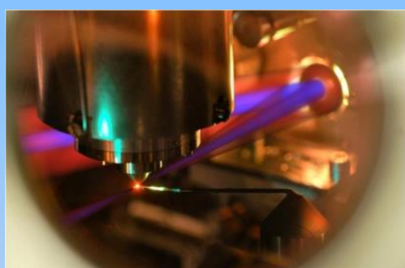
PXRNMS Workshop 2016

Optimization and application of attosecond multilayers



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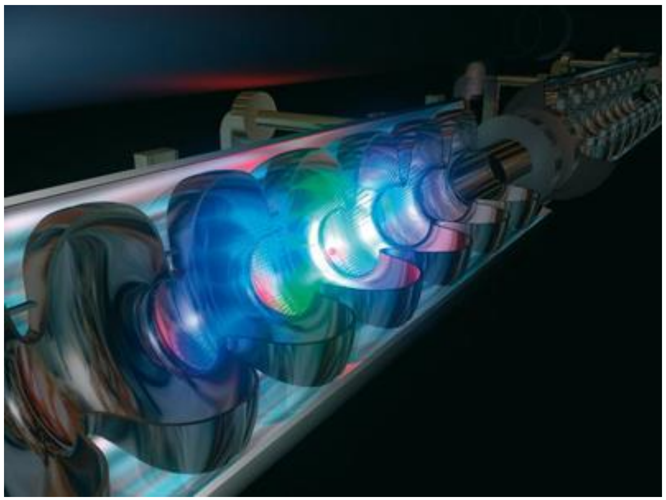
www.xray.physik.lmu.de

Motivation

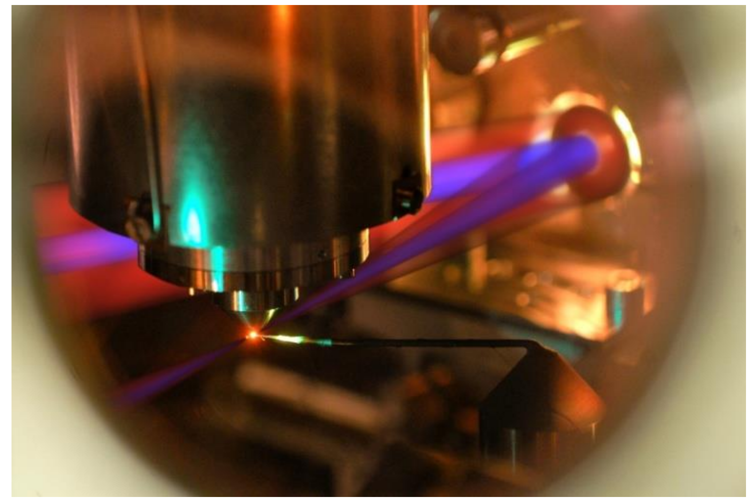
Excellent XUV/soft x-ray optics for sources emitting ultra short pulses:

(X)FEL/LCLS



grazing optics due to high intensities
High intensities in the
200 eV – keV range
Goal: shorter pulses (fs→as)

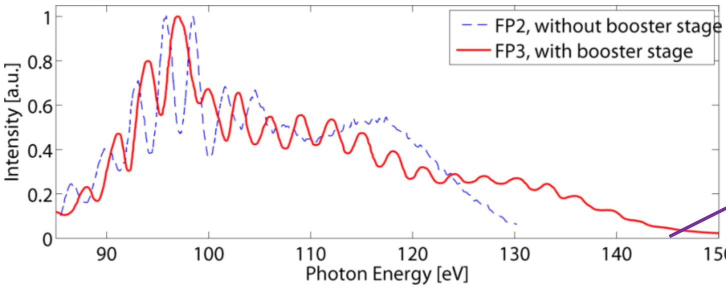
OUR FOCUS: HHG



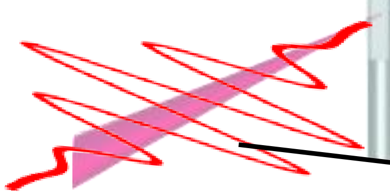
normal incidence optics possible
as pulses (requires large ΔE)
High intensities only < 200 eV
Goal: higher energies
Photon flux essential!

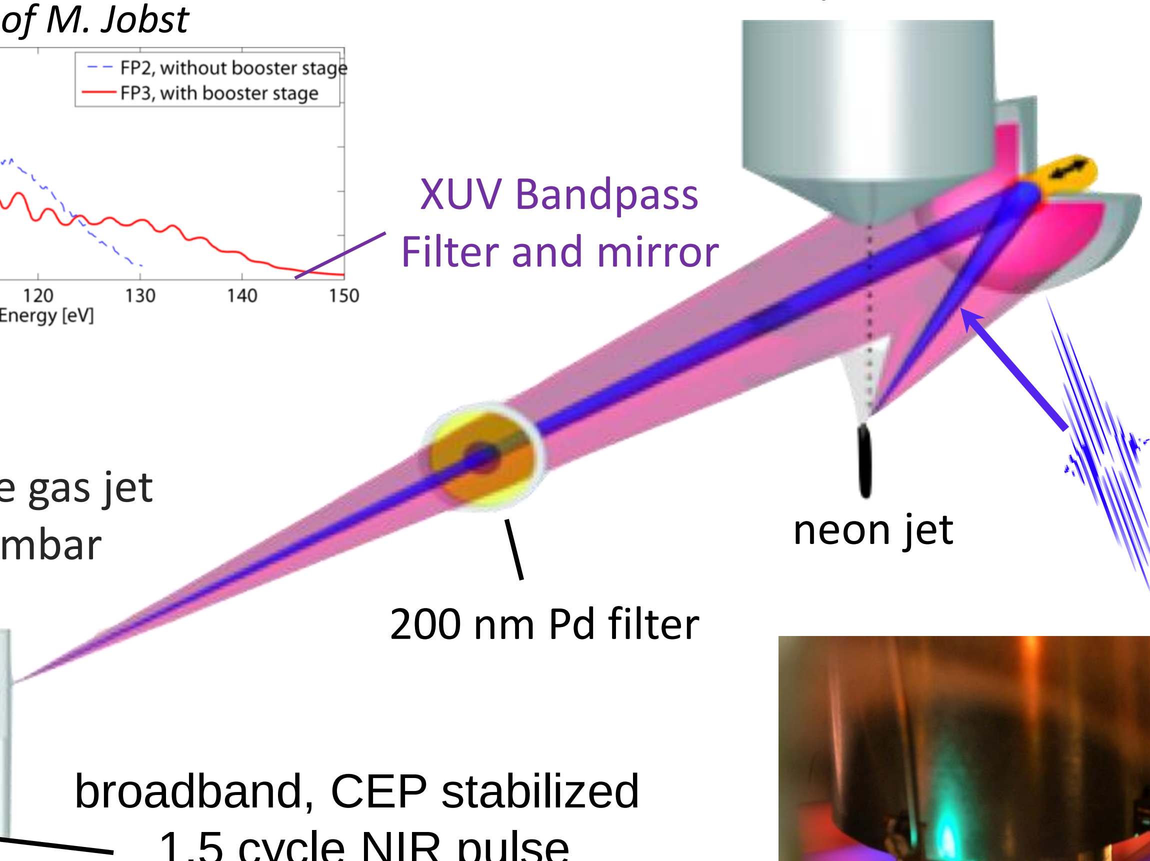
Both require optics for spectral filtering, phase shaping, …

Attosecond electron streaking

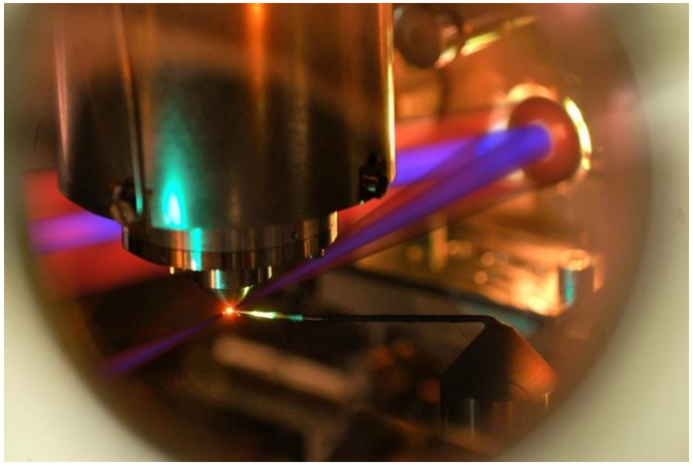


Courtesy of M. Jobst





double mirror XUV coating

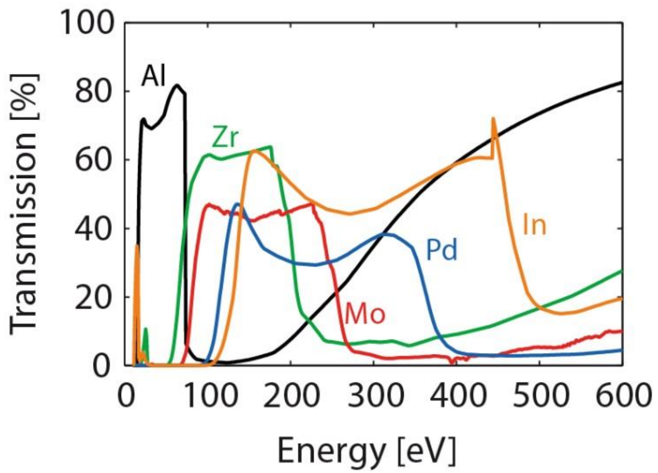


- to delay the XUV in respect to the laser pulse
- to focus the beams into the target
- to shape the reflectivity and phase of XUV

