Position sensitive x-ray detectors applied to Compton polarimetry of hard x-ray radiation

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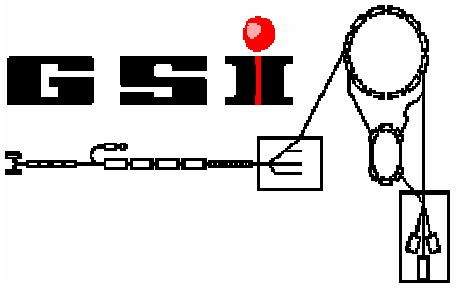
Physikalisches Institut

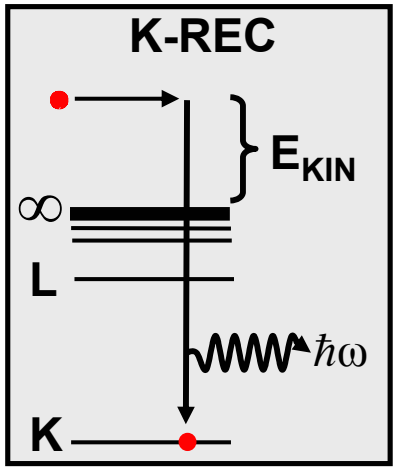


Outline of the Talk

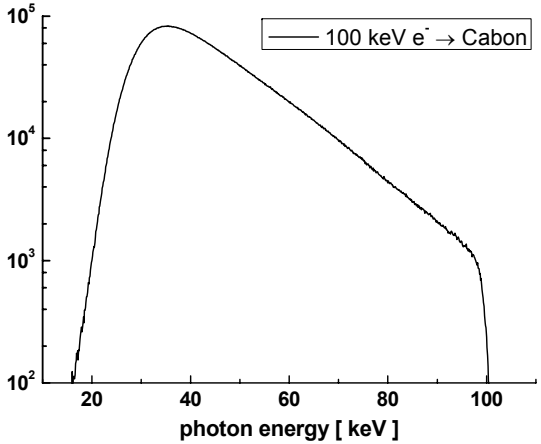
- Introduction to Compton Polarimetry
- Recent measurements at the ESR storage ring
  → Radiative Electron Capture (REC)
  → Lyman-α_1 radiation
  → Elektron-Nucleus Bremsstrahlung
- Bremsstrahlung measurements at the polarized electron source SPIN at TU Darmstadt
  (very preliminary)
- Summary & Outlook

Where do we find polarized x-rays?

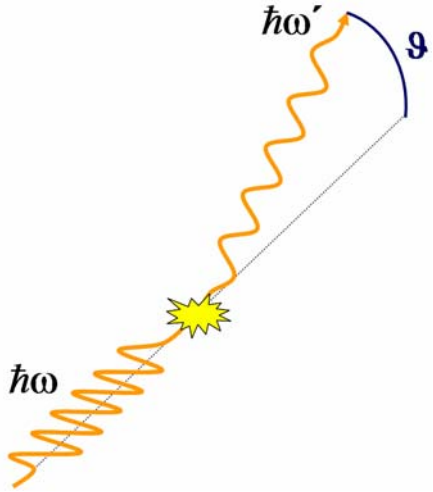
RR/REC process



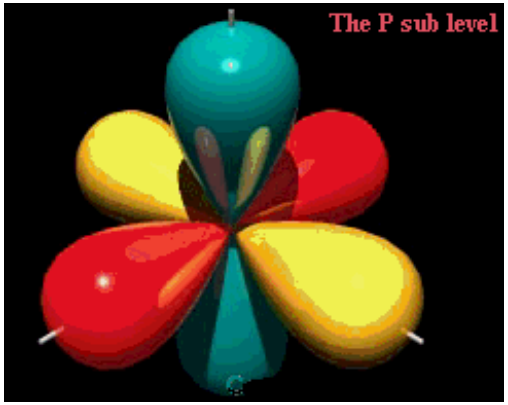
Bremsstrahlung



X-ray scattering (Compton, Rayleigh)



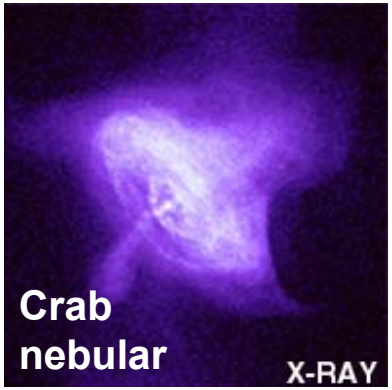
Aligned atomic systems



Synchrotron radiation

ESRF

Astronomy



Why should we care?

General interest

Revealing subtle details of atomic dynamics and structure
(Lyman radiation in H-like systems)

Of special interest, if angular distribution is not accessible
(EBIT, Astronomy)

Possible applications ?
(Ion beam spin diagnosis, Imaging, Material science)

But: Precise polarimetry studies in the hard x-ray regime are quite challenging.

Polarimetry Techniques

Liquid Crystals

Crystal Optics

Bragg Reflection

Photoionization

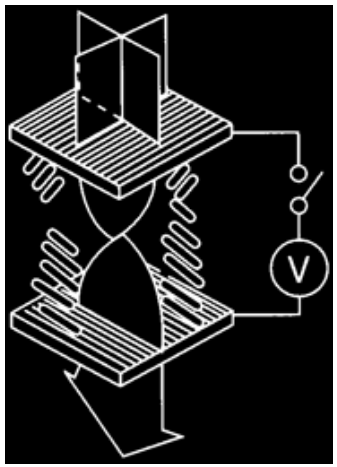
Thomson Scattering

Compton Scattering

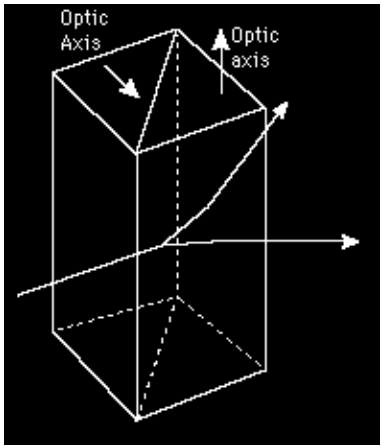
Pair Production

10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

photon energy [keV]



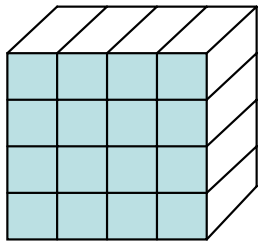
LCD



Prism

Micropattern Gas Counters

x-ray Optics

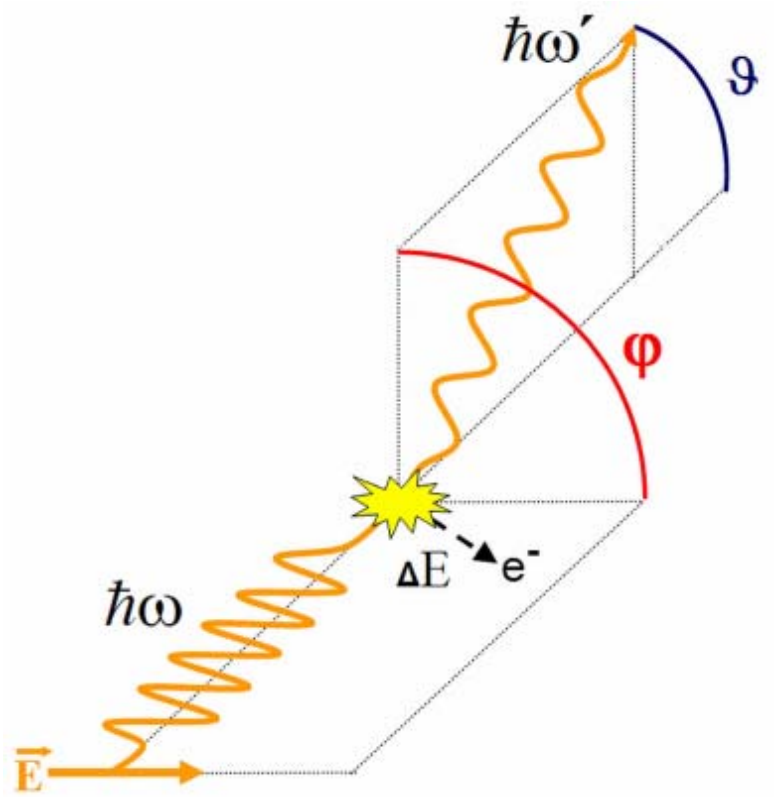


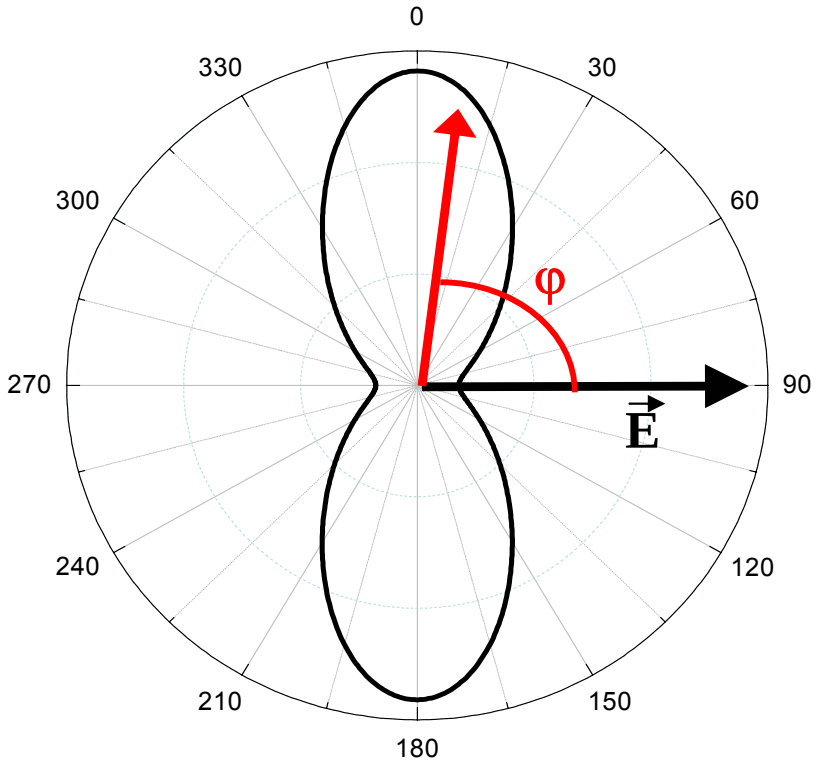
Segmented Solid State Detectors

Polarization Measurement via Compton Scattering

Klein-Nishina Equation for Compton Scattering:

