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energy agency

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international centre for theoretical physics

ICTP 40th Anniversary

SCHOOL ON SYNCHROTRON RADIATION AND APPLICATIONS
In memory of J.C. Fuggle & L. Fonda

19 April - 21 May 2004

Miramare - Trieste, Italy

1561/13

Multilayers

W. Jark

Multilayers in SR research

μXFA beamline and multilayer laboratory

Werner Jark

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http://www.elettra.trieste.it/organisation/experiments/laboratories/multilayer_technology/index.html

Structure of lecture

Answers to questions:

a) where do we need them?

b) how can we produce them?

c) can we simulate and predict their performance?

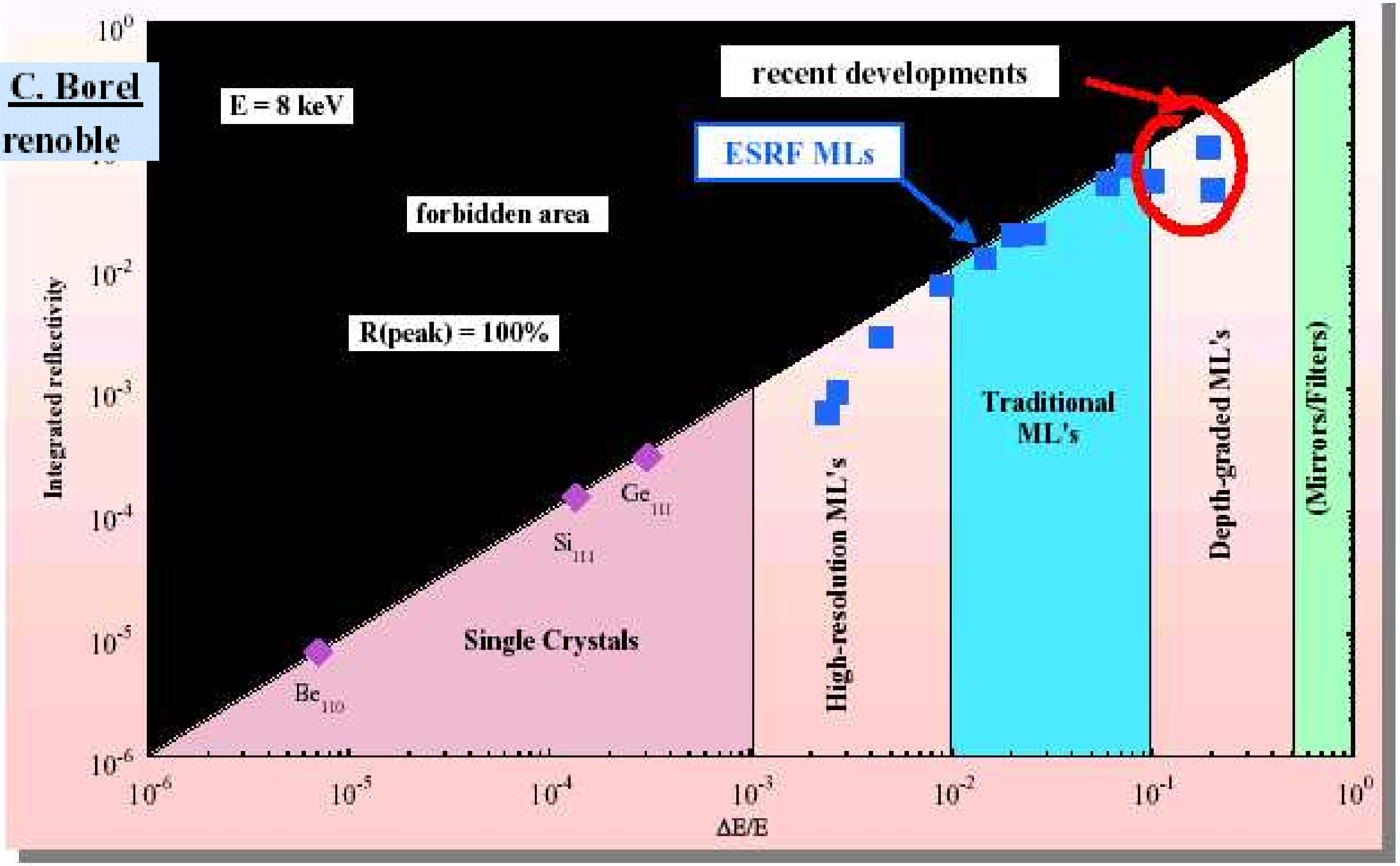
d) how can we test them?

e) where are they in use?

Where do we need them?

Reflecting x-ray optics - Overview

C. Morawe, J-C Peffen, C. Borel
X-Ray Optics Group-Grenoble



Costp7.free.fr

WG 3: Fabrication and tests of interfacial mirrors 2003/11/21

Production

Is it so simple, without problems? NO!

Problems:

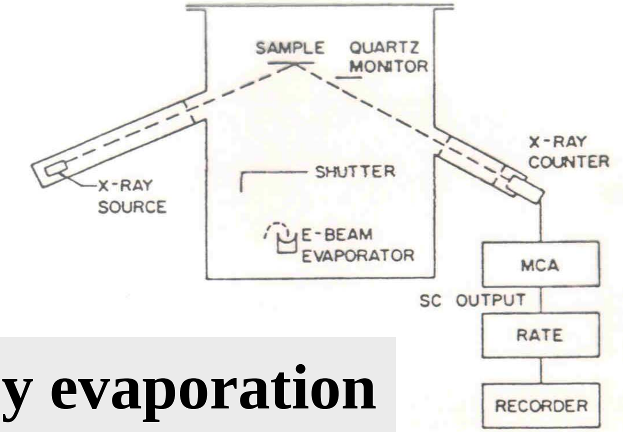
evaporation

- repeatibility
- cluster evaporation
- sublimation
- thickness monitoring
- homogeneity in large samples

sputtering

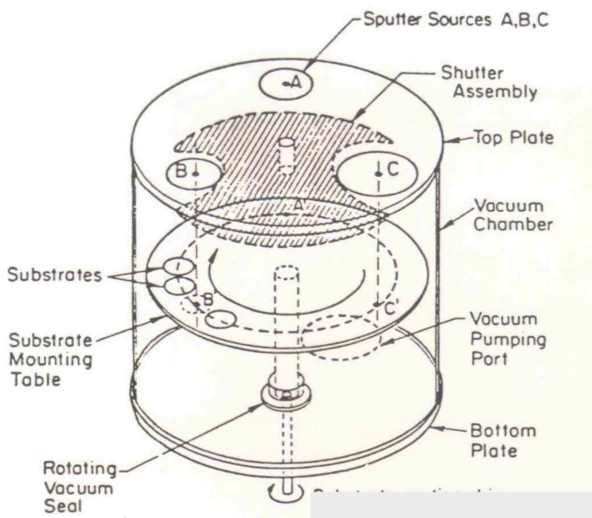
- homogeneity in large samples
- electron bombardement of growing film
- plasma gas inclusions
- reactions with restgas

BUT: repeatable --> thickness = f(t)



By evaporation

Multilayer production



By sputtering

Field propagation into thin films

Solution of Parratt (Phys. Rev. 95, 359 (1954))

$$E_{\text{tang}} = \text{const} \quad \text{at} \quad \text{interface}$$

$a_j =$ amplitude factor $\qquad a_j = \exp\left(-i\pi \frac{g_j\, d_j}{\lambda}\right)$

$d_j =$ thickness, $\quad \lambda =$ wavelength,

$g_j = \tilde{n}_j \sin\theta_j \qquad \tilde{\varepsilon}_j = \tilde{n}_j^2 \qquad \tilde{n}_j = 1 - \delta + i\beta$

$$a_j\, E_j + a_j^{-1}\, E_j^R = a_{j+1}^{-1}\, E_{j+1} + a_{j+1}\, E_{j+1}^R$$

$$g_j\left(a_j\, E_j - a_j^{-1}\, E_j^R\right) = g_{j+1}\left(a_{j+1}\, E_{j+1} - a_{j+1}\, E_{j+1}^R\right)$$

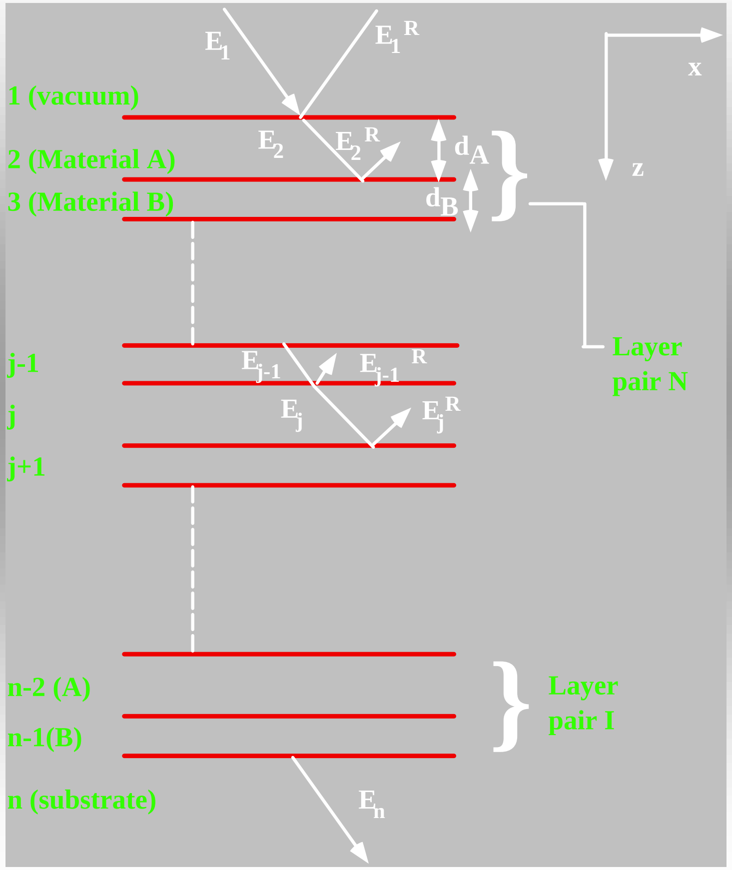
Solution => Recursion equation

$$R_{j,j+1} = a_j^4\left[\frac{R_{j+1,j+2} + J_{j,j+1}}{R_{j+1,j+2}\;J_{j,j+1} + 1}\right] \qquad \mathbf{R} = \frac{I}{I_0} = \left|R_{12}\right|^2$$

$$R_{j,j+1} = a_j^2\,\frac{E_j^R}{E_j}$$

$$J_{j,j+1}(s-pol) = \frac{E_j^R}{E_j} = \frac{g_j - g_{j+1}}{g_j + g_{j+1}}$$

$$J_{j,j+1}(p-pol) = \frac{g_j/\tilde{n}_j^2 - g_{j+1}/\tilde{n}_{j+1}^2}{g_j/\tilde{n}_j^2 + g_{j+1}/\tilde{n}_{j+1}^2}$$



Field propagation into thin films

Do not be afraid of the programming.

