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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/1013-31

SCHOOL ON THE USE OF SYNCHROTRON RADIATION IN SCIENCE AND TECHNOLOGY:
"John Fuggle Memorial"

3 November - 5 December 1997

Miramare - Trieste, Italy

Photoelectron Emission Microscopy (PEEM, PEM)

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Johannes Gutenberg - Universität
Mainz - Germany

Photoelectron Emission Microscopy (PEEM, PEM)

- A mesoscopic method of surface imaging:
  lateral resolution: 10 nm - 10 µm
  field of view: 5 - 500 µm

- Image acquisition: parallel ↔ sequential: PEEM ↔ SPM

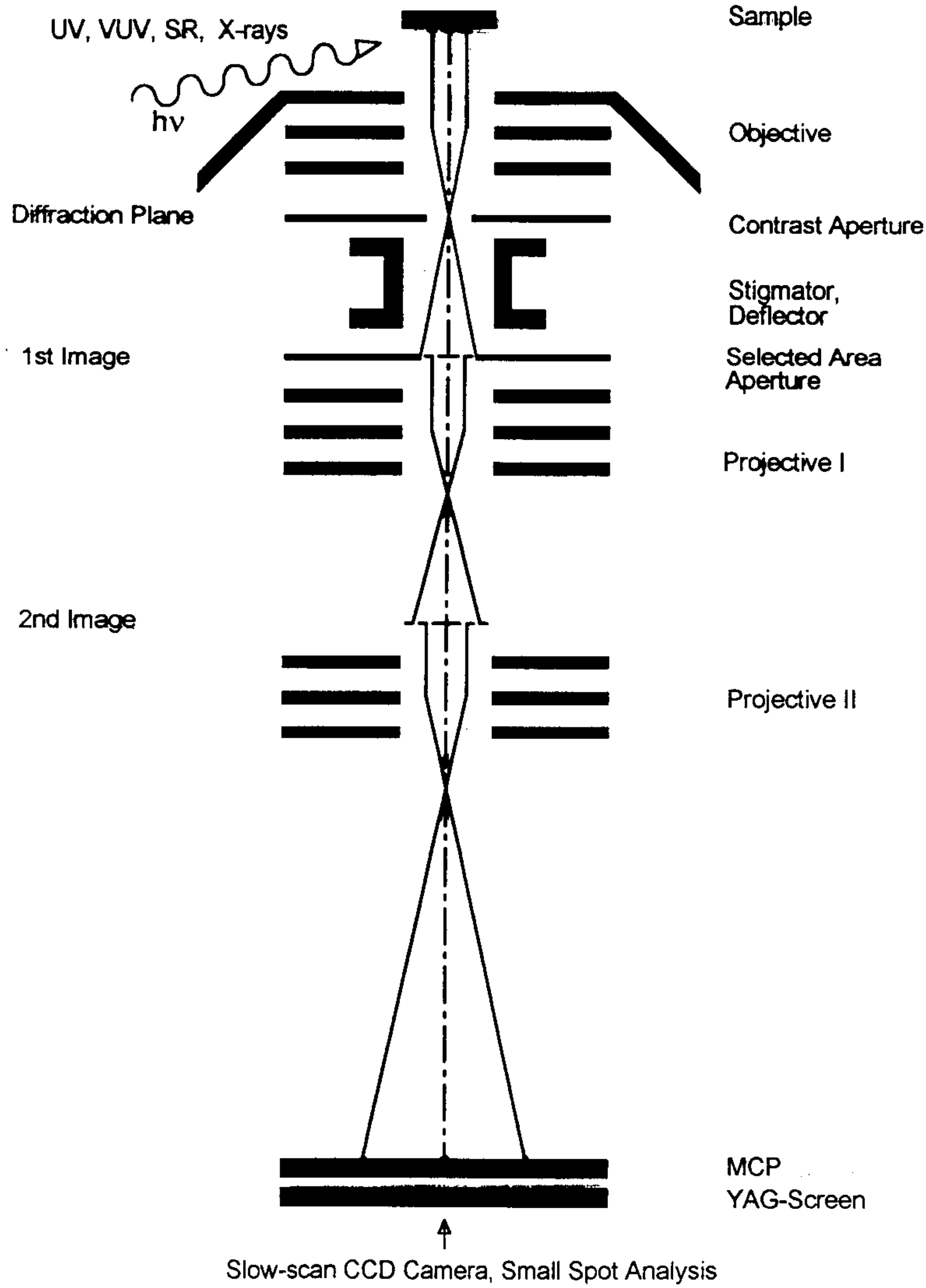
- Energy range: UV-PEEM ↔ X-PEEM (VUV-PEEM)

- Electrons used for imaging:
  „true“ or „resonant“ photoelectrons ↔ secondary electrons
  PEEM ↔ SEM (second. emiss. !)

- Transmitted energy range: total yield ↔ partial yield
  (i.e. spectroscopic) imaging

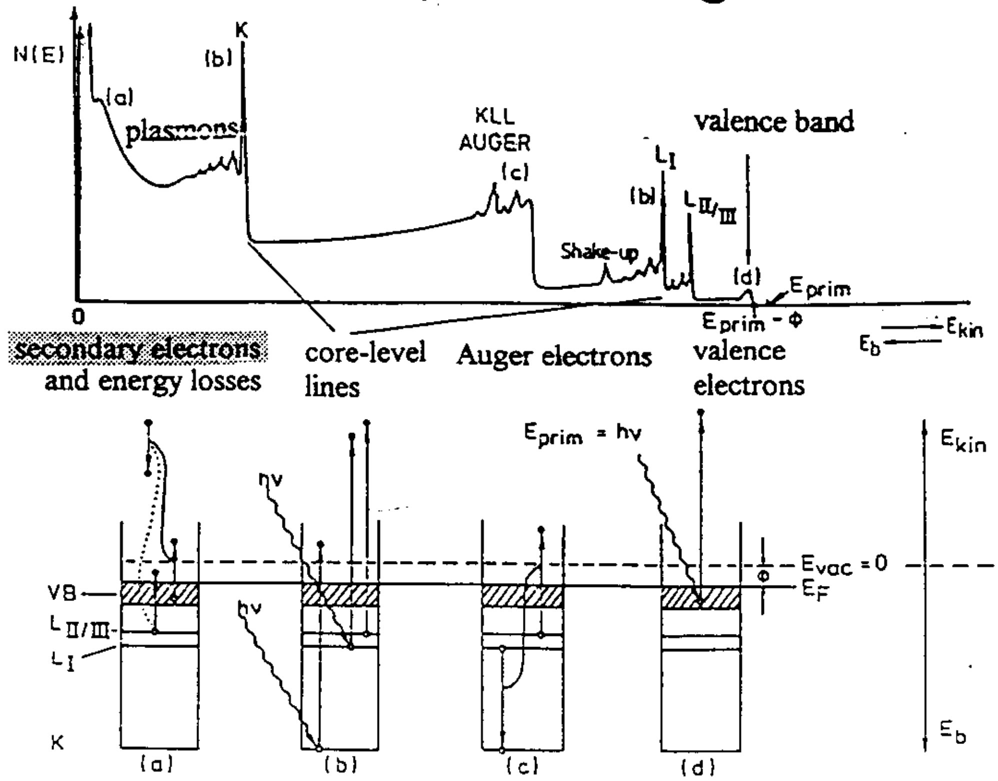
- Spectromicroscopy ↔ microspectroscopy
  energy filters ↔ energy analysers (spectrometers)

- Outlook: atomic structures via XPD



Schematic of the photoemission electron microscope

Photoelectron yield using soft X-rays

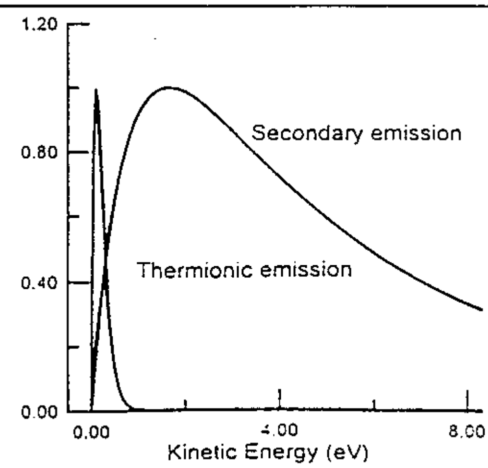


Schematics of the energy distribution of electrons emitted due to photon absorption and characteristic excitation processes in metals.

a) secondary elctron excitation and energy losses during inelastic electron scattering prior to emission process
b) emission from core levels
c) Auger prcesses
d) emission from valence band

The shape of the secondary yield energy distribution for soft X-rays is given by: $N(E) = E/(E+\varphi)^4$

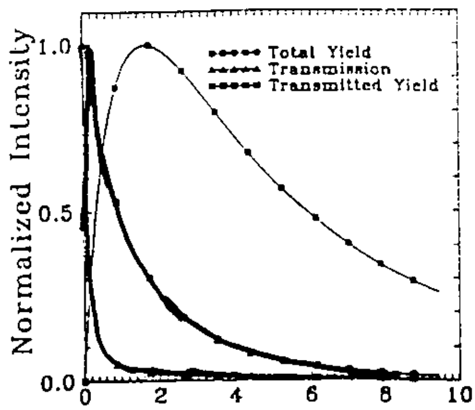
Y_{max} @ 1/3 φ
FWHM $\approx 1.1\ \varphi$