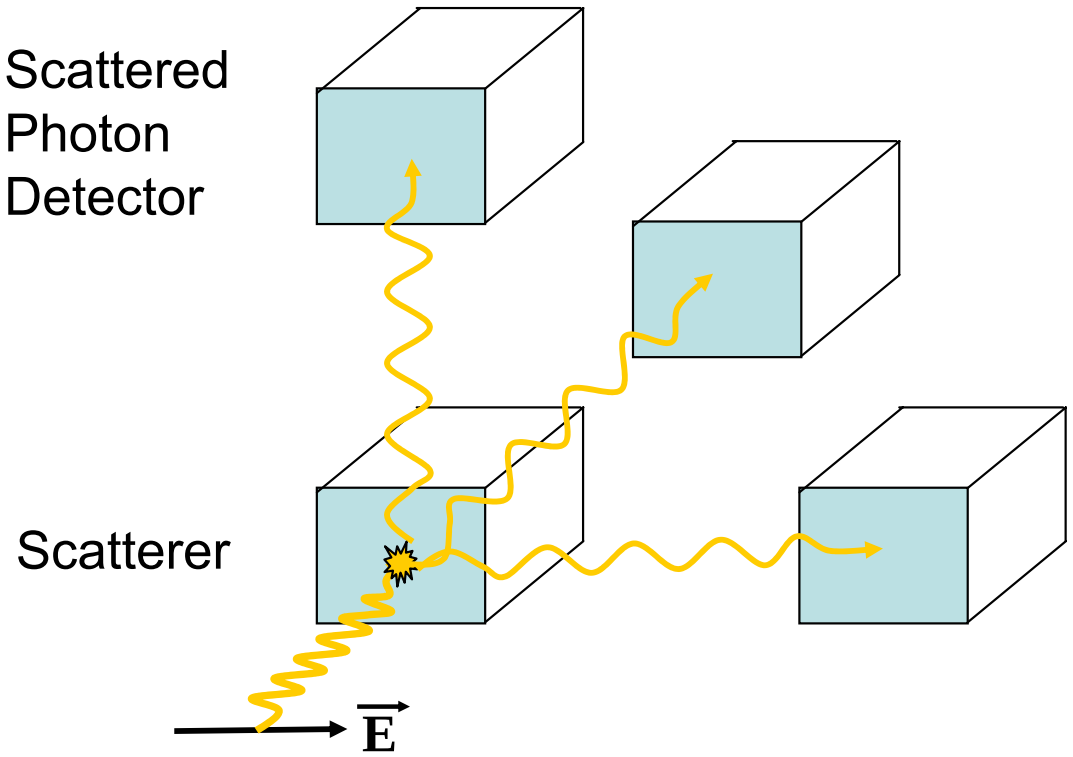
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_0^2 \left(\frac{\hbar\omega'}{\hbar\omega}\right)^2 \left(\frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - 2\right)$$