The job is already done by the Center for X-ray Optics at LBNL at Berkeley, CA (USA): look under

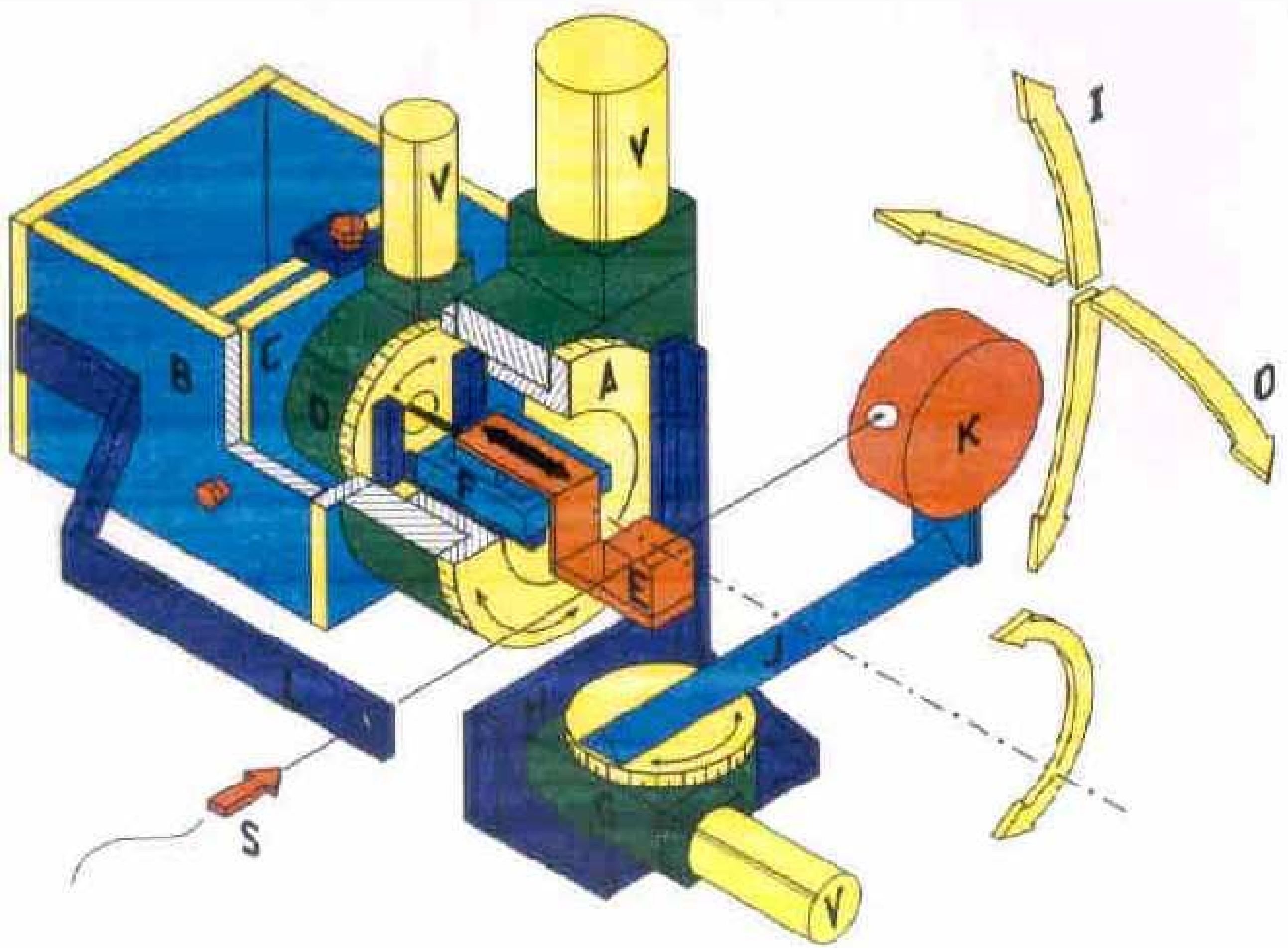
http://www-cxro.lbl.gov/optical-constant
http://www-cxro.lbl.gov/optical-constant/multi2.html

If you want to analyse data, ask the ESRF for the XOP software package, which contains the program IMD of David Windt.

Vacuum Diffractometer

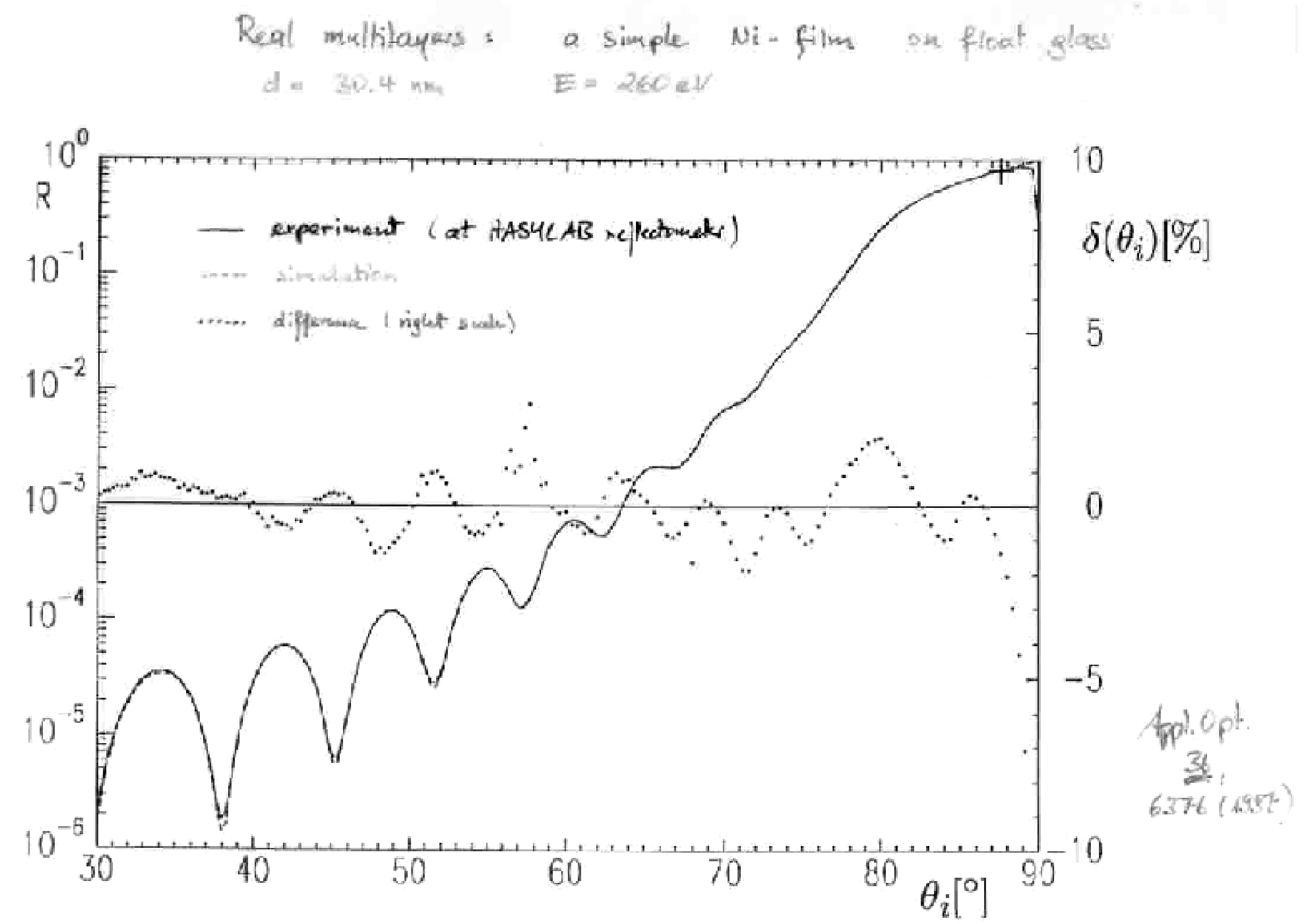
W. Jark and J. Stöhr
A High-Vacuum Triple-Axis Diffractometer for Soft X-ray Scattering Experiments,
Nucl. Instr. and Meth.
A266, 654 (1988)

now operated at BESSY



Reflectivity measurements

For derivation of refractive index



Real multilayers : a simple Ni-film on float glass
d = 30.4 nm E = 260 eV

Appl. Opt. 34, 6376 (1995)

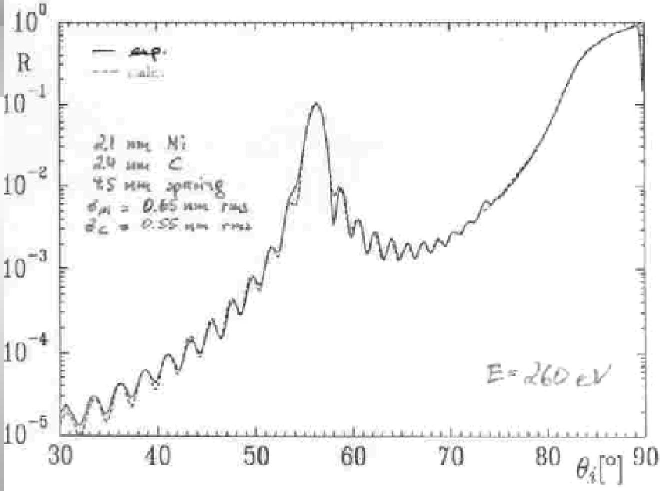
Reflectivity measurements

Everything fits perfectly!?!?

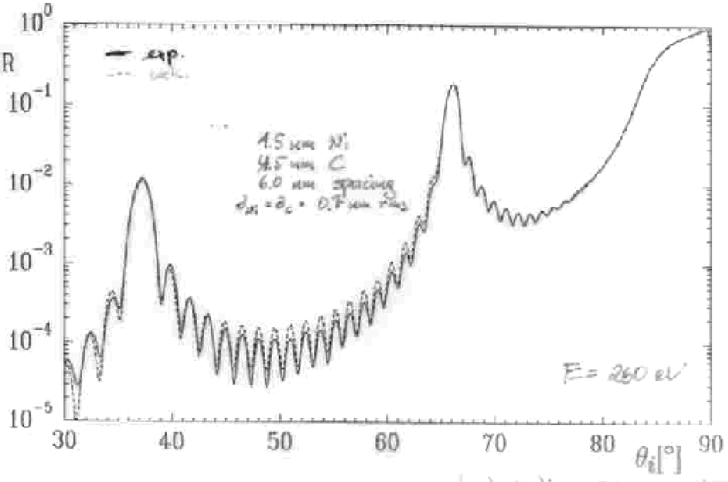
Appl. Opt. 36, 6329 (1997)

260 eV photon energy

top: d=4.5 nm
bottom: d=6.0 nm



Real multilayer : N= 20 periods Ni/C



Appl. Optics, 36, 6329 (1997)

Reflectivity measurements

μXFA beamline and multilayer laboratory

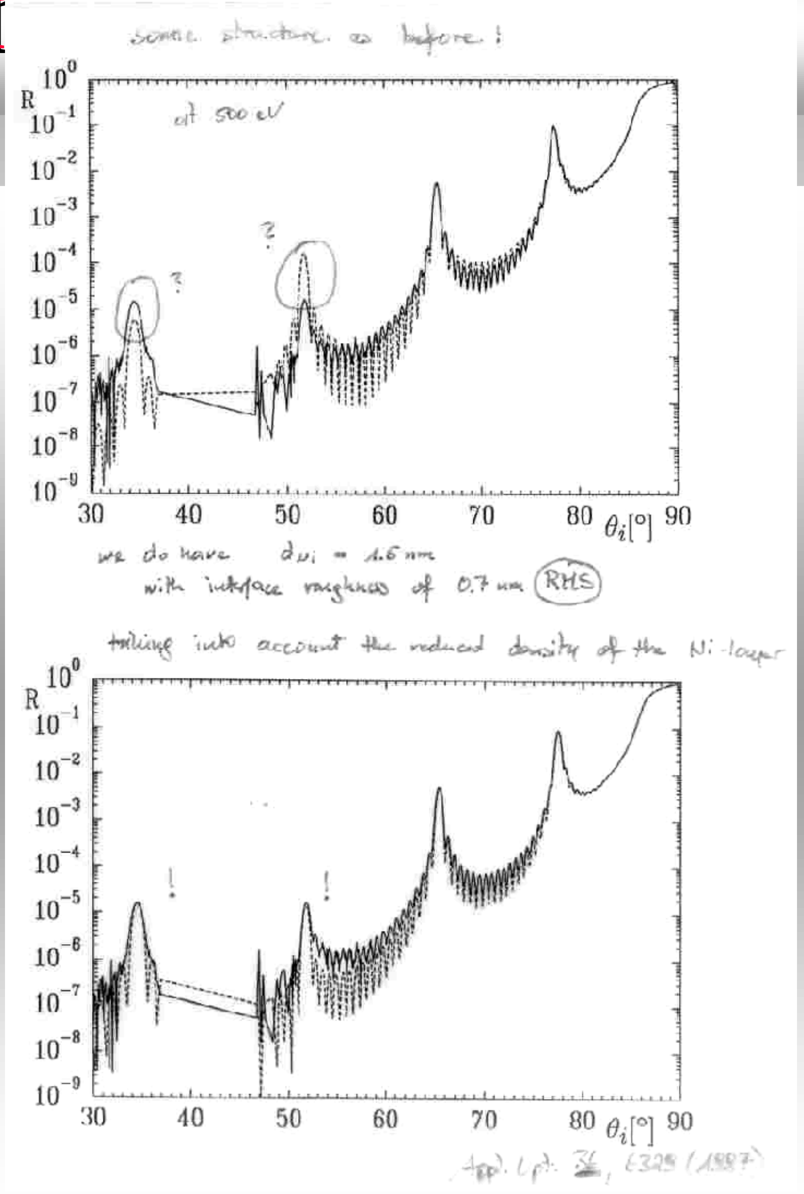
Everything fits perfectly!?!?