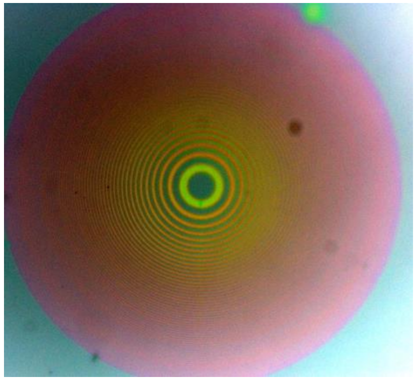
key component: optics

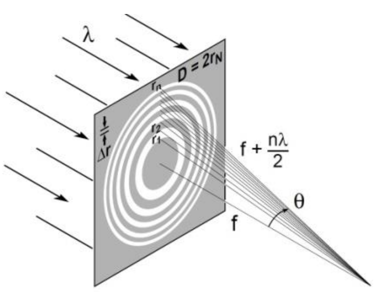
XUV attosecond optics

Transmissive optics



Diffraction optics



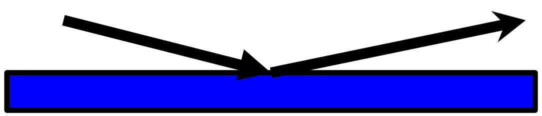


Zone plate image (light microscope)

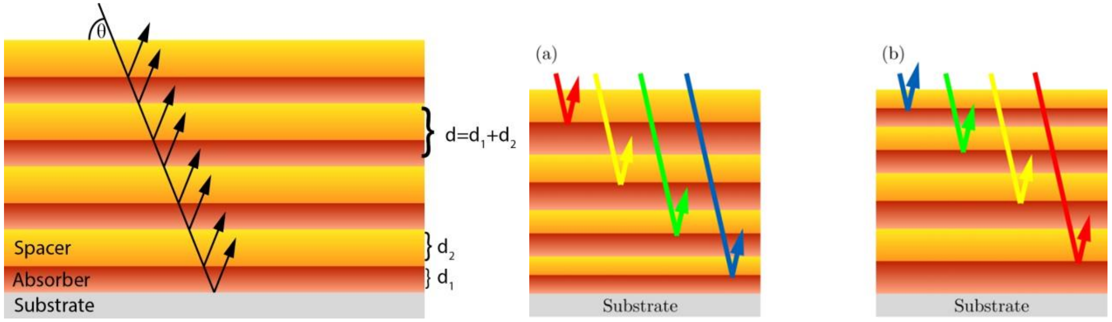
Courtesy of C. Späth

Reflective optics

Bulk reflectors

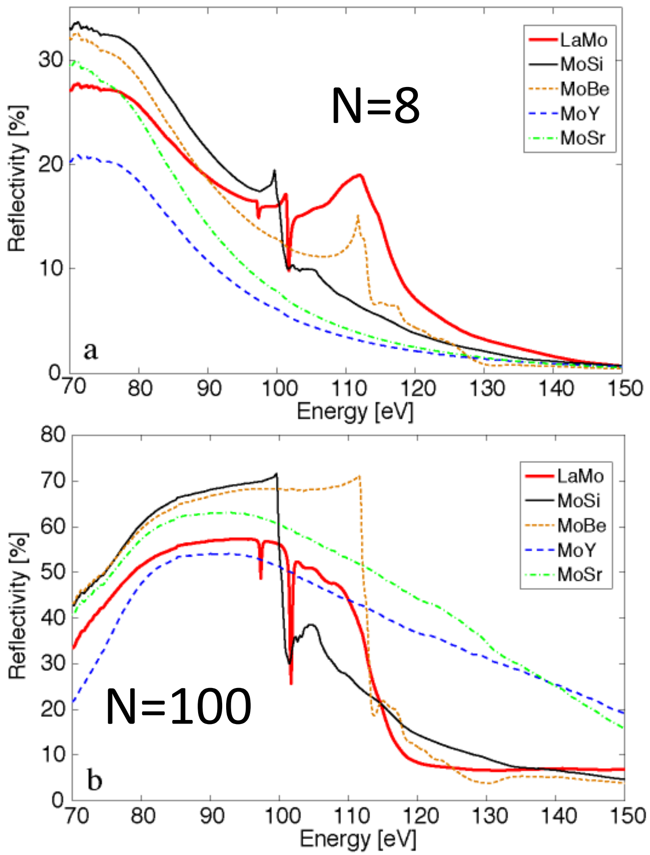


Multilayer mirrors

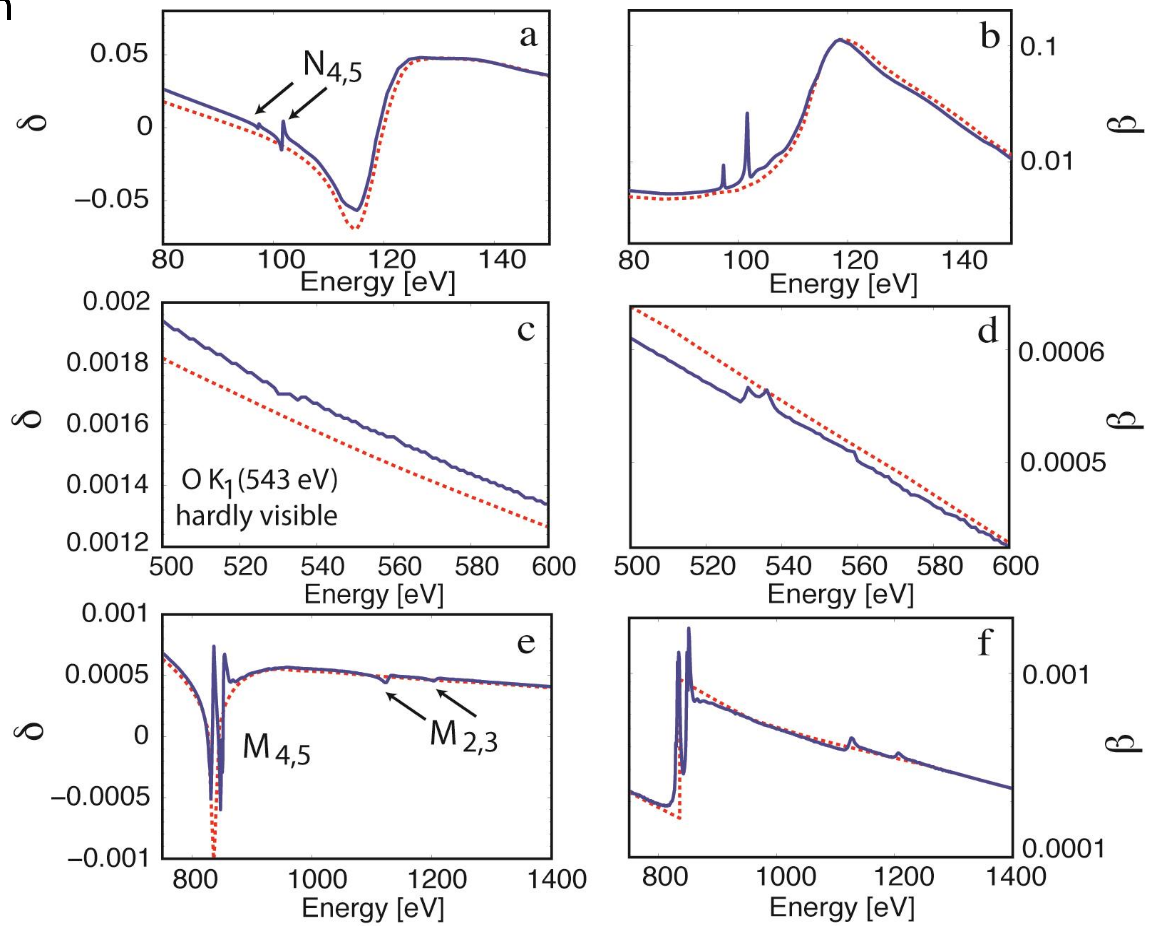


Test new material systems: LaMo (80-130 eV)

Maximum reflectivity simulation



Lanthanum: measurement of optical constants*



* Available at http://www.cxro.lbl.gov/

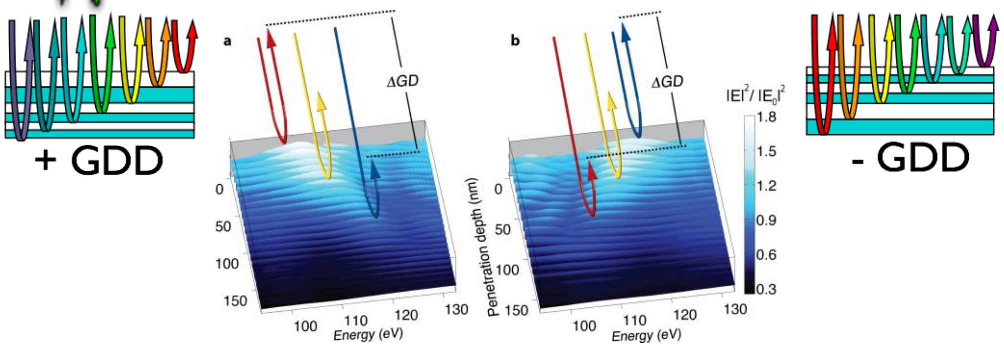
Lanthanum-molybdenum multilayer mirrors for attosecond pulses between 80 and 130 eV

Hofstetter *et al.* Optics Express **19**, 1767 (2011)