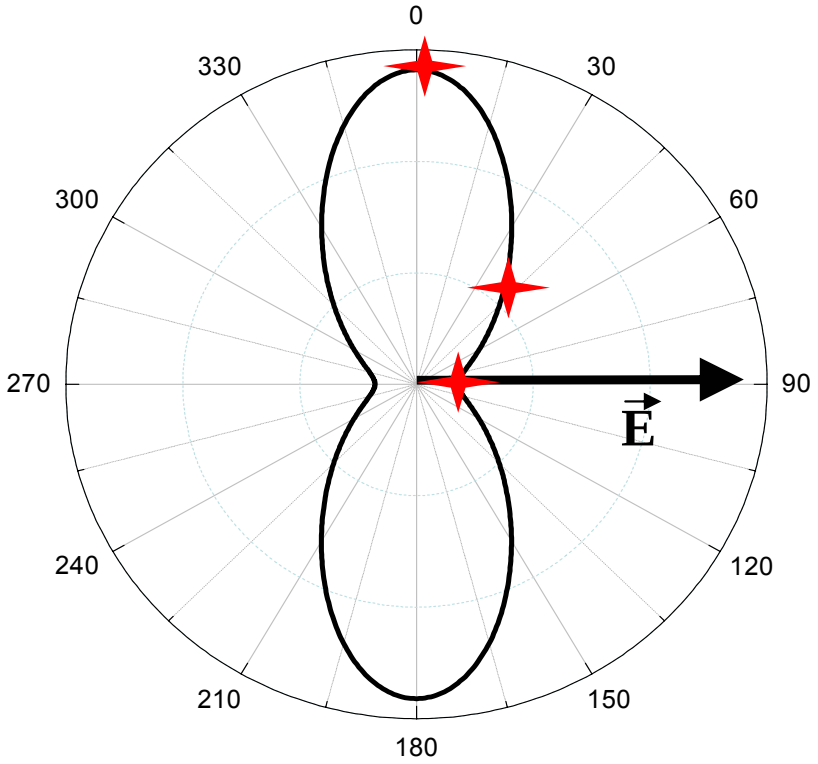




Compton Polarimeter Setups

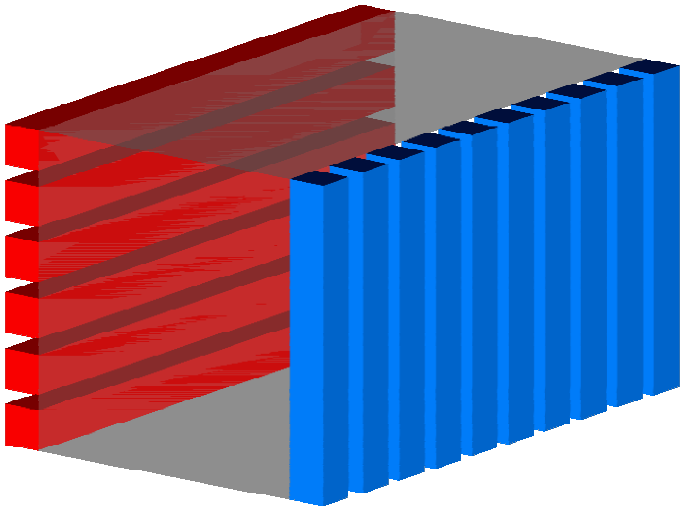
Standard Solid State Detectors



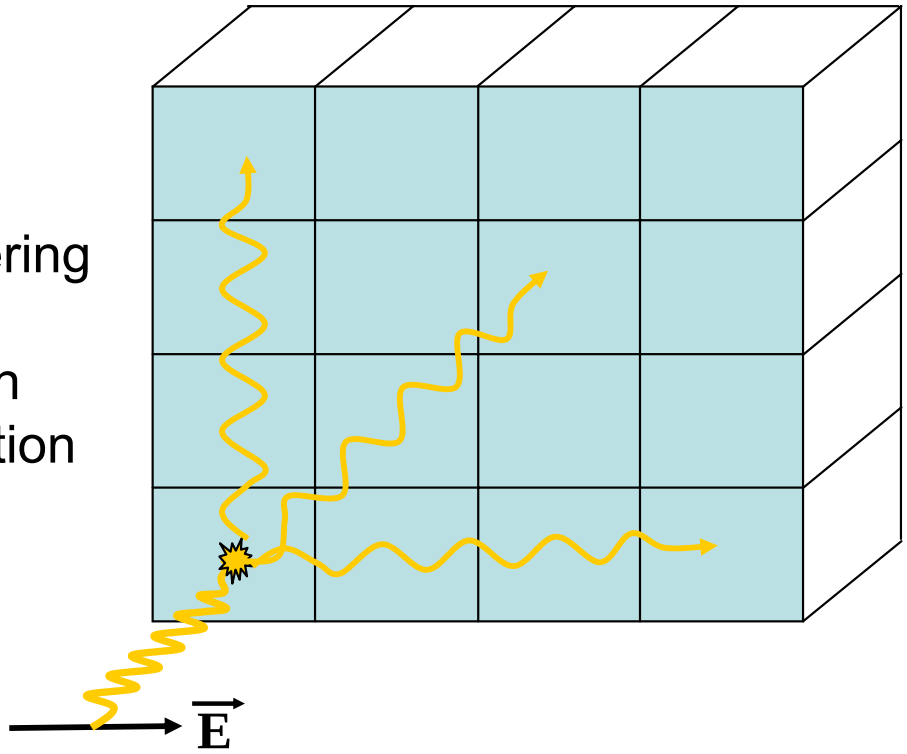


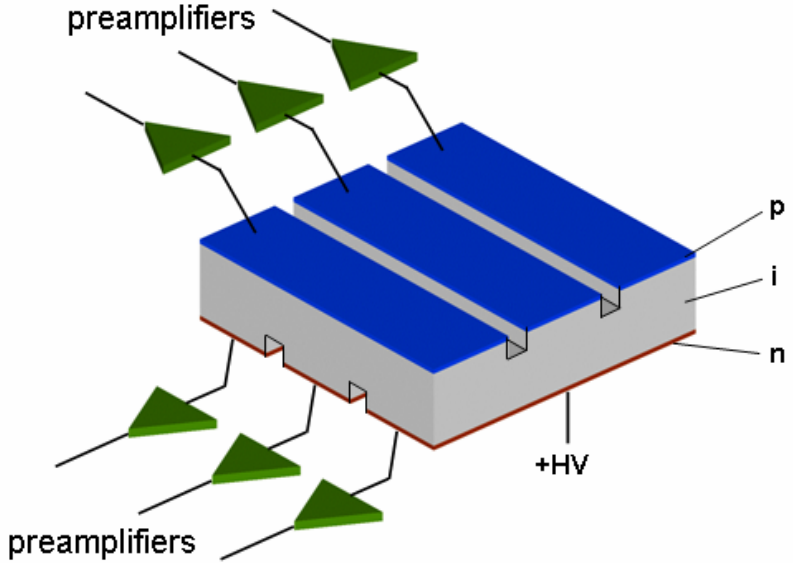
Compton Polarimeter Setups

Segmented X-ray Detector

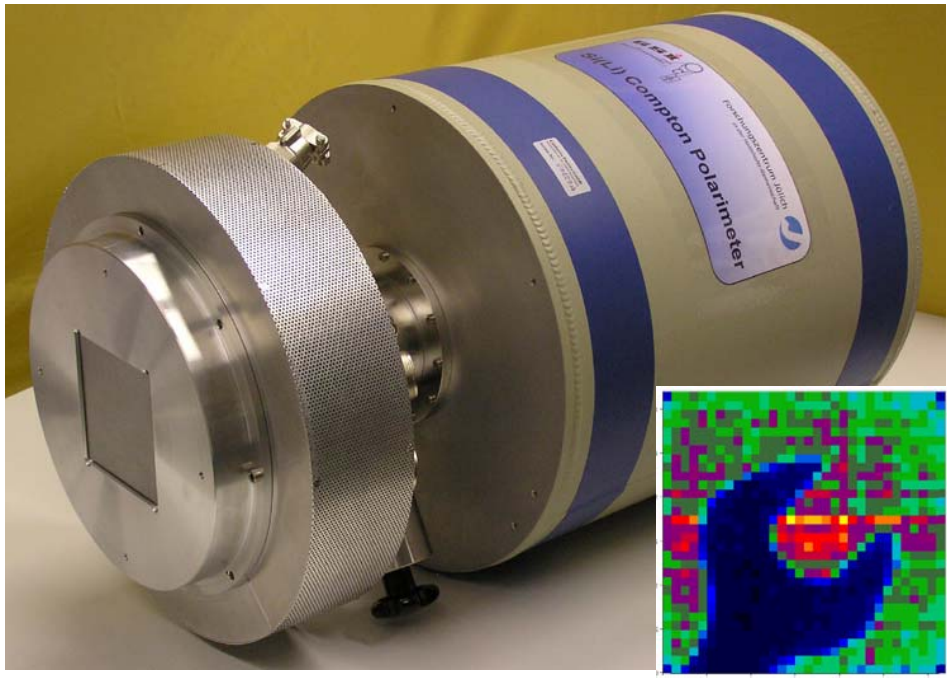


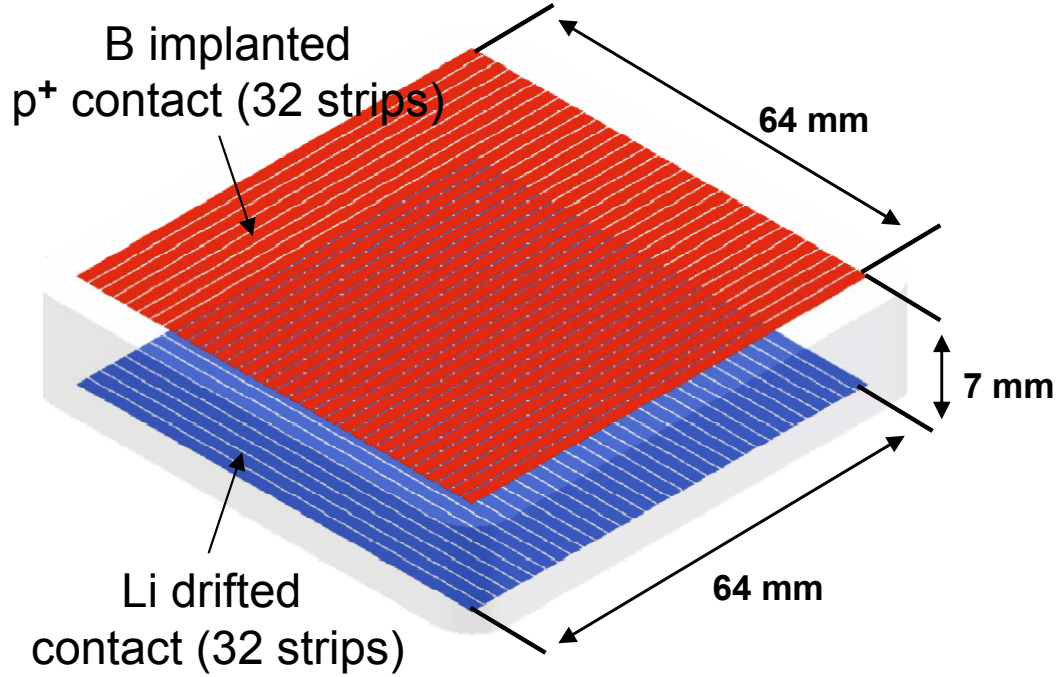
Scattering and Photon Detection





Position sensitive Si(Li) detector as a Compton Polarimeter





32x32 strips → 1024 pixels

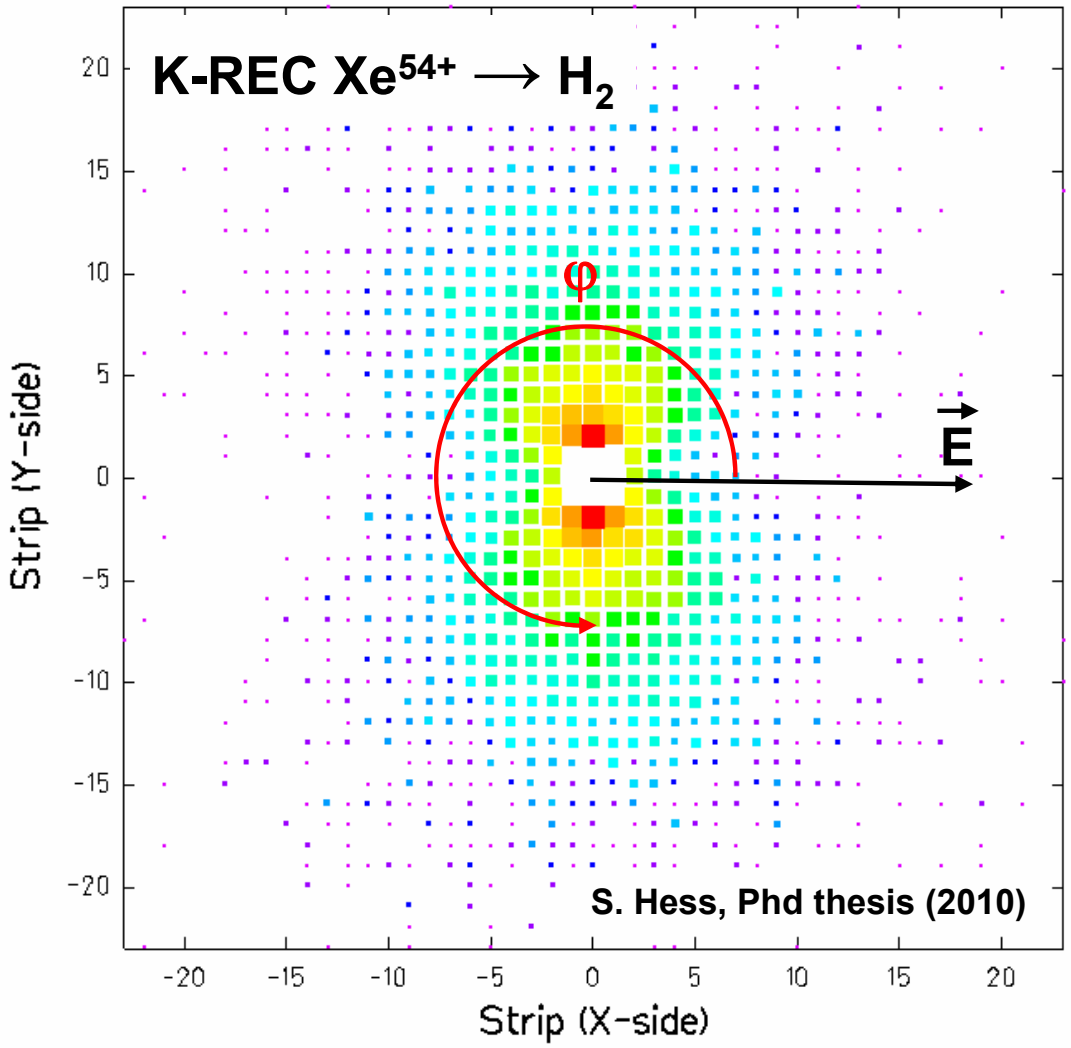
64x64 mm → 4096 mm² active area

Energy (2.5 keV FWHM) **+ Timing** (100 ns) **+ 2D Position** (2 mm) **+ Multihit Capability**

Dedicated for efficient and precise polarization studies from 70 keV to a few 100 keV

From φ Distribution to Polarization

Compton scattered photon distribution

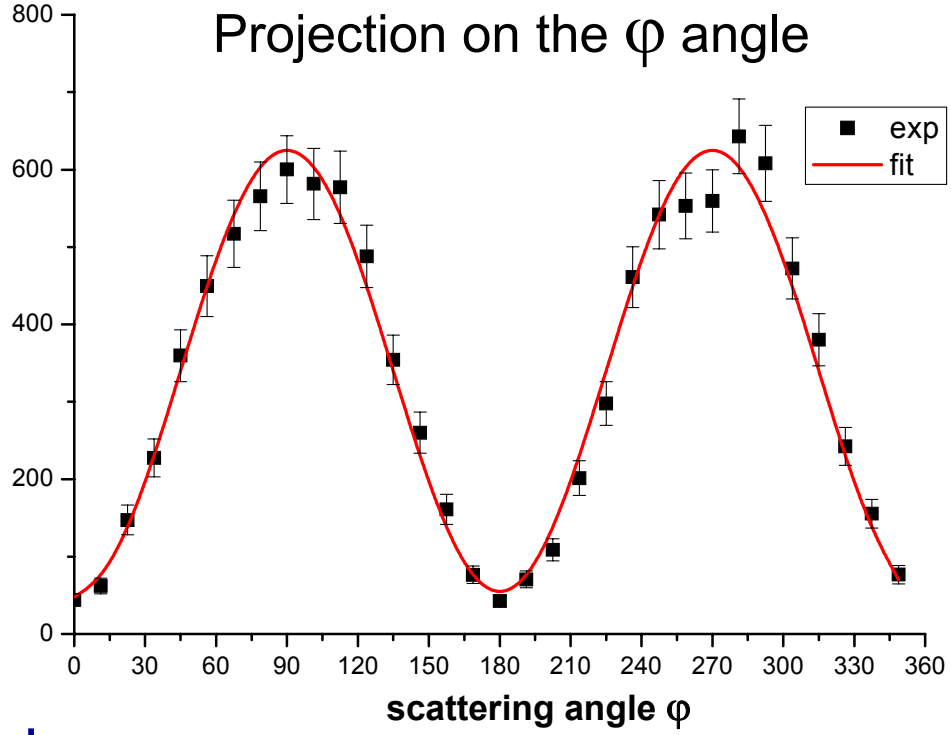


Klein-Nishina formular

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

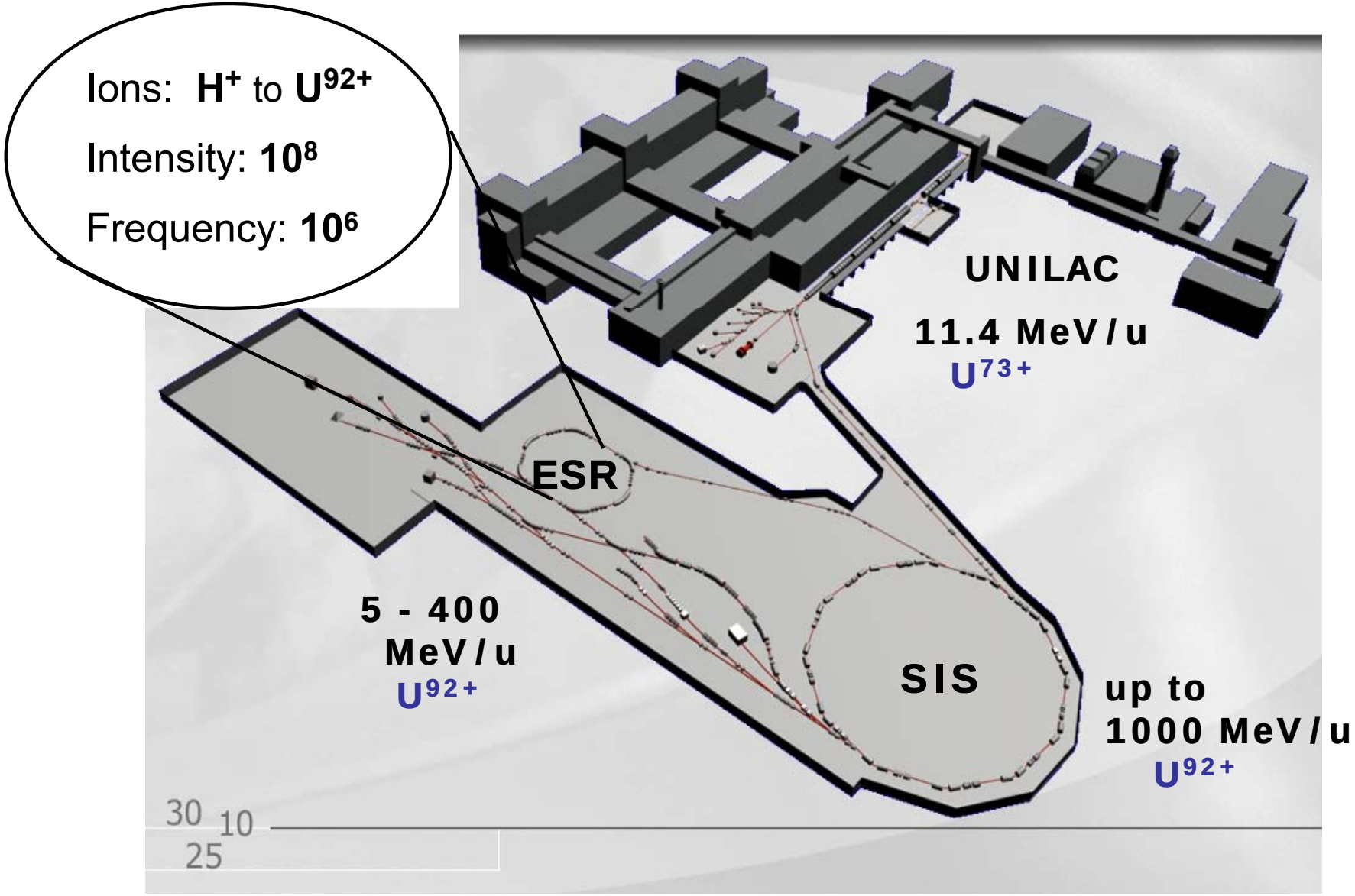
$$\cos^2\varphi \rightarrow \frac{1}{2}(1-P) + P\cos^2\varphi$$