But why not at 500 eV?

500 eV photon energy

top: d=4.5 nm, sharp interfaces
bottom: with interdiffusion

Appl. Opt. 36, 6329 (1997)



same structure as before !

at 500 eV

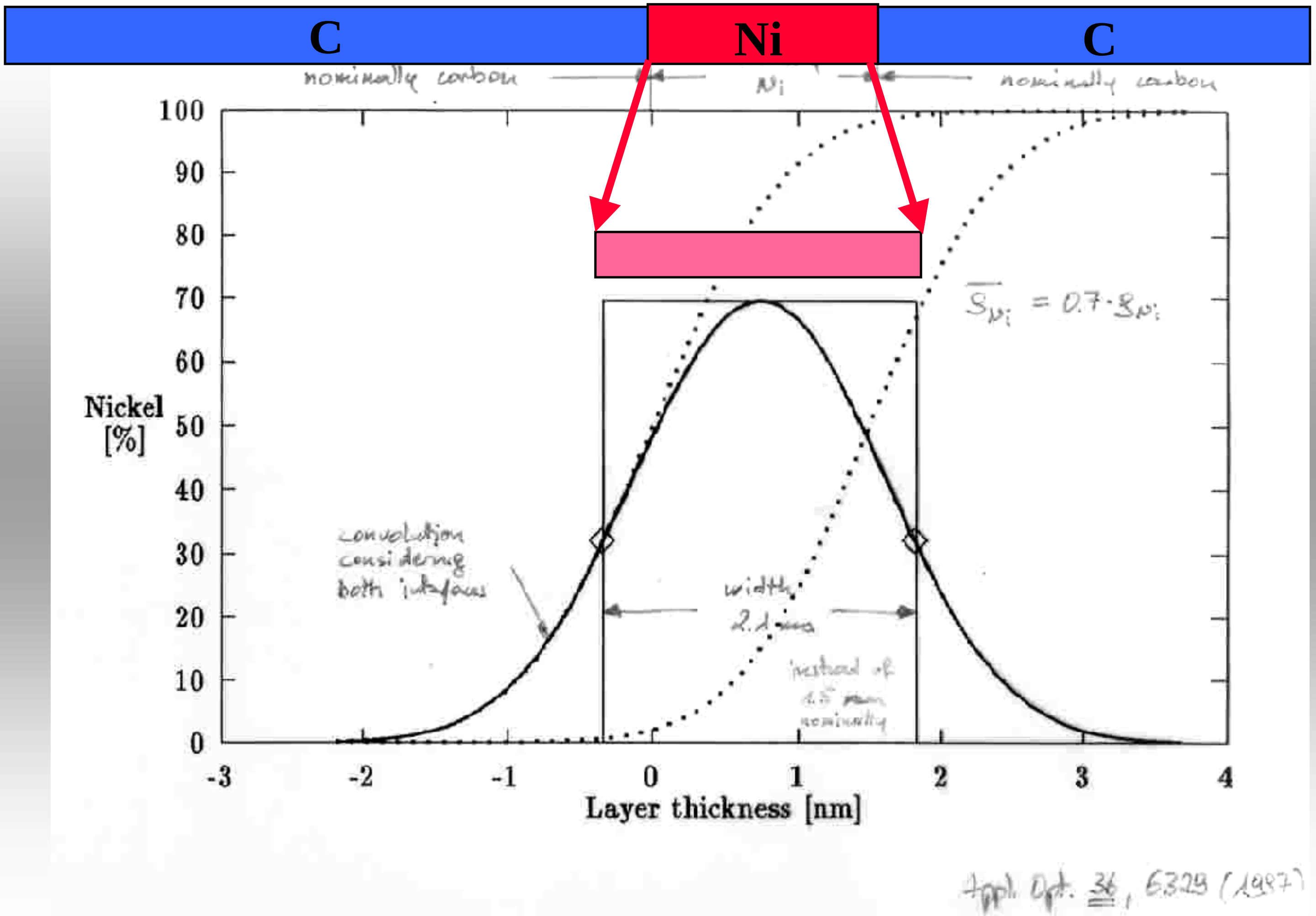
we do have d_{Ni} = 1.6 nm
with interface roughness of 0.7 nm (RMS)

taking into account the reduced density of the Ni-layer

Appl. Opt. 36, 6329 (1997)

Reflectivity measurements

Excessive interdiffusion in the system Ni/C

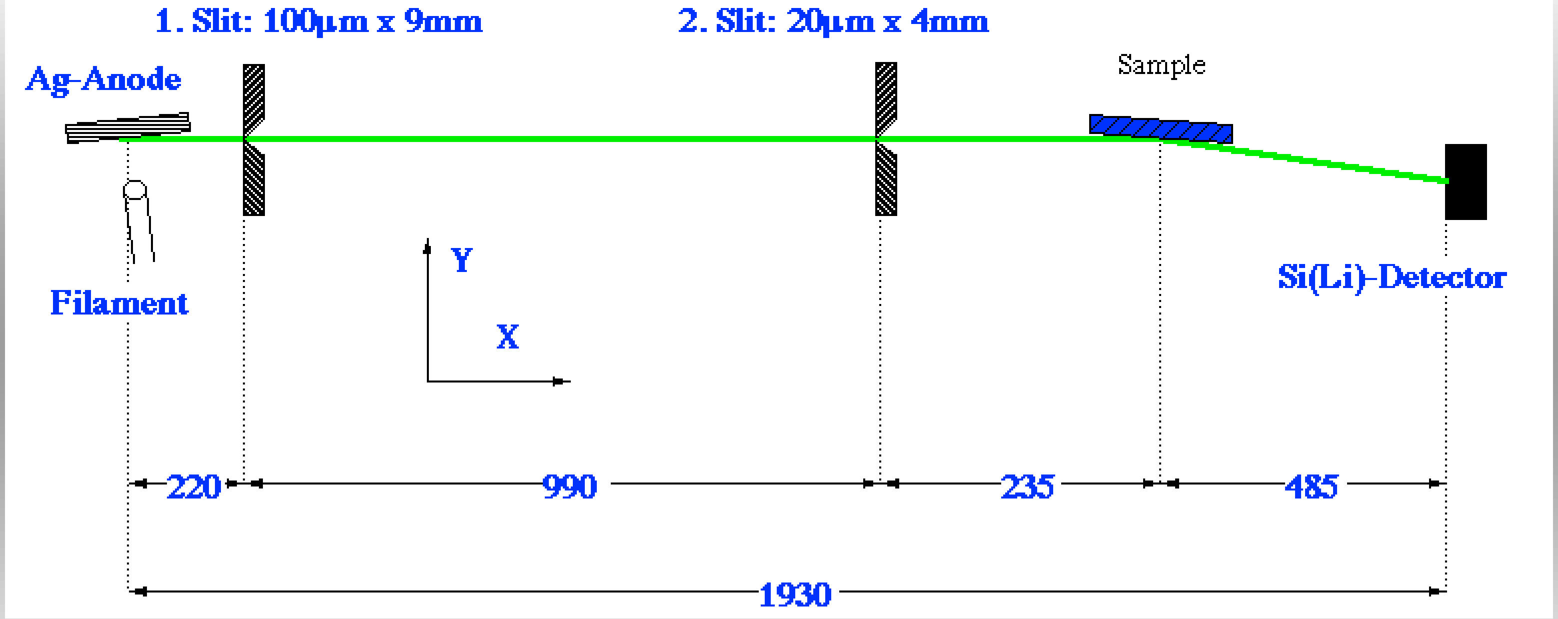


Appl. Opt. 36, 6329 (1997)

White Light Diffractometer

Low cost

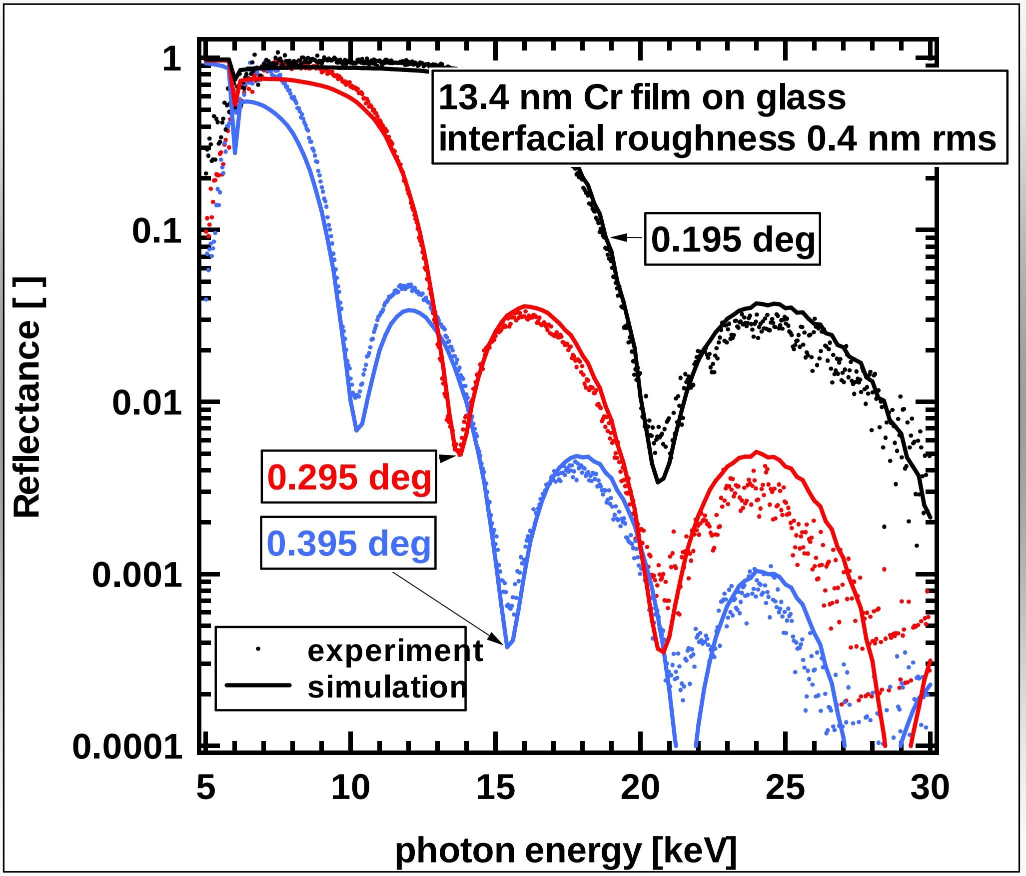
This technique is discussed in detail by P. Dhez et al, J. X-ray Sc. and Techn. 3, 176 (1992)



- **uses Bremsstrahlung background of x-ray tube (e.g. Ag-anode)**
- **registers energy dispersed reflected spectrum at fixed angle**
- **needs no motion during multichannel data acquisition**

