Overview of Critical Dimension Small Angle X-ray Scattering (CD-SAXS)

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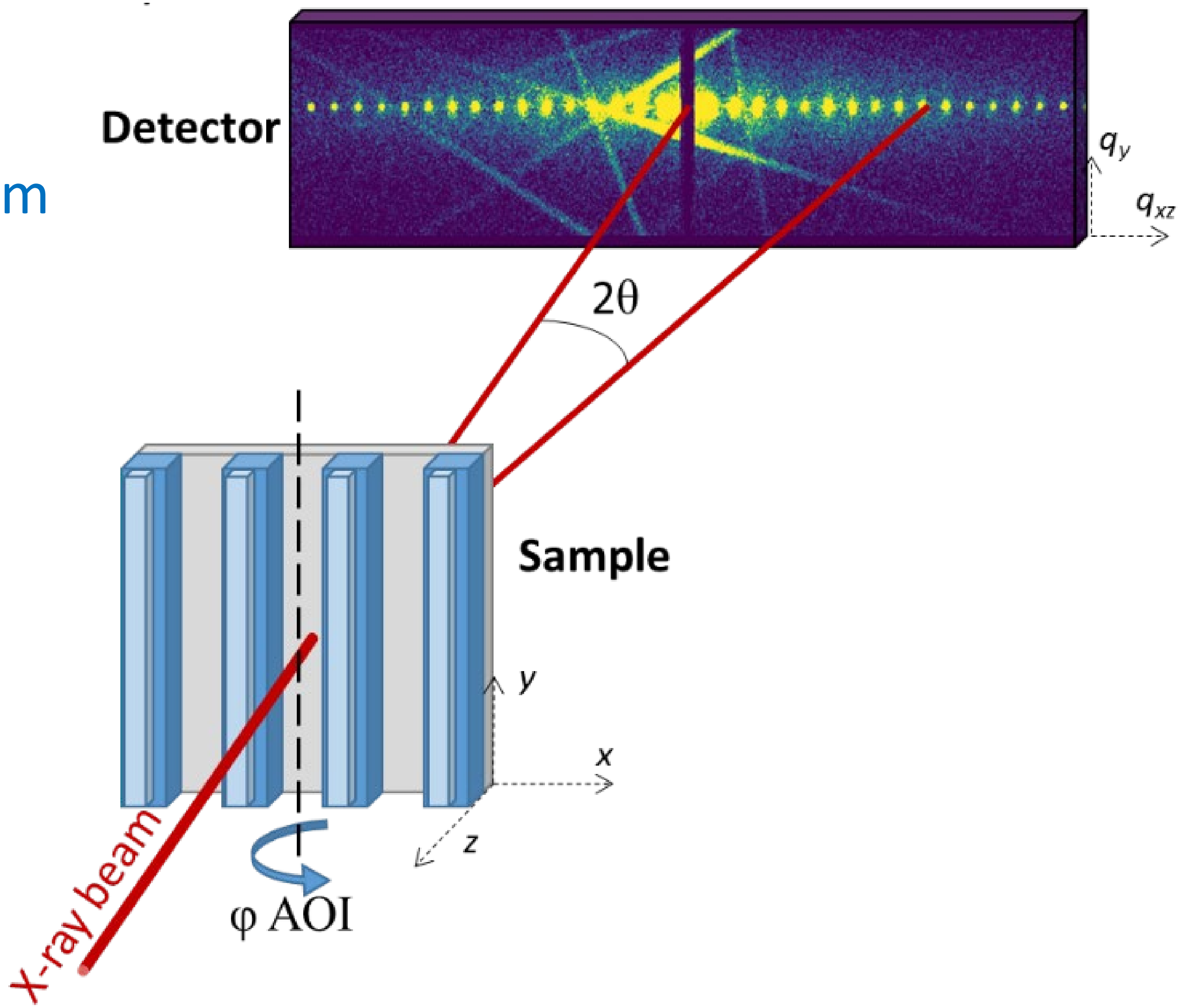
Small Angle x-ray scattering (SAXS)

- ✓ X-ray => Wavelength from ~ 0.1 nm
- ✓ Small angle scattering: probe 0.1-1000 nm

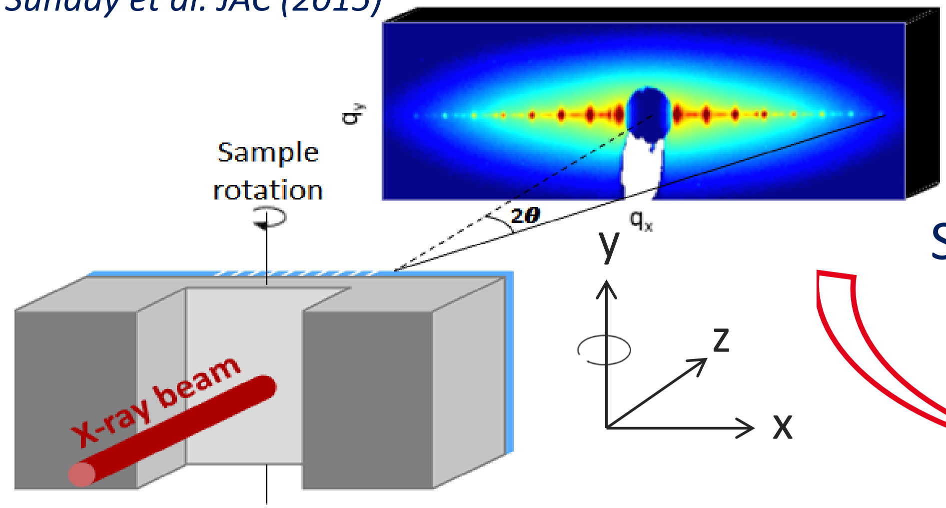
$$q = \frac{2\pi}{\lambda} \sin 2\theta$$

- ✓ Probe electronic density contrast
- ✓ Transmission geometry
- ✓ Indirect technique
- ✓ Averaging over the beam

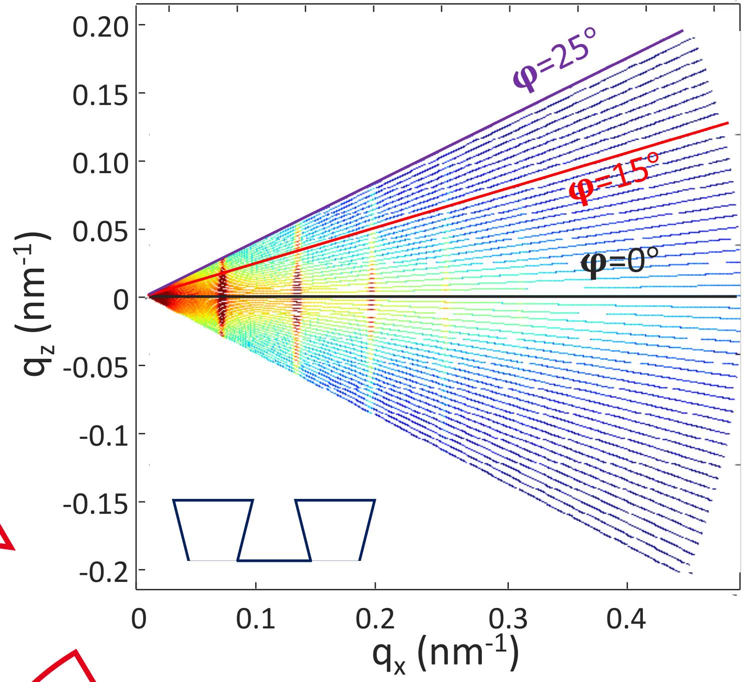


CD-SAXS : principle

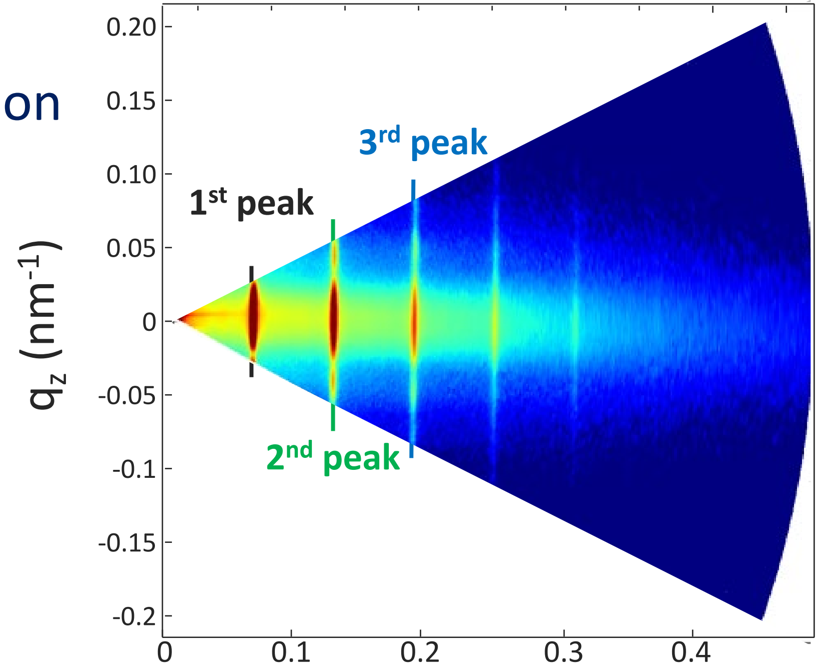
D. Sunday et al. JAC (2015)



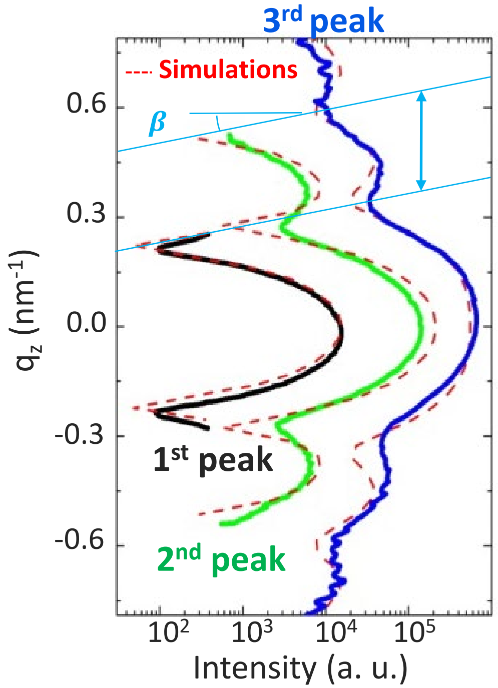
Sample rotation
φ: -25 => 25°



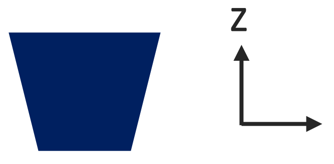
Interpolation



1D Vertical cut
(Extraction of the form factor)