Projection on the φ angle



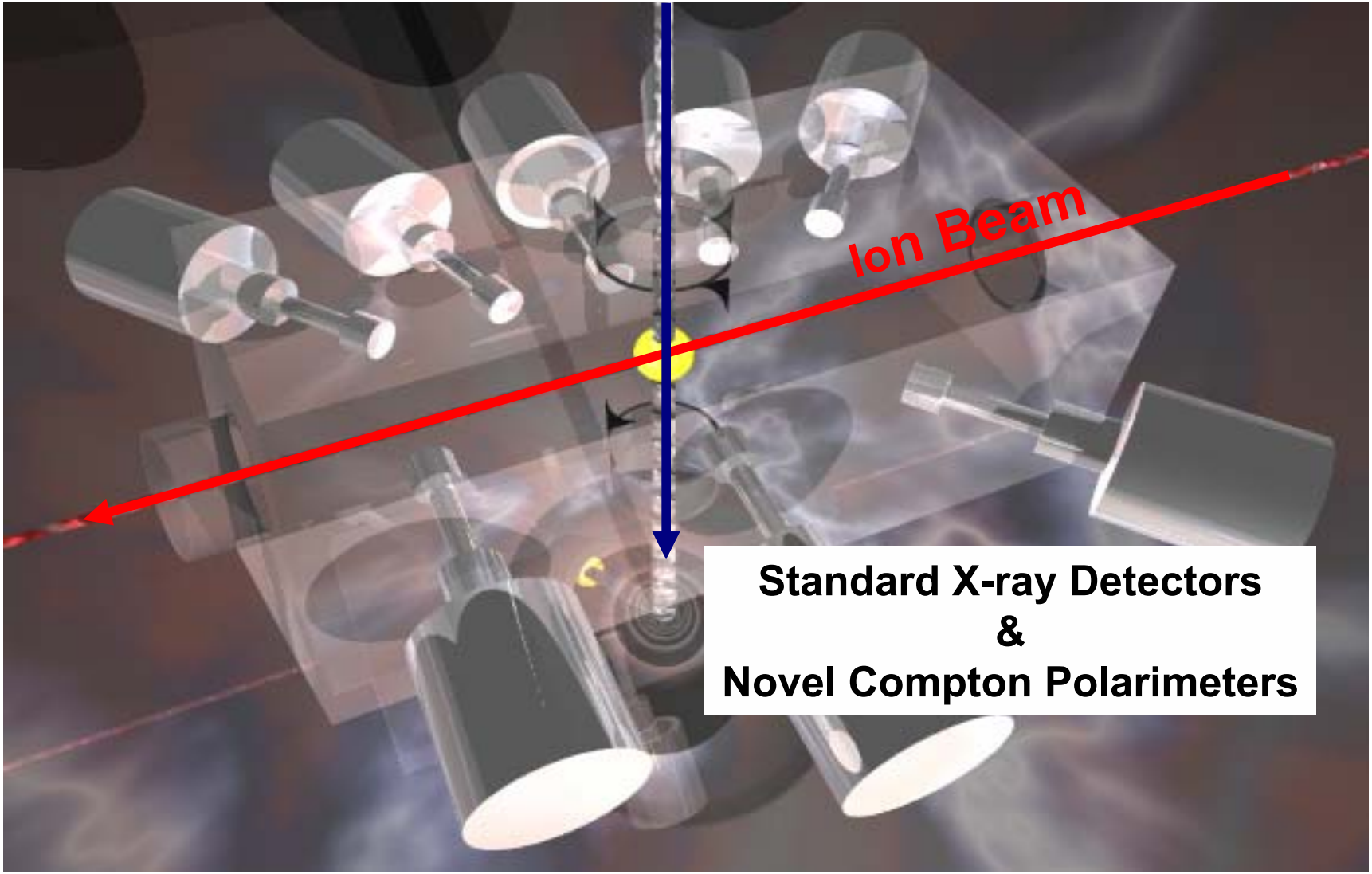
Online analysis already yields qualitative results!

The GSI Accelerator Facility

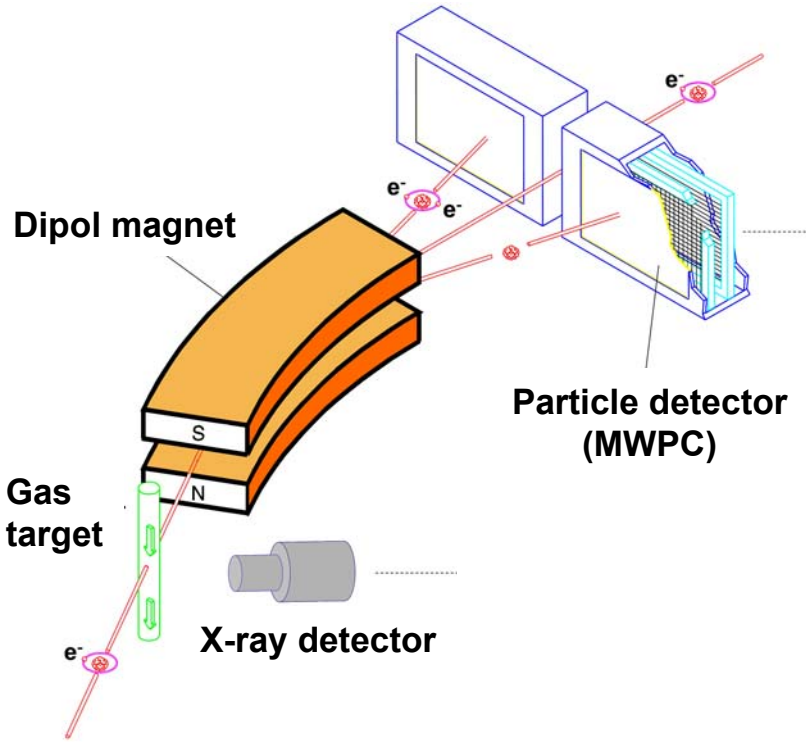


The ESR internal gas target

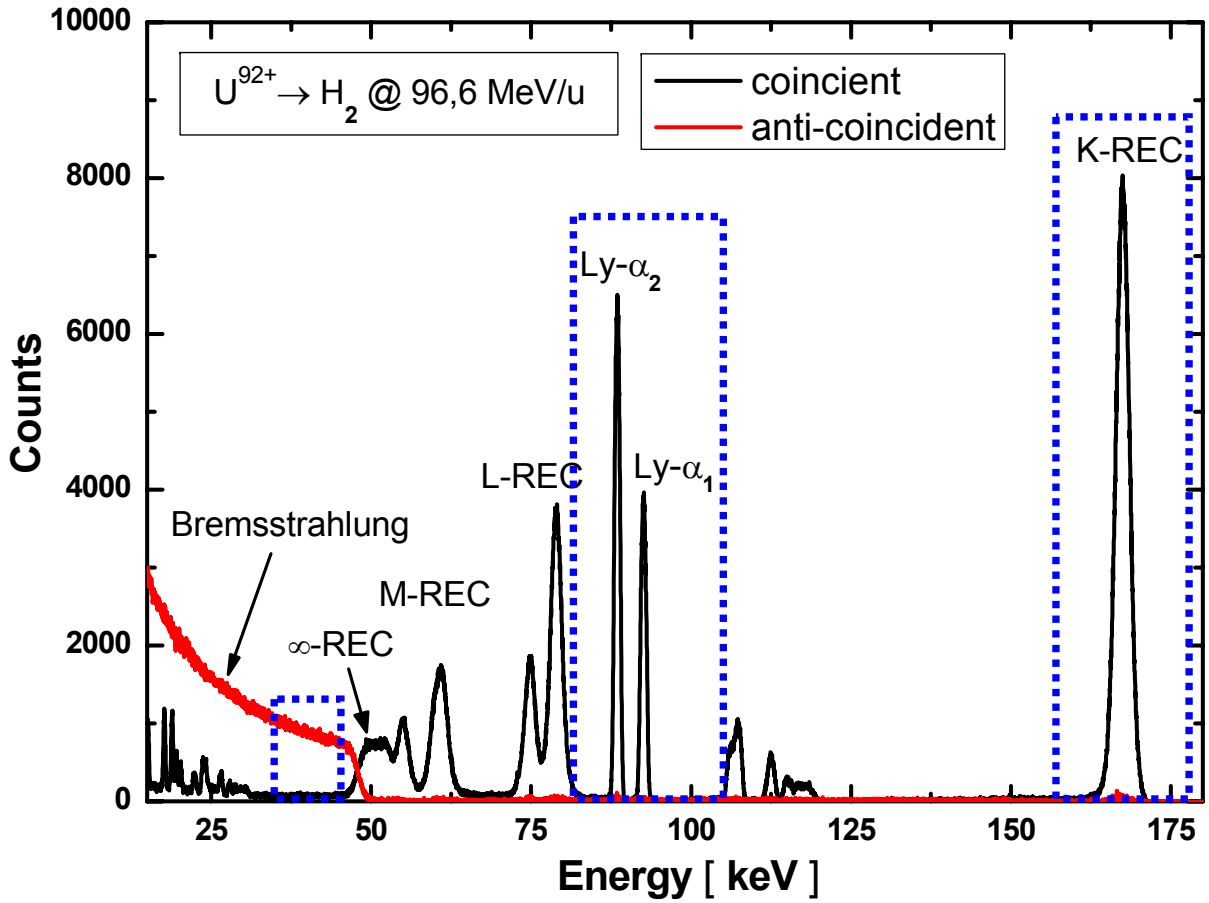
Gas Target (H_2, N_2, He, Ne, Ar, Xe)