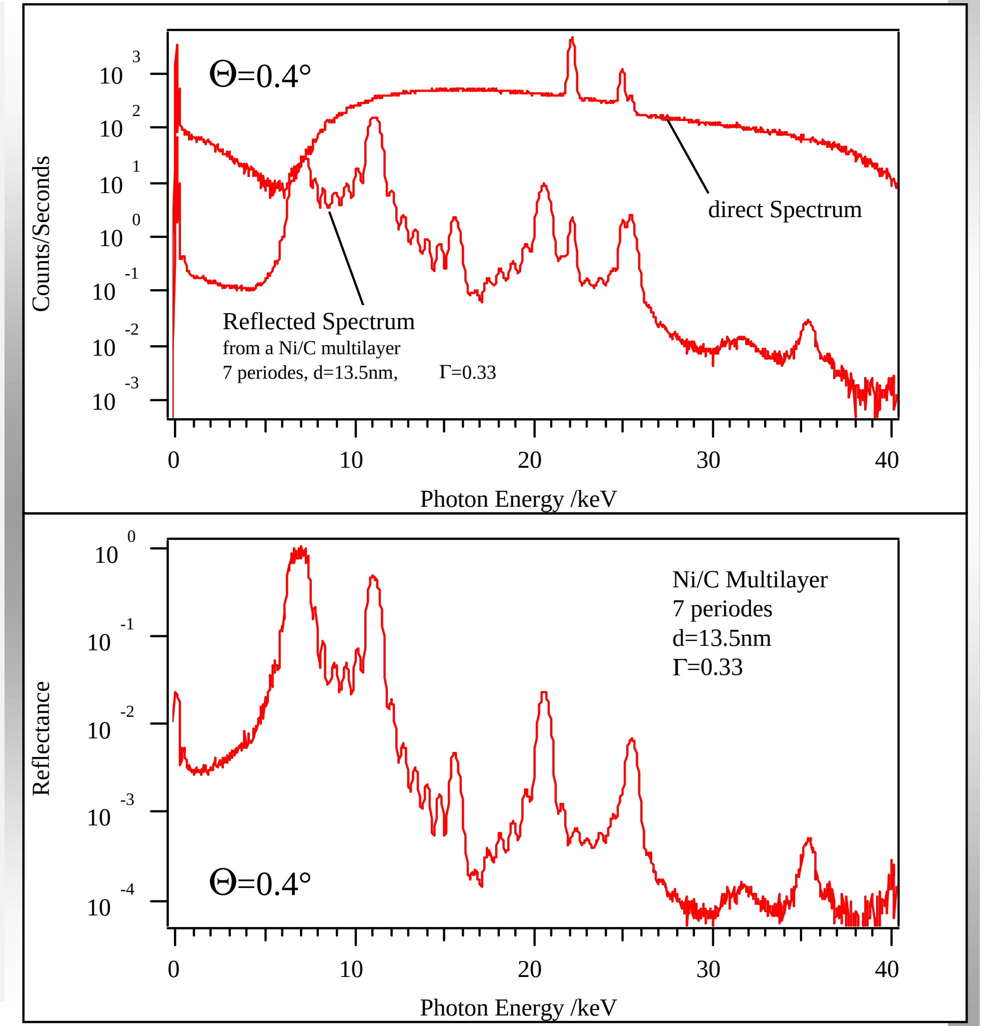
Calibration of deposition rate

- Measure thin film at a few angles of grazing incidence
- Simulate the reflectivity for
  - varying thickness
  - a small possible angle offset



Sample characterization

- See also P. Dhez et al, J. X-ray Sc. and Techn. 3, 176 (1992)
- 7 period multilayer mirror produced in collaboration with K. Randall (APS) requested: high reflectivity at 1.25° grazing angle for 3 keV photon energy
- direct and reflected spectrum are registered typically in about 30 minutes
- the result (reflected/direct spectrum) can be confronted with simulations for parameter verification



Polarization analysis of SR

Collaboration project:

Sincrotrone Trieste: **S. Di Fonzo, B. R. Mueller, G. Soullie',**
R.P. Walker, E. Meltchakov, M. De Gregorio, W. Jark
BESSY, Berlin, Germany: **F. Schaefers, H. Petersen, A. Gaupp,**
H. C. Mertins, W. Gudat, I. Packe, M. Mertin, F. Schmolla
Center for X-ray Optics, LNBL Berkeley, CA (USA):
J. H. Underwood
ETH and PSI, Villigen, CH: **H. Grimmer, P. Boeni, D. Clemens,**
M. Horisberger
Institute for Physics of Microstructures, Nizhny Novgorod, Russia:
N. N. Salashchenko, E. A. Shamow
MAX-Lab, Lund, Sweden: **R. Nyholm, X. Le Cann**
Uppsala University, Sweden: **D. Arvanitis, D. Hunter-Dunn**

Polarization analysis of SR

Device for the production of circularly polarized synchrotron radiation

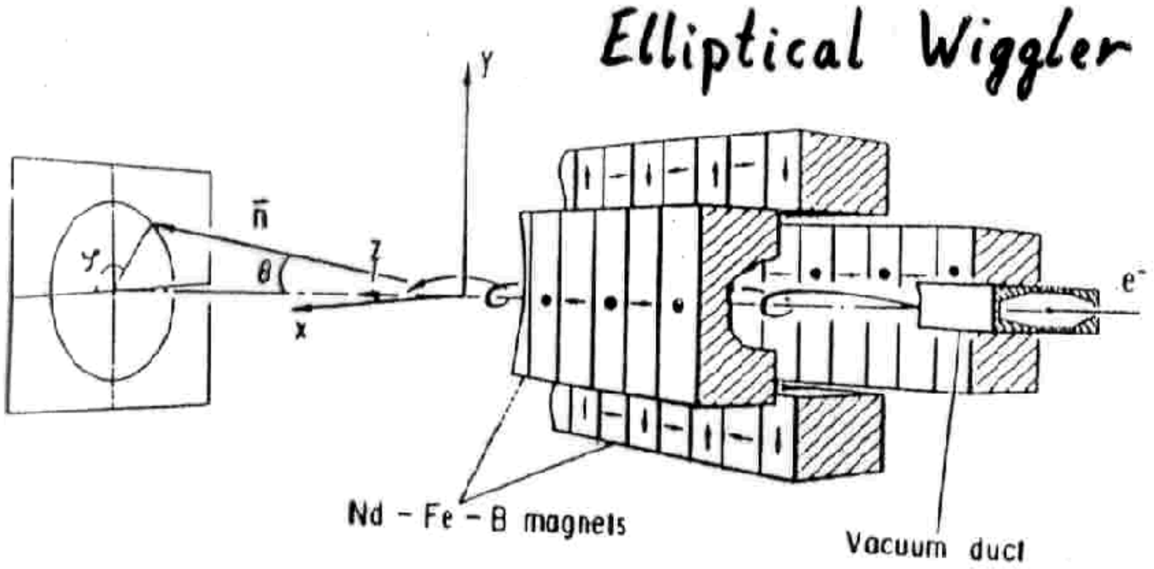


FIG. 2. Schematic illustration of the mechanism of the present insertion devices. Arrows denote the magnetization direction of each magnet, which totally forms the magnetic field given by Eq. (1) on the axis of the device.

$$\mathrm{B} = \pm\, \mathrm{e}_x B_{x0} \cos(2\pi z/\lambda_u) - \mathrm{e}_y B_{y0} \sin(2\pi z/\lambda \;) \quad (1)$$

Polarization analysis of SR

- **Only phase retarders allow complete beam polarisation analysis**
- **visible light: quarter-waveplates (linear --> circular)**
- **soft x-rays: transmission multilayers (with only few degrees of retardation)**

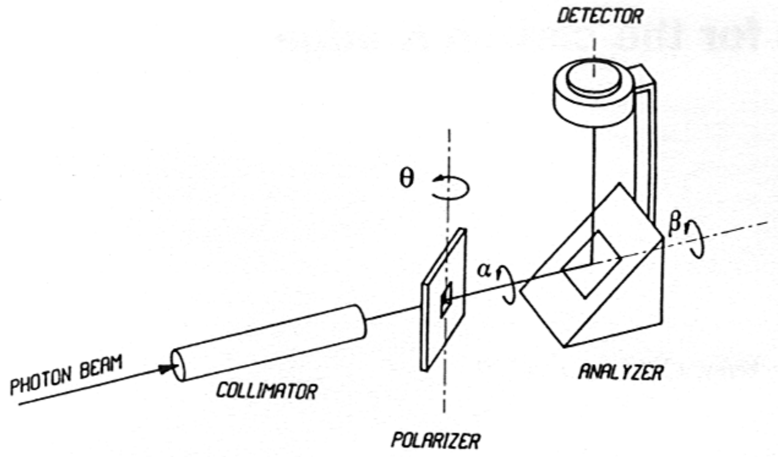


FIG. 1. Scheme of the polarimeter. After passing a collimator the beam impinges onto the transmission multilayer polarizer with an angle of incidence Θ. At the analyzer (a multilayer mirror) it is deflected by 90° to a diode detector. α and β are the azimuth angle positions of the polarizer and the analyzer, respectively.

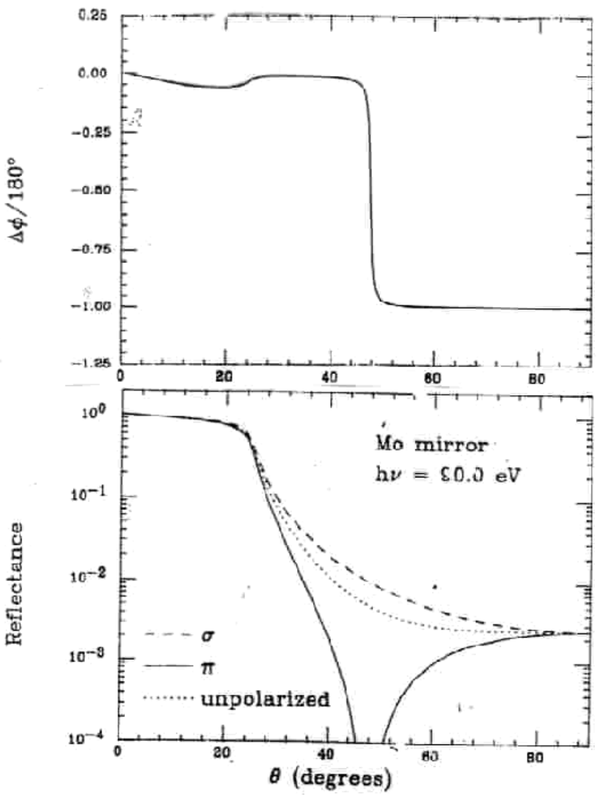
Polarization analysis of SR

μXFA beamline and multilayer laboratory

90 eV PHASE RETARDATION in SIMPLE mirrors:

J.B. Kortright and J.H. Underwood

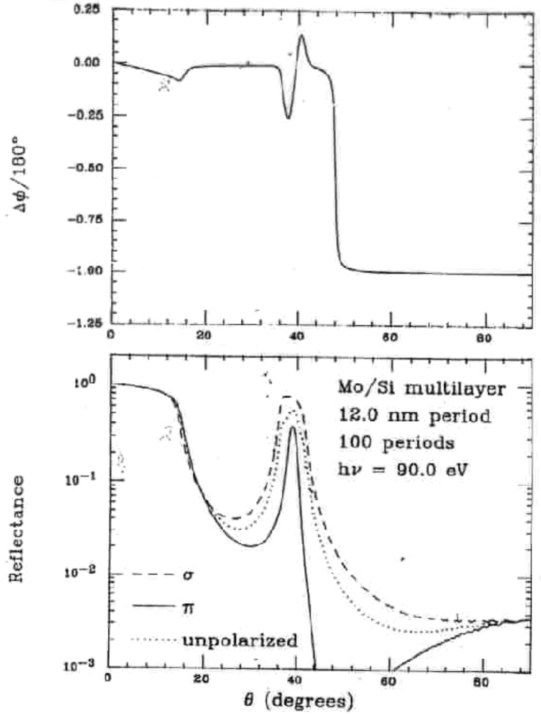
Nucl. Instrum. Methods* A291, *272 (1990)



90 eV PHASE RETARDATION in MULTILAYER mirrors:

J.B. Kortright and J.H. Underwood

Nucl. Instrum. Methods* A291, *272 (1990)