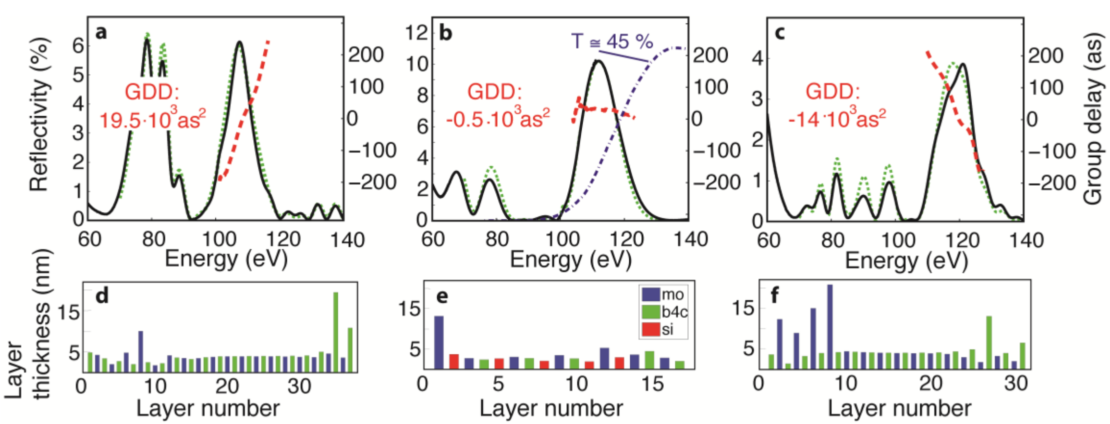
Characterization by attosecond streaking

www.attoworld.de

Chirped XUV multilayer mirrors



Design/Spectra



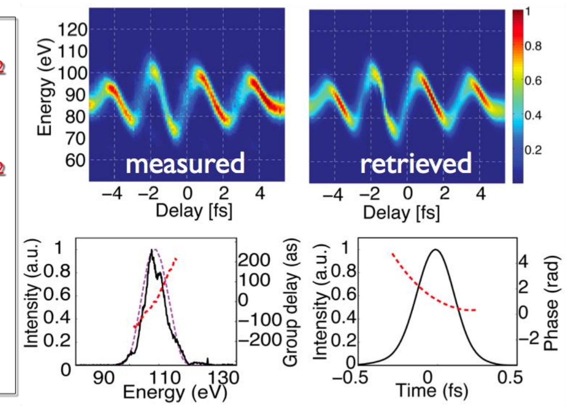
Streaking retrieval

design:
gdd: 20 x10³ as²

retrieval
gdd: 16 x10³ as²

duration:
280 as

fourierlimit
200 as

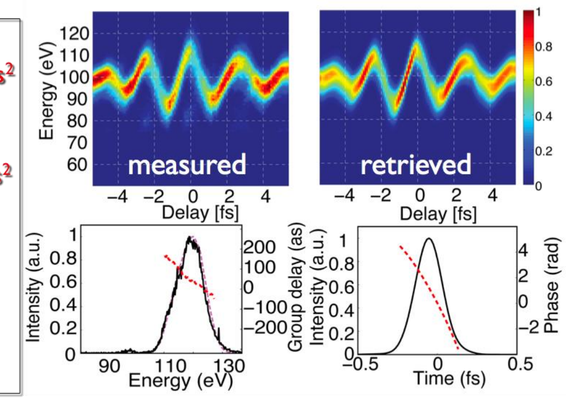


design:
gdd: -14 x10³ as²

retrieval
gdd: -8 x 10³ as²

duration:
200 as

fourierlimit
175 as



Attosecond dispersion control by extreme ultraviolet multilayer mirrors

Hofstetter *et al.* Optics Express **19**, 1767 (2011)

Attosecond Spectroscopy Requirements

Attosecond XUV/soft x-ray multilayer optics

Support of attosecond beamlines
for current experiments

≈ 120 eV (MoSi, LaMo, MoB4C)

- Selectable central energy
  20 eV – 120 eV
- Selectable bandwidth
  1 eV – 30 eV
- High temporal resolution
  as – fs
- Selectable spectral phase
  0 – ± 20000 as^2
- High efficiency

✓ Hofstetter *et al.*
New J. Phys. **13**, 063038 (2011)
→LaMo as mirrors

✓ Goulielmakis *et al.*
Science **320**, 1614 (2008)
→80 as pulses

✓ Schultze *et al.*
Science **328**, 1658 (2010)
→Delay in photoemission

✓ Hofstetter *et al.*
Optics Express **19**,1767 (2011)
→Attosecond chirp control

✓ for this energy range with MoSi or LaMo system already given

Attosecond Spectroscopy Requirements

Attosecond XUV/soft x-ray multilayer optics

≈ 400 eV (CrSc)

Support of attosecond beamlines for current experiments

Development of optics for future experiments at higher energies

- Selectable central energy
  20 eV – 1~~2~~0 400 eV ✔
- Selectable bandwidth
  1 eV – 30 eV ✔
- High temporal resolution
  as – fs ✔
- Selectable spectral phase
  $0 - \pm 20000\ \text{as}^2$ ✔
- High efficiency ✔

Chromium/Scandium multilayer mirrors

Cr/Sc used for multilayer mirrors for quite a while

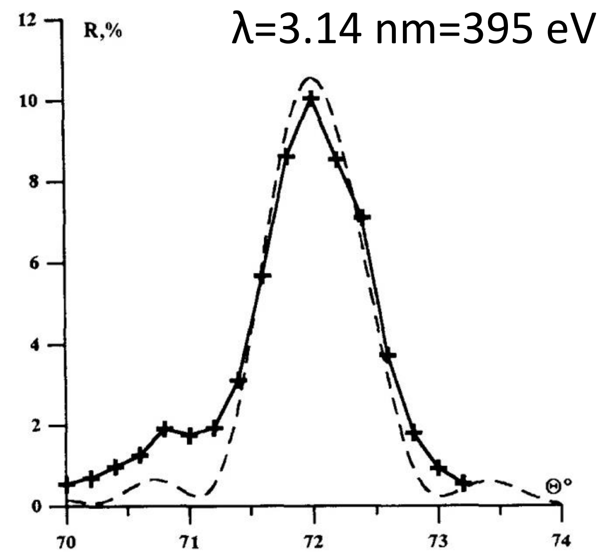
- Salashchenko *et al.* (1996)

Short-period X-ray multilayers based on Cr/Sc

N.N. Salashchenko, E.A. Shamov

Institute for Physics of Microstructures RAS, Nyzhni Novgorod, GSP-105, Russia

Received 6 June 1996; revised version received 15 August 1996; accepted 21 August 1996



Chromium/Scandium multilayer mirrors

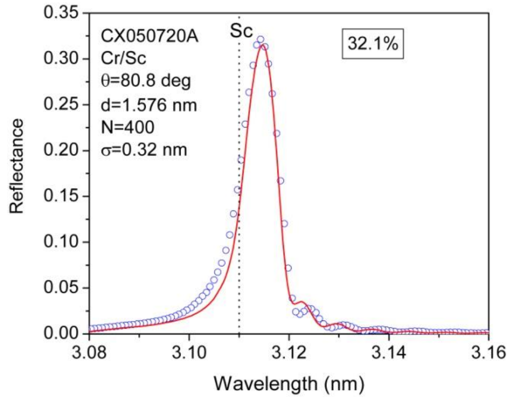
Cr/Sc used for multilayer mirrors for quite a while

- Salashchenko *et al.* (1996)
- Schäfers *et al.* (2000)
- Eriksson *et al.* (2003)
- Gullikson *et al.* (2006)

Progress in short period multilayer coatings for water window applications

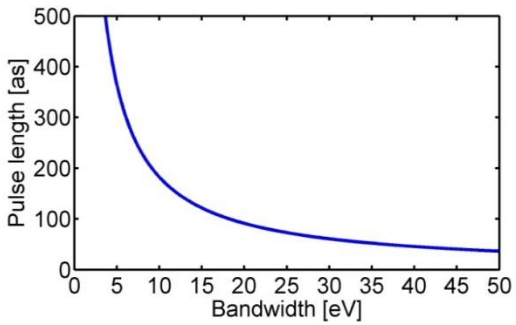
E.M. Gullikson, F. Salmassi, A.L. Aquila and F. Dollar