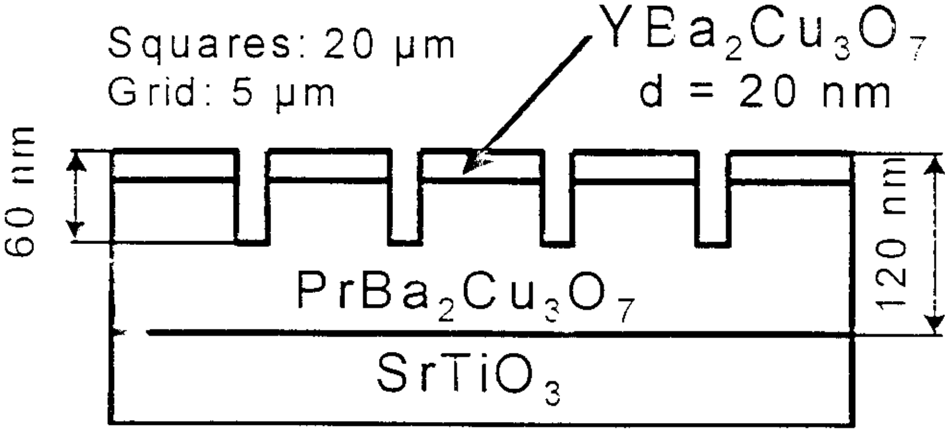


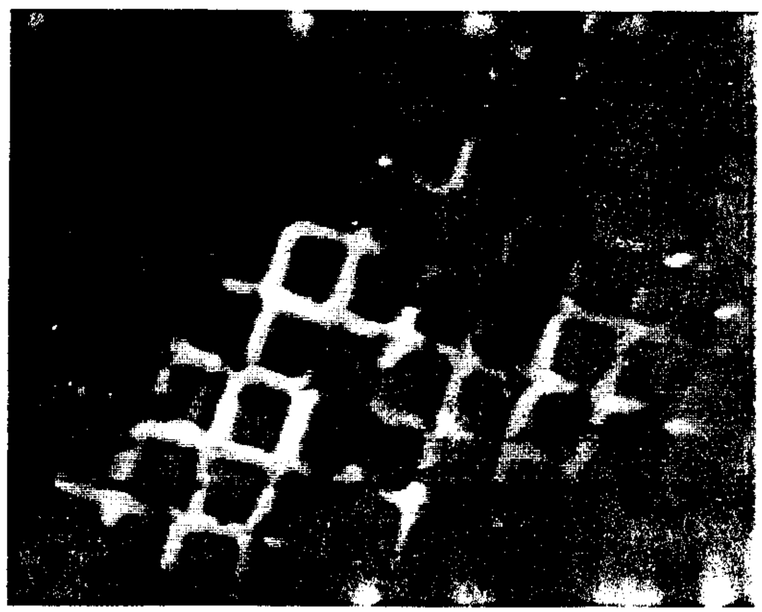
However, a PEEM with an immersion objective requires a contrast aperture in its back focal plane.
The transmission function through the objective is thus given by:

$$T(E) \approx 1 - \left[1 - \frac{4}{9}\left(\frac{r_{aperture}}{f_{objective}}\right)^2 \frac{eV}{E}\right]^{\frac{1}{2}}$$

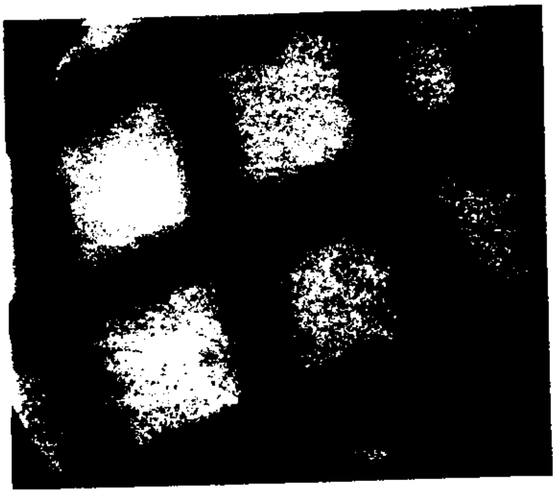
Hence: $Y_{transmitted} = Y_{total} \times T(E)$