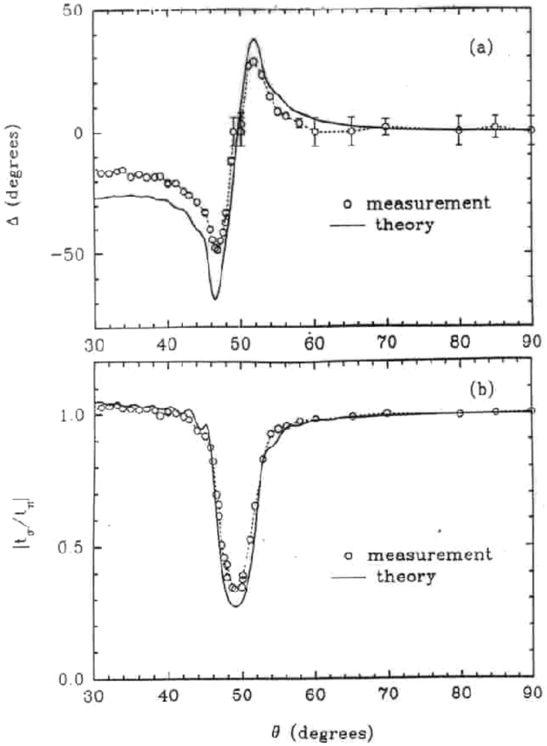


100 periods Mo/Si with d = 12 nm (2/3 Si and 1/3 Mo)

97 eV PHASE RETARDATION: PLASMA - SOURCE

J.B. Kortright, H. Kimura, V. Nikitin, K. Mayama, M. Yamamoto and M. Yanagihara

Appl. Phys. Lett.* 60, *2963 (1992)



20 periods Mo/Si with d = 8.75 nm (2/3 Si and 1/3 Mo)

effect 2/3 of theory with 70% transmission

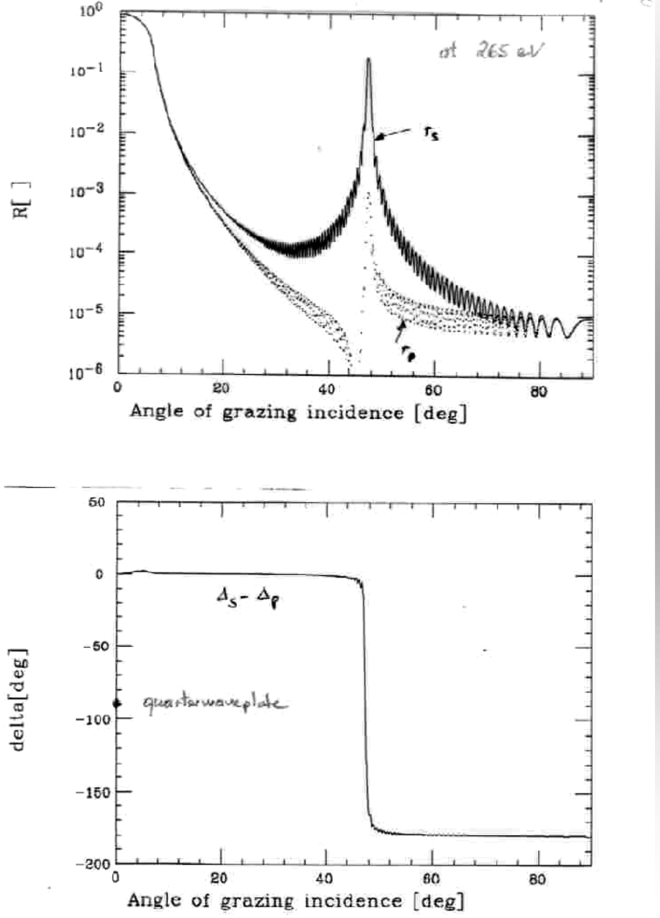
Polarization analysis of SR

μXFA beamline and multilayer laboratory

Soft x-rays at C K-edge

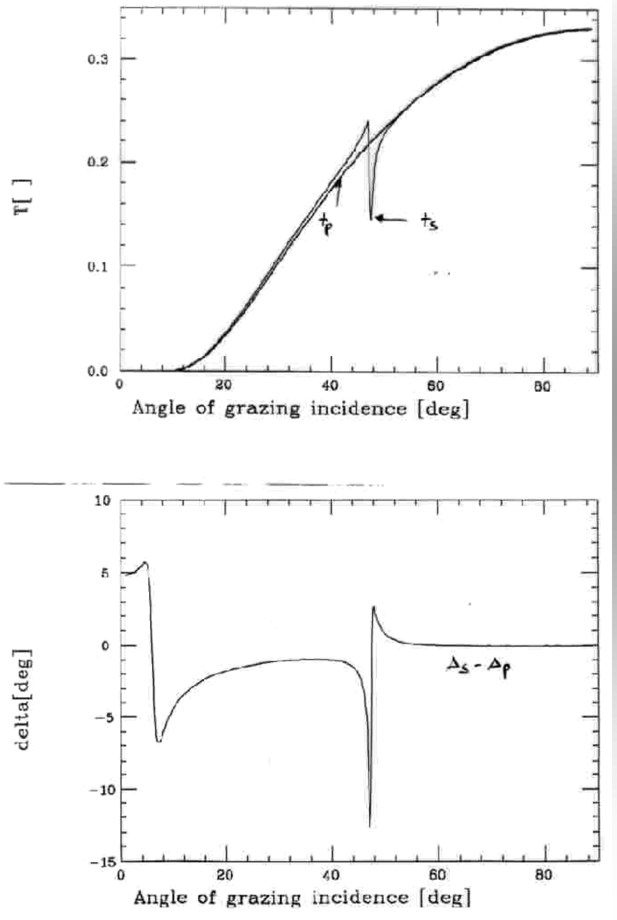
In reflection

40 periods of 1.07 nm Cr / 2.14 nm C
σ = 0.6 nm rms 3.21 nm spacing



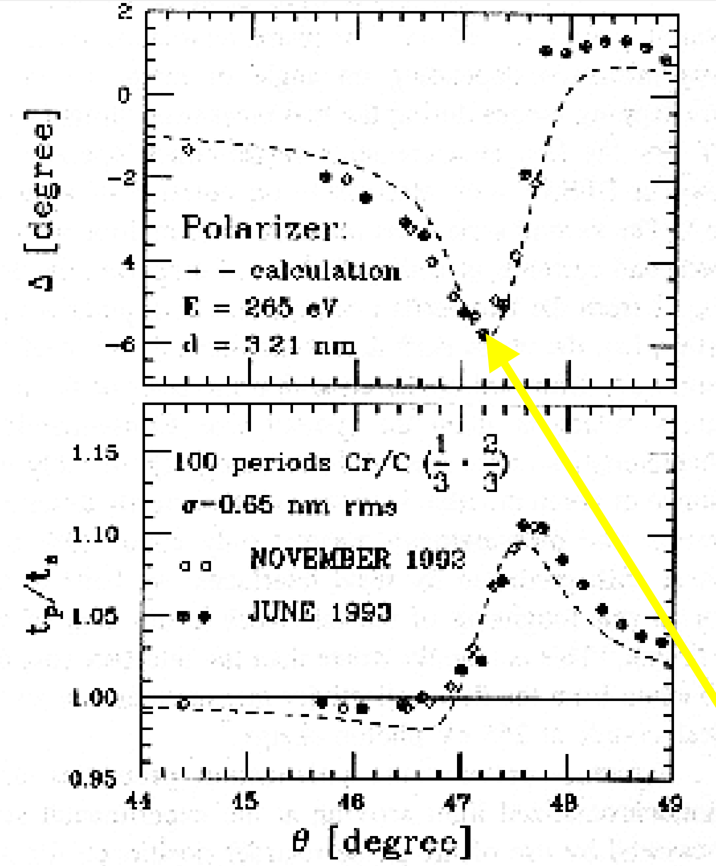
In transmission

simulation for the same objects:



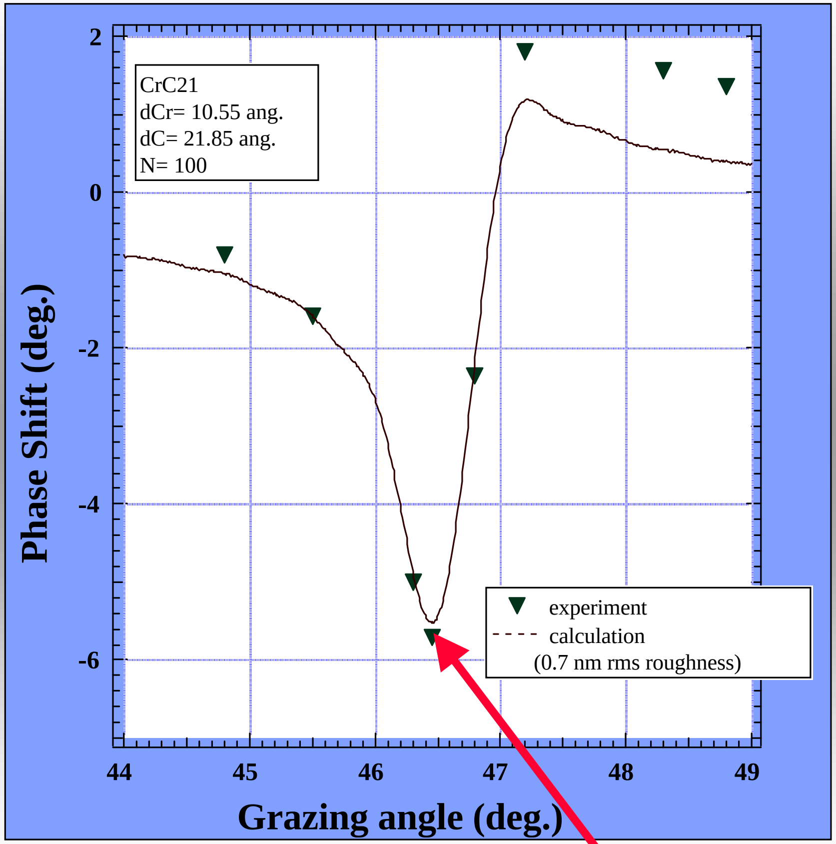
C K-edge phase retarders

sample from J. Underwood (CXRO) in 1992



Phase shift 5.9^{o}

our sample produced in 1996

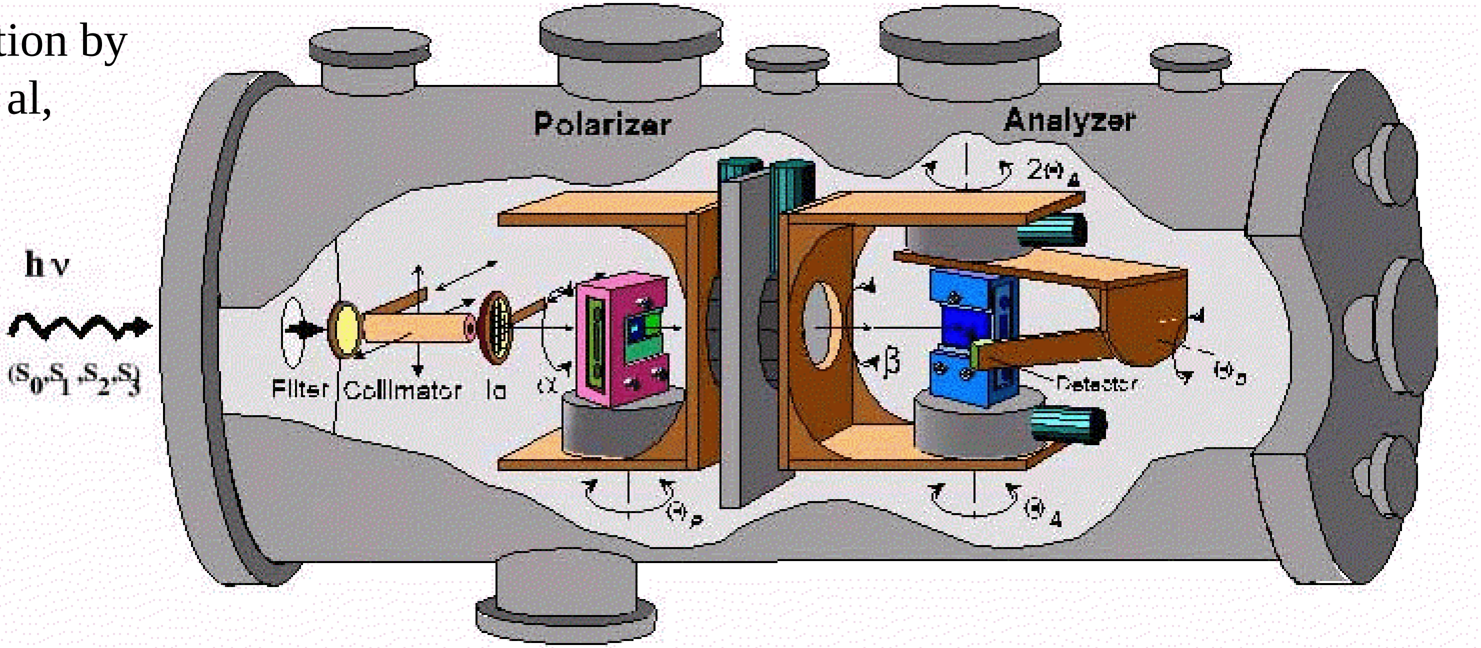


Phase shift 5.9^{o}

Soft X-Ray Polarimeter

Instrument optimized in collaboration with BESSY colleagues

Detailed description by H.-C. Mertins et al, Appl. Opt. 38, 4074 (1999)



