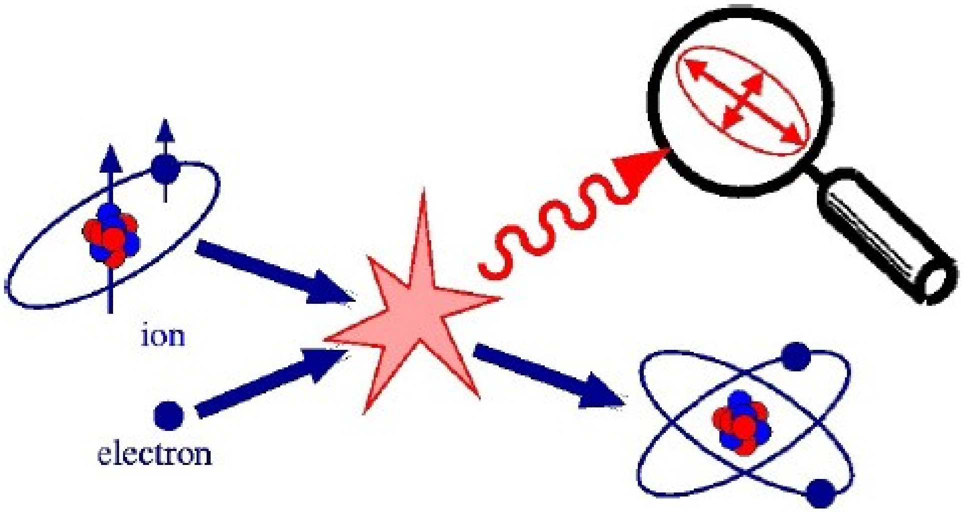
Future Applications in Beam Diagnostics

REC as a 'probe' for measuring the ion spin-polarization

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

spin-polarized, heavy ions (Z > 54)

- parity non conservation studies
- permanent electric dipole moment
- spin effects in collisions
- . . .

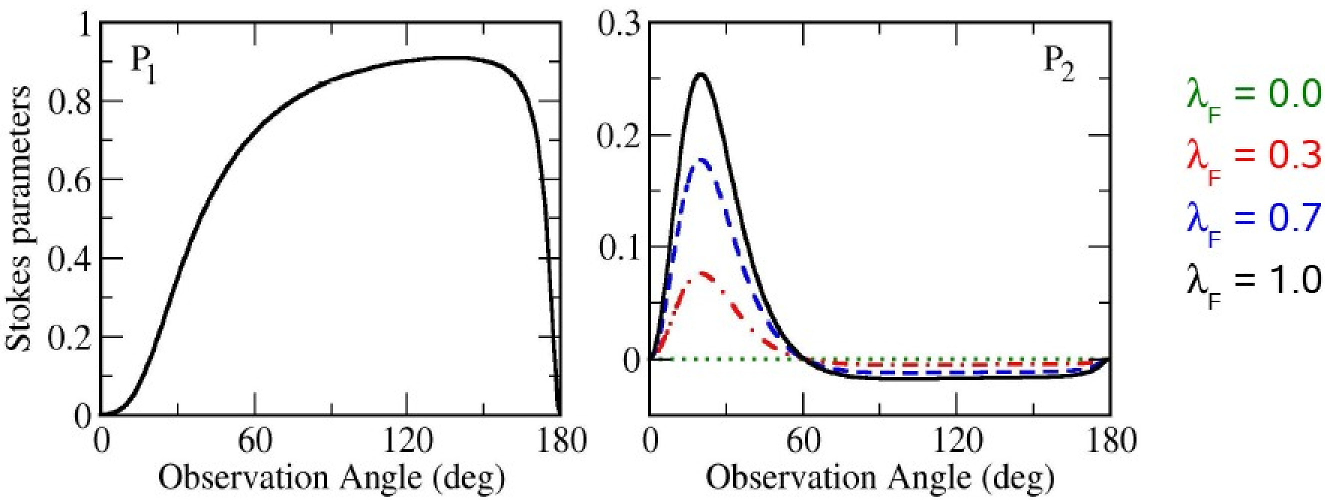


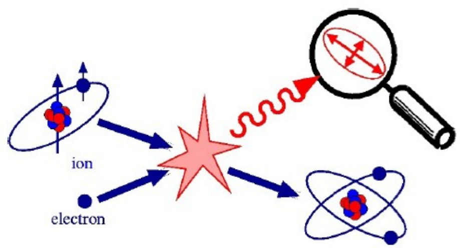
Future Applications in Beam Diagnostics

REC as a 'probe' for measuring the ion spin-polarization

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

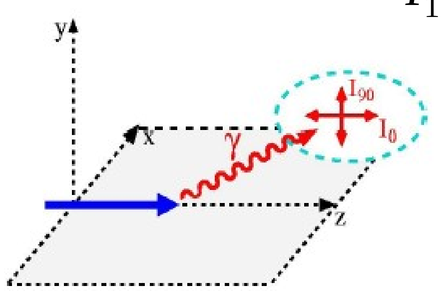
420 MeV/u Bi^{82+} (I=9/2)

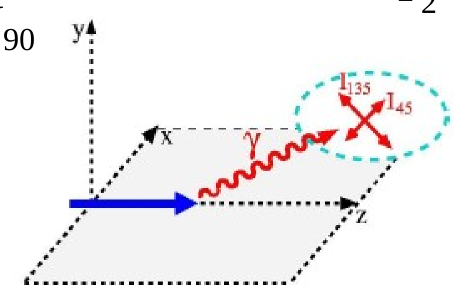




$$P_1 = \frac{I_0 - I_{90}}{I_0 + I_{90}}$$

$$P_2 = \frac{I_{45} - I_{135}}{I_{45} + I_{135}}$$





Future Applications in Beam Diagnostics

REC as a 'probe' for measuring the ion spin-polarization

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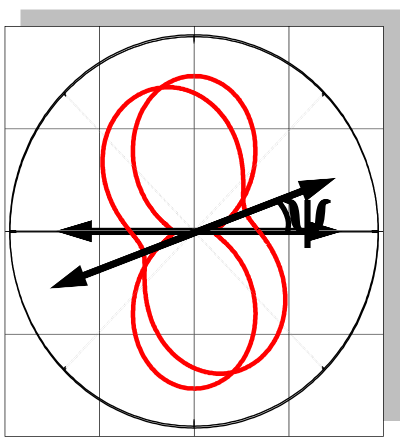
Stokes parameter P_1 is polarization independent

Stokes parameter P_2 is strongly dependent on degree of polarization

spin polarization leads to a rotation of the polarization plane



<unpolarized ion beam>

<spin polarized ion beam>

unpolarized ion beam: $P_2 = 0$

polarized ion beam: $P_2 \neq 0$

$$\tan 2\Psi = \frac{P_2}{P_1}$$

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

The Crew

rov, R. Reuschl, D. Protic, U. Spillmann, Th. Stöhlker, M. Trassinelli, S. Trotsenko, G. Webe

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. . . and many more

Ende