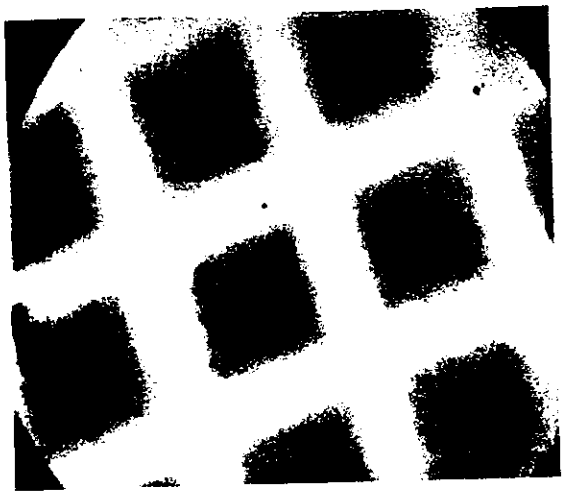




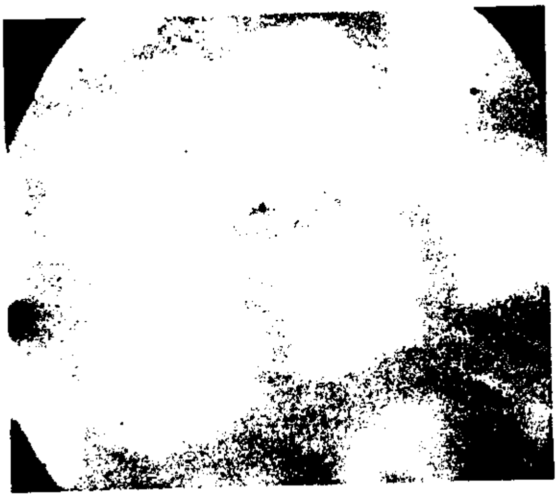
HTC-Insulator Multilayer



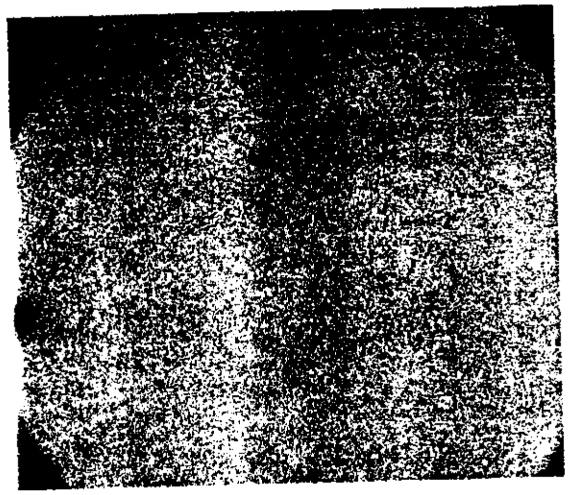
(a) 532eV



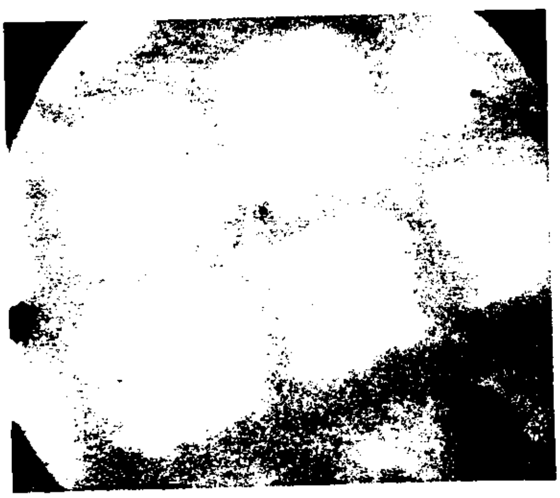
(d) 937eV



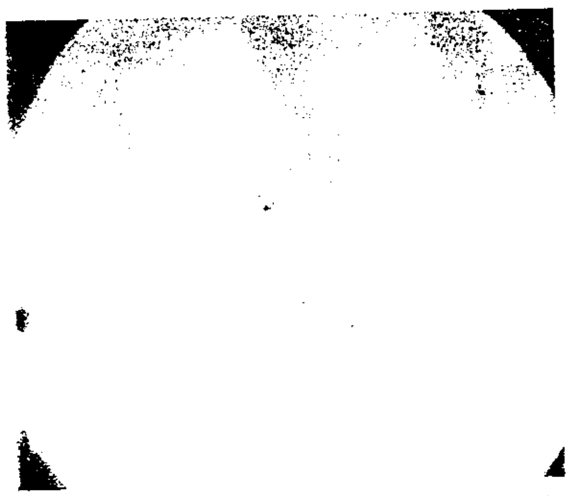
(b) 539eV



(e) 940eV



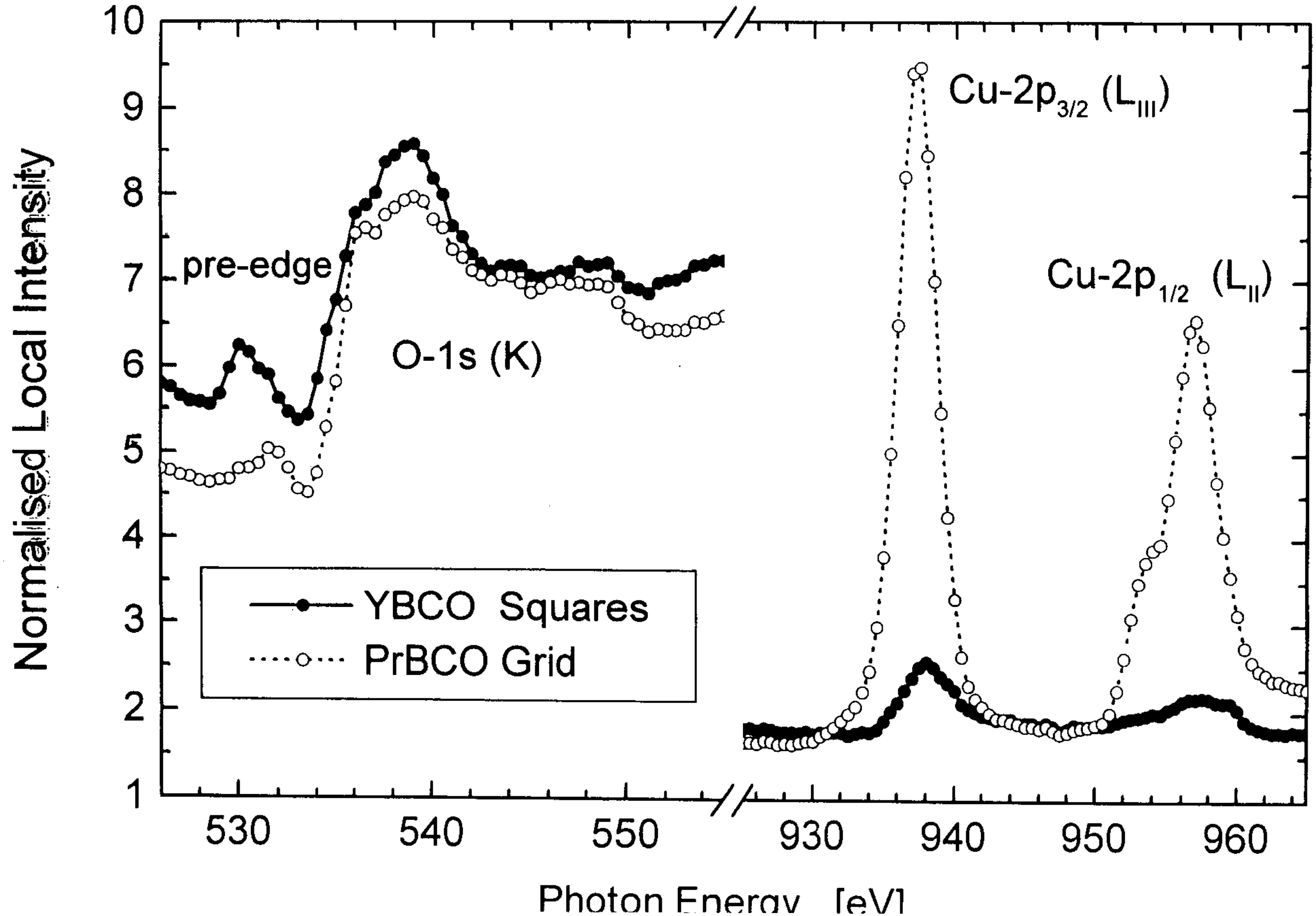
(b) 550eV

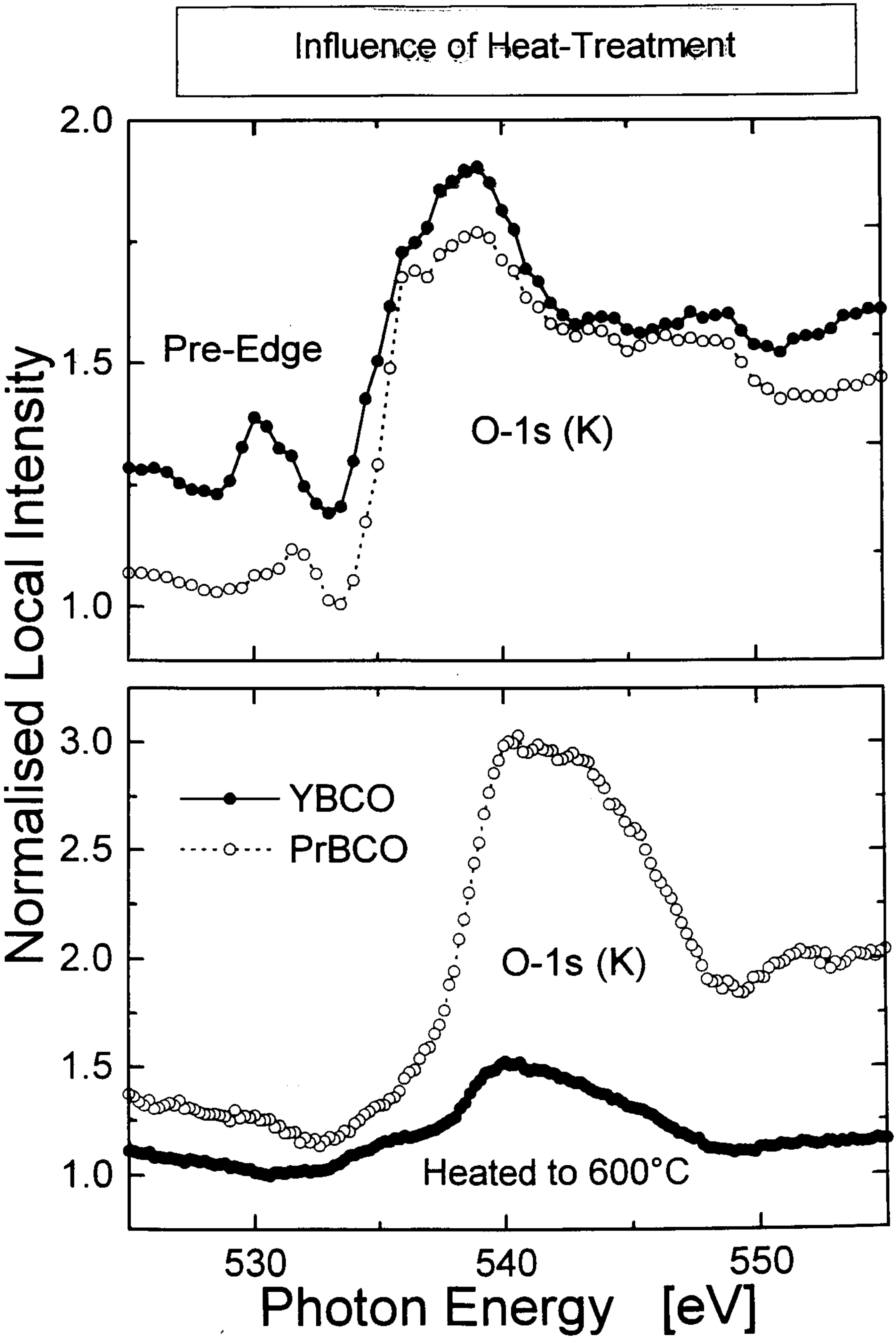


(f) 950eV

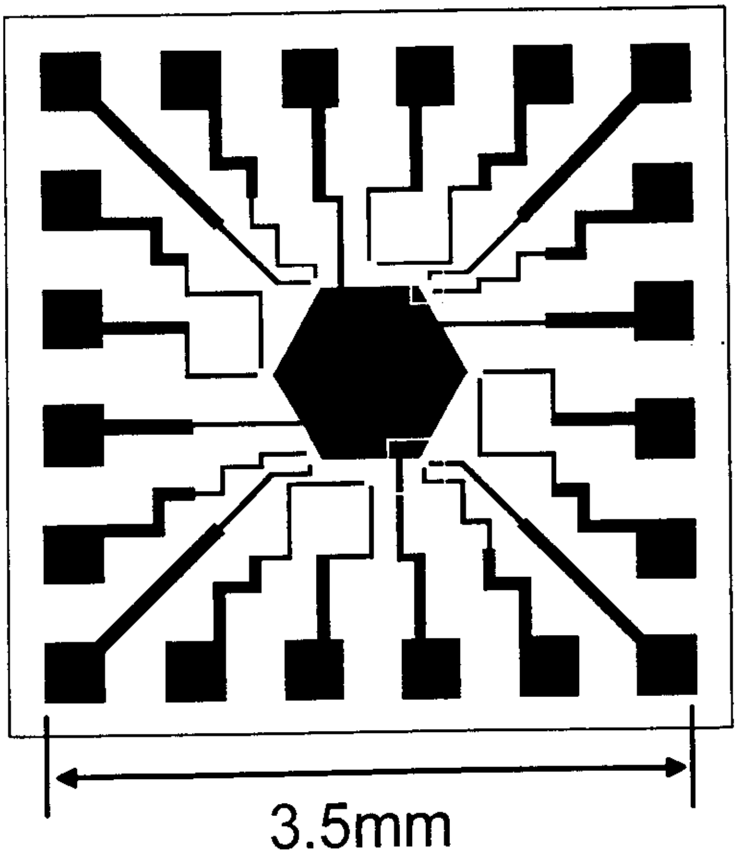
left: at O K-edge

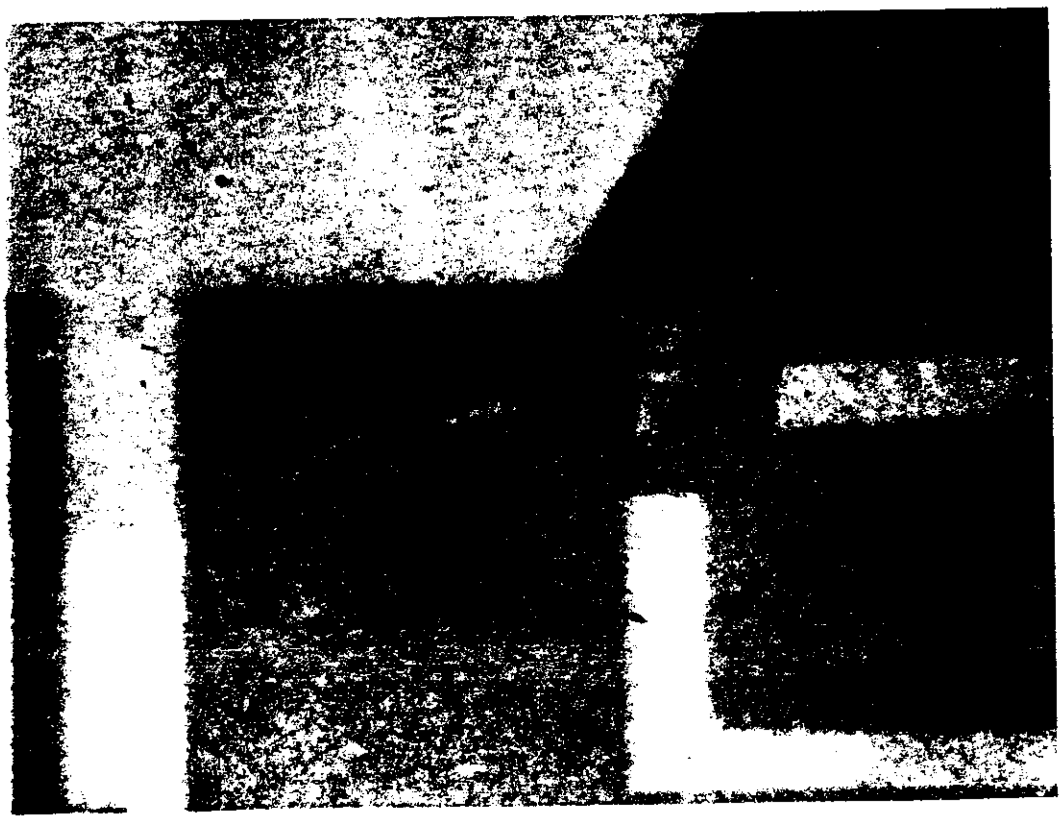
right: at Cu $L_{II/III}$-edge


Normalised Local Intensity
Photon Energy [eV]
pre-edge
O-1s (K)
Cu-2p3/2 (LIII)
Cu-2p1/2 (LII)
YBCO Squares
PrBCO Grid
10
9
8
7
6
5
4
3
2
1
530
540
550
930
940
950
960