- **Working principle:**
  a) Polarizer introduces phase retardation
  b) Analyser suppresses one polarization

To register signal at about 20 different analyser angles β and 8 different polarizer angles α

Soft X-Ray Polarimeter

operation parameters

- Allows to determine the Stokes parameters, which characterize the polarization of a light beam:
  S_0 = incident intensity, S_1 and S_2 = linearly polarized intensities
  S_3 = circularly polarized intensity
- from the visible spectral range to the soft x-ray range by means of optical components
  - continuously from about 5 eV to 95 eV and
  - unambigously at 280 eV, 400 eV and 575 eV
- employing as polarizers: quarterwaveplates (MgF_2), triple-reflection polarizers and multilayer transmission filters
- and as analysers: thin film and multilayer reflection mirrors

Soft X-Ray Polarimeter

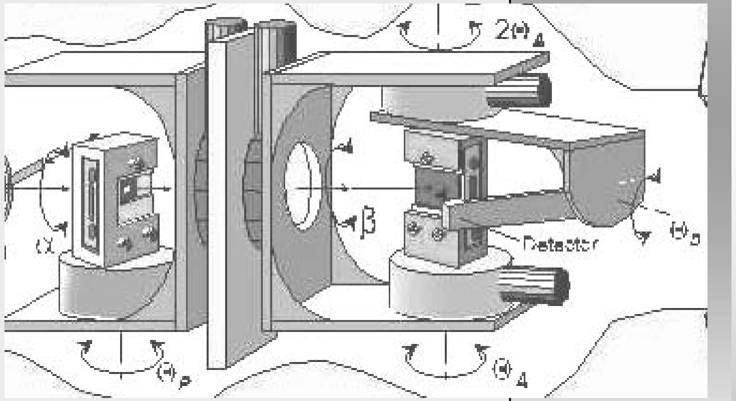
operation parameters

- The 6 axes of the polarimeter cover the following ranges (with stepper motors providing a resolution of > 1000 steps/°

polarizer:
$-180^{\circ} < \alpha < 180^{\circ}$
$-180^{\circ} < \Theta_P < 180^{\circ}$

analyser:
$-180^{\circ} < \beta < 180^{\circ}$
$-180^{\circ} < \Theta_A < 180^{\circ}$

GaAsP detector:
$0^{\circ} < 2\Theta_A < 180^{\circ}$
$-20^{\circ} < \Theta_D < 20^{\circ}$



- 10 polarizers/analysers can be exchanged in situ

Soft X-Ray Polarimeter

µXFA beamline and multilayer laboratory

fit procedure

More details presented by A. Gaupp and M. Mast: Rev. Sci. Instrum. **60**, 2213 (1989)

$t_{s1} = |t_{s1}| \exp(i\delta_{s1})$ $\quad$ $r_{s2} = |r_{s2}| \exp(i\delta_{s2})$

$t_{p1} = |t_{p1}| \exp(i\delta_{p1})$ $\quad$ $r_{p2} = |r_{p2}| \exp(i\delta_{p2})$

Polarizer phase shift $\Delta_1 = \delta_{p1} - \delta_{s1}$ $\quad$ **Analyser phase shift** $\Delta_2 = \delta_{p2} - \delta_{s2} = 0$

$\tan \Psi_1 = |t_{p1}|/|t_{s1}|$ $\quad$ $\tan \Psi_2 = |r_{p2}|/|r_{s2}|$

Stokes-parameters: S_0, S_1, S_2 and S_3

$I_{pass} =$ $\quad$ $^1/_2\, (ts1^2 + tp1^2) *$ $\quad$ $^1/_2\, (rs2^2 + rp2^2) *$

$\{$ $\quad$ S_0

$+ \cos 2\alpha$ $\quad$ $[-S_1 \cos 2\Psi_1]$ $\quad$ $+ \sin 2\alpha$ $\quad$ $[-S_2 \cos 2\Psi_1]$

$+ \quad \cos 2\beta$ $\quad$ $[-S_1 \cos 2\Psi_2 * (1 + \sin 2\Psi_1 \cos \Delta_1)/2]$ $\quad$ $+ \quad \sin 2\beta$ $\quad$ $[-S_2 \cos 2\Psi_2 * (1 + \sin 2\Psi_1 \cos \Delta_1)/2]$

$+ \cos 2\alpha \cos 2\beta$ $\quad$ $[+S_0 \cos 2\Psi_1 * \cos 2\Psi_2]$ $\quad$ $+ \sin 2\alpha \cos 2\beta$ $\quad$ $[+S_3 \sin 2\Psi_1 * \cos 2\Psi_2 \sin \Delta_1]$

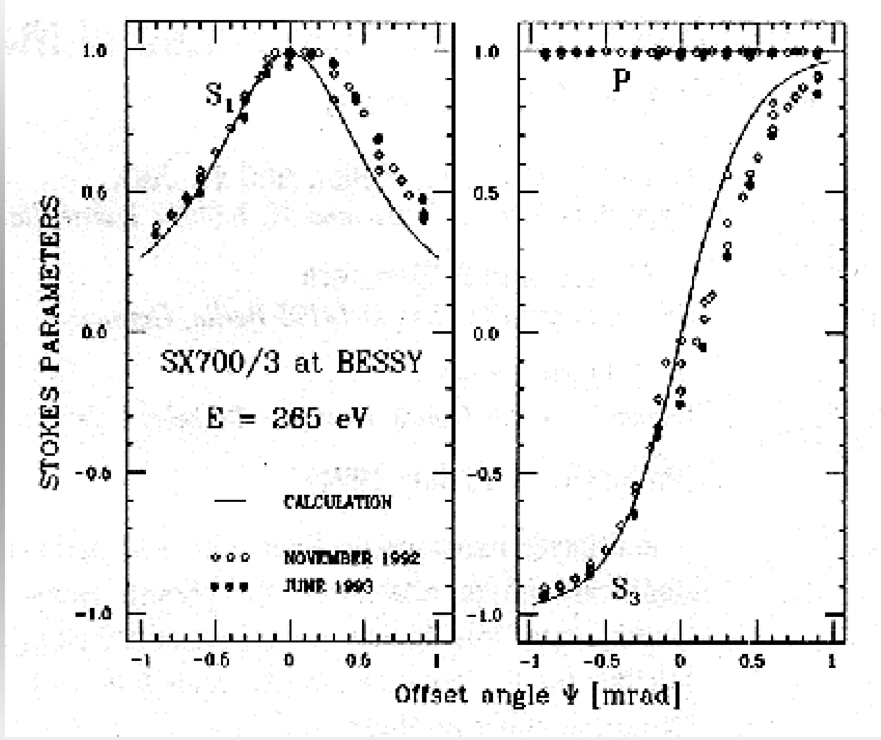
$+ \cos 2\alpha \sin 2\beta$ $\quad$ $[-S_3 \sin 2\Psi_1 * \cos 2\Psi_2 \sin \Delta_1]$ $\quad$ $+ \sin 2\alpha \sin 2\beta$ $\quad$ $[+S_0 \cos 2\Psi_1 * \cos 2\Psi_2]$

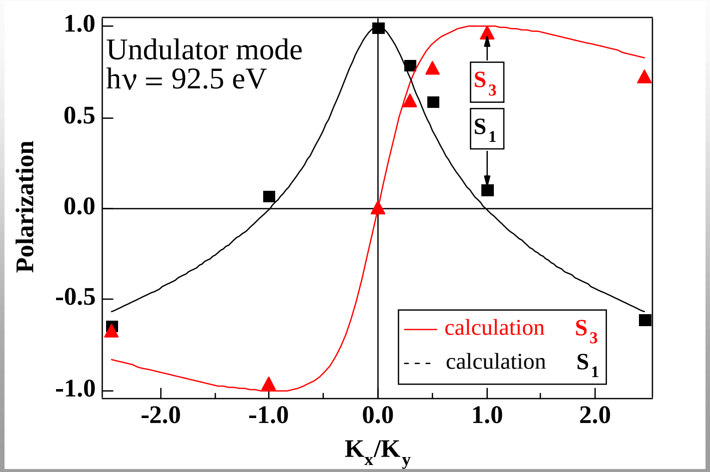
$+ \cos 4\alpha \cos 2\beta$ $\quad$ $[-S_1 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$ $\quad$ $+ \sin 4\alpha \cos 2\beta$ $\quad$ $[-S_2 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$

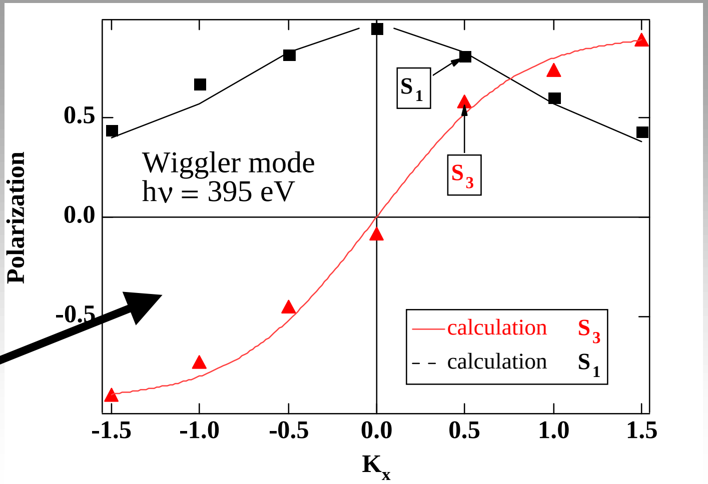
$+ \cos 4\alpha \sin 2\beta$ $\quad$ $[+S_2 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]$ $\quad$ $+ \sin 4\alpha \sin 2\beta$ $\quad$ $[-S_1 \cos 2\Psi_2 * (1 - \sin 2\Psi_1 \cos \Delta_1)/2]\}$