Measurements at the ESR storage ring



Typical HCI x-ray spectrum at the ESR

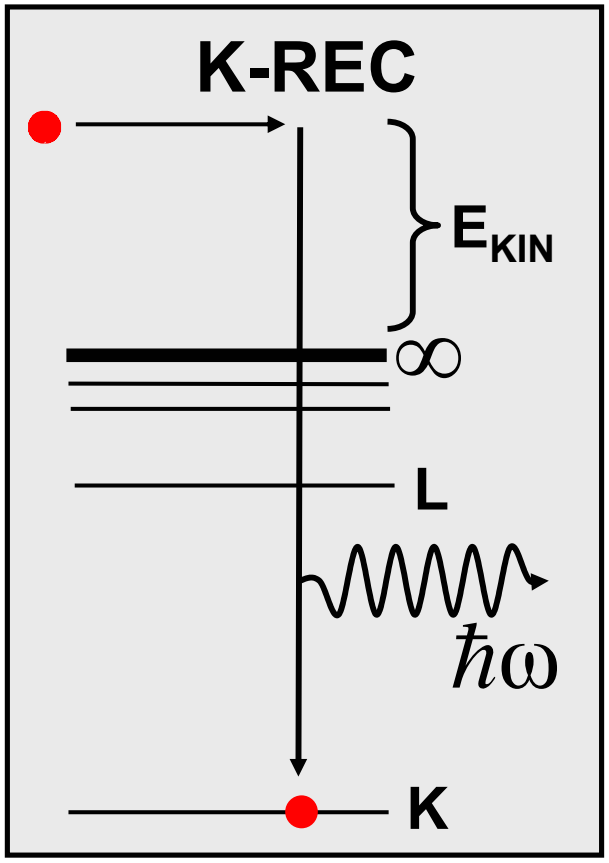


Inverse kinematics

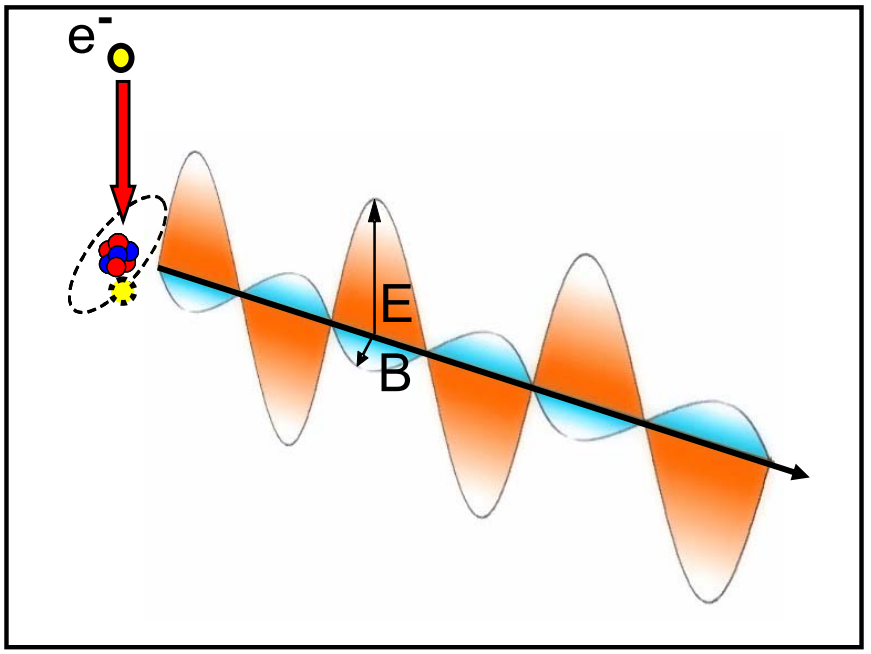
→ Coincidence measurements between x-rays and ions!

Polarization of the K-REC radiation

Radiative Recombination (RR)
Radiative Electron Capture (REC)



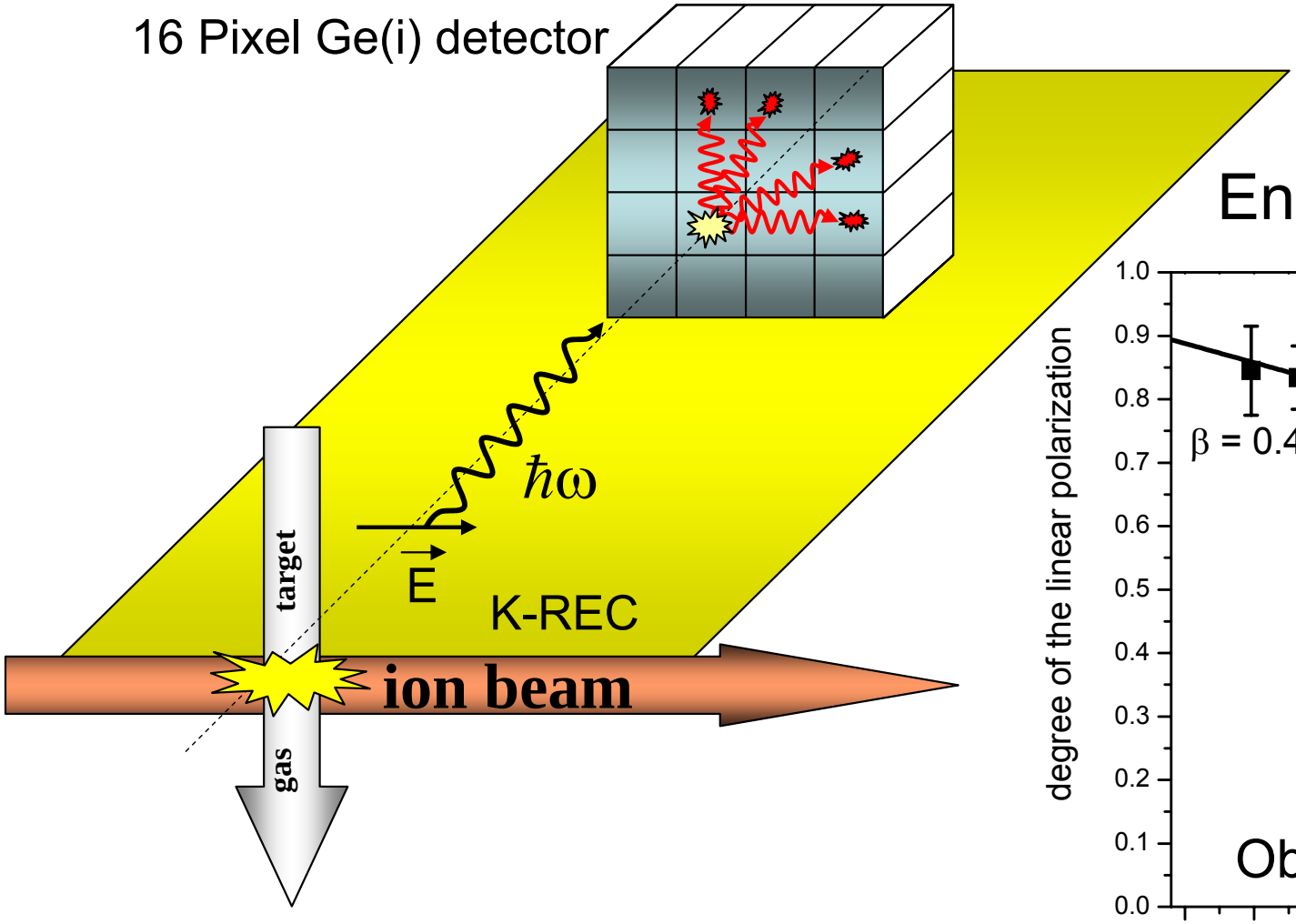
Time reversal process of photoionization

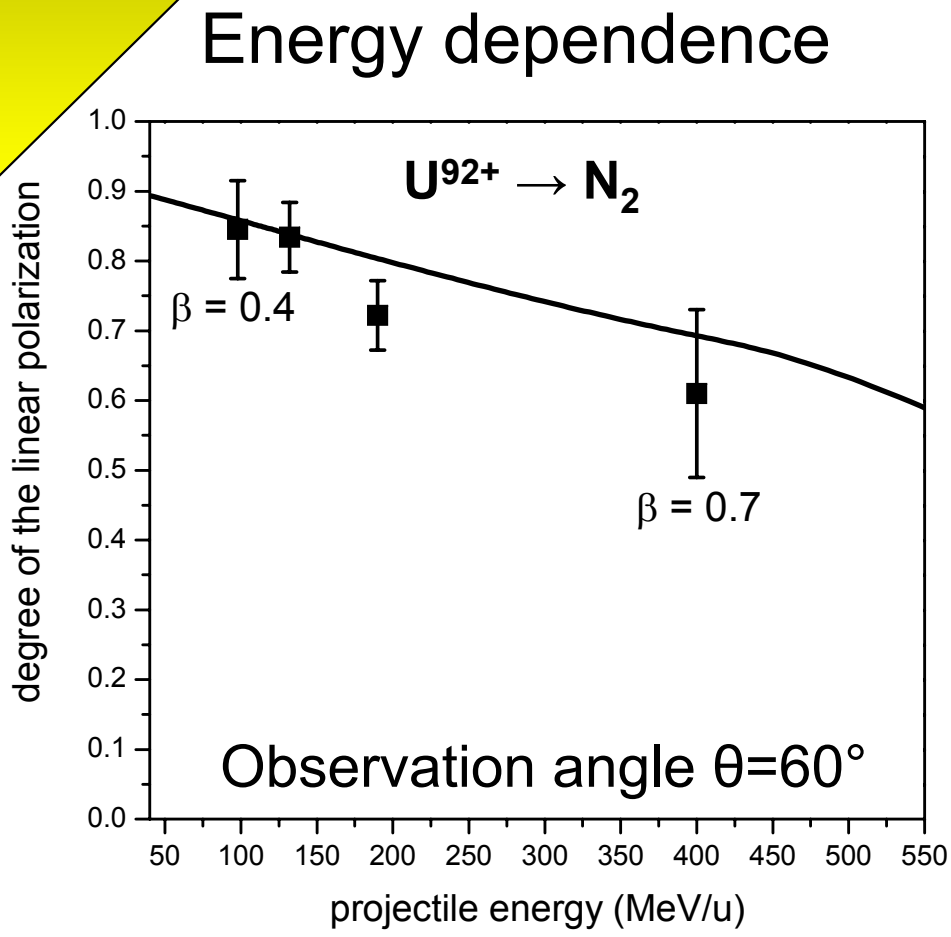


In the non-relativistic approximation the REC radiation has dipole characteristics:

- **$\sin^2\theta$ angular distribution**
- **100% linear polarization**

First REC polarization measurements



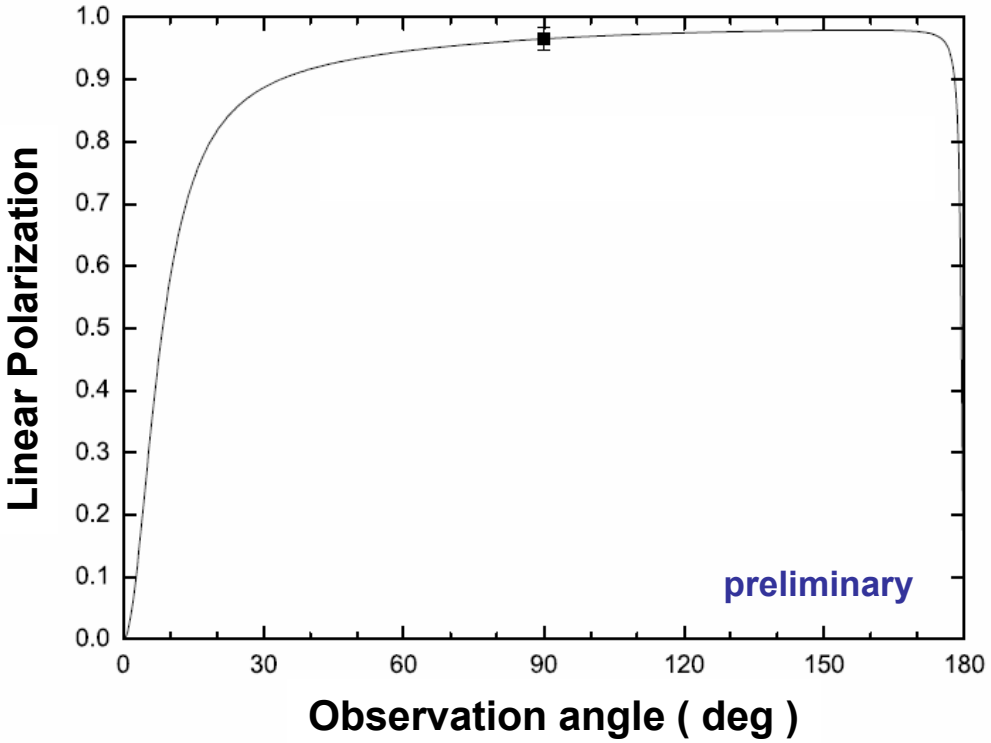


S. Tashenov, Phd thesis (2005)

Recent K-REC polarization measurements

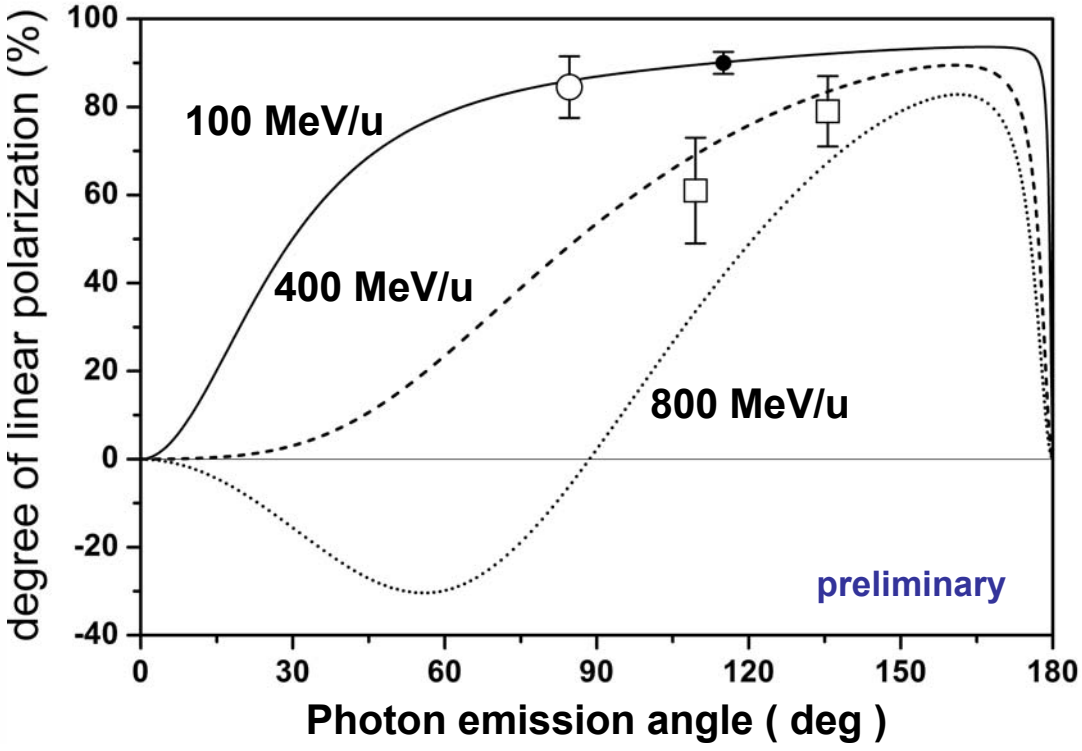
mid-Z

$Xe^{54+} \rightarrow H_2$ @ 150 MeV/u



high-Z

$U^{92+} \rightarrow N_2, H_2$



○□ **16 pixel detector** S. Tashenov *et al.*, PRL **97** (2006)

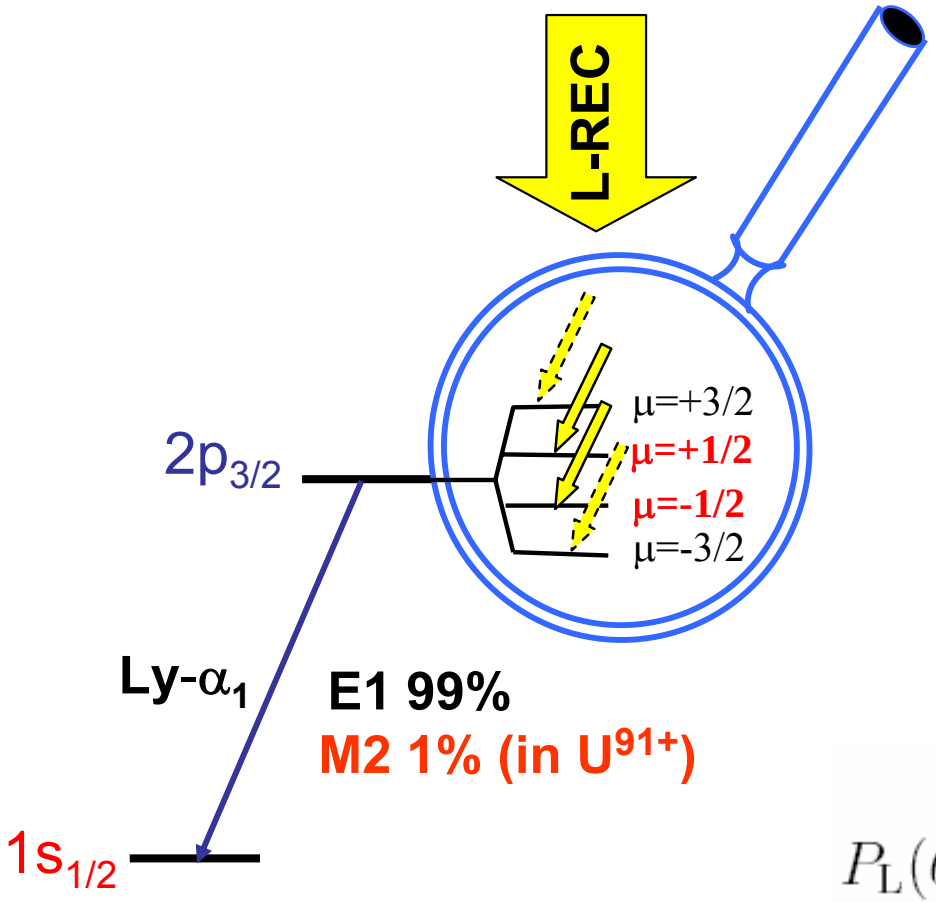
● **Si(Li) Polarimeter** S. Hess, Phd thesis (2010)

A gain by a factor 3 to 5 in precision!

Polarization of the Lyman-α_1 radiation in U^{91+}

Study of Lyman-α_1 polarization in H-like, high-Z systems

Revealing details of the population mechanism



Alignment of the excited $2p_{3/2}$ state:

$$\mathcal{A}_2 = \frac{\sigma\left(\pm\frac{3}{2}\right) - \sigma\left(\pm\frac{1}{2}\right)}{\sigma\left(\pm\frac{3}{2}\right) + \sigma\left(\pm\frac{1}{2}\right)}$$

Ly-α_1 linear polarization:

$$P_{\mathrm{L}}(\theta) = \frac{-\frac{3}{2}\frac{\mathcal{A}_2}{2}\sin^2\theta}{1 + \frac{\mathcal{A}_2}{2}\left(1 - \frac{3}{2}\sin^2\theta\right)}$$

Taking into account E1-M2-interference:

$$P_{\mathrm{L}}(\theta) = \frac{-\frac{3}{2}\frac{\mathcal{A}_2}{2}\left(1 - \frac{2}{\sqrt{3}}\frac{\langle \mathrm{M2}\rangle}{\langle \mathrm{E1}\rangle}\right)\sin^2\theta}{1 + \frac{\mathcal{A}_2}{2}\left(1 + 2\sqrt{3}\frac{\langle \mathrm{M2}\rangle}{\langle \mathrm{E1}\rangle}\right)\left(1 - \frac{3}{2}\sin^2\theta\right)}$$

Lyman-α_1 Polarization of U^{91+}

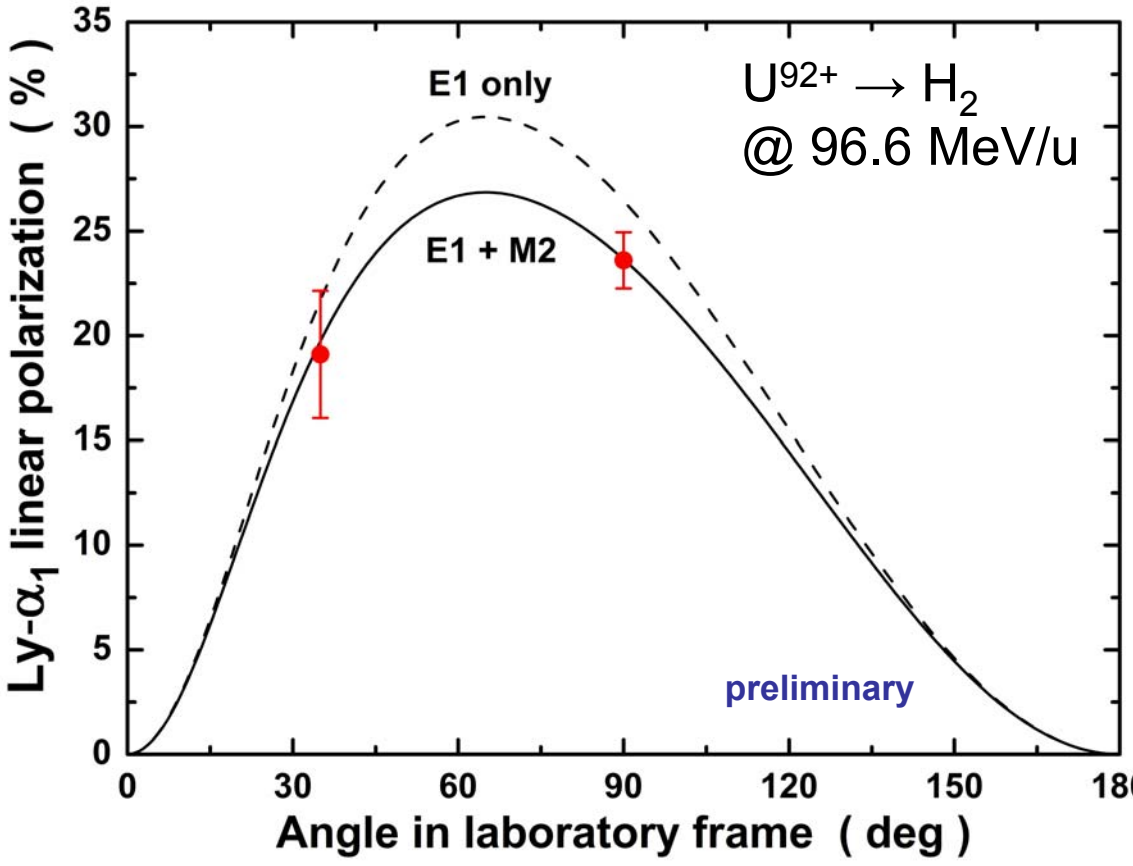
Exakt relativistic calculations by A. Surzhykov:

E1-M2 interference in Ly-α_1 leads to

Hyperf. Interact. **146-147** (2003)

→ **Increased Anisotropy**

→ **Decreased Polarization**



G. Weber, unpublished

A model independent estimation of the E1-M2 transition ratio

Observable	Equation	Experiment	Theory	
			only E1	E1 + M2
$P(58°)\,[\%]$	$\frac{-\frac{3}{2}\mathcal{A}_2/2\left(1-\frac{2}{\sqrt{3}}\alpha\right)\sin^2\theta}{1+\mathcal{A}_2/2\left(1+2\sqrt{3}\,\alpha\right)\left(1-\frac{3}{2}\sin^2\theta\right)}$	$19{,}1 \pm 3{,}1$	21,7	19,7
$P(115°)\,[\%]$		$23{,}6 \pm 1{,}4$	26,4	23,6
β_{20}^{eff}	$\mathcal{A}_2/2\left(1+2\sqrt{3}\,\alpha\right)$	$-0{,}29 \pm 0{,}005$	0,226	0,288

Decoupling of the collision dynamics (alignment parameter A_2) and the atomic structure (amplitude ratio α = M2/E1) leads to a model independent estimation of both values.