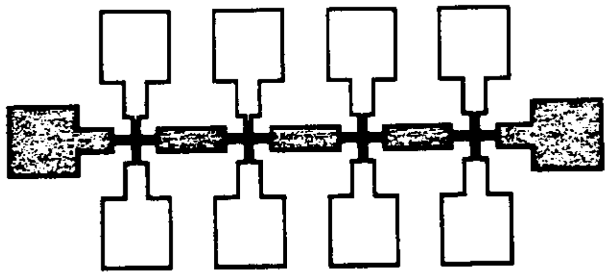

Influence of Heat-Treatment
Pre-Edge
O-1s (K)
YBCO
PrBCO
O-1s (K)
Heated to 600°C
Normalised Local Intensity
Photon Energy [eV]
2.0
1.5
1.0
3.0
2.5
2.0
1.5
1.0
530
540
550

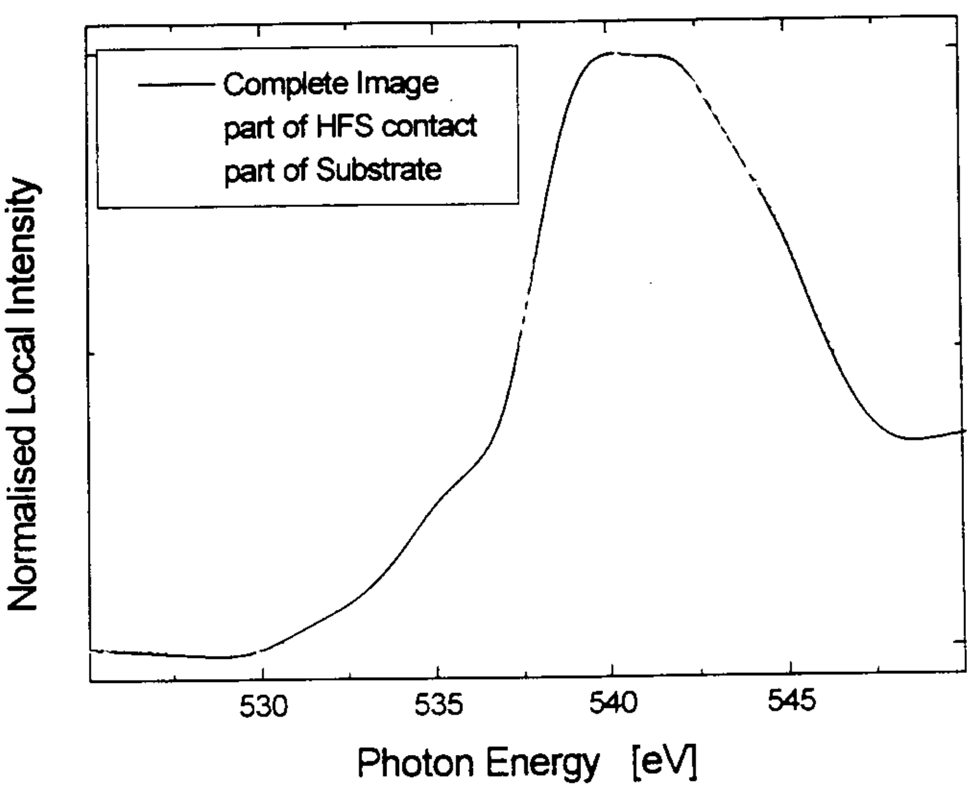
Heavy-Fermion SQUID (UPd_2Al_3)
PEEM Image taken at O K-edge





sample made by group of Prof. H.Adrian, Uni Mainz

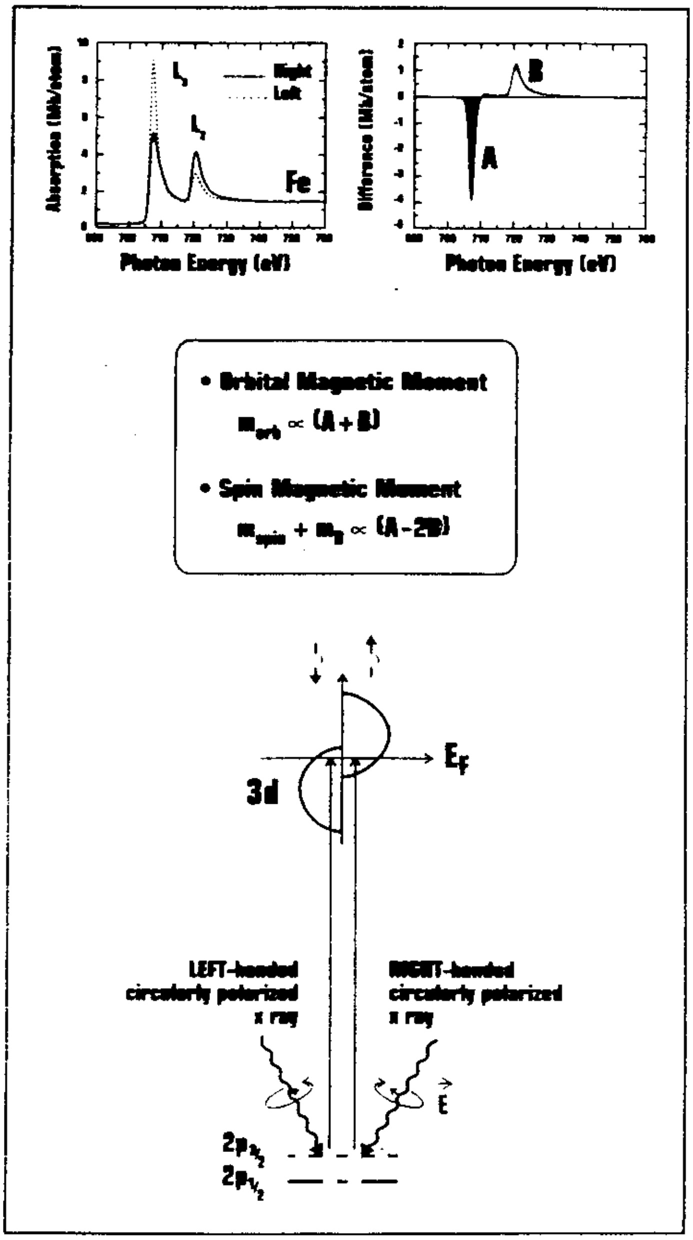




sample made by group of Prof. H.Adrian, Uni Mainz

Polarization

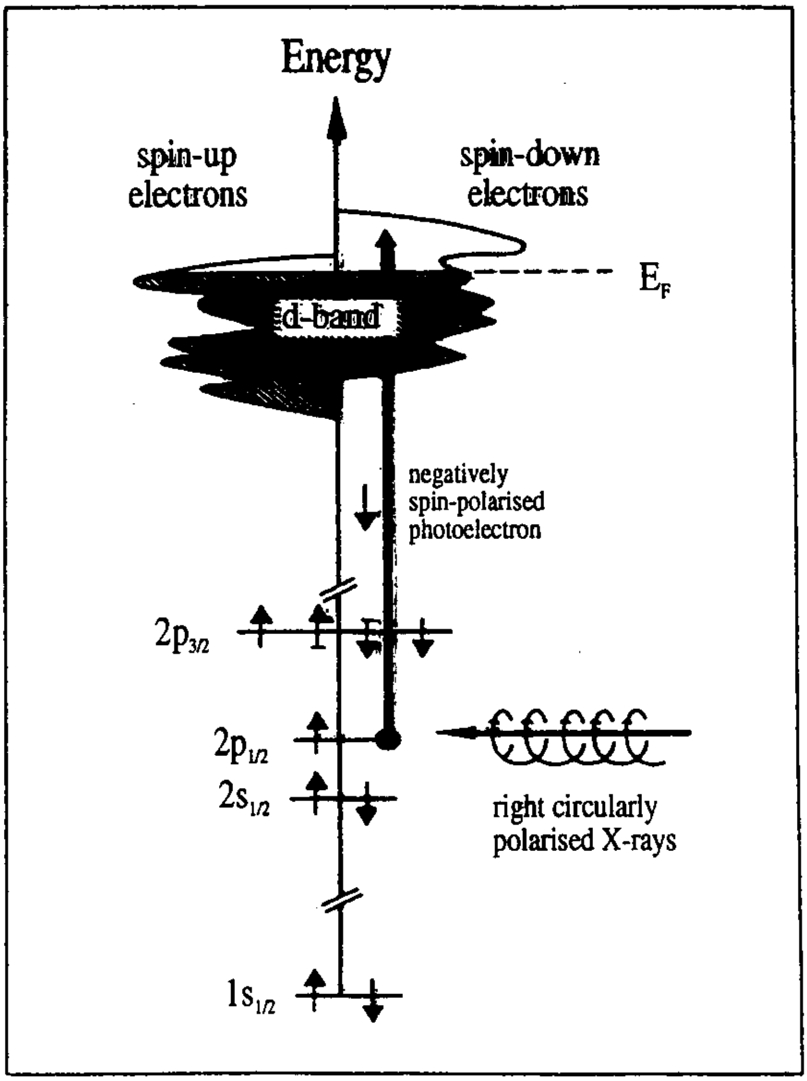
Enhancing The Capability of X-Ray Spectroscopy



In an elemental ferromagnet the differential absorption of left and right circularly polarized x rays propagating parallel to an applied magnetic field results from an imbalance in the spin occupancy of the partially occupied valence band and from quantum mechanical selection rules that apply to the absorption transitions. From the difference it is possible to extract the separate spin and orbital contributions to the total local magnetic moment. The spin density m_T in the figure is an orientation dependent term that vanishes in isotropic materials and certain experimental geometries.