Polarisation analysis

at BESSY BM in 1992





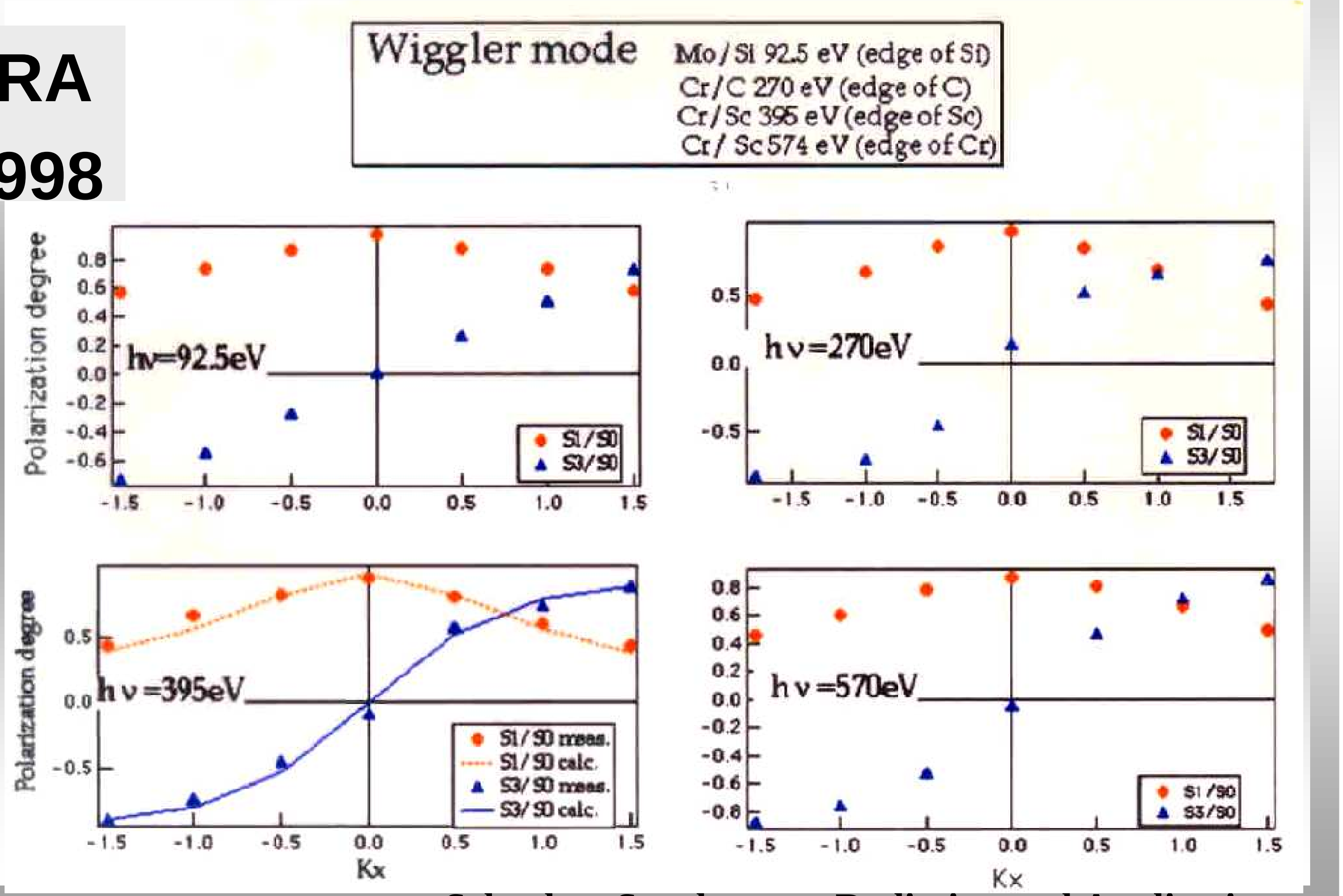


at ELETTRA EEW in 1998

Polarisation analysis

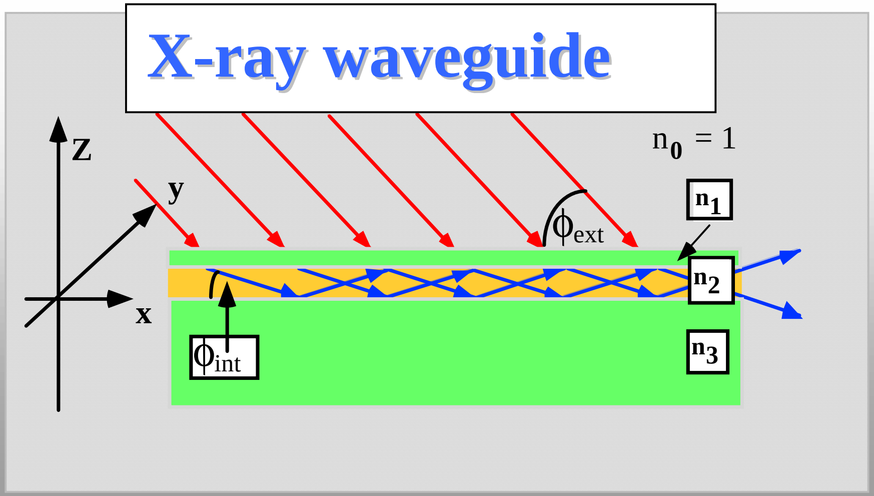
at ELETTRA

EEW in 1998

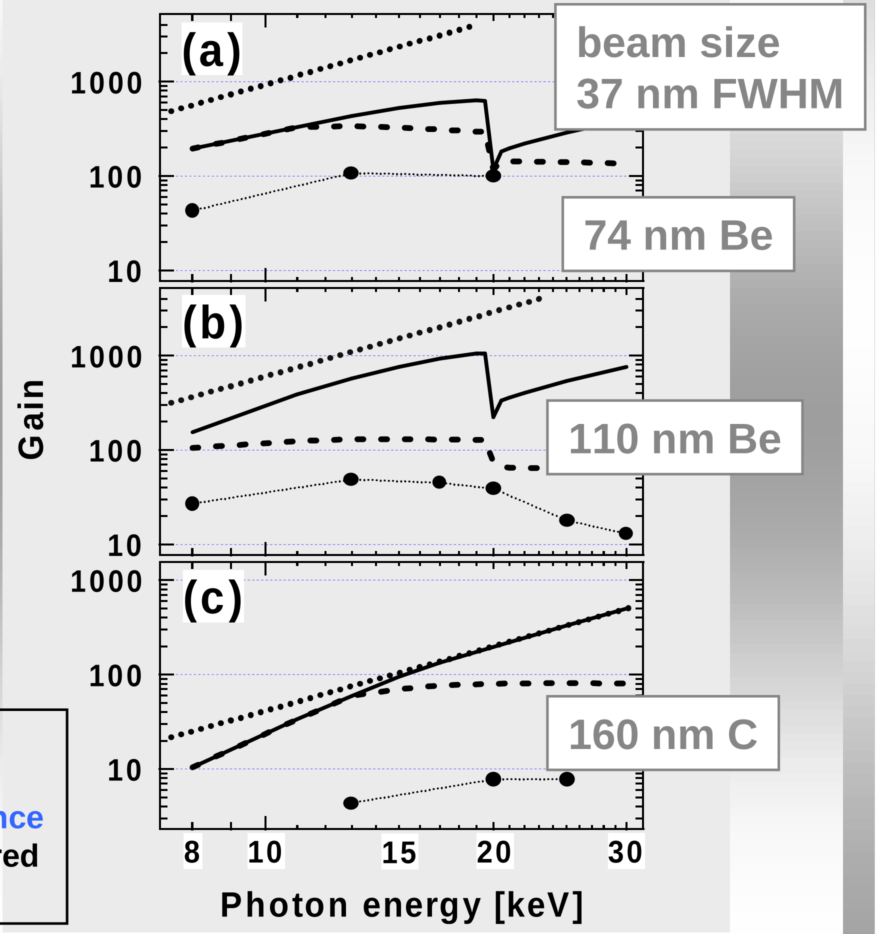


Travelling standing waves

μXFA beamline and multilayer laboratory



W. Jark et al, APL 78, 1192 (2001)

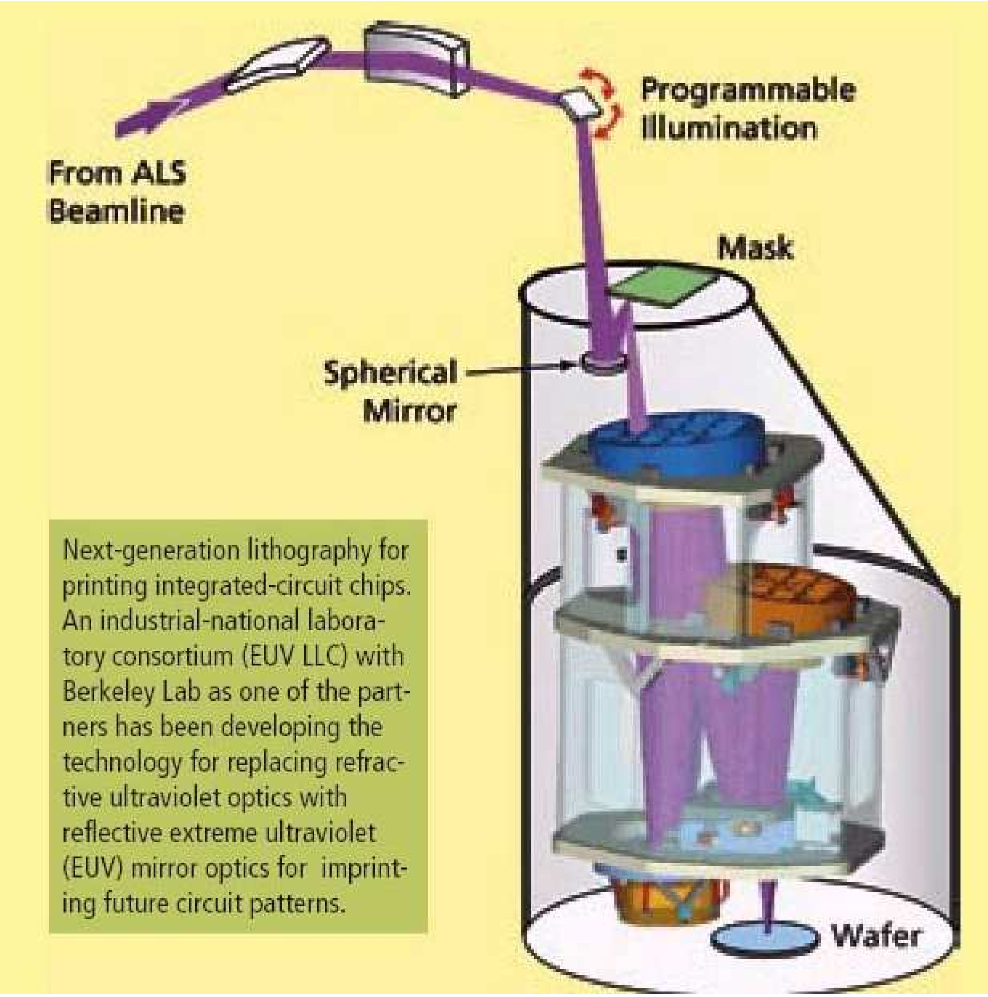


Collaboration with N.V. Kovalenko and V.A. Chernov from multilayer laboratory at Budker Institute for Nuclear Physics, Novosibirsk, Russia

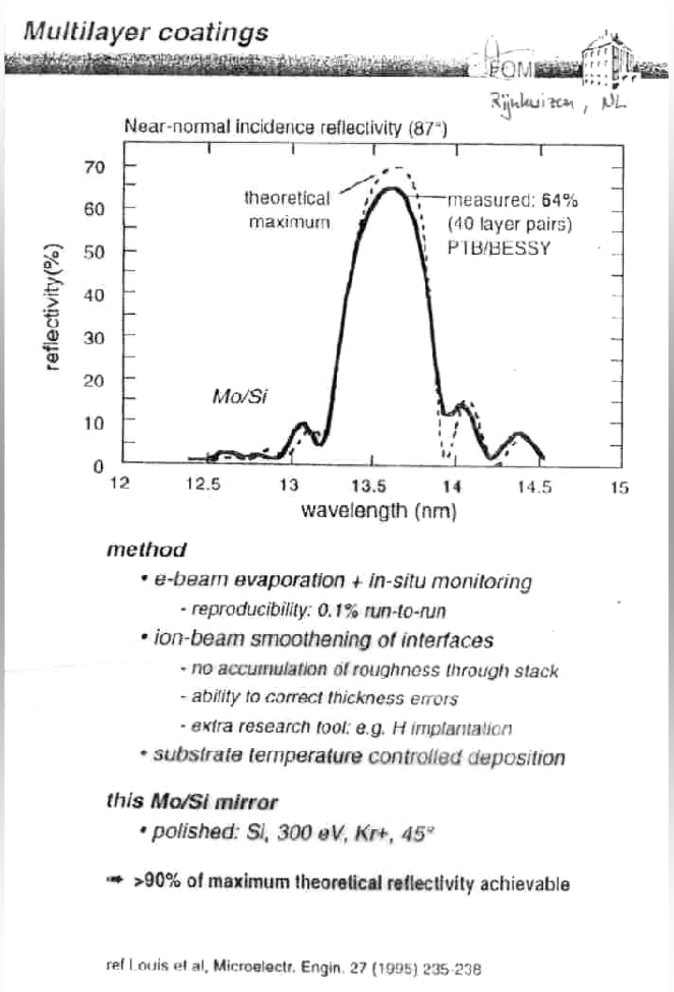
Dots: ideal interfaces, no absorption in top and bottom layer
Line: rigorous calculation
Dashes: rigorous calculation corrected for finite beam divergence
The indicated films are deposited onto 20 nm Mo and are covered with 5.5 nm Mo (for C: 20 nm and 4 nm Cr)

EUV lithography

At normal incidence and at 95 or 113 eV



Next-generation lithography for printing integrated-circuit chips. An industrial-national laboratory consortium (EUV LLC) with Berkeley Lab as one of the partners has been developing the technology for replacing refractive ultraviolet optics with reflective extreme ultraviolet (EUV) mirror optics for imprinting future circuit patterns.