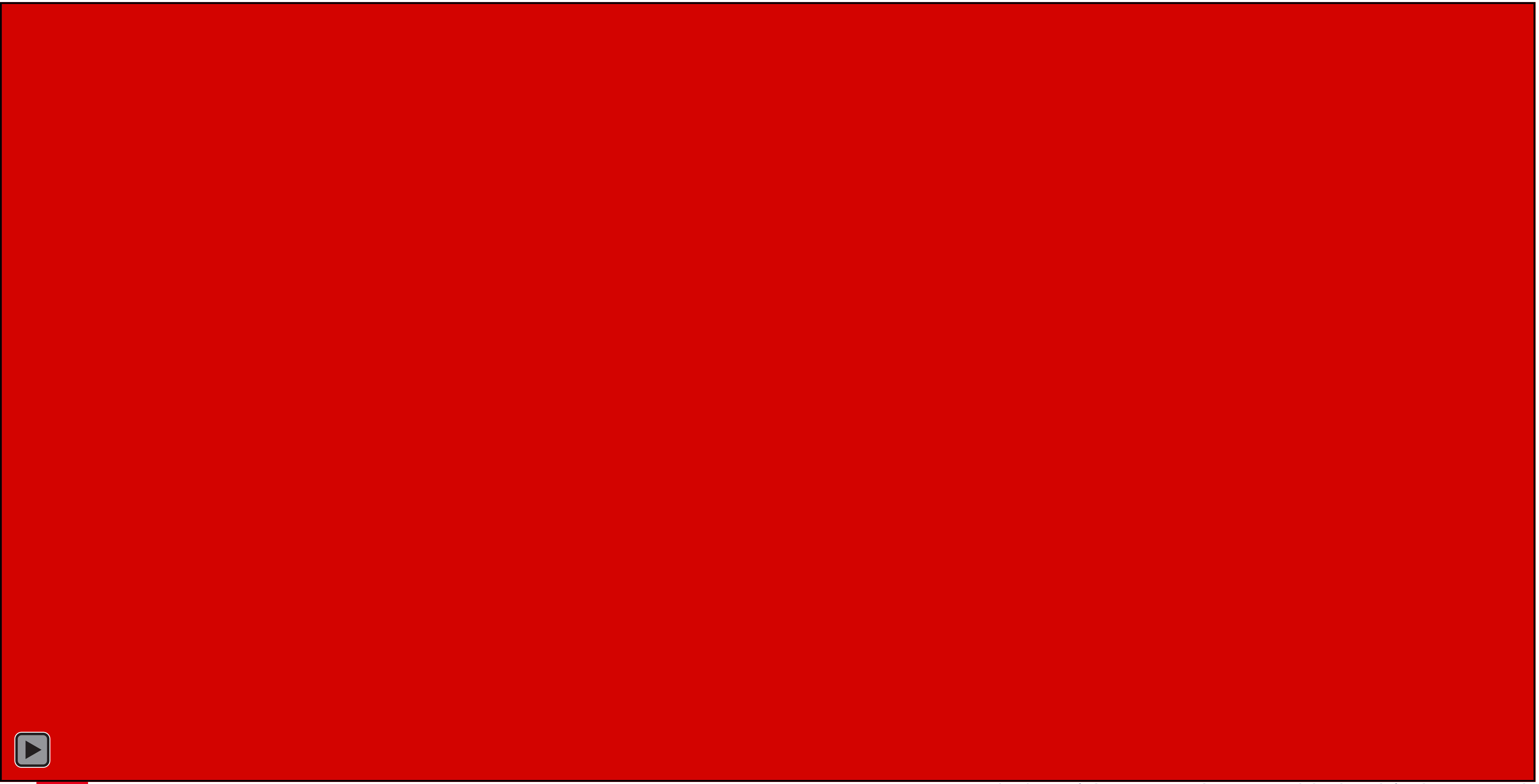
Line profile in xz



Fit the experimental data

Python package for CD-SAXS (Xicam)

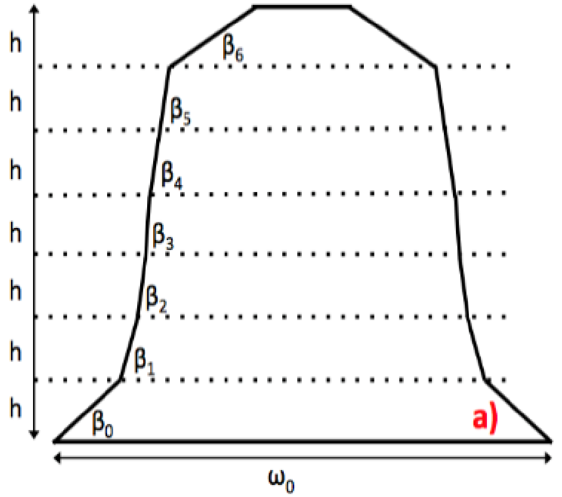
Collaboration with NIST (J. Kline, D. Sunday, C. Liman, D. Delongchamp)



R. Pandolfi

D. Kumar

CD-SAXS : principle



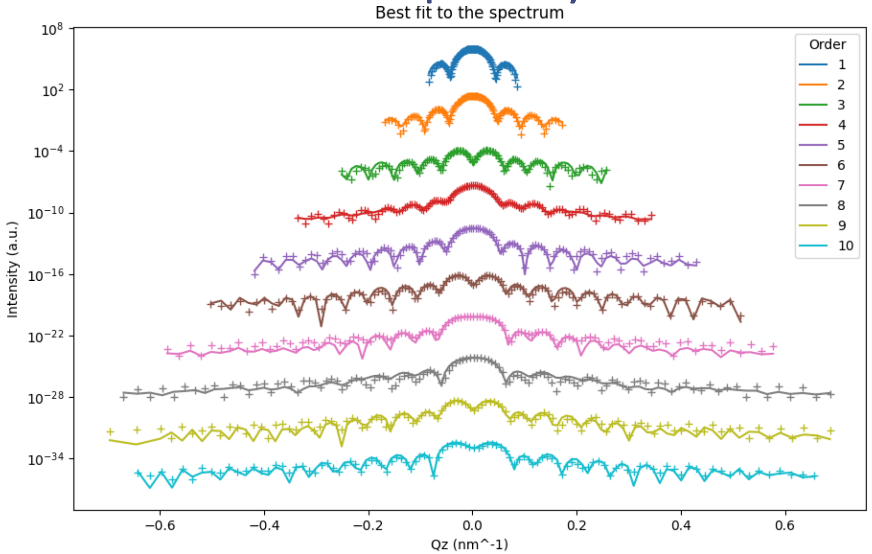
- ✓ Fourier transform of a trapezoid (L = ω0 and m = tan β):

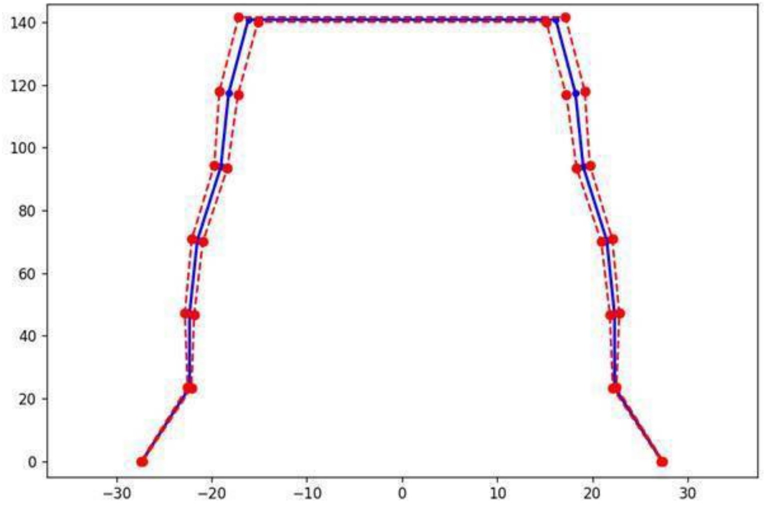
$$F(q_y, q_z) = \frac{1}{q_y}\left[-me^{jh(q_y L/2)}\left(1 - e^{-jh[(q_y+m\,q_z)/m]}\right) + me^{-jh(q_y L/2)}\left(1 - e^{-jh[(q_y+m\,q_z)/m]}\right)\right],$$

- ✓ Minimize the difference between I_{exp} and $I_{sim}=\left|F(q_y,q_z)\right|^2$

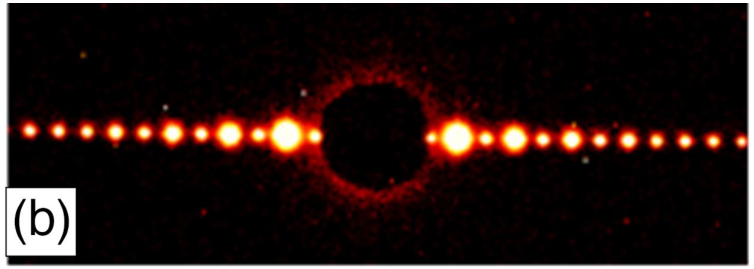
Genetic algorithm to converge to the best profile