Center for X-Ray Optics, Lawrence Berkeley National Lab, Berkeley, CA 94720



Attosecond pulses: large bandwidth ΔE

$$E[\mathrm{eV}]\times t[\mathrm{as}]=1824$$



High-periodic multilayer mirrors: intrinsically low bandwidth ΔE

$$\frac{\Delta E}{E}=\frac{1}{N}$$

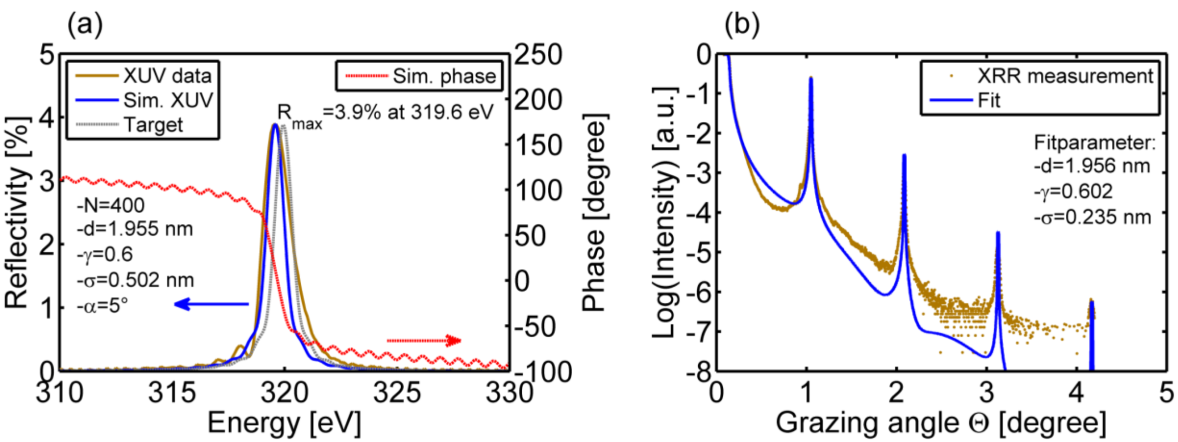
Threshold:
Ref. > 10% at 5°

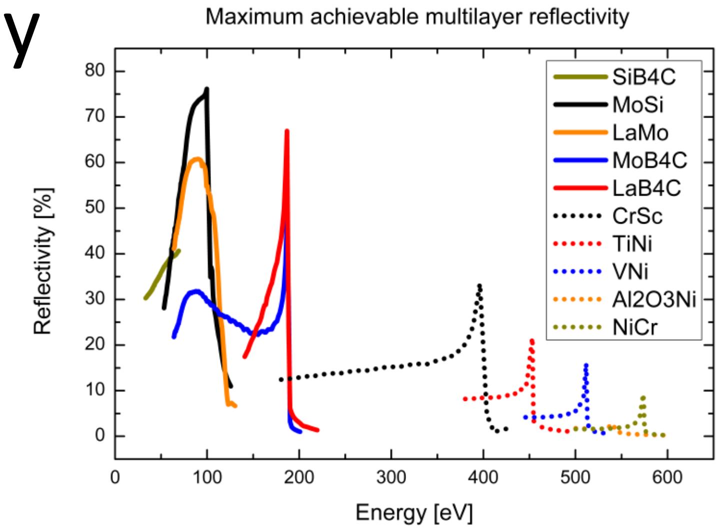
System	E [eV]	N	ΔE [eV]
Si/B4C	50	6	6
Mo/Si	93	6	13
Cr/Sc	150	70	3
Cr/Sc	300	400	1

Layer accuracy

- Selectable central energy

20 eV – 400 eV





(up to 400 eV)

Deviation: <0.05 angstrom

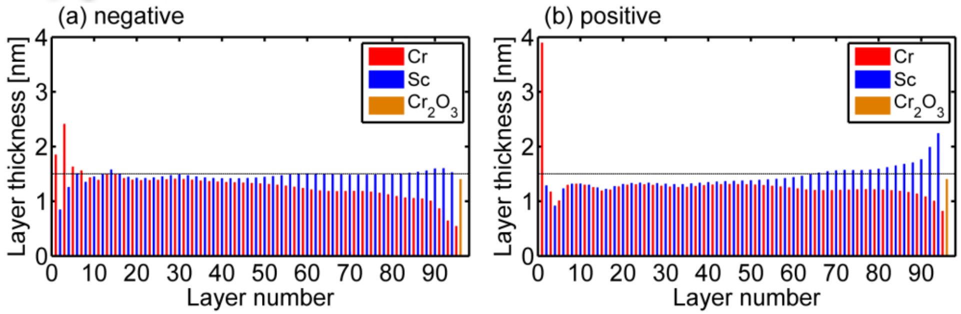
Guggenmos *et al.*

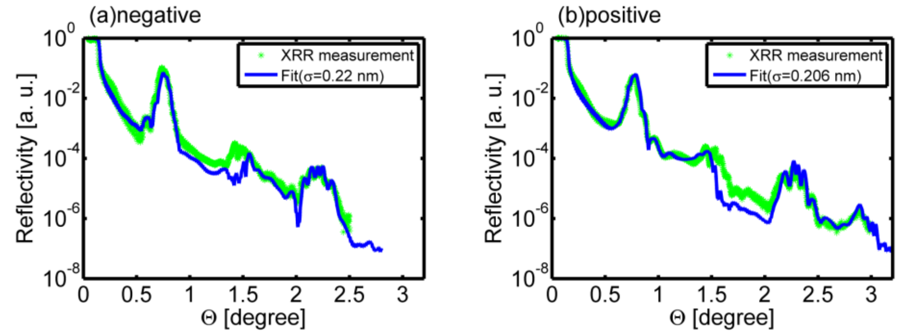
Optics Express **21**,21728 (2013)

Method	Total [nm]	Period [nm]	σ [nm]	gamma	Deviation [%]
Target:	782.3	1.953		0.6	
Profilometry:	782.959	1.9546			0.08
XRR:	783.5	1.956	0.235	0.602	0.15
XUV:	783.1	1.955	0.502	0.6	0.10

Chirped CrSc multilayer mirrors above 300 eV

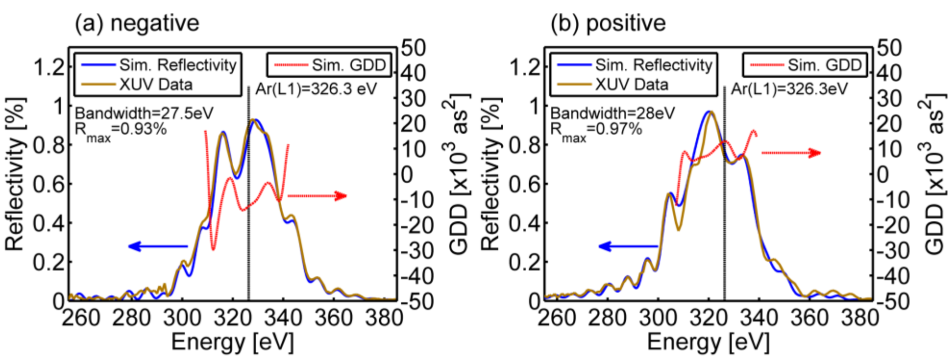
GDD=-8000as² **GDD=+8000as²**

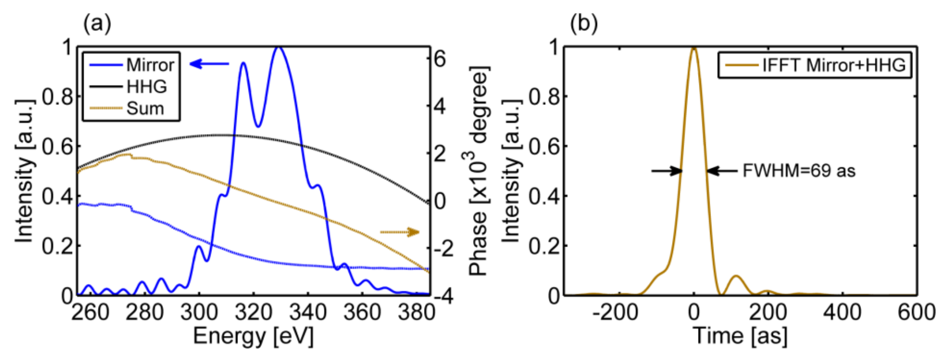




- Selectable bandwidth
  1 eV – 30 eV
- High temporal resolution
  as – fs
- Selectable spectral phase
  0 – ± 20000 as^2

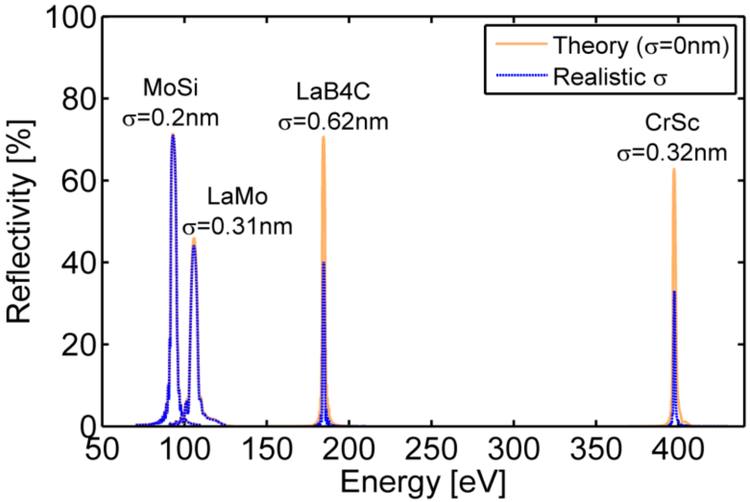
Aperiodic CrSc multilayer mirrors for attosecond water window pulses
Guggenmos *et al.* Optics Express **21**,21728 (2013)