Origin of X-ray Magnetic Circular Dichroism (XMCD):

absorption of circularly polarised X-rays measured at an inner-shell absorption edge in magnetic materials

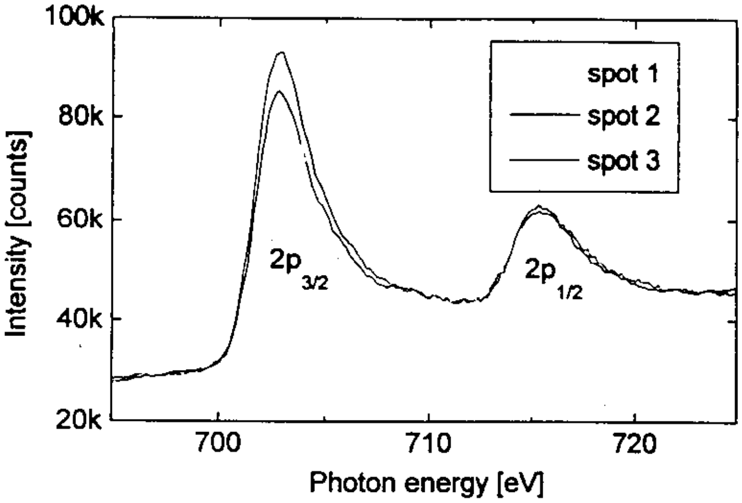


adapted from:

G. Schütz, Phys. Bl., **46** (1990) 475

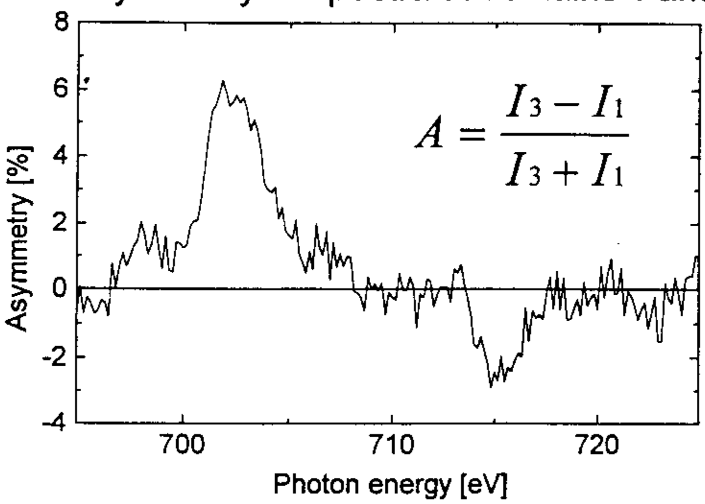
Magnetic contrast in PEEM

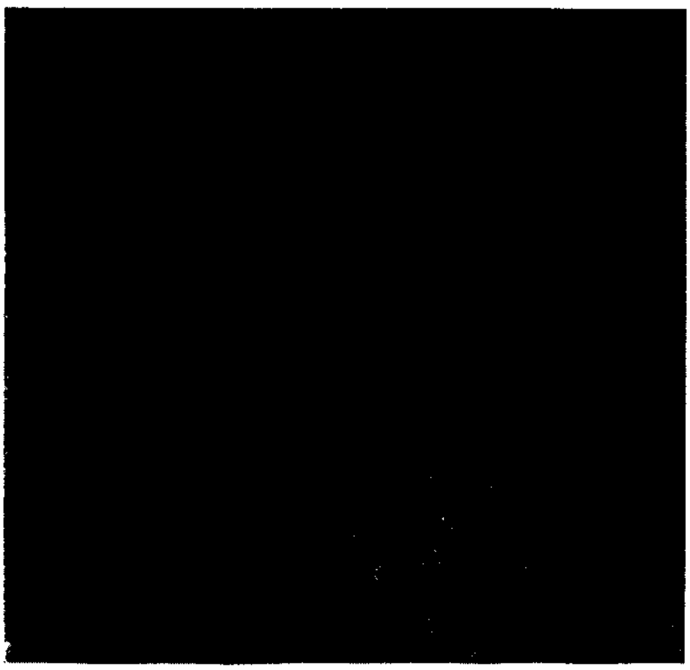
Local absorption spectra on individual domains



Fe-whisker:
local x-ray absorption spectra and PEEM image.

Asymmetry of spectra at domains 1 and 3





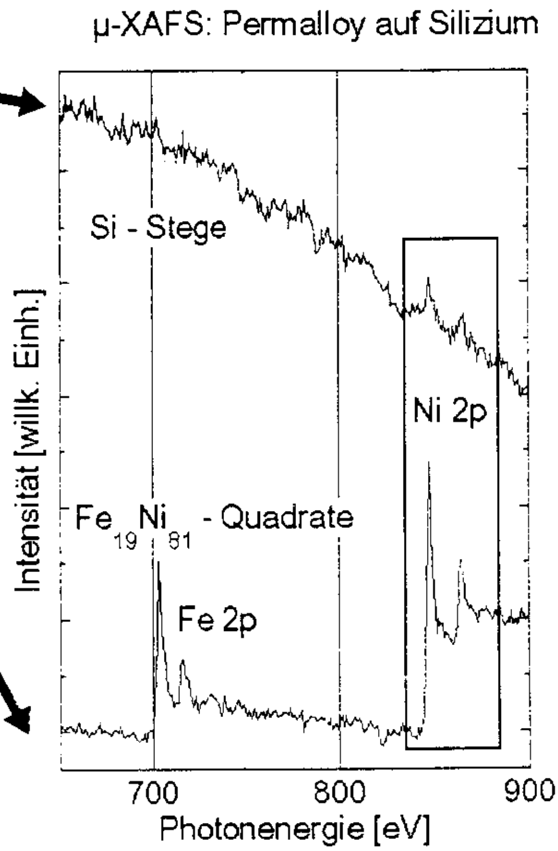
- Magnetic Circular Dichroism (MCD) generates image contrast
- use of circularly polarized monochromatic synchrotron radiation
- magnetic resolution of 300 nm achieved
- contrast of 12 % in single raw image (on Fe-whisker)
- live domain imaging possible with sufficient photon flux

PEEM kombiniert mit μ-XAFS

Permalloy ($Fe_{19}Ni_{81}$) auf Si-Kristall

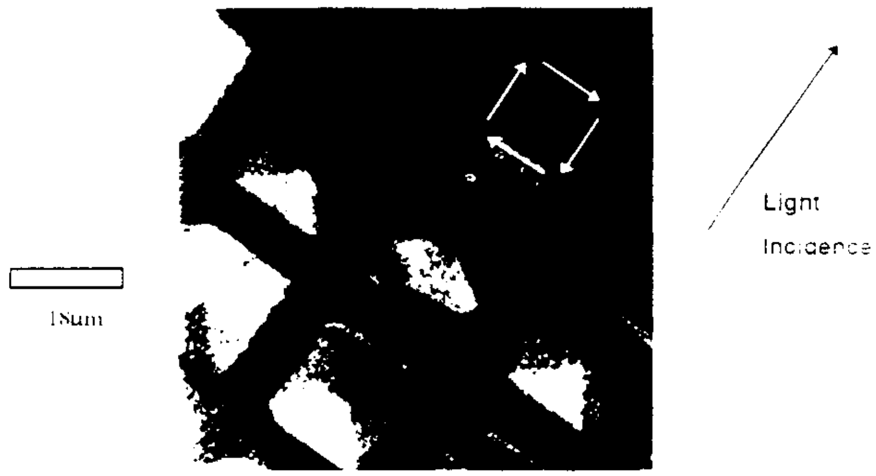
Das Siliziumsubstrat wurde durch ein Netz mit Permalloy bedampft. Dabei entstehen Permalloy- Quadrate mit einer Kantenlänge von 20μm und Siliziumstege mit 7 μm Breite. Mit **μ-XAFS** kann **<u>auf die Si-Stege diffundiertes Nickel</u>** nachgewiesen werden.

Aufnahme mit <u>Röntgen-Strahlung bei 706,8 eV</u>. Dieses Bild zeigt **<u>keine chemische Differenzierung</u>**.

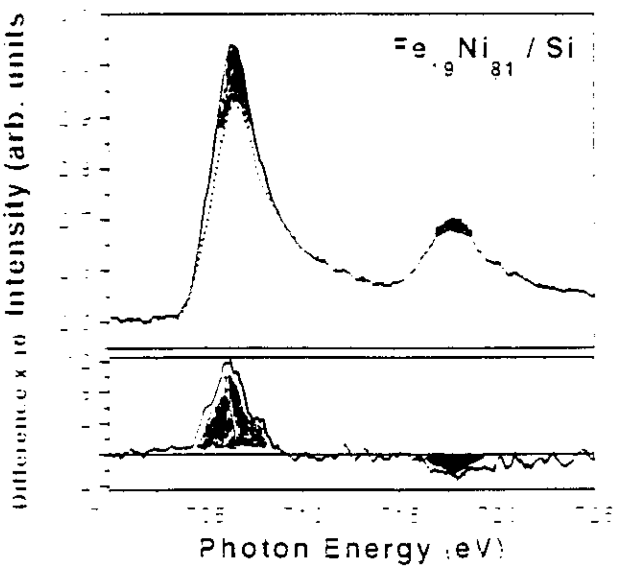


<u>Differenzbild</u> aus 706,8 eV (Fe $2p_{1/2}$) und dem 'Untergrund' bei 700,0 eV. Dieses Bild zeigt die **<u>räumliche Verteilung von Eisen</u>**

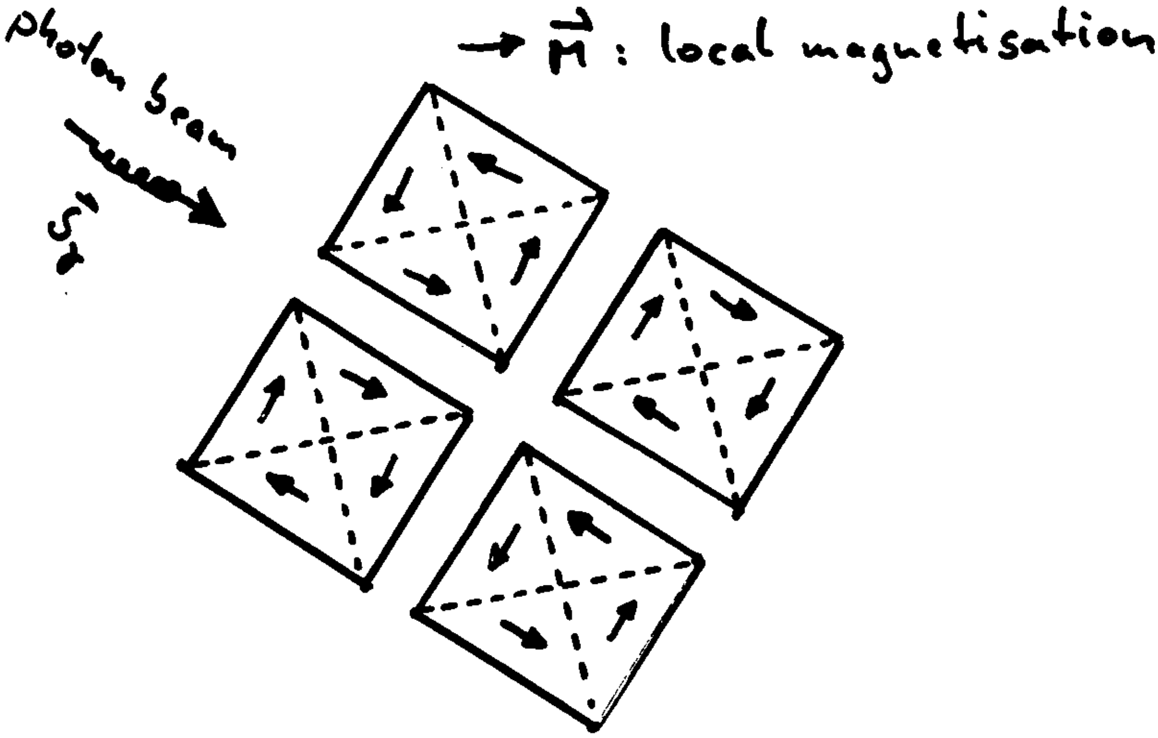
Micro-XCMD: PEEM in the Secondary Yield Mode: magnetic domain pattern in permalloy on Si