Monte-Carlo Markov Chain to quantify the uncertainty on each profile





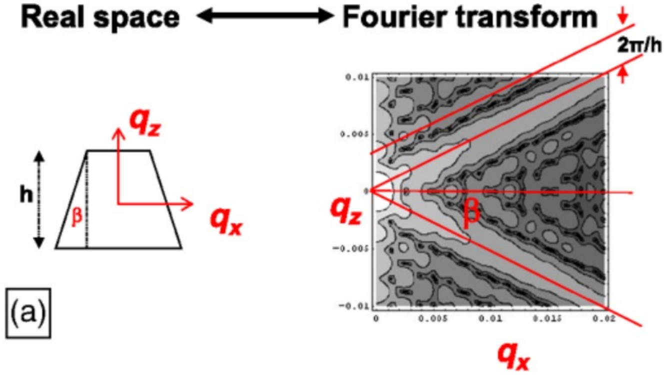
CD-SAXS : History



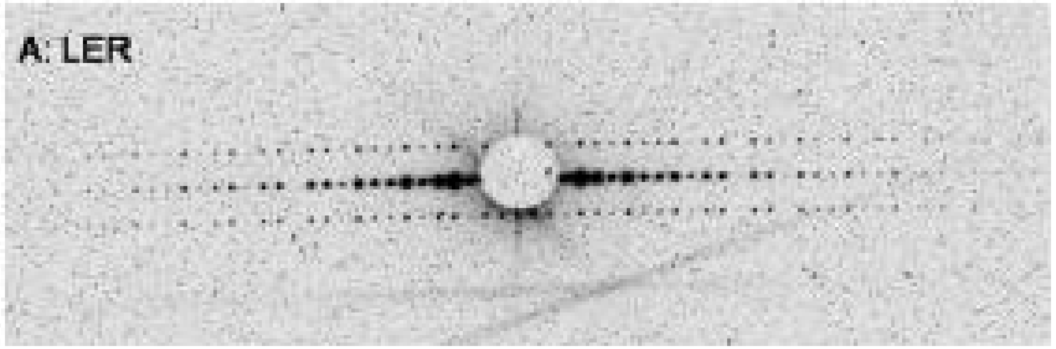
✓ Early 2000s: First measurements at APS by NIST

W-L. Wu et al. JM3, Vol. 22, Issue 3, 031206 (2023)

✓ 2000-2013: Exploration of possibilities with CD-SAXS: Sidewall angle, roughness, …



W-L. Wu et al. JM3, Vol. 22, Issue 3, 031206 (2023)



Wang et al. J. Appl. Phys. 102, 024901 (2007)

✓ 2013-2020:

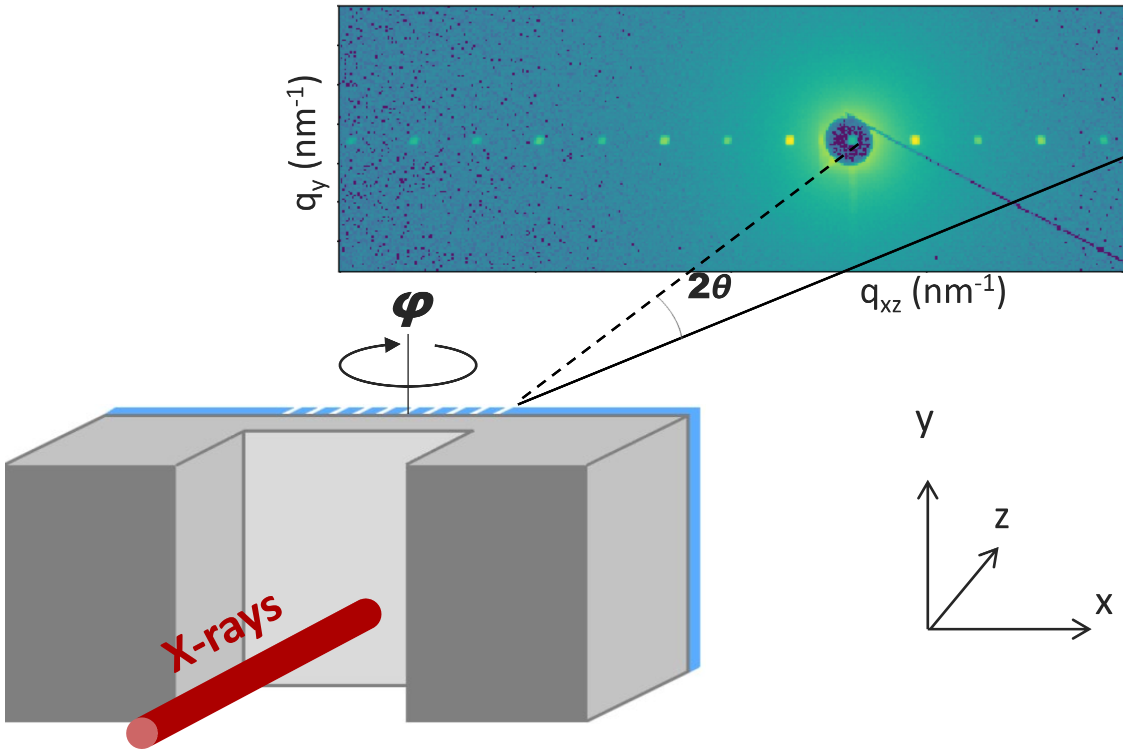
Strengthen the robustness of the analysis (genetic algorithm)

Test measurements with laboratory sources

Explore more complex system (BCP polymers, contacts, …)

https://www.nist.gov/programs-projects/metrology-nanolithography

CD-SAXS: Advantages and drawbacks



✓ Provide the line profile with a sub-nm resolution

✓ **Challenges link to the transmission geometry (i.e. cross a silicon wafer):**

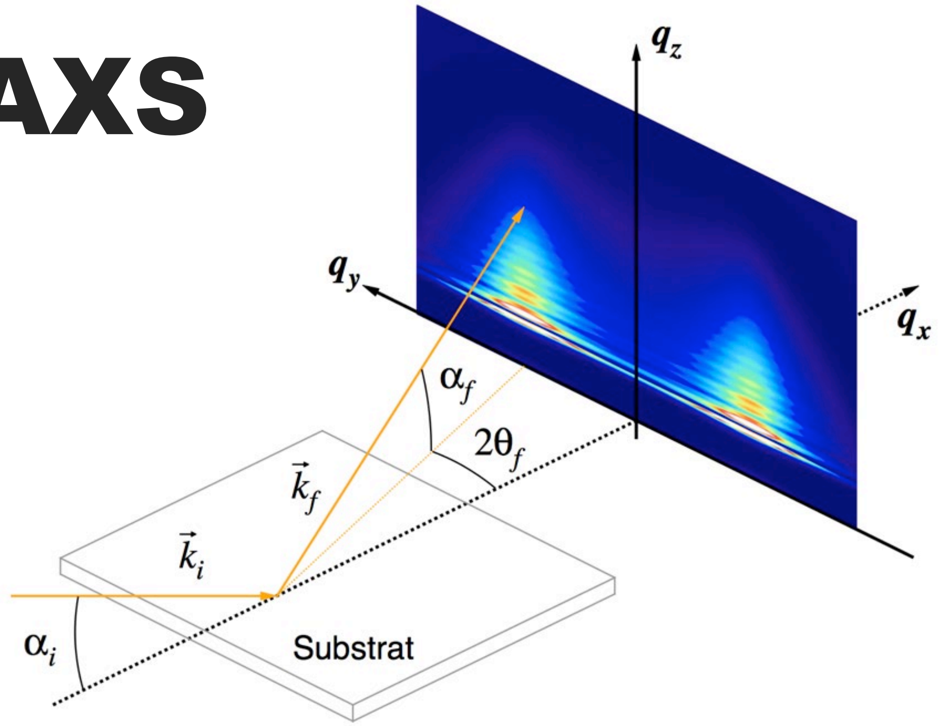
- Work well with synchrotron
- CD-SAXS in-line equipment => focused on HAR structure
- Requires significant improvement of laboratory high energy source in term of flux

Measurement in grazing incidence: CD-GISAXS

2. Critical Dimension Grazing Incidence SAXS (CD-GISAXS)

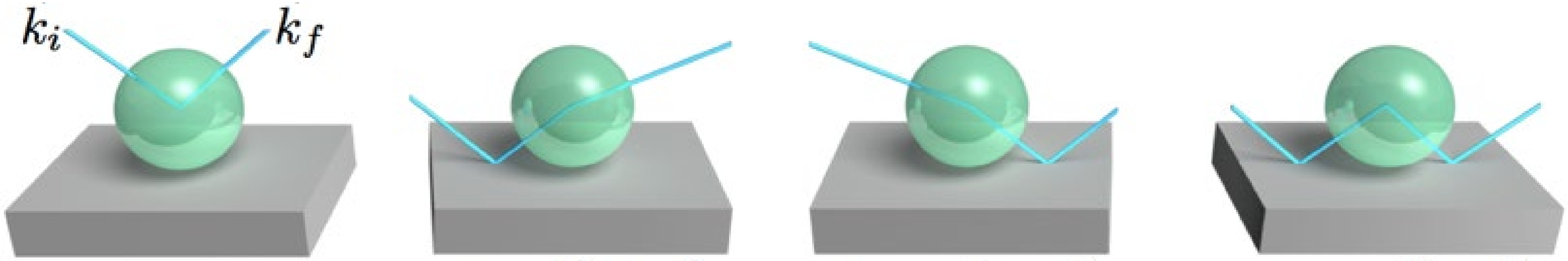
Grazing-incidence SAXS (GISAXS)

- ✓ Grazing incidence geometry
- ✓ Thin films
- ✓ Large footprint



Distorted Wave Born Approximation (DWBA)

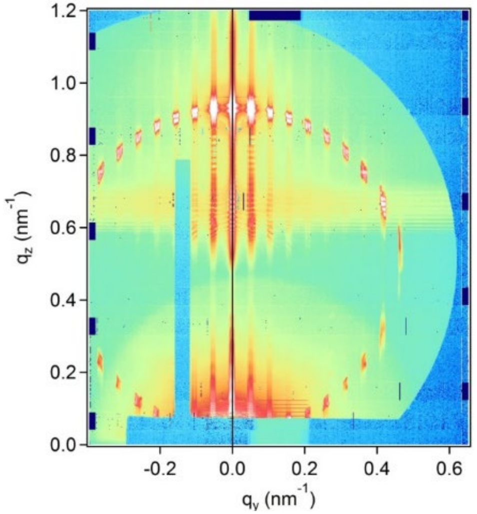
$$\mathcal{F}(q_{||}, k_z^i, k_z^f) = F(q_{||}, q_z^1) + r(\alpha_f)F(q_{||}, q_z^2) + r(\alpha_i)F(q_{||}, q_z^3) + r(\alpha_i)r(\alpha_f)F(q_{||}, q_z^4)$$