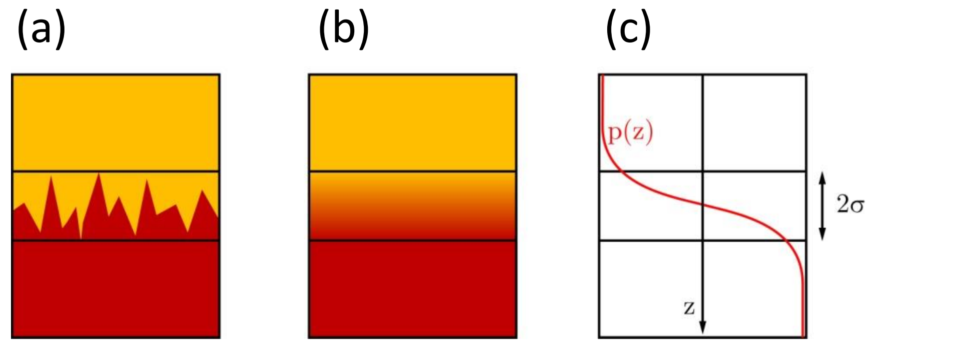




Attosecond physics towards water window

- High efficiency

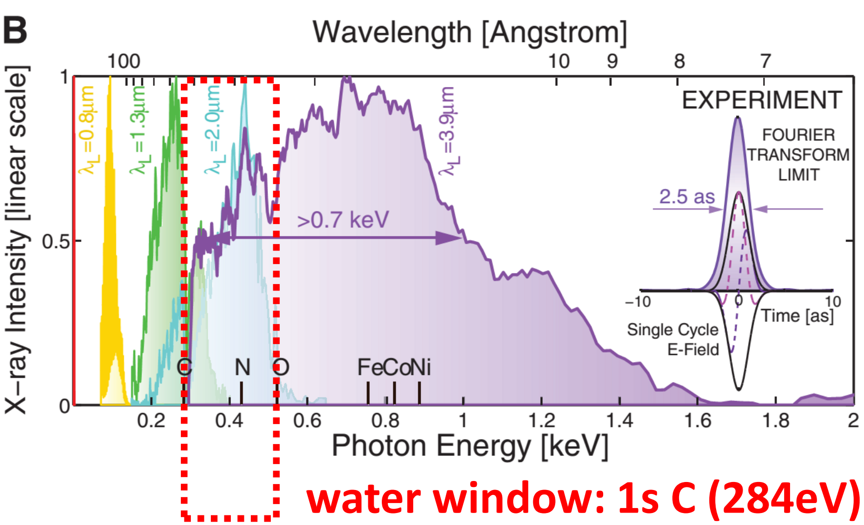




a) roughness
b) interdiffusion/intermixing
c) interface profile function

$$R = R_0 \exp(-2\pi m \frac{\sigma}{\lambda})^2$$

HHG Supercontinua already measured:

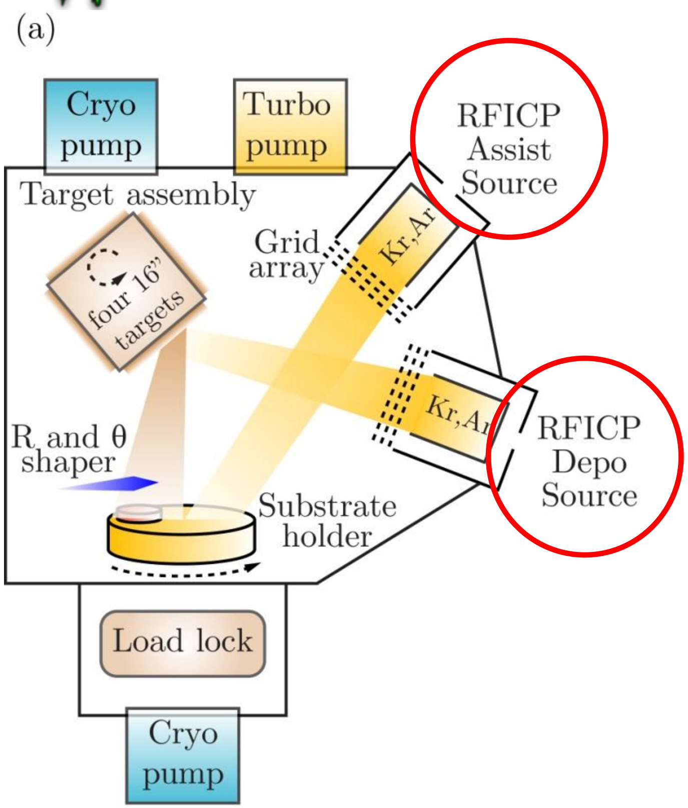


water window: 1s C (284eV) – 1s O (543eV)

Bright Coherent Ultrahigh Harmonics in the keV X-ray Regime from Mid-Infrared Femtosecond Lasers
Popmintchev *et al.* Science **336**, pp. 1287-1291 (2012)

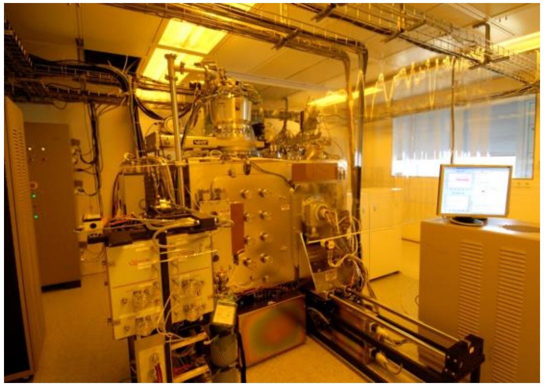
Potential applications:
- access to deeper core states dynamics
- access to biological relevant edges(C,Ca,K,N,O)
- shorter pulses due to larger bandwidth access

Ion Beam Deposition - Multilayer realization

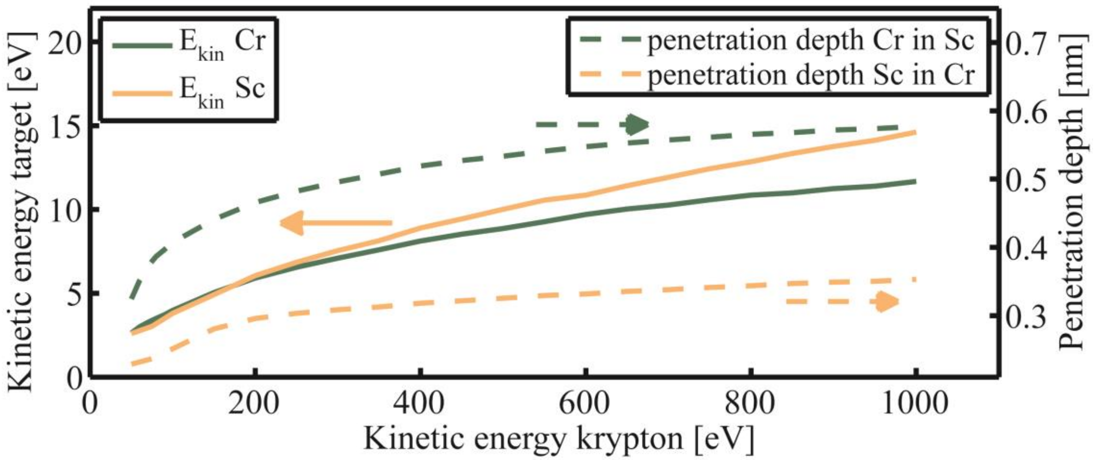


1) **variation of ion energy**

2) **interface polishing**



Using Monte-Carlo simulation method:



10eV for layer-by-layer growth

Hubler *et al.* Surf. Coat. Tech. **81**, pp. 29 (1996)

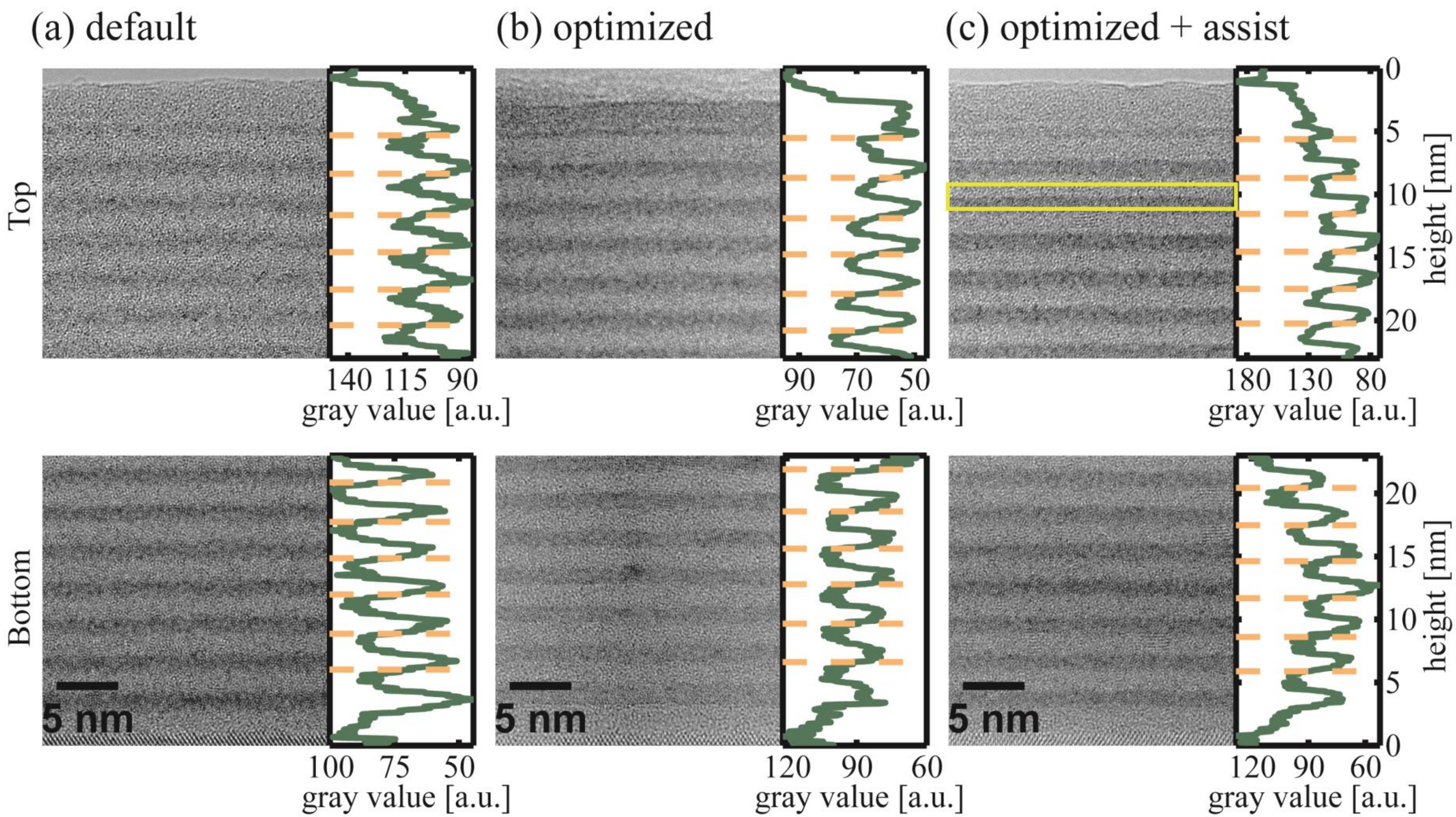
- four target materials possible
- in-situ ellipsometric control possible
- load-locked system
- shaper for homogenous layer
- high reproducibility (background pressure 10^{-9} mbar)