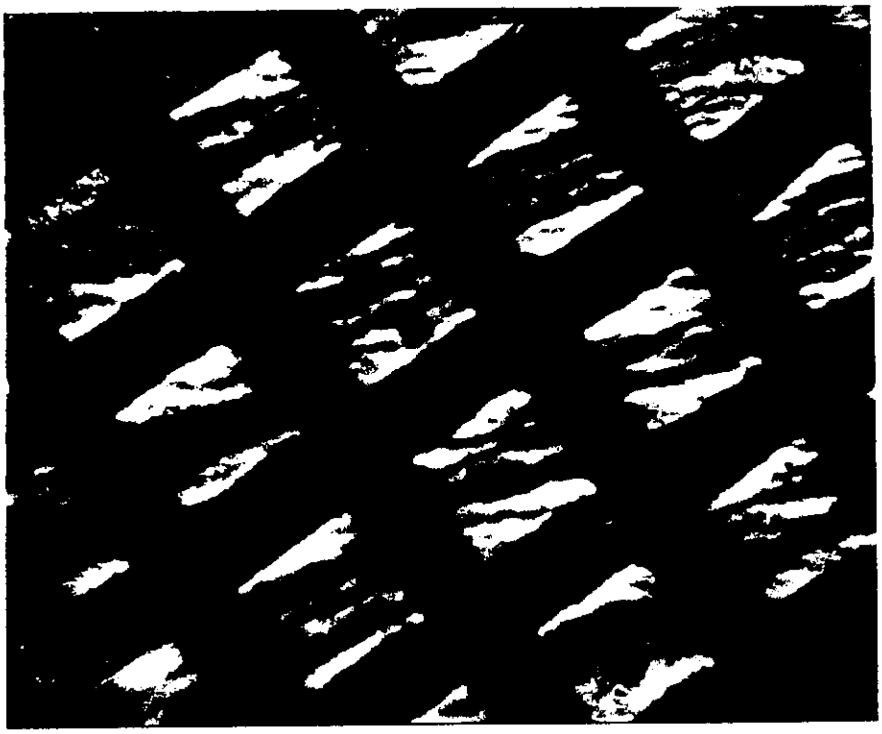
XCMD spectromicroscopy:
pixel-by-pixel difference of images taken at photon energies corresponding to Fe L_3 and L_2 absorption edges, respectively.

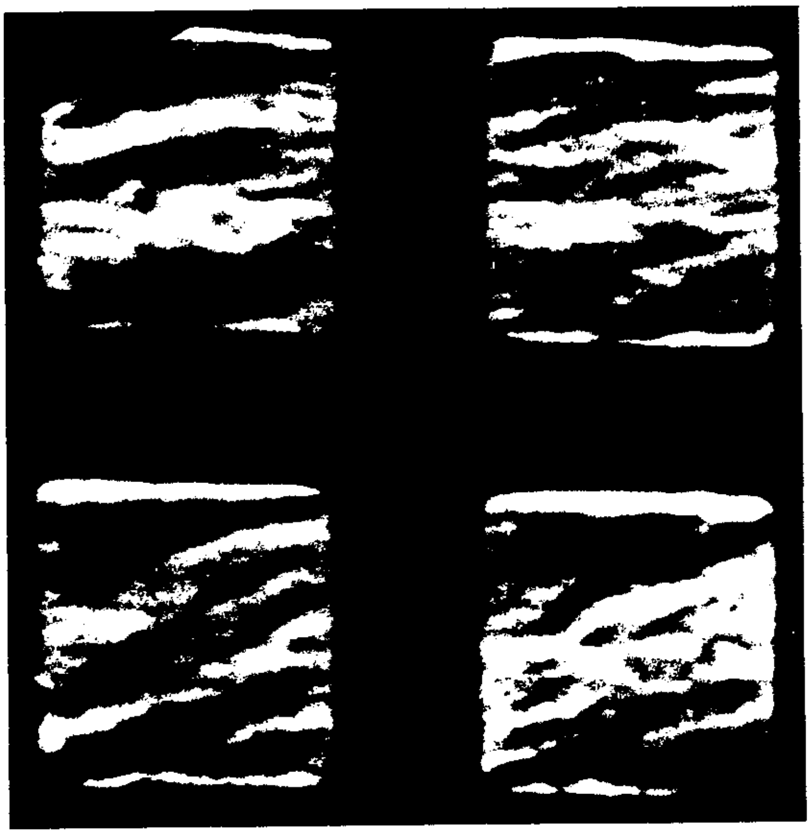


XCMD microspectroscopy:
"local" constant final state spectra taken from the two opposite domains in one of the permalloy squares.