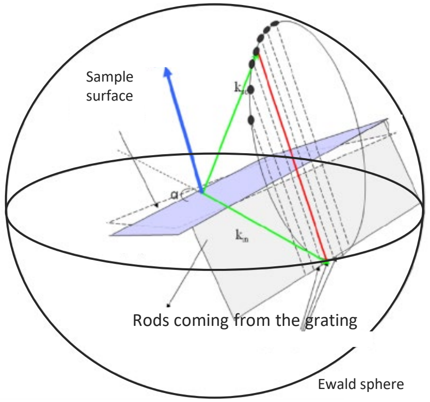


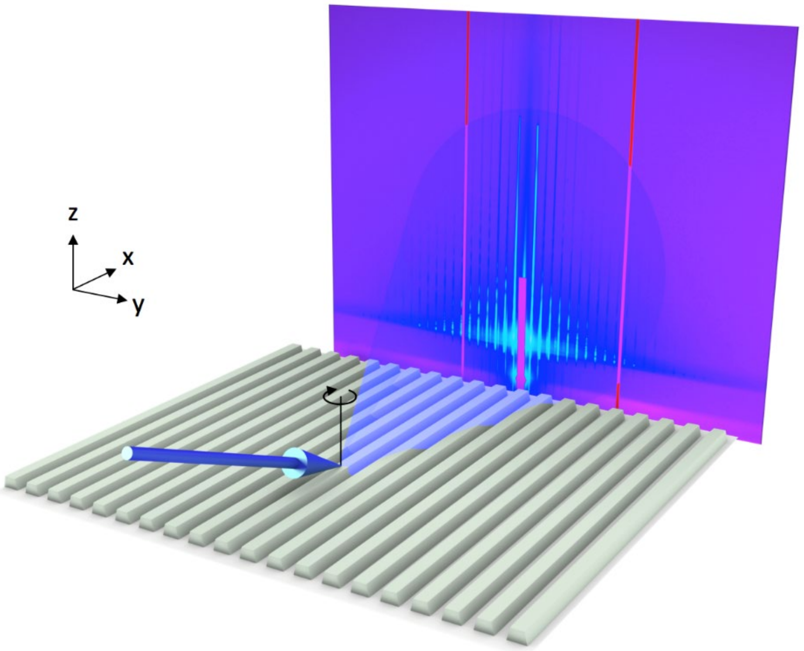
$\vec{q}_1 = \vec{k}_f - \vec{k}_i$ $\quad$ $\vec{q}_3 = \vec{k}_f + \vec{k}_i$ $\quad$ $\vec{q}_2 = -\vec{k}_f - \vec{k}_i$ $\quad$ $\vec{q}_4 = -\vec{k}_f + \vec{k}_i$

Critical Dimension GISAXS (CD-GISAXS)

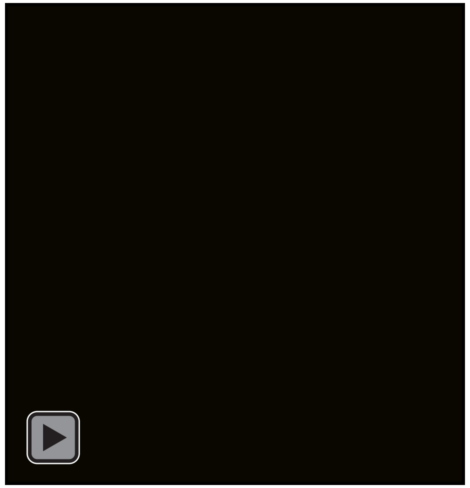
Hofmann et al. J. Vac. Sci. Tech. (2009)
Lu et al. App. Cryst. (2012)
Suh et al. J. Appl. Cryst. (2016)





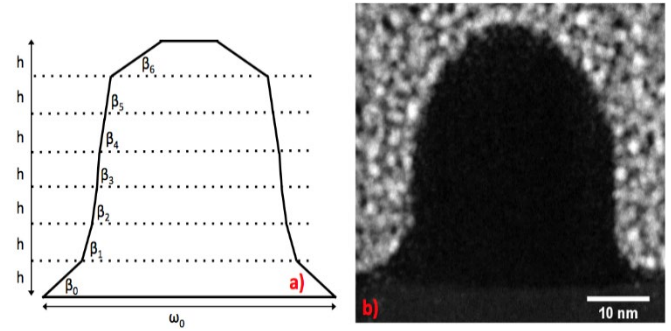


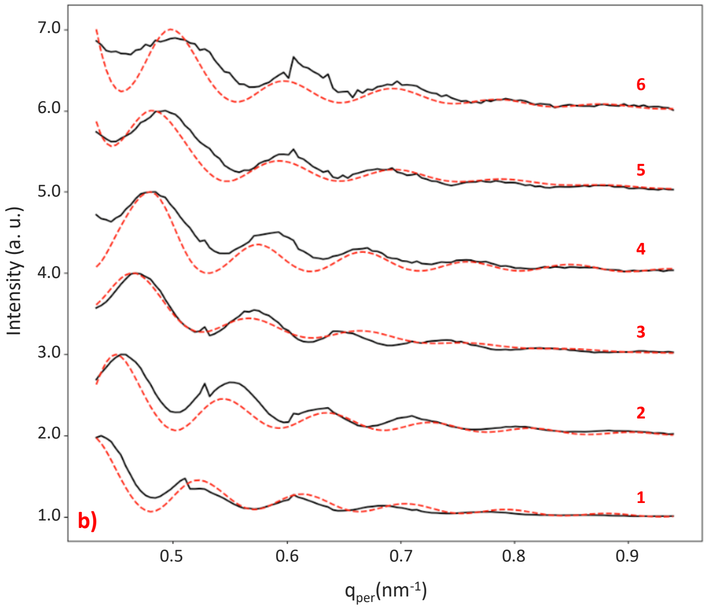
Rotation of the gratings (along z)

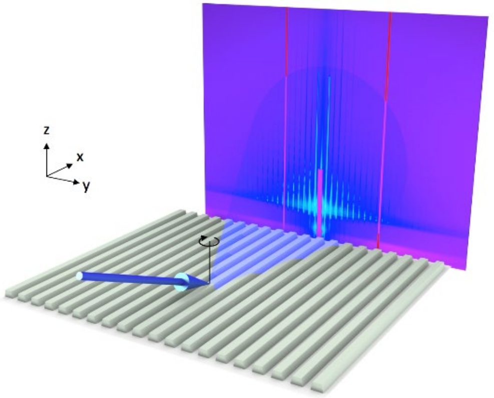


Full intersection of the Bragg rods and the Ewald sphere recorded

Critical Dimension GISAXS (CD-GISAXS)





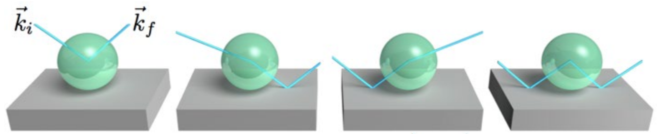


1D vertical cut

Good agreement between the cross-section TEM and the CD-GISAXS

Freychet et al. Proc. SPIE (2018)
Freychet et al. Phys. Rev. Appl. (2019)

Distorted Wave Born Approximation



- ✓ Complexity of the model
- ✓ Bigger footprint on the sample
- ✓ No need to cross a silicon wafer => **doable with a laboratory / Soft x-ray sources**

3. CD-GISAXS with a Laboratory equipment

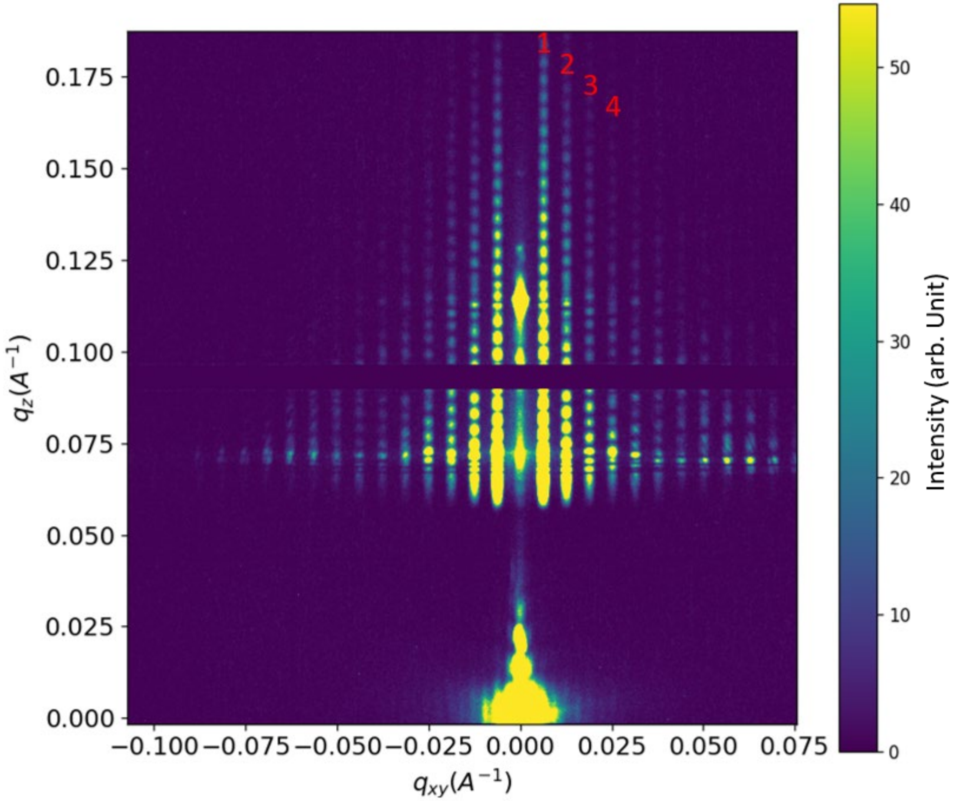
CD-GISAXS with a Laboratory equipment

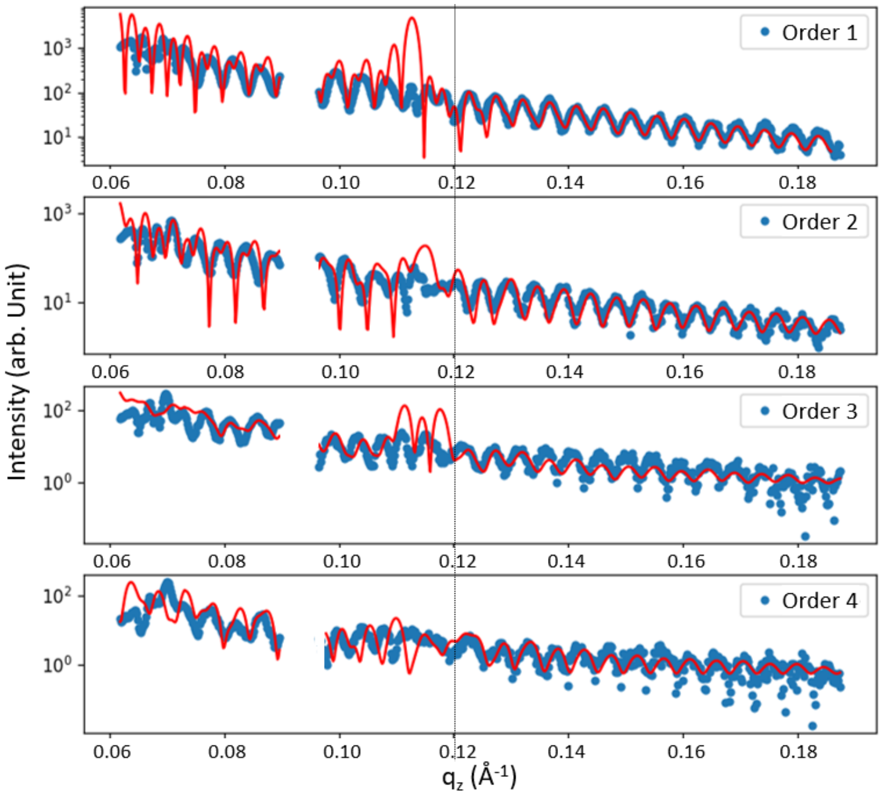
- ✓ Source Cu K-α (8.047 keV)
- ✓ Sample to detector distance: 1.8 m
- ✓ Transmission and Reflection