Multilayer coatings

Rijnhuizen, NL

method

- *e-beam evaporation + in-situ monitoring*
  - *reproducibility: 0.1% run-to-run*
- *ion-beam smoothening of interfaces*
  - *no accumulation of roughness through stack*
  - *ability to correct thickness errors*
  - *extra research tool: e.g. H implantation*
- *substrate temperature controlled deposition*

this Mo/Si mirror

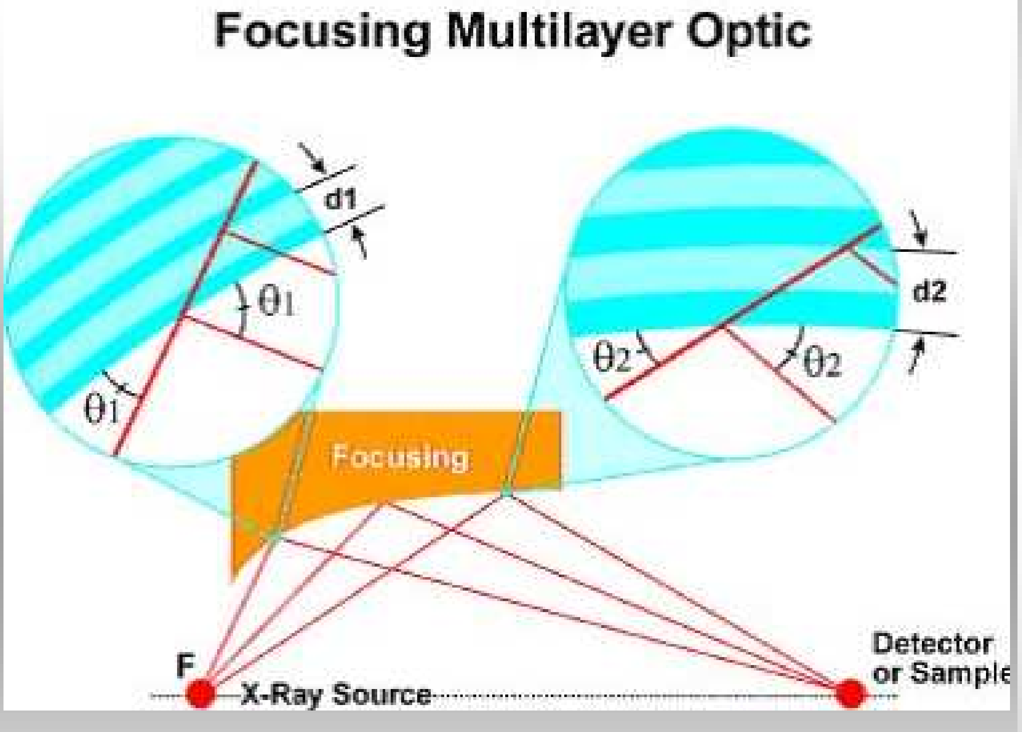
- *polished: Si, 300 eV, Kr+, 45°*

➡ >90% of maximum theoretical reflectivity achievable

ref Louis et al, Microelectr. Engin. 27 (1995) 235-238

X-ray beam transfer

Goebel mirrors
see e.g.
www.bruker-axs.de/products/gd/goebel_mirrors.php

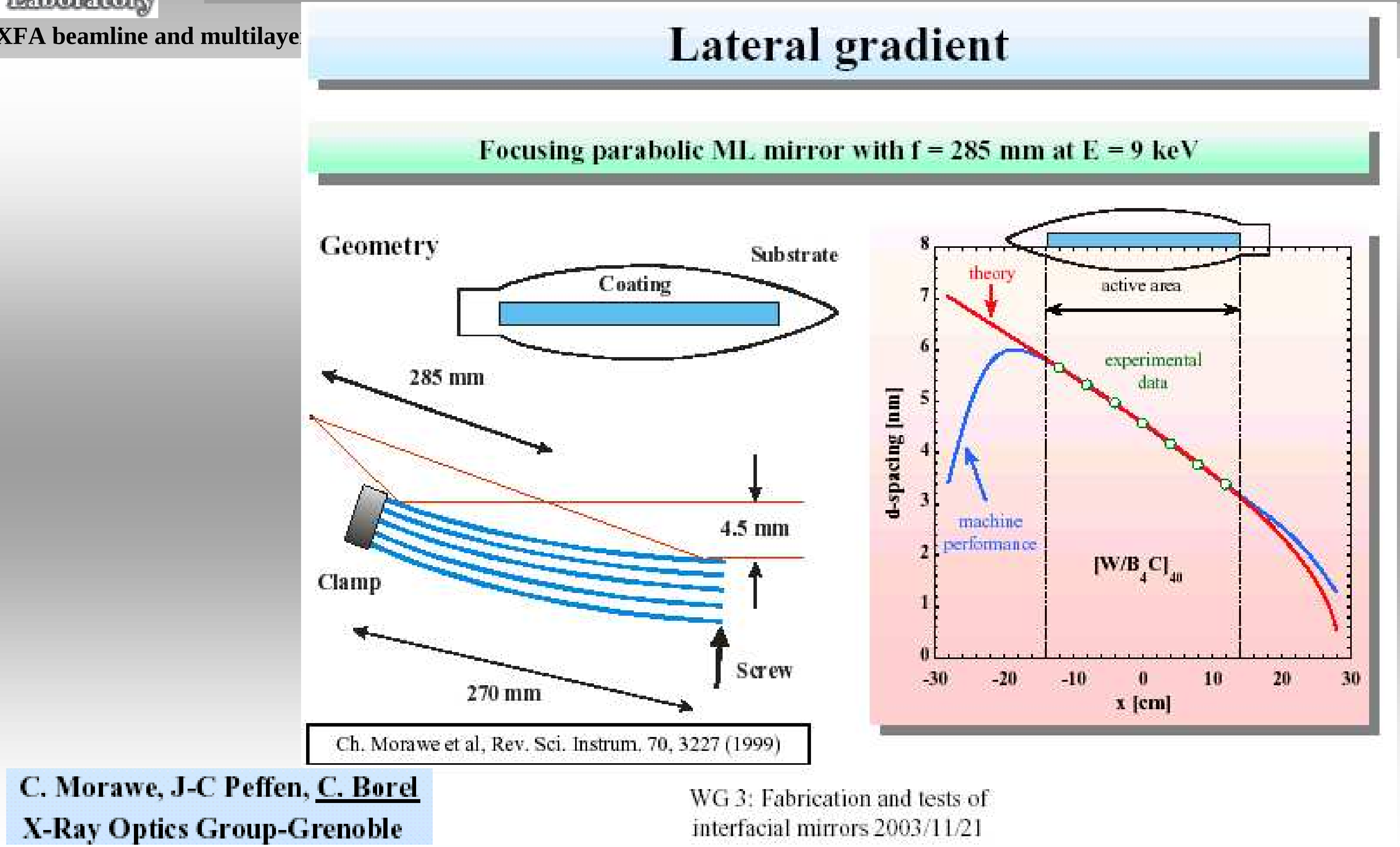


- **collimation**
- **focusing**
- **monochromatization**

MaxFlux®
http://www.osmic.com/products_maxflux_focusing.asp

X-ray beam transfer

μXFA beamline and multilaye



Lateral gradient

Focusing parabolic ML mirror with f = 285 mm at E = 9 keV

Ch. Morawe et al, Rev. Sci. Instrum. 70, 3227 (1999)

C. Morawe, J-C Peffen, C. Borel
X-Ray Optics Group-Grenoble

WG 3: Fabrication and tests of
interfacial mirrors 2003/11/21

X-ray beam collection

μXFA beamline and multilayer laboratory

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Focusing multilayer mirror detection system for carbon *K* edge soft x-ray absorption spectroscopy (invited)

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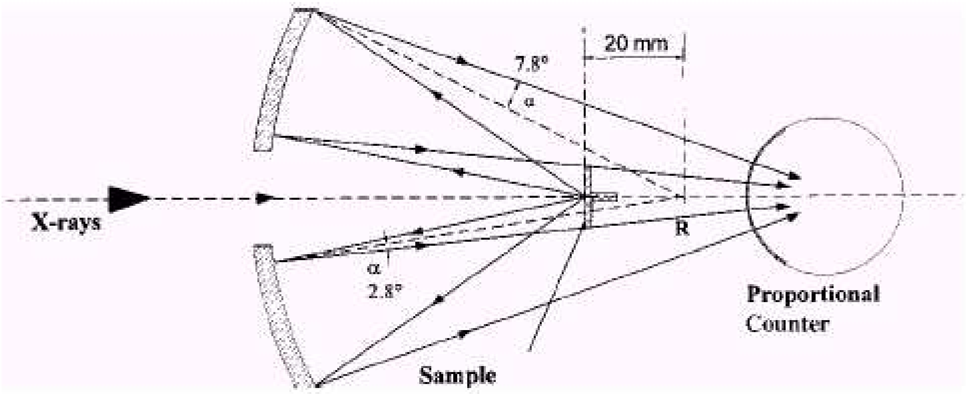


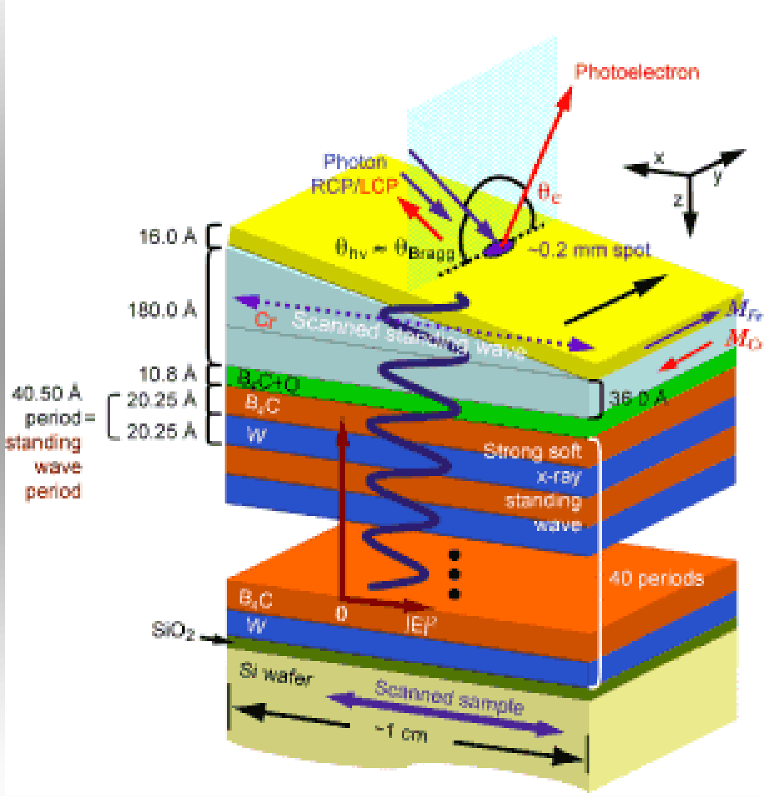
FIG. 3. Optical layout of MLM prototype 1 which utilizes a uniform *d* spacing and consists of a spherical optic 76.2 mm in diameter with a radius of curvature of 83.6 mm.

C K-fluorescence

150 bi-layers
16% of solid angle
average R 7%
rel. bandpass 1%

STANDING waves

http://www-als.lbl.gov/als/science/sci_archive/55wave_probe.html



Principle idea:
Create internal standing wave for probing properties in the wedge depending on thickness and depth