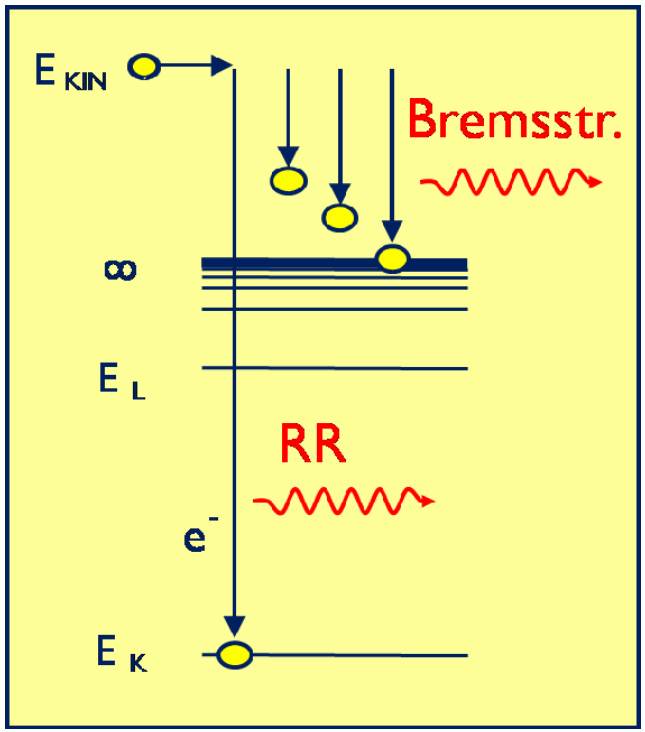
Alignmentparameter $\mathcal{A}_2$		Amplitude ratio $\alpha = \langle M2\rangle/\langle E1\rangle$	
Experiment	Theory	Experiment	Theory
$-0{,}450 \pm 0{,}017$	-0,452	$0{,}083 \pm 0{,}014$	0,080

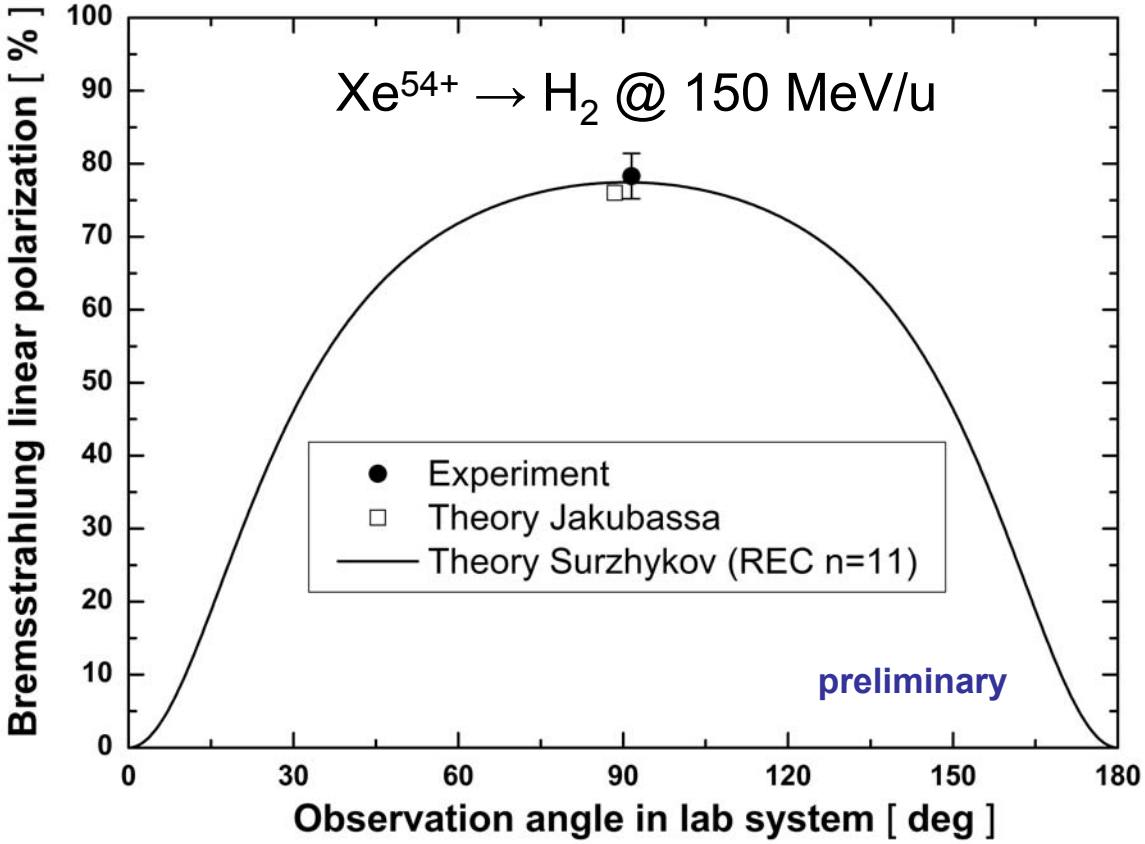
-> Precise estimation of the E1-M2 transition ratio!

Polarization of Electron Bremsstrahlung

First Bremsstrahlung polarization study with inverse kinematics

Bremsstrahlung high energy end-point = REC/RR into Rydberg series limit





G. Weber, unpublished

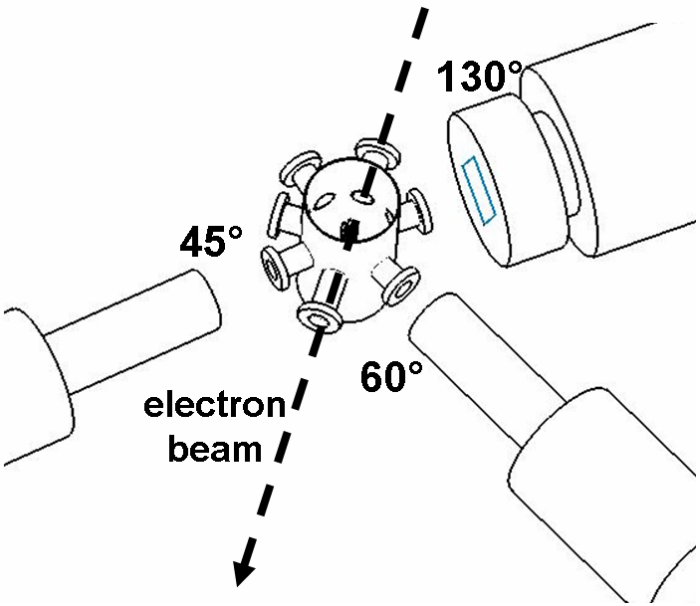
Next step:

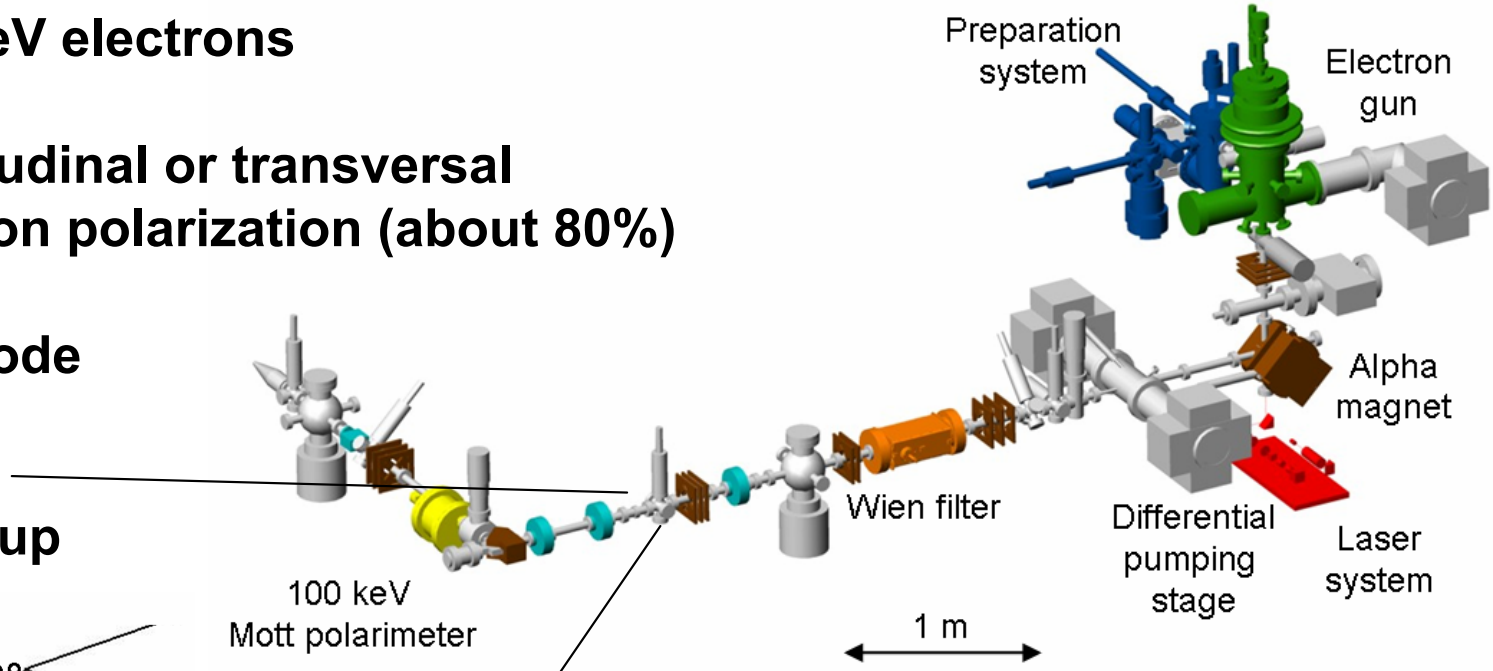
Bremsstrahlung polarimetry + electron spectroscopy -> correlation study

Measurements at the polarized electron source SPIN at TU, Darmstadt

- 100 keV electrons
- longitudinal or transversal electron polarization (about 80%)
- DC mode