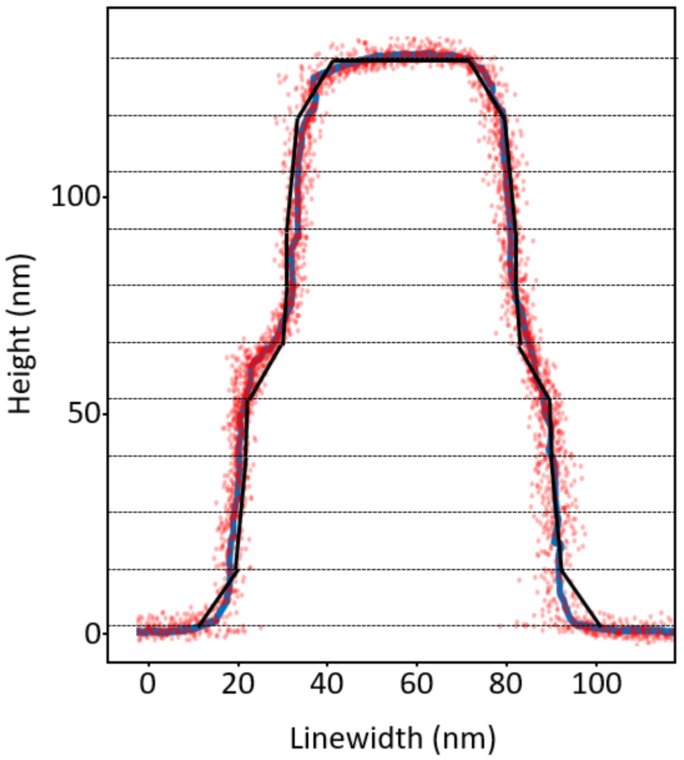
Freychet et al. JM3 2023

CD-GISAXS with a Laboratory equipment

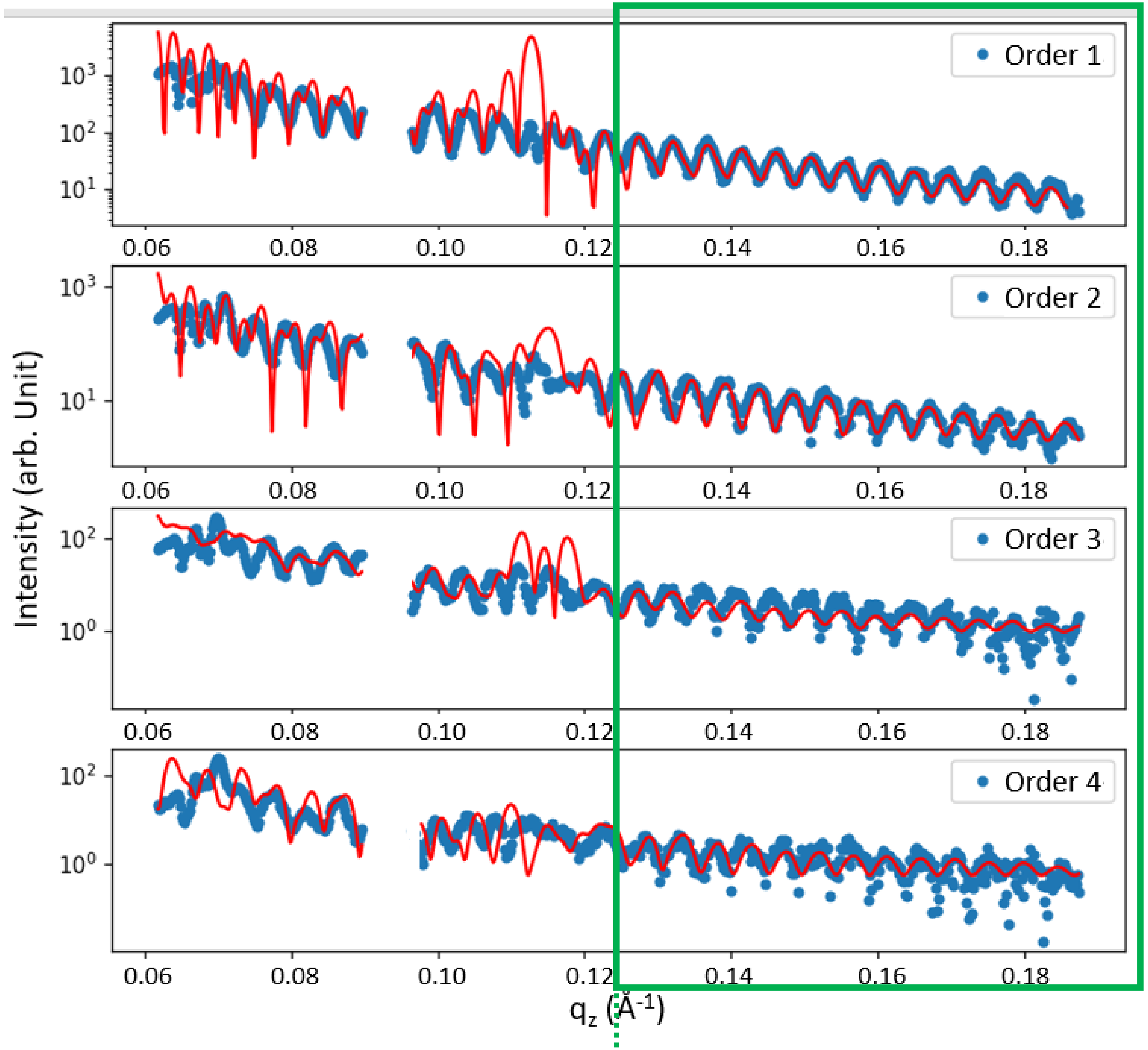
Freychet et al. JM3 2023

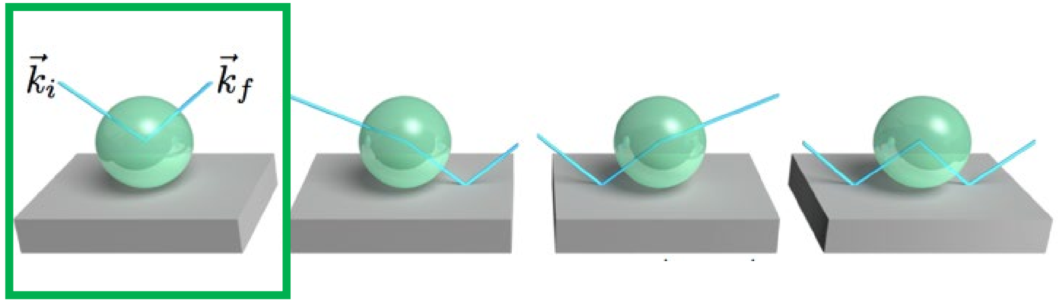






CD-GISAXS with a Laboratory equipment

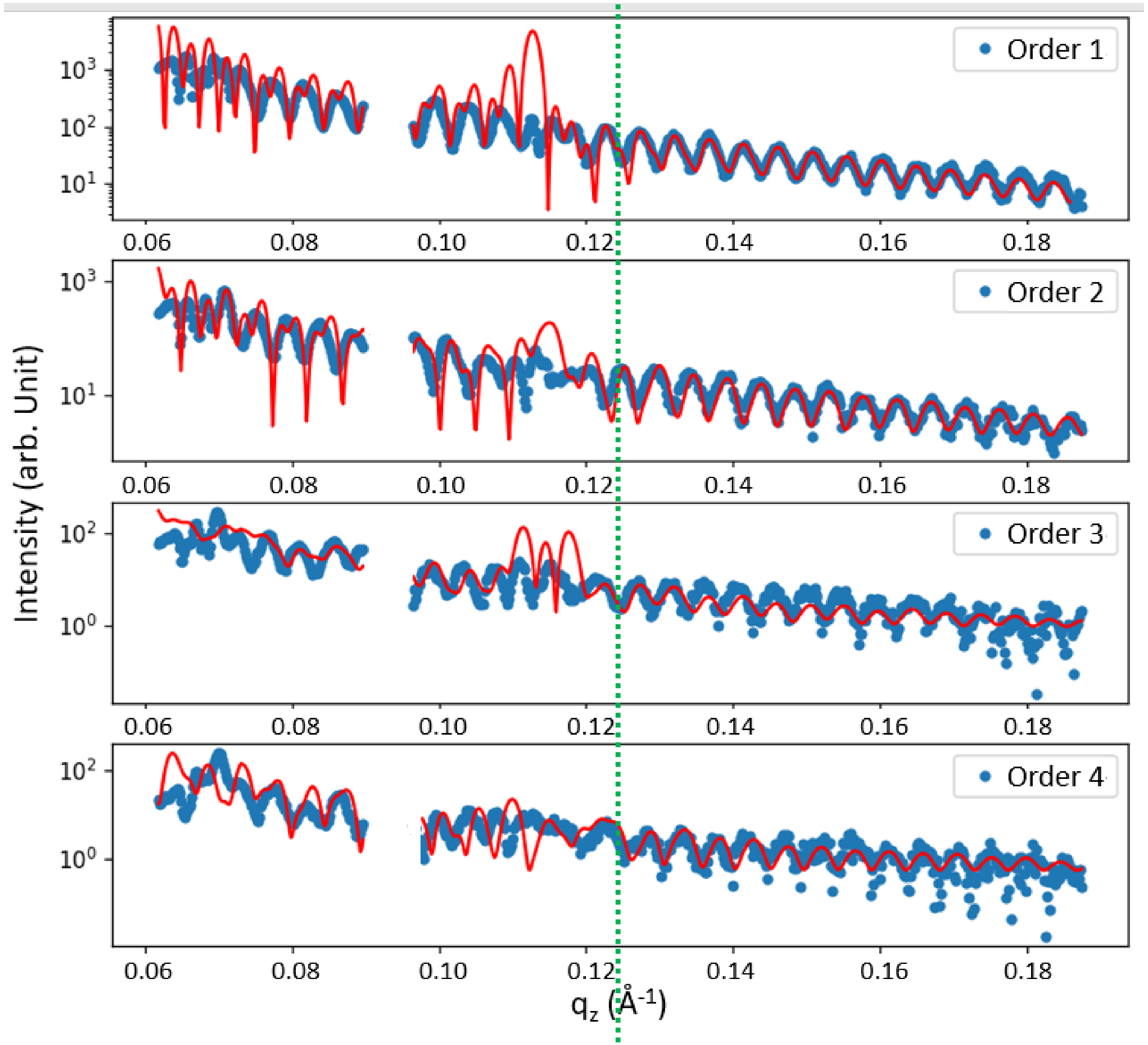


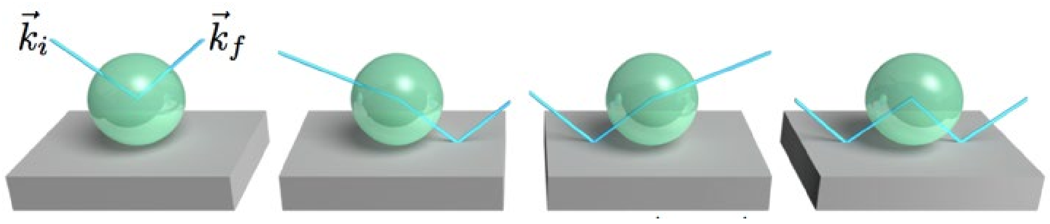


DWBA:

✓ α_i and $\alpha_f > 3 \times \alpha_c$: minimize the multi-reflection effect

CD-GISAXS with a Laboratory equipment

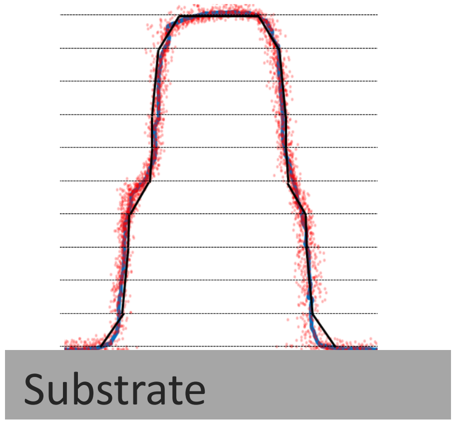




DWBA:

✓ α_i and α_f > 3 x α_c: minimize the multi-reflection effect

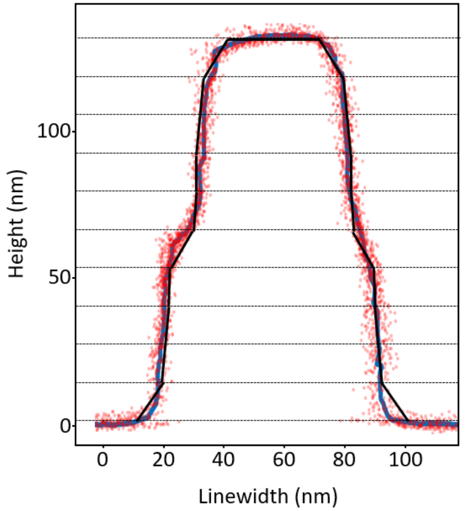
✓ Multi-reflection



Perfect interface (No roughness)

CD-GISAXS: Advantages and drawbacks

- ✓ CD-GISAXS brings a sub-nm resolution