Photon beam
→ M : local magnetisation

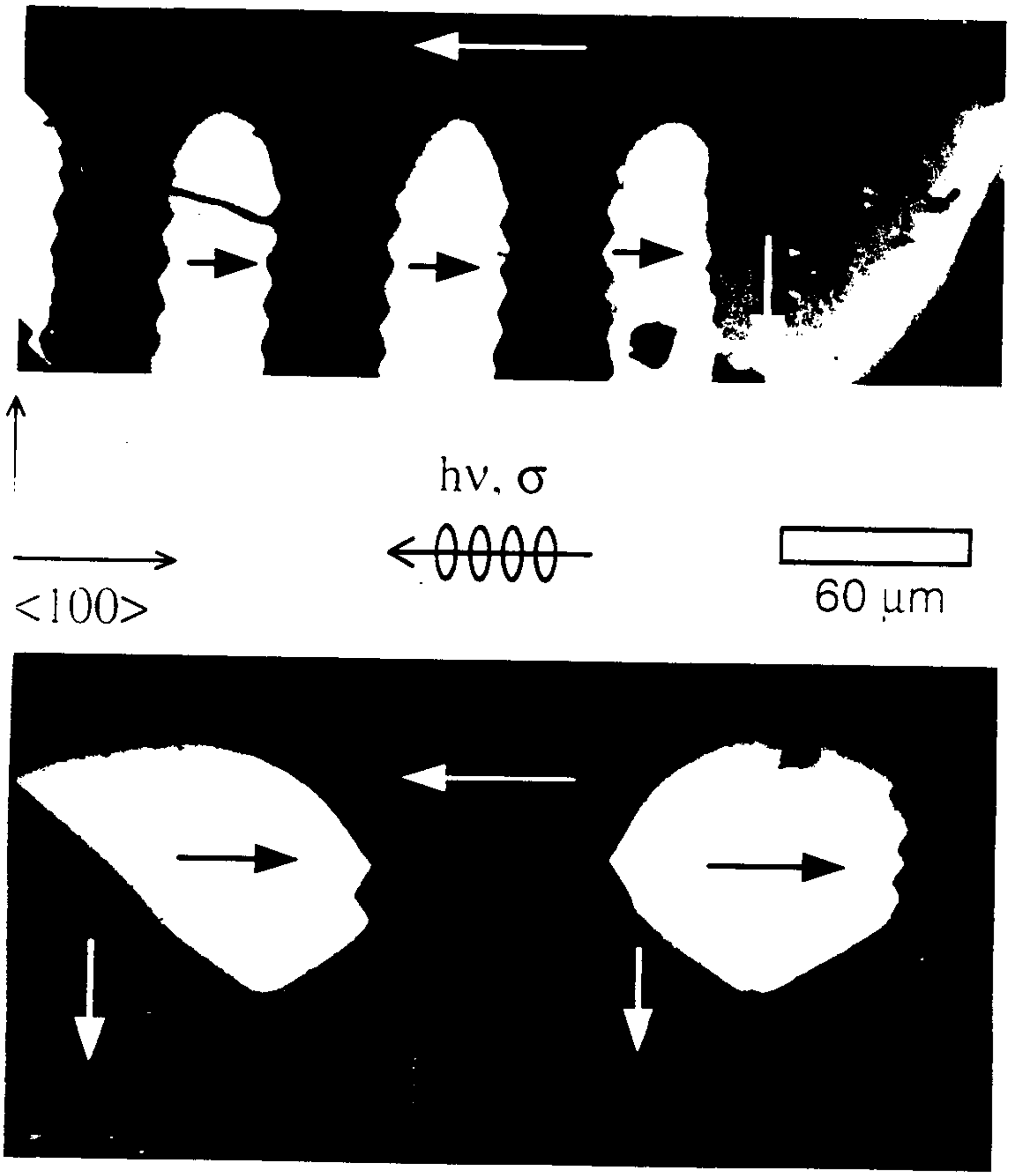
Pt/Co/Pt Multilayer



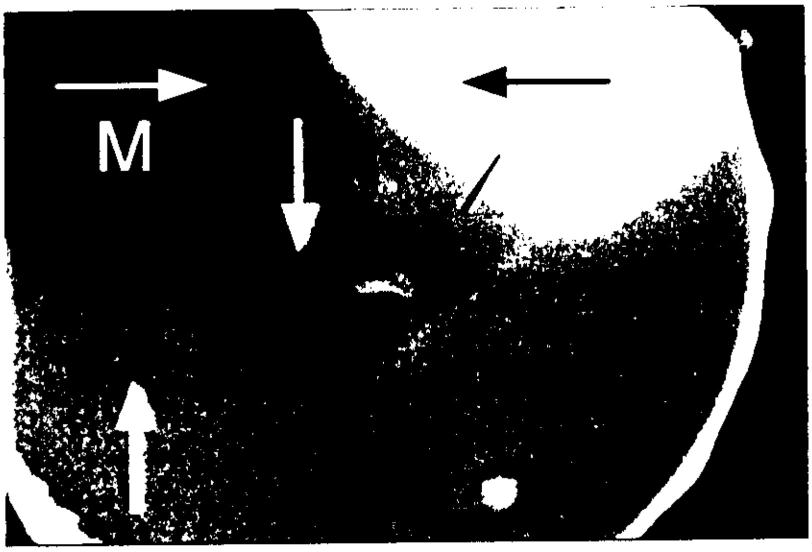


Co 2p XMCD

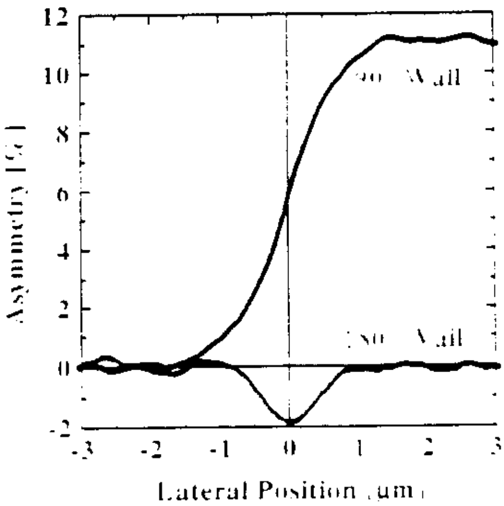
Magnetic domains and domain walls in Fe(001) imaged at the Fe L_3 absorption line utilizing MCD effect.

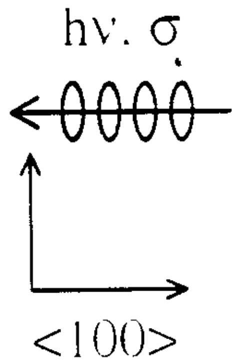


Domain walls on Fe (100) Whisker



Intensity asymmetry variation across Néel-like domain walls.



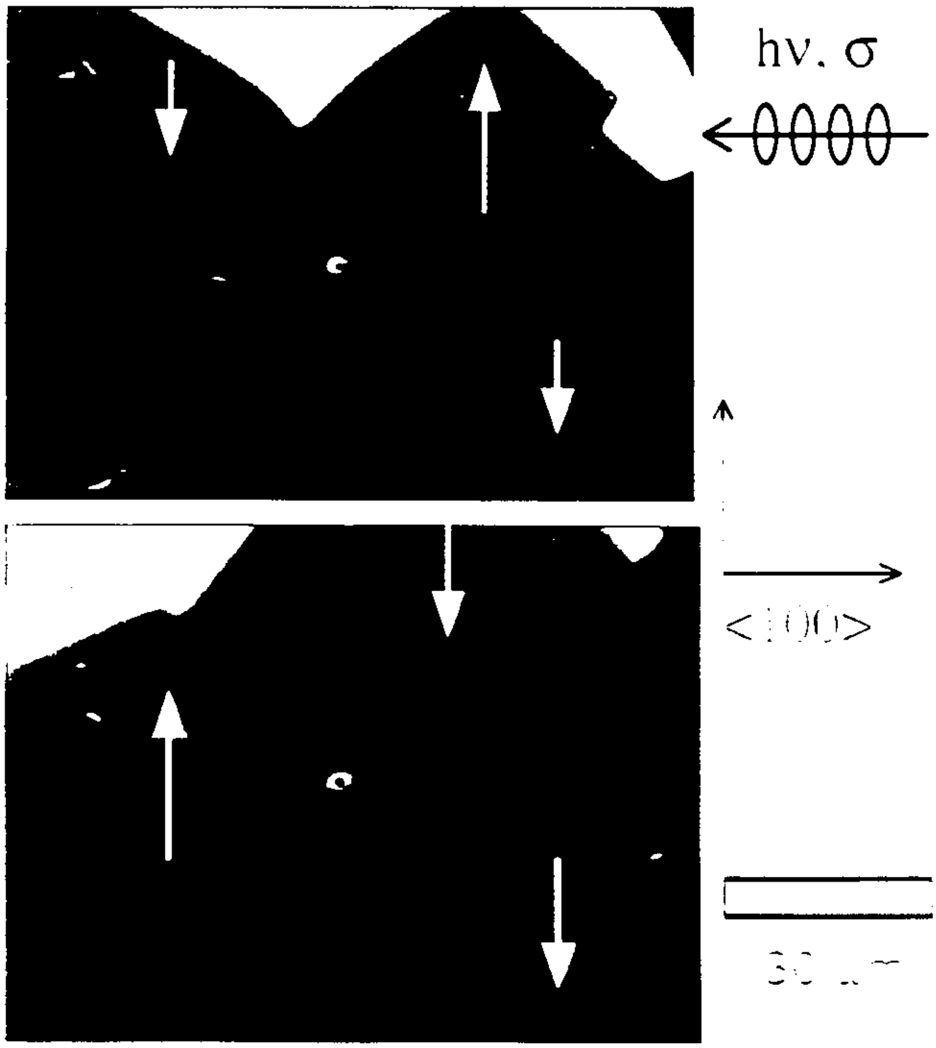


$$I_{Magnetic}(x,y) = I_{RCP}(x,y) - I_{LCP}(x,y)$$

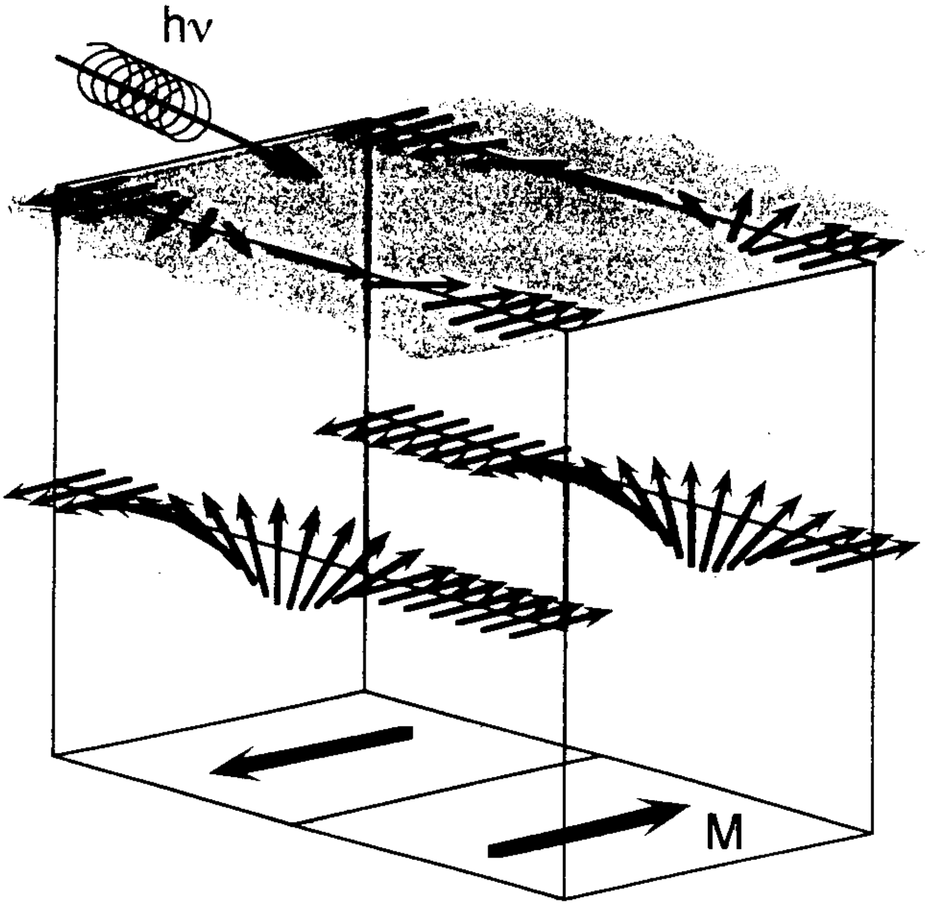
$$I_{NonMagnetic}(x,y) = I_{RCP}(x,y) + I_{LCP}(x,y)$$

$$A_{symmetry}(x,y) = I_{M}(x,y) / I_{NM}(x,y)$$

180 degree magnetic domain walls in Fe(001) imaged at the Fe L_3 absorption line utilizing MCD effect. They occurrence is due to the Néel-like termination of the domain walls at the surface. The contrast difference between the dark and bright domain wall segments is due to the opposite chirality of the spin rotation within the wall. The domain walls shown are so called V-lines and represent a rather complex pattern of three-dimensional closure domains