TEM - Cross Section Analysis

mirror specs for TEM analysis: N = 80, d = 2.95 nm, α = 45°

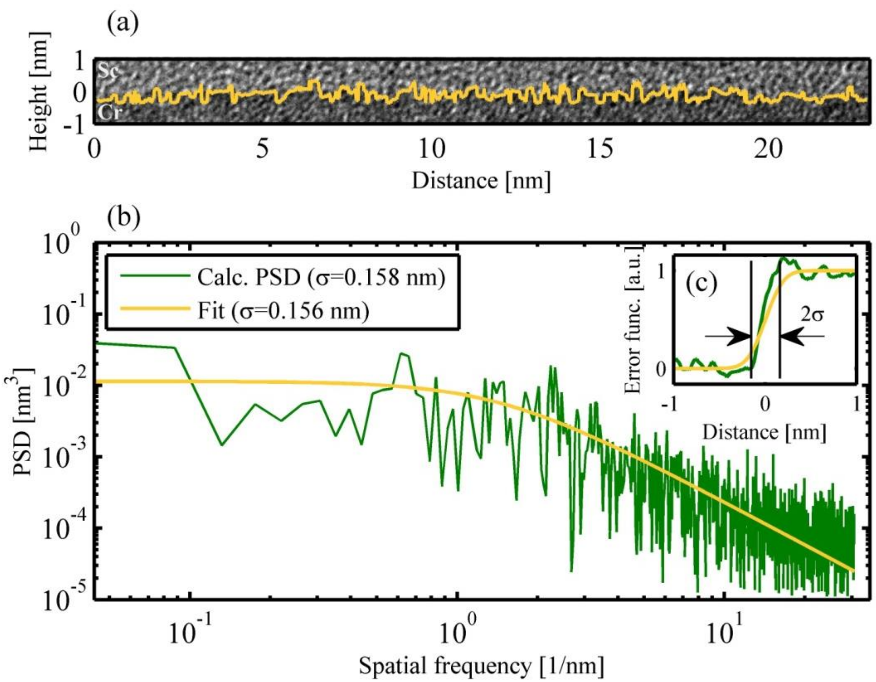
Sc
Cr

1) variation of ion energy for better layer growth
2) every 10 periods assist-ions for polishing the Cr layer



PSD – Power Spectral Density – TEM data analysis

Horizontal gray value analysis:



Roughness σ dependence on interface „fluctuations“:

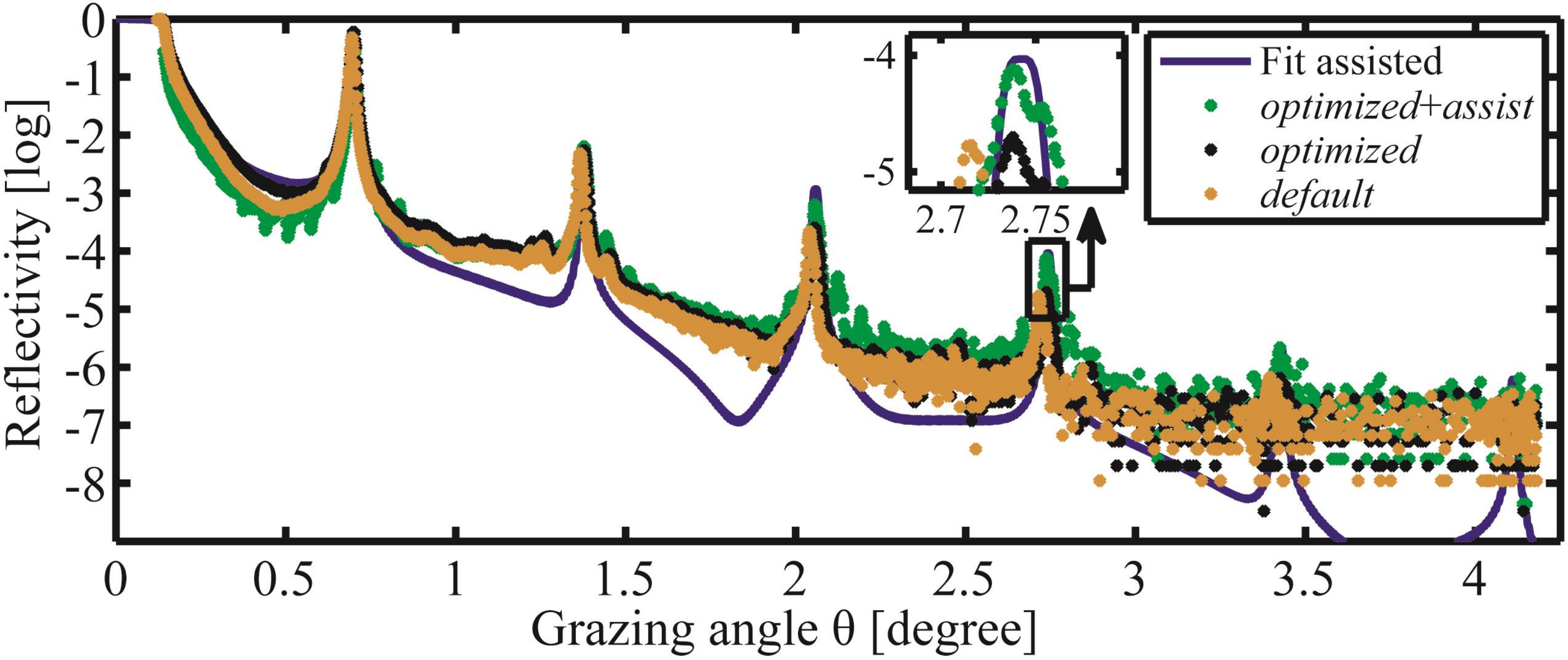
$$\sigma = \left(\int_{f_{min}}^{f_{max}} \mathrm{PSD}(f_x)\, df_x \right)^{1/2}$$

Roughness evolution:

	default	optimized	optimized + assist
σ_{top} (nm)	too blurry	0.3	0.24
σ_{bottom} (nm)	0.25	0.18	0.18

XRR analysis

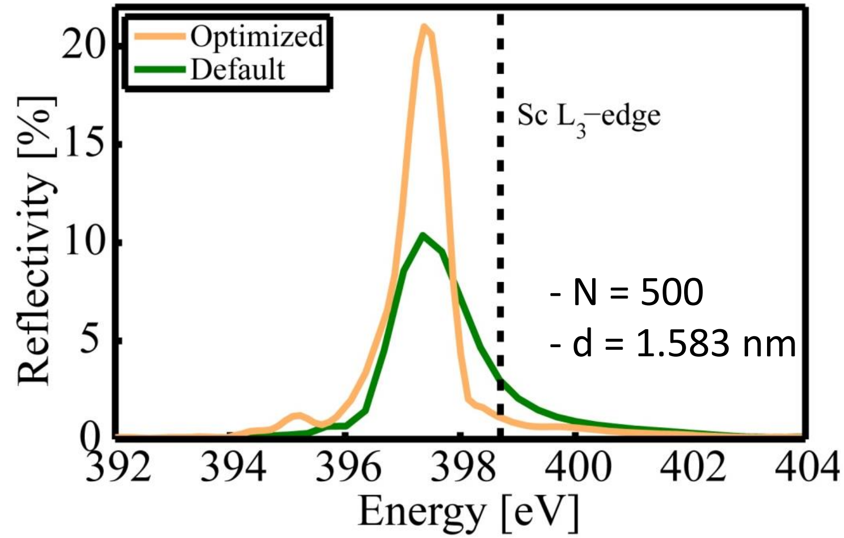
XRR analysis (Mo K_α at **λ=0.07nm**) of TEM-designed mirrors



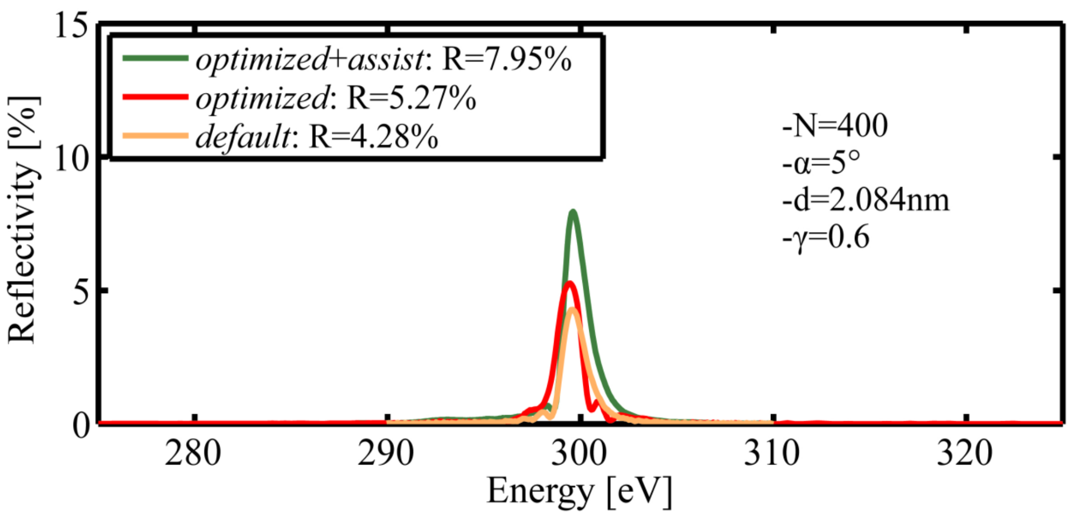
	default	optimized	optimized + assist
Roughness σ [nm]	0.26	0.24	0.21