- ✓ In grazing incidence configuration, Cu K-α x-ray source can be used



- ✓ Quick measurements (currently 10s minutes with a standard micro-source Cu K-α source)
- ✓ Large footprint (couple mms)
- ✓ HAR samples

4. CD-GISAXS with lower energy source

CD-GISAXS with a soft x-ray source

Hard x-ray (8 keV)

α_c(Si) = 0.2 deg

Beam footprint α 1/sin(α_i) α 200

Soft x-ray (200 eV):

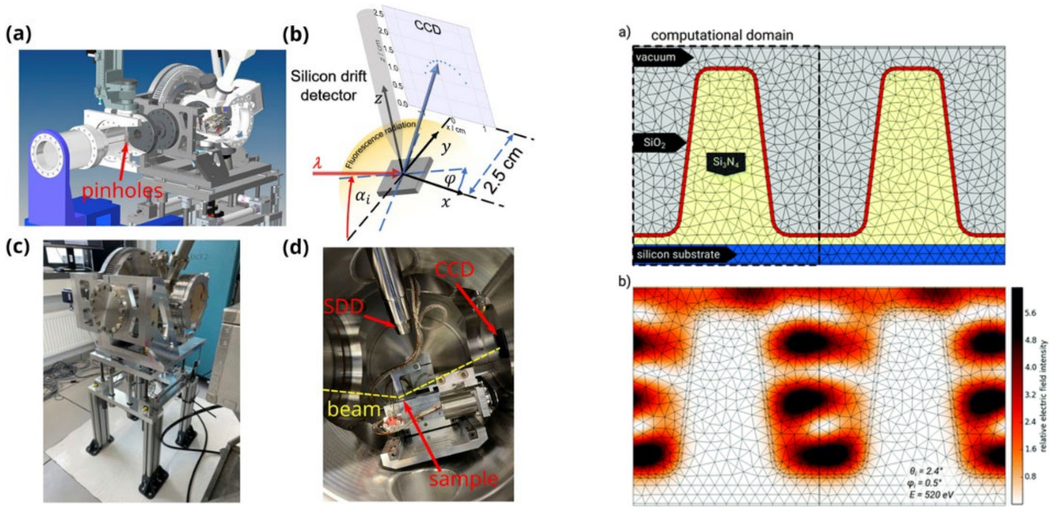
α_c(Si) = 10 deg

Beam footprint α 1/sin(α_i) α 4

No footprint issue

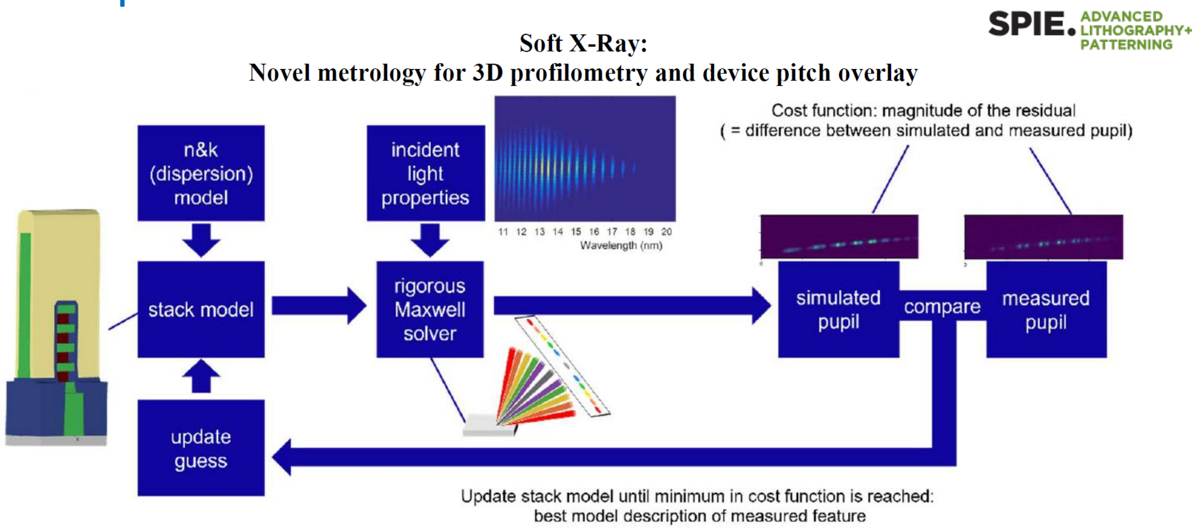
PTB is working with EUV source since 2014

- ✓ Synchrotron device
- ✓ Major development in terms of analysis software



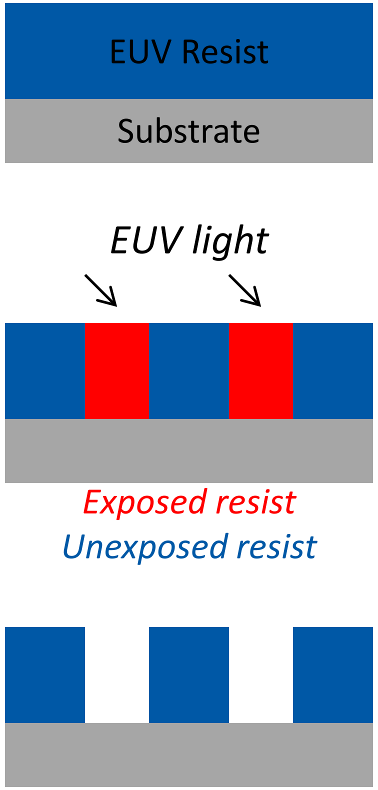
ASML (C. Porter) proposed the 1st laboratory equipment results in 2023 using HHG source