Experimental Set-up

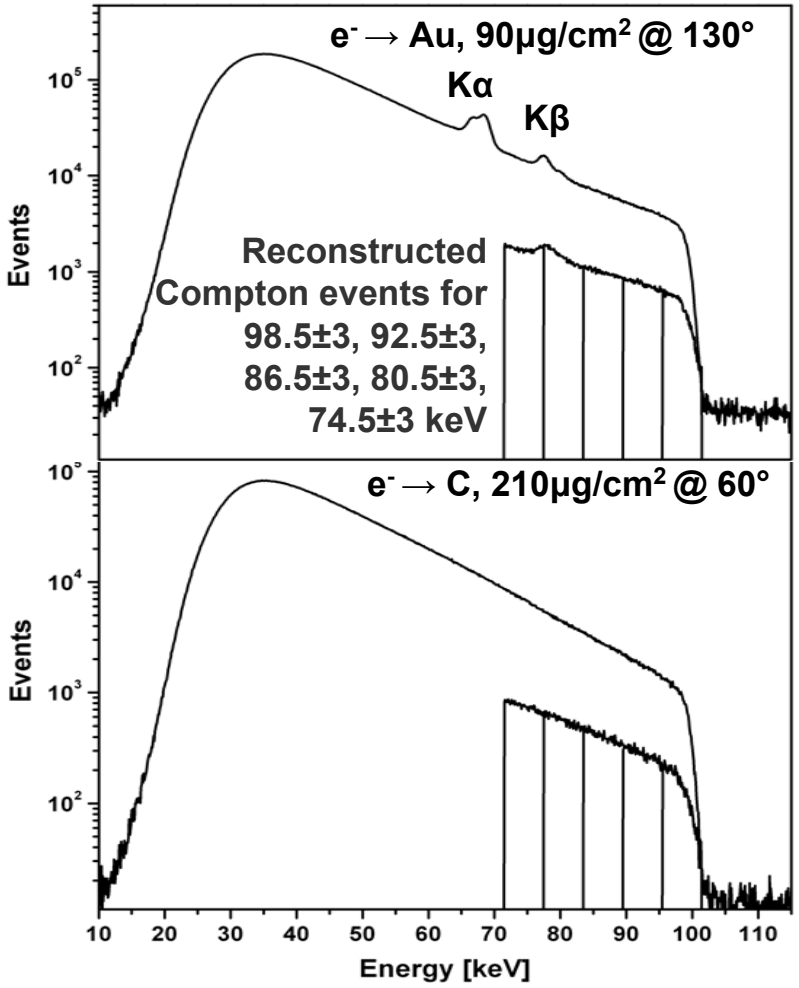




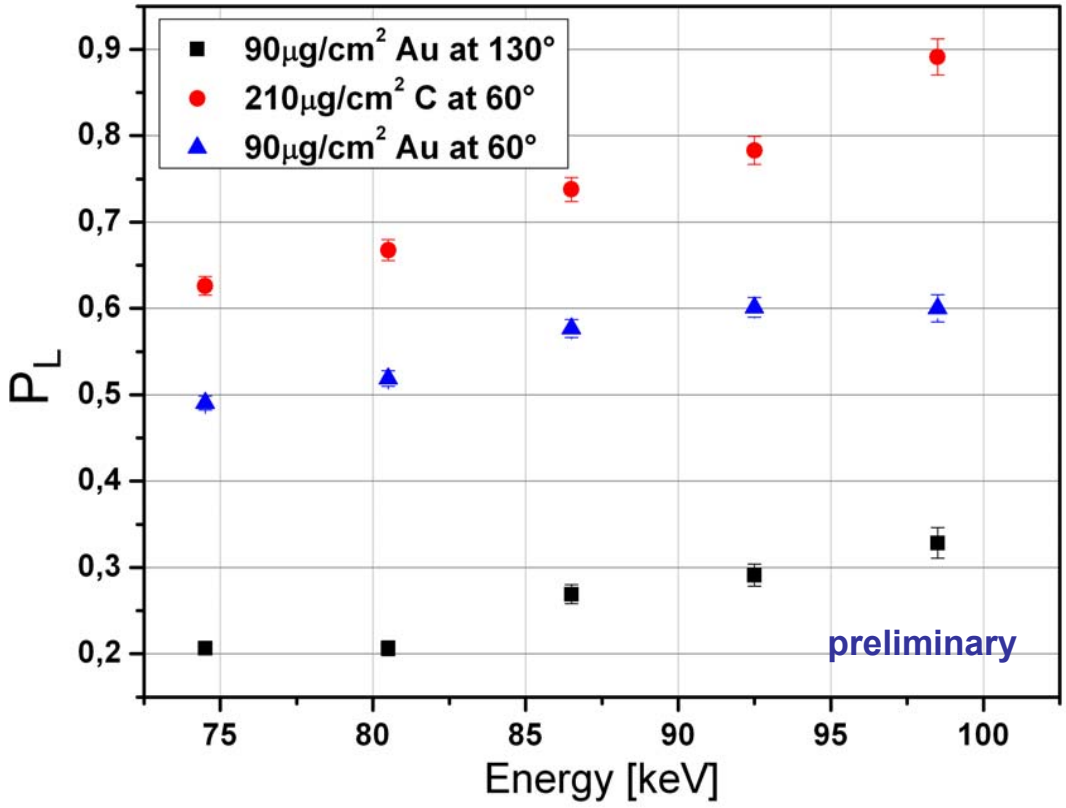
C. Heßler, Conf. Proc. EPAC08 (2008)

Linear Bremsstrahlung polarization measurements (unpolarized electrons)

Bremsstrahlung



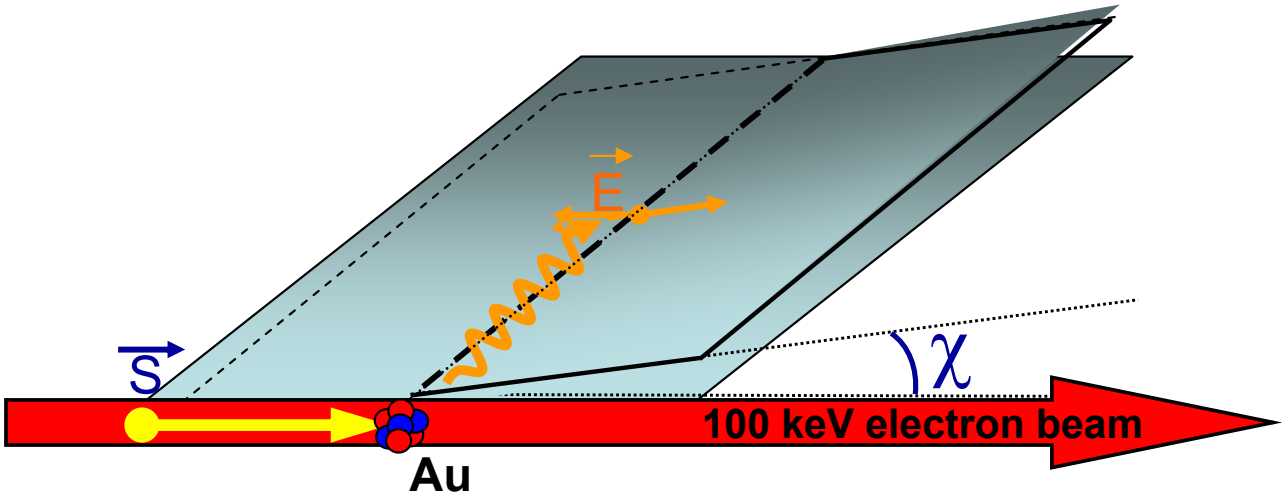
Linear Polarization



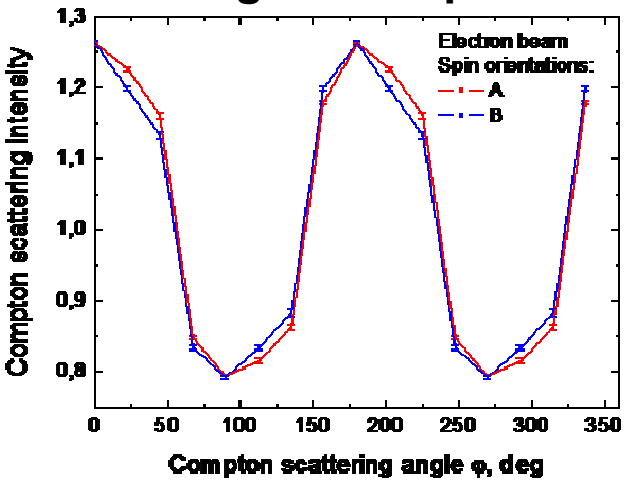
No corrections for systematic effects (electron scattering, polarimeter efficiency, etc.) done yet.

R. Märtin, unpublished

The effect of spin polarized collision systems on Bremsstrahlung polarization



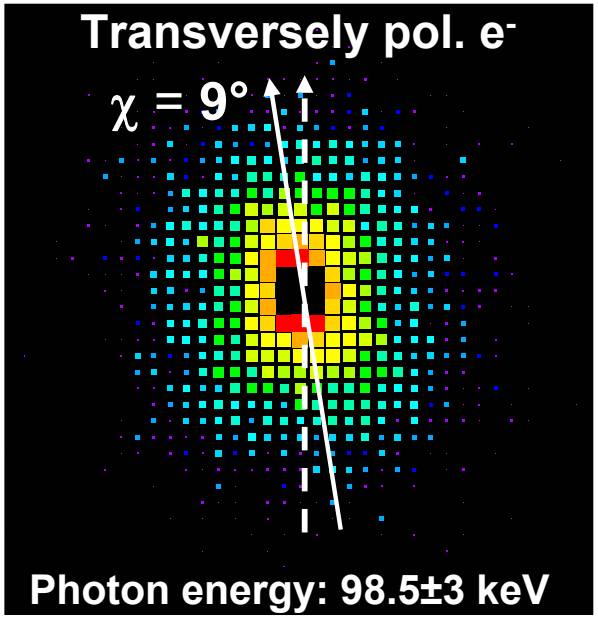
Longitudinal pol. e⁻



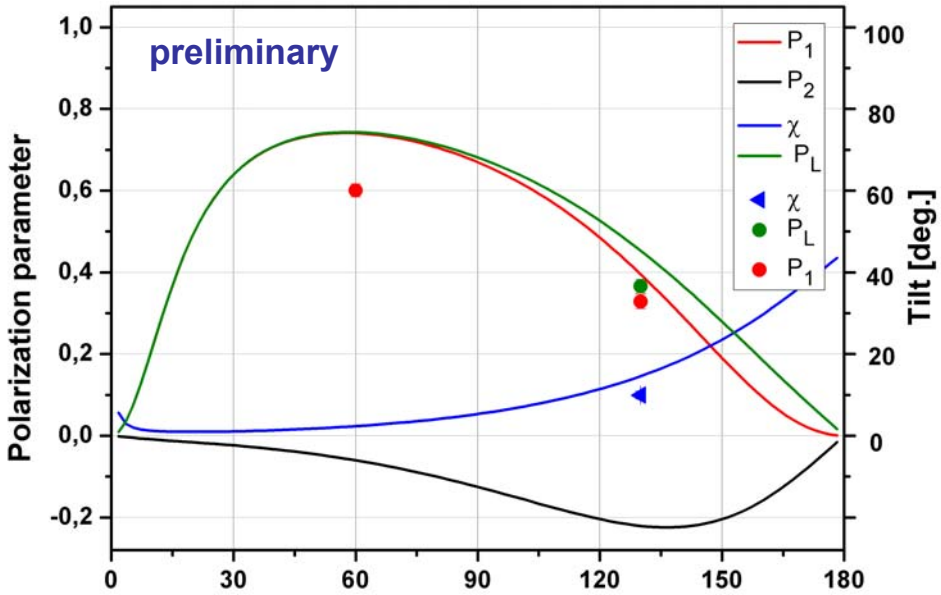
$$\tan 2\chi = \frac{P_2}{P_1}$$

P_2 is proportional to the degree of spin polarization

Transversely pol. e⁻



S. Tashenov, unpublished



R. Märtin, unpublished

Summary & Outlook

- ✓ Effifcient and precise Compton polarimeters are available (only small systematic corrections needed)
- ✓ Photon energies from about 70 keV to several 100 keV
- ✓ Experiments have already revisited a variety of radiative processes with respect to linear polarization (e.g. REC, Lyman, Bremsstrahlung)

Future plans:

- ✓ Studies of scattered x-rays at DESY
- ✓ Photon-photon and photon-electron correlations
- ✓ Measurements at EBIS/T facilities

Thank you for your attention!