Soft X-ray measurement

doubled the reflectivity at Sc L_3-Edge
with optimized parameters
(ion polish data still pending)



Measured at ALS in Berkeley

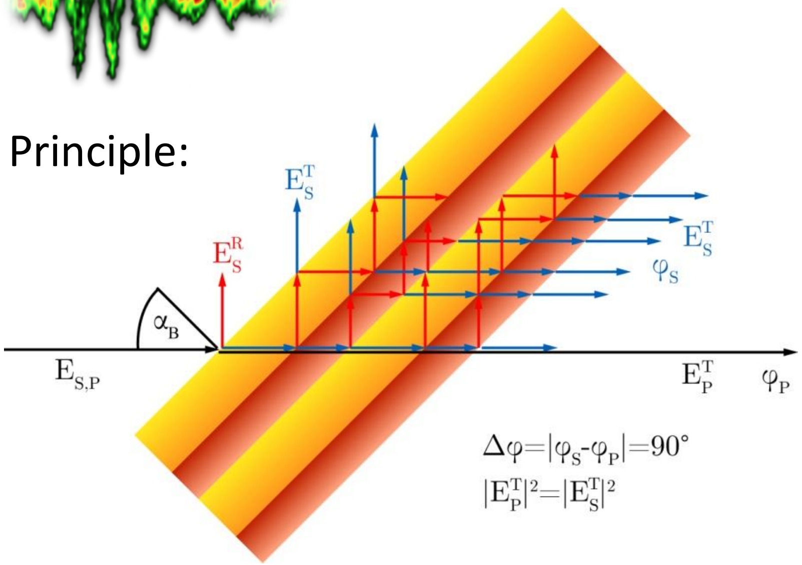


Measured at PTB (BESSY II in Berlin)

Ion polished Cr/Sc attosecond multilayer mirrors for high water window reflectivity
Guggenmos *et al.* Optics Express **22**, 26526 (2014)

Polarizer (for circularly polarized XUV)

Principle:

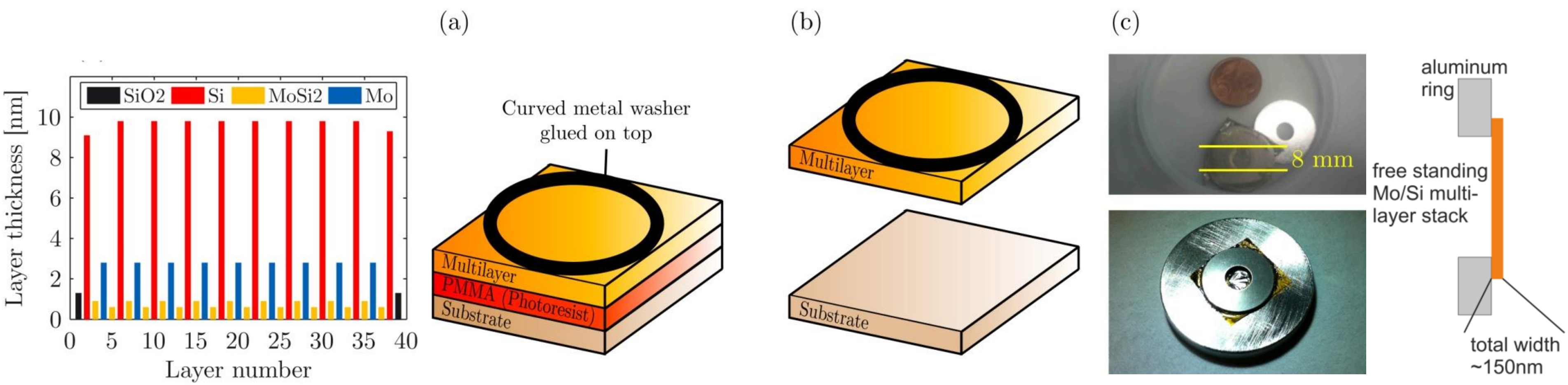


Application:

- access to M3 p-splitting of Ni
→ spin dependent electron emission
due to left or right handed circular XUV
- XUV magnetic circular dichroism (XMCD)
→ time-resolved utilizing attosecond pulses

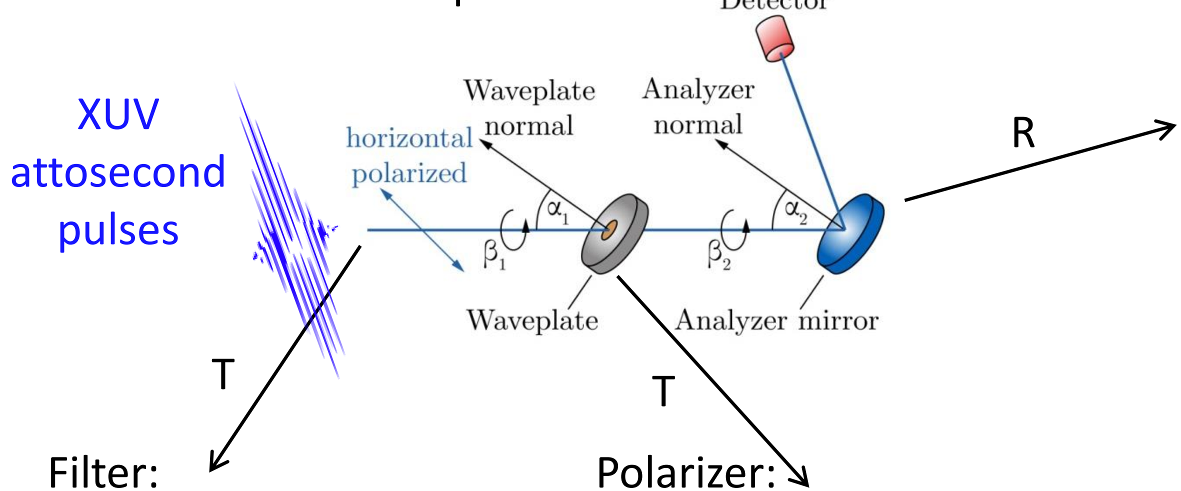
Distinguishing the ultrafast dynamics of spin and orbital moments in solids
Boeglin *et al.* Nature **465**, 458 (2010)

Realization:

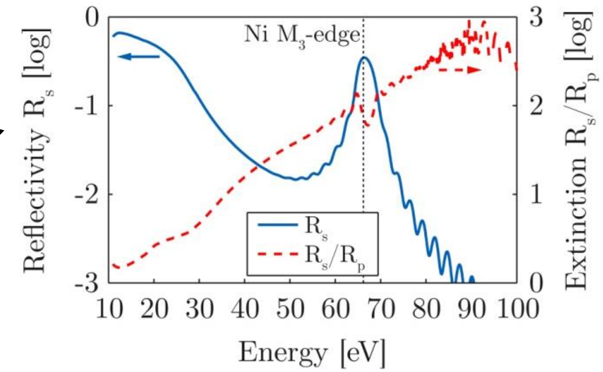


Polarizer (for circularly polarized XUV)

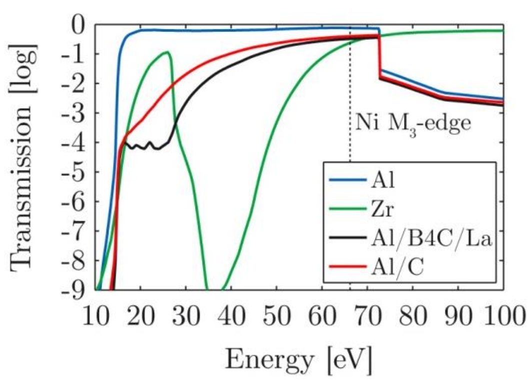
Setup:



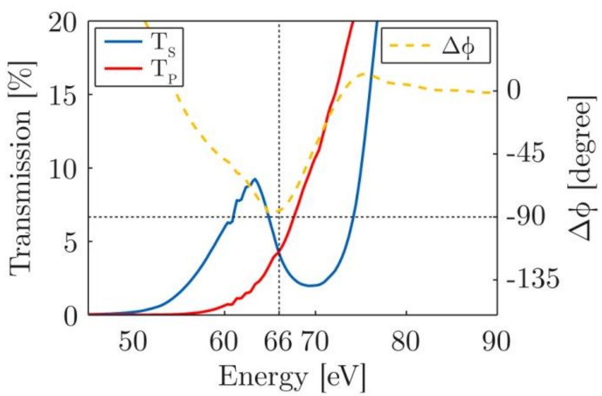
Analyzer:



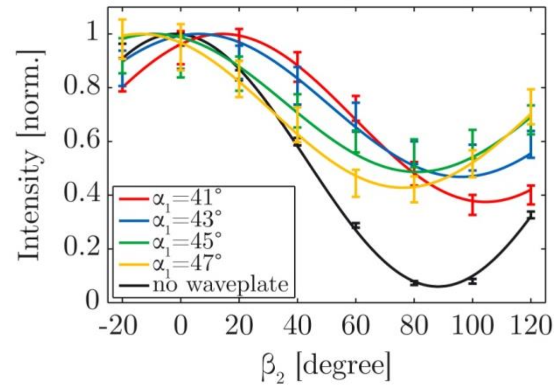
Filter:



Polarizer:



Results:

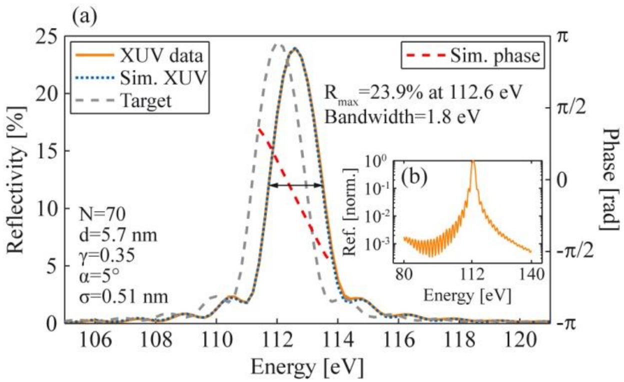


Ellipticity (measured): ε=0.75
Ellipticity (simulated): ε=0.79

Generation of circularly polarized high harmonic radiation using a transmission multilayer quarter waveplate
Schmidt, Guggenmos *et al.* Optics Express **23**, 33564 (2015).