- ✓ Footprint < 50 µm
- ✓ Acquisition time around 200 s



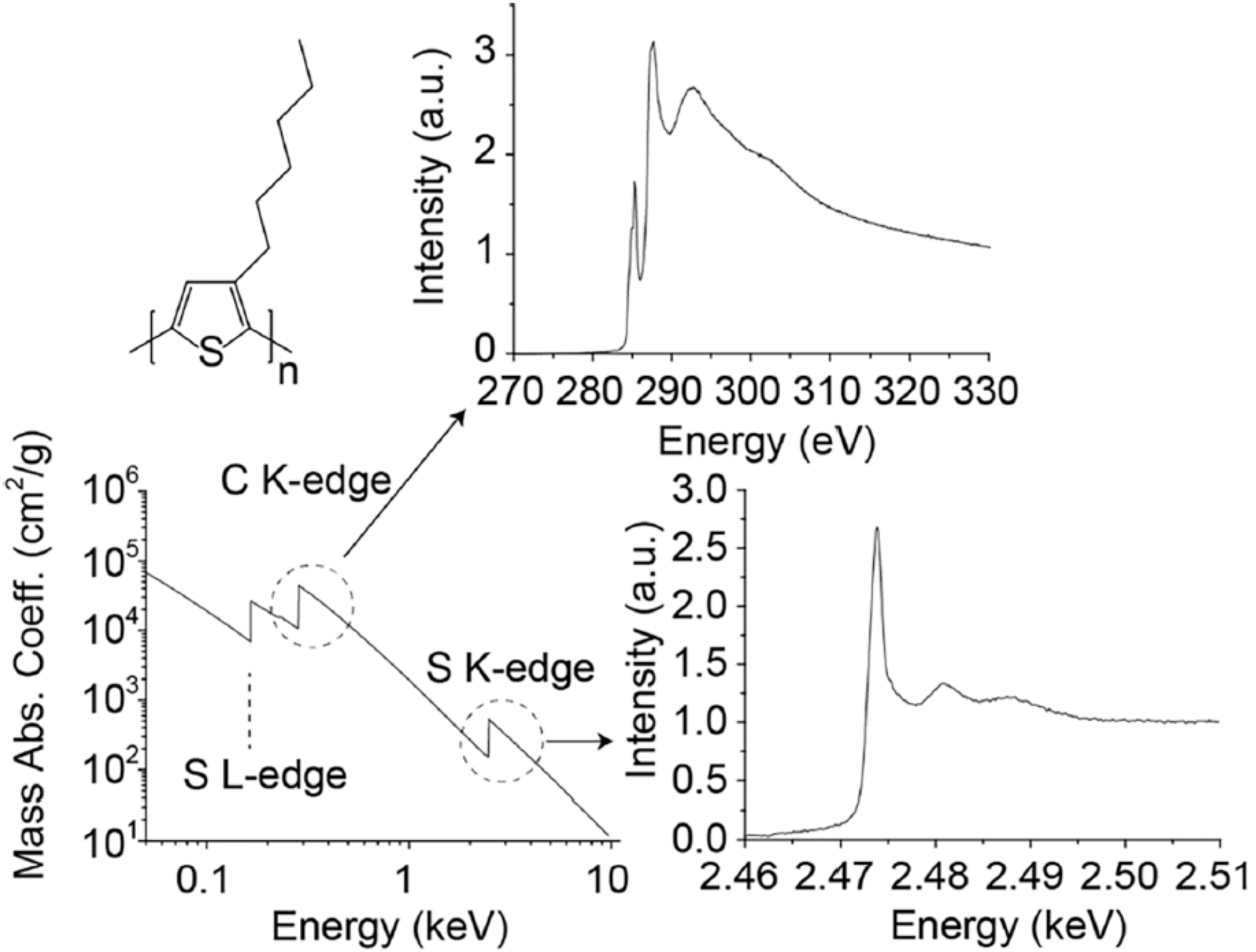
Resonant Soft X-Ray Scattering (RSoXS)

EUV lithography process simplified



Exposed resist
Unexposed resist

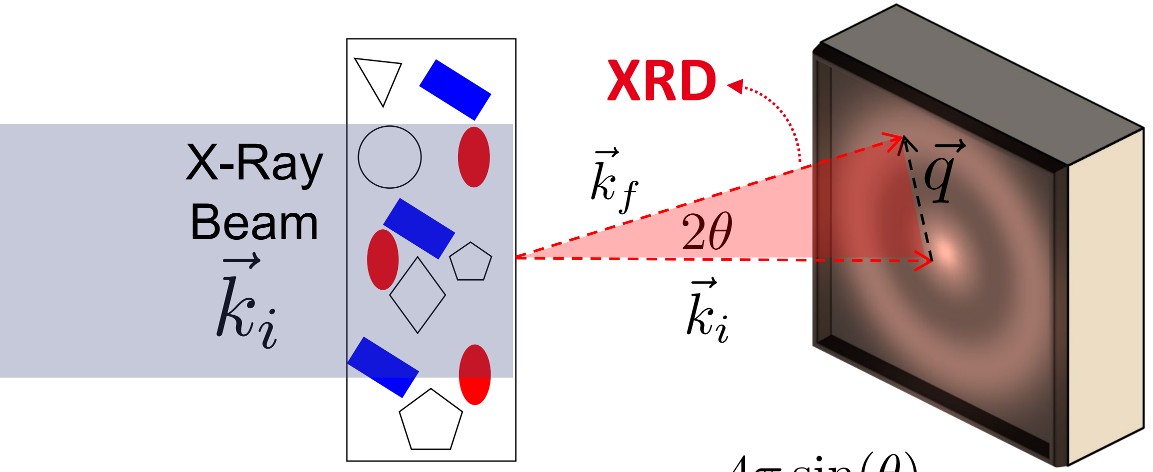
Latent imaging => Electronic density contrast between exposed and unexposed resist?



Resonant **So**ft **X**-Ray **S**cattering (**RSoXS**)

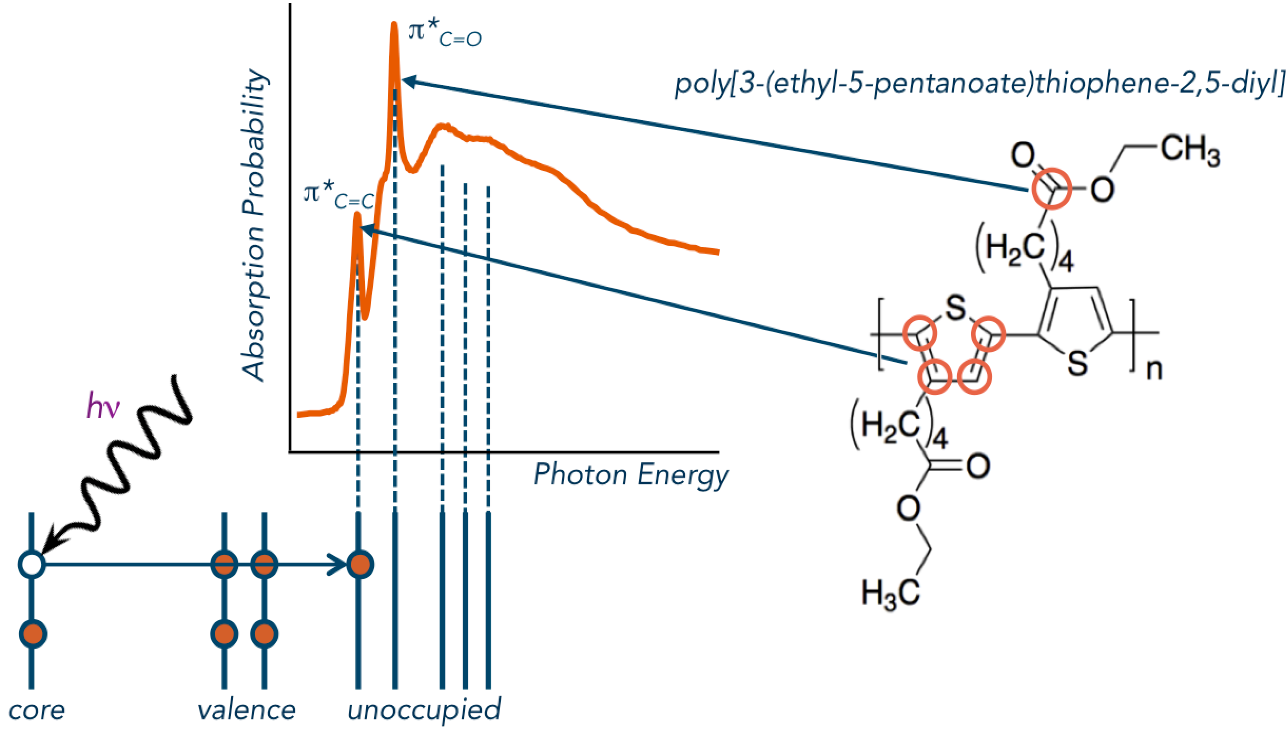
Resonance (Anomalous) Effect $f = f_0 + f' + if''$

Small Angle X-Ray Scattering



$$\vec{q} = \vec{k}_f - \vec{k}_i = \frac{4\pi \sin(\theta)}{\lambda}$$

X-ray Absorption Spectroscopy (β)



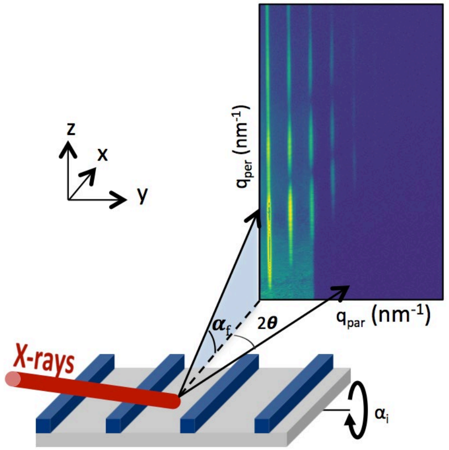
Refractive Index

$n(E) = 1 - \delta + i\beta$

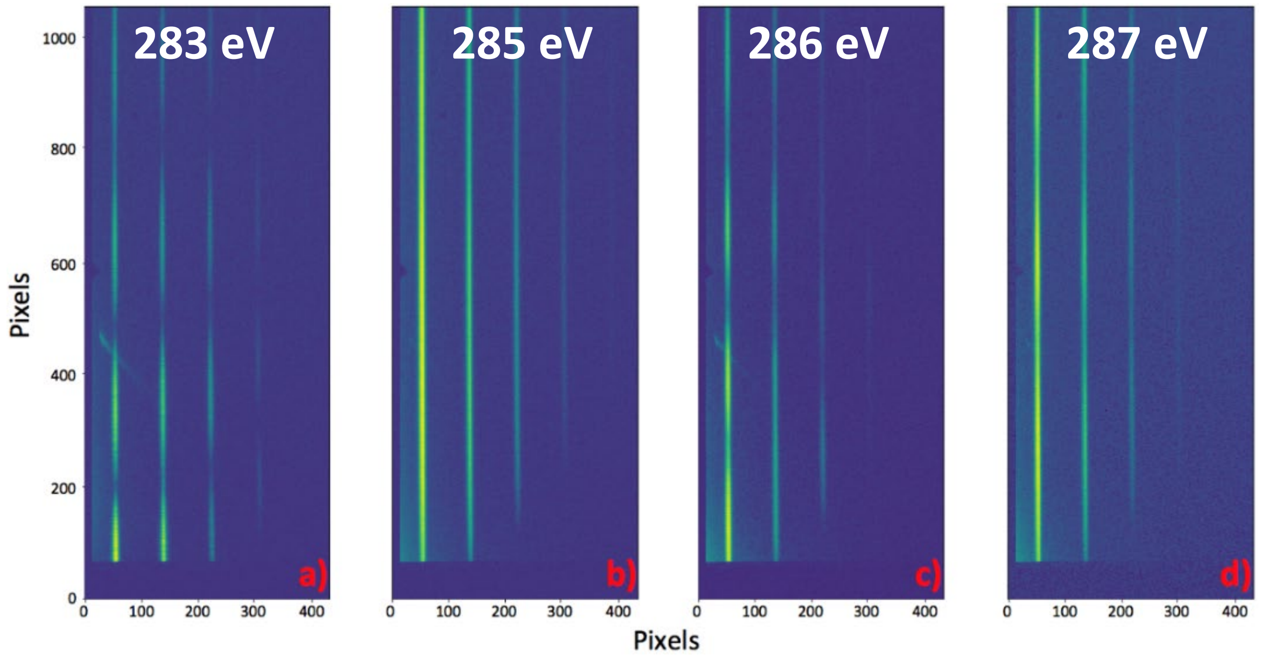
Scattering Intensity

$I(q) \; \alpha \; |\Delta n|^2 = |\Delta\delta^2 + \Delta\beta^2| E^4$

CD-GIRSOXS of latent image

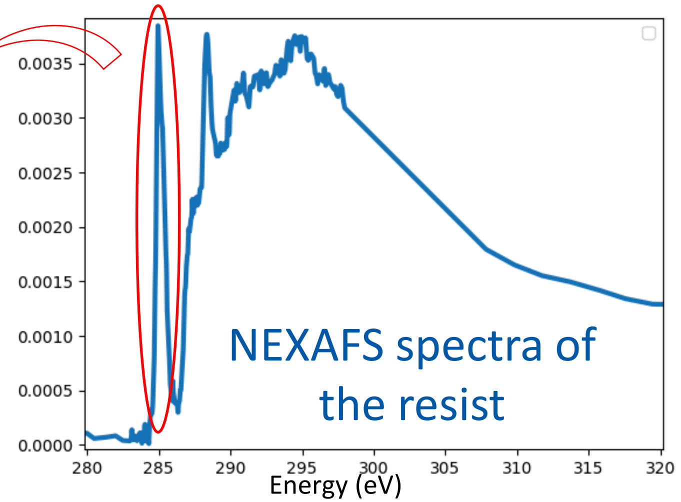


Exposed resist
Unexposed resist



Chemically amplified resist:

Peak related to a specific carbon bonds



NEXAFS spectra of the resist

✓ **283 and 286 eV: Modulations in Q_z=contrast!**

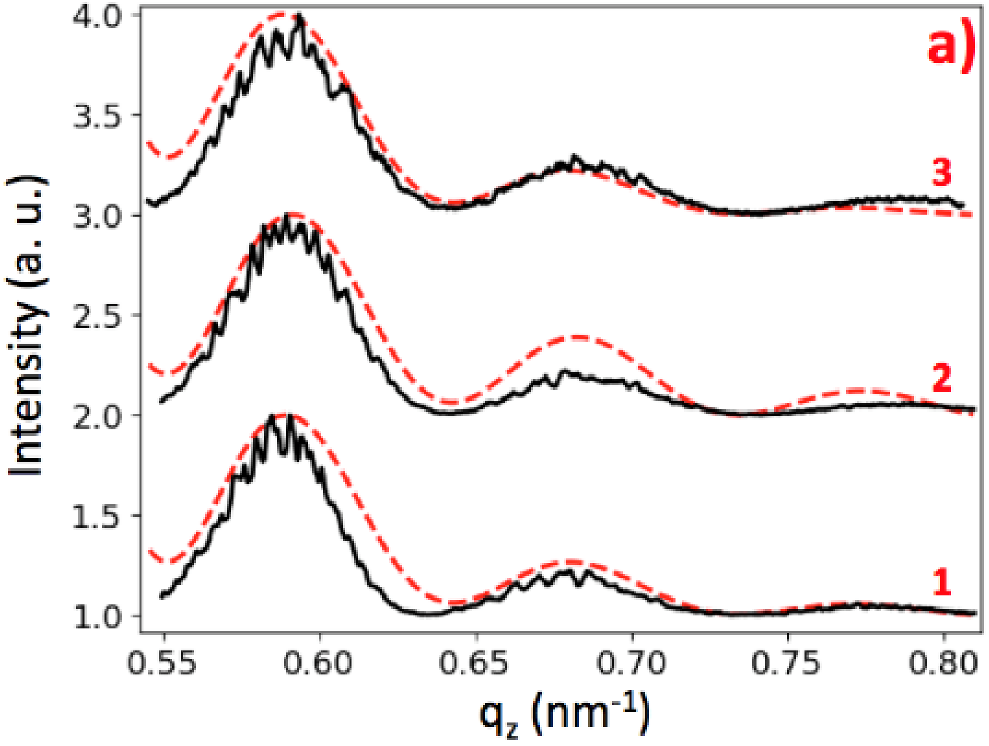
X **285 and 287 eV: No contrast observed…**

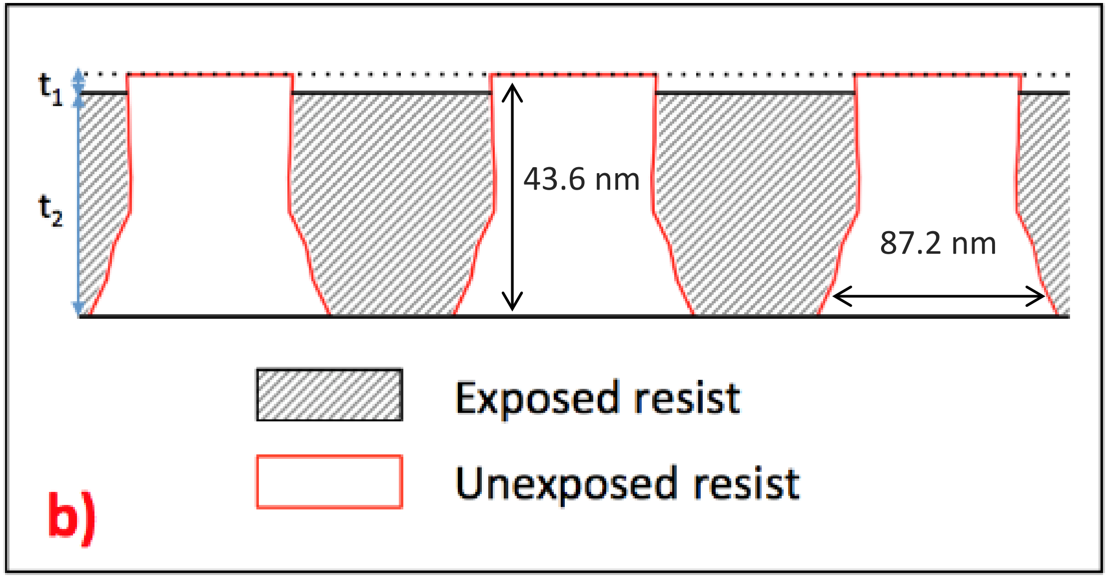
Contrast between exposed/unexposed resist

Freychet et al. Proc. SPIE EUV lithography (2019)
Freychet et al. J. Micro. Nanolith. MEMS, and MOEMS (2019)

CD-GIREXS of latent image

Reconstruction of the 3D shape of a latent image (283 eV)





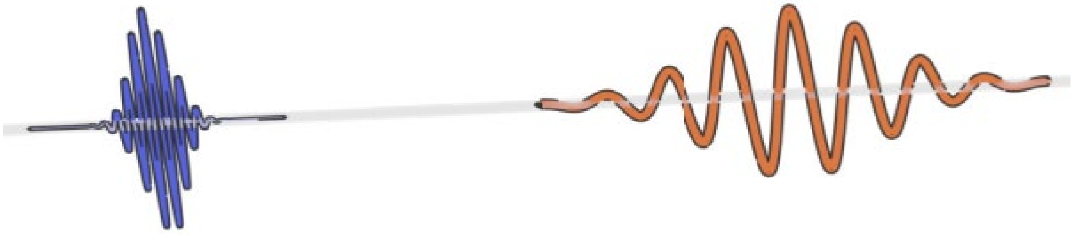
- ✓ **New perspectives to control the 3D shape of a latent image**
- ✓ **Short measurement time: 10 seconds**

Freychet et al. Proc. SPIE EUV lithography (2019)
Freychet et al. J. Micro. Nanolith. MEMS, and MOEMS (2019)

Perspectives / Challenges

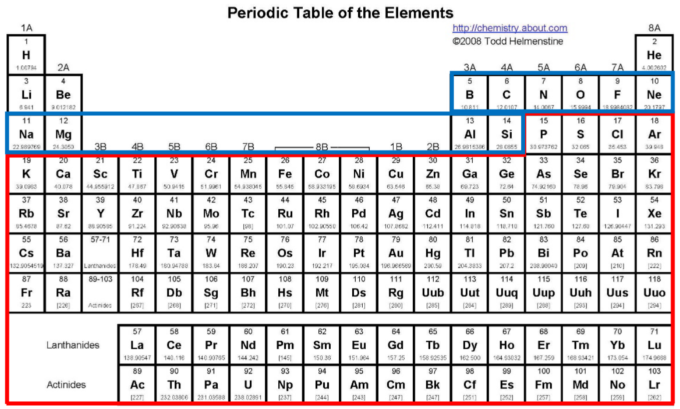
<u>Hardware improvement requirements towards in-line equipment:</u>

- ✓ For transmission CD-SAXS: Gain of an order of magnitude on flux in hard x-ray laboratory
- ✓ For Grazing Incidence CD-SAXS: Development in soft x-ray sources => smaller size and more stable over time



<u>Challenges to tackle for SAXS in the future:</u>

- ✓ Can line roughness be extracted?
- ✓ Hybrid/Combine model based methods to gain certainty and unicity of solution
- ✓ Explore and develop soft x-ray scattering at the C-edge to probe latent imaging and extend to new edges for new resists (Sn, …)



Aknowledgements

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Cheng Wang
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Applied Math

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