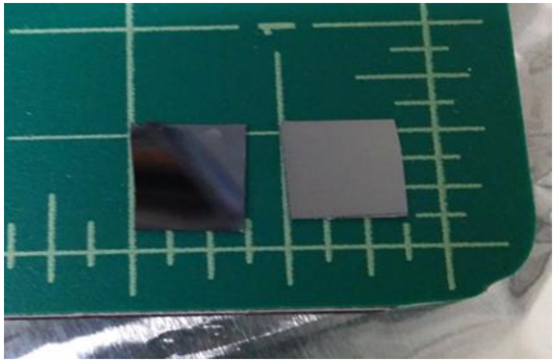
GaAs at 112 eV - Limitations – Experimental bottlenecks

XUV multilayer mirror
with a spectral bandwidth of 1.8 eV



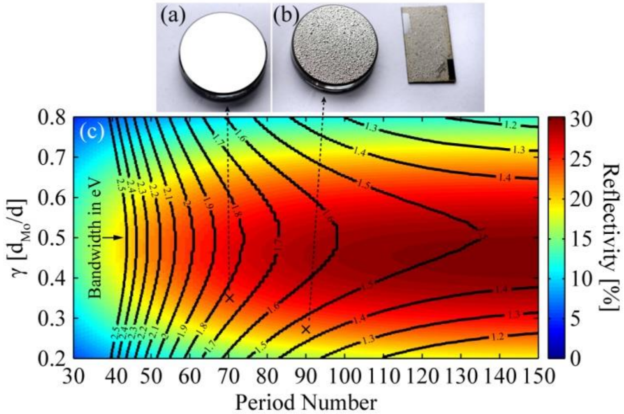
Characterized at PTB, BESSY II in Berlin

As-capped GaAs for pure GaAs after bake out



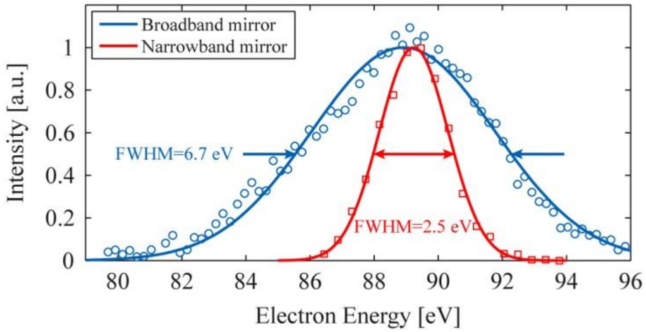
Collaboration with Prof. Amann from the WSI in Garching

Material dependent limitations



Delamination for detuned Mo/B4C material system
Optimizing deposition process for finetuning the bandwidth

Spectral resolution for GaAs



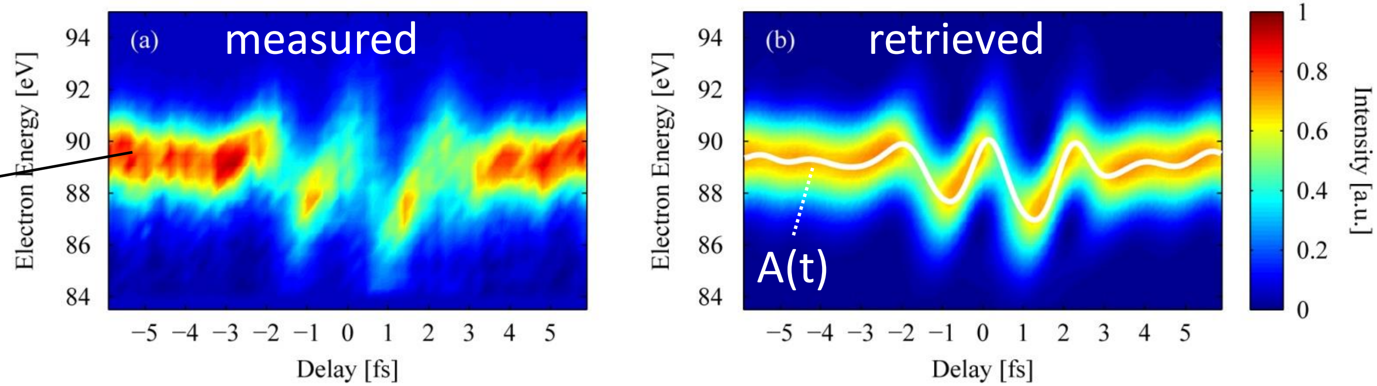
Unstreaked photoelectron spectra of the gallium 3d peak

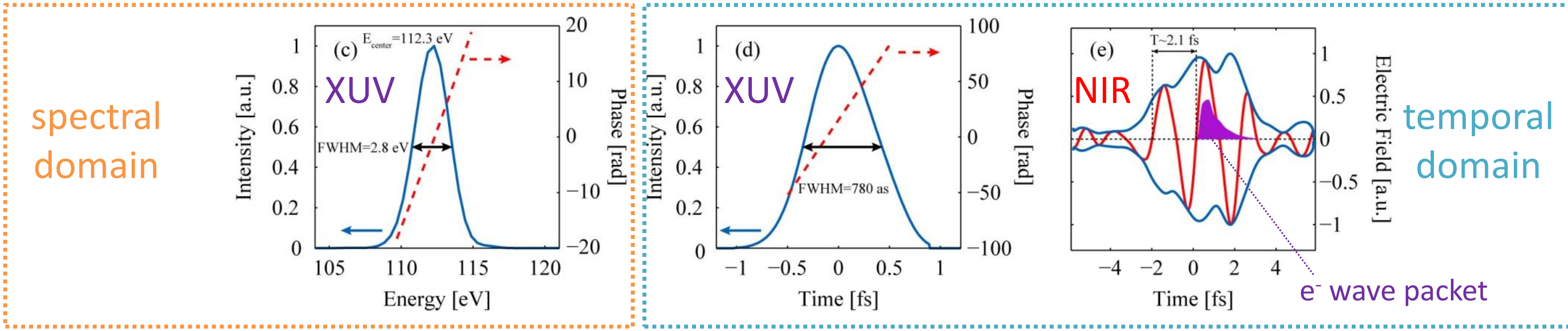
First clean electron streaking measurement on GaAs

Frequency-**r**esolved **o**ptical **g**ating for **c**omplete **r**econstruction of **a**ttosecond **b**ursts:
FROG/CRAB – analysis for attosecond pulse characterization

Trebino *et al.* Rev. Sci. Instrum.**68**, (1997)
J. Gagnon *et al.* Appl. Phys. B **92**, (2008)

shifted by the binding energy of Ga 3d electrons (18.7 eV) and the work function of GaAs (4.69 eV)



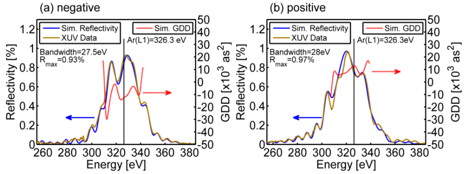


Simulated electron wave packet duration : 870 as (*2.5~$T_{E\text{-}Field\ NIR}$)

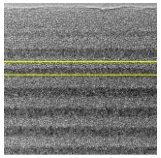
Attosecond photoelectron streaking with enhanced energy resolution for small-bandgap materials
Guggenmos *et al.* Optics Letters 41, 3714 (2016)

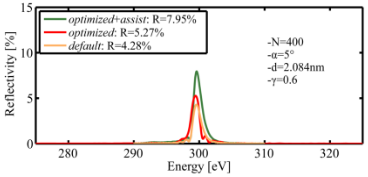
Conclusions

First aperiodic mirrors for chirped attosecond water window pulses



Interface optimization by optimized kinetic energy and ion polishing

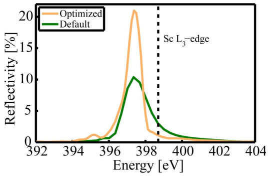




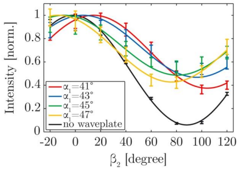
Up to now, doubled the reflectivity at Sc L_3-edge

>20% for a pure Cr/Sc multilayer (without barrier layers)

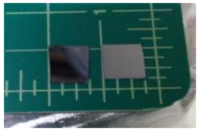
(Assisted one should show an even higher value.)



Generation of circularly polarized high harmonic radiation utilizing a transmission multilayer quarter waveplate



The first time-resolved attosecond measurement of GaAs, one of the most important direct bandgap semiconductor



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Team Attoworld

Thank you for your attention – Questions?