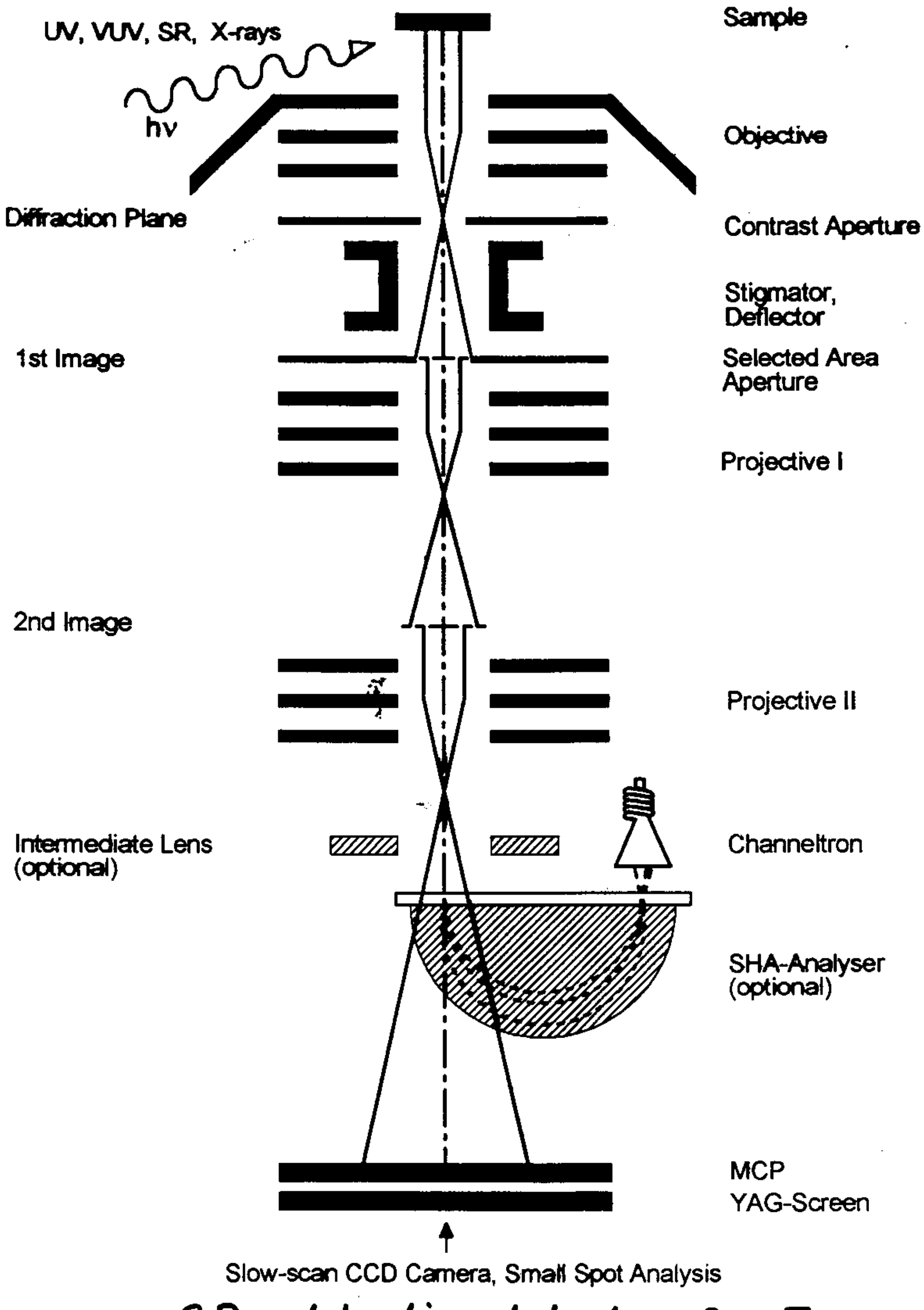


Imaging a 180°- domain wall at the surface



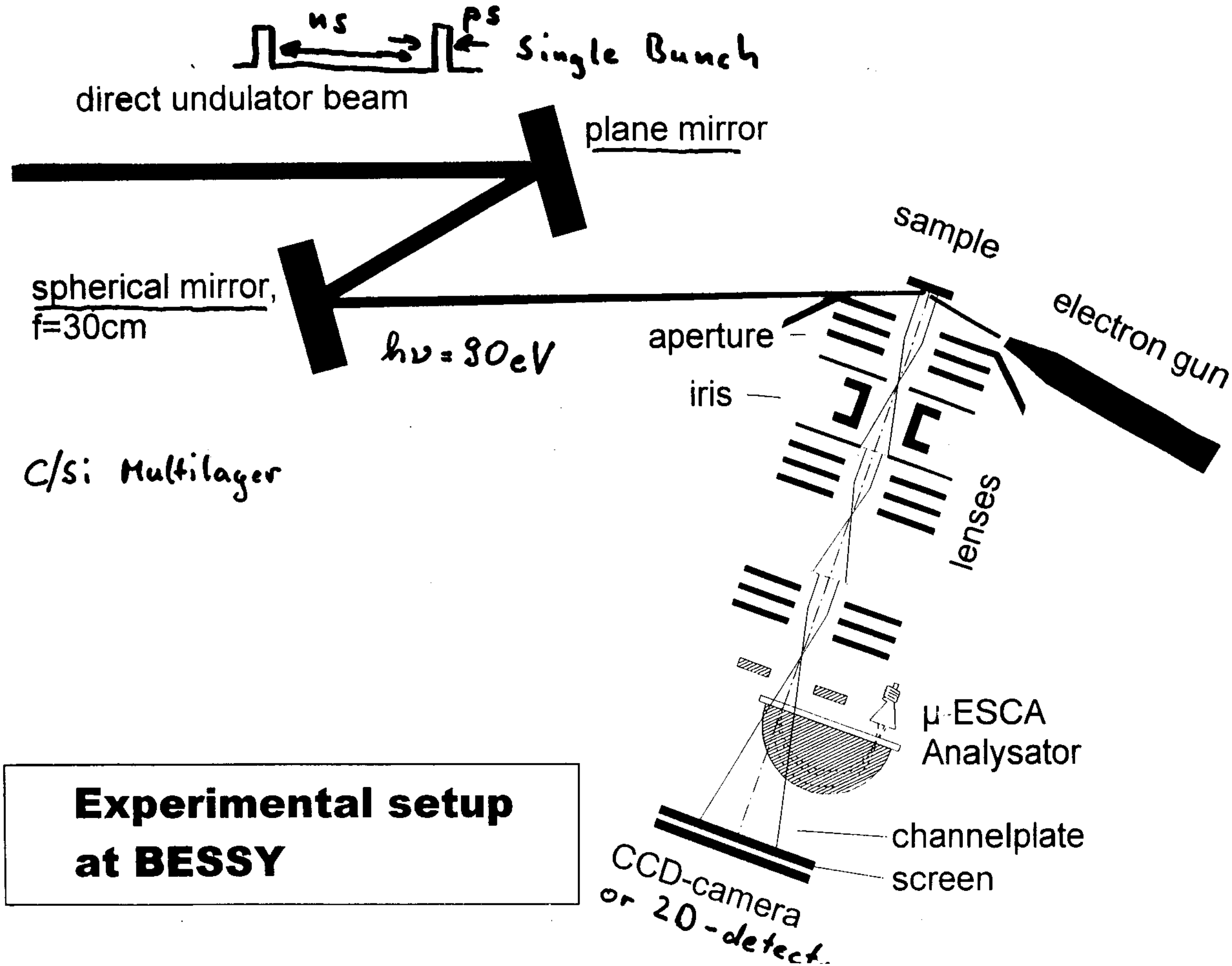
H.P. Oepen and J. Kirschner, Phys. Rev. Lett. **62** (1989) 819

M.R. Scheinfein, J. Unguris, R.J. Celotta, and D.T. Pierce, Phys. Rev. Lett. **63** (1989) 668



2D - delay line detector for TOF

Schematic of the photoemission electron microscope with (optional) energy analyser for microspectroscopy



Experimental setup at BESSY

PAPERS ON CIRCULAR DICHROISM, SPIN POLARISATION, AND RELATED STUFF MEASURED BY THE MAINZ GROUP

1) C.Westphal, J.Bansmann, M.Getzlaff, G.Schönhense
Circular Dichroism in the Angular Distribution of Photoelectrons from Oriented CO Molecules
Phys.Rev.Lett. **63** (1989) 151

2) C.Westphal, J.Bansmann, M.Getzlaff, G.Schönhense
Experimental observation of circular dichroism in photoemission
Vacuum **41** (1990) 87

3) G.Schönhense
Spin-dependent effects in photoemission
Vacuum **41** (1990) 506

4) G.Schönhense
Circular Dichroism and Spin Polarization in Photoemission from Adsorbates and Non-Magnetic Solids
Physica Scripta **T31** (1990) 255

5) C.Westphal, J.Bansmann, M.Getzlaff, G.Schönhense
Information on Structure and Photoemission Dynamics of Molecular Adsorbates from Circular Dichroism in Photoemission
J.Elec.Spect. Rel.Phen. **52** (1990) 613

6) C.Westphal, J.Bansmann, M.Getzlaff, G.Schönhense, N.A.Cherepkov, M.Braunstein, V.McKoy, R.L.Dubs
Circular dichroism in photoemission from oriented molecules at surfaces
Surf.Sci. **253** (1991) 205

7) G.Schönhense, C. Westphal, J.Bansmann, M.Getzlaff, J.Noffke, L.Fritsche
Circular dichroism in photoemission from surfaces
Surf.Sci. **251/252** (1991) 132

8) G.Schönhense, C.Westphal, J.Bansmann, M.Getzlaff
Circular dichroism in photoemission from nonmagnetic low-Z solids: a conspicuous effect of the photon spin
Europhys.Lett. **17** (1992) 727

9) J.Bansmann, C.Westphal, M.Getzlaff, F.Fegel, G.Schönhense
Magnetic circular dichroism in valenceband photo-emission from Fe(100)
J.Magn.Magn.Mat. **104-107** (1992) 1691

10) J.Bansmann, M.Getzlaff, C.Westphal, F.Fegel, G.Schönhense
Magnetic circular dichroism in valenceband photoemission from iron (100)
Surf.Sci. **269/270** (1992) 622

11) J.Bansmann, Ch.Ostertag, G.Schönhense, F.Fegel, C.Westphal, M.Getzlaff, F.Schäfers, H.Petersen
Circular dichroism in X-ray photoemission from core levels of nonmagnetic species
Phys.Rev. B **46** (1992) 13496

12) M. Getzlaff, J. Bansmann, C. Westphal und G. Schönhense
Exchange splitting of adsorbate-induced bands on thin iron films
J. Magn. Magn. Mat. **104-107** (1992), 1781

13) J. Bansmann, M. Getzlaff, C. Westphal und G. Schönhense
Surface hysteresis curves of Fe(110) and Fe(100) crystals in ultrahigh vacuum : evidence of adsorbate influences
J. Magn. Magn. Mat. **117** (1992), 38

14) M. Getzlaff, J. Bansmann und G. Schönhense
Spin polarization effects for electrons passing through thin iron and cobalt films
Sol. State Comm. **87** (1993), 467

15) M. Getzlaff, J. Bansmann und G. Schönhense
Spin-resolved photoemission from physisorbed xenon on ferromagnetic surfaces: evidence for magnetic interactions
Phys. Rev. Lett. **71** (1993), 793

16) M. Getzlaff, J. Bansmann und G. Schönhense
Iodine on a magnetized iron film - evidence for a magnetic coupling -
Phys. Lett. A **182** (1993), 153

17) G. Schönhense und H.C. Siegmann
Transmission of electrons through ferromagnetic material and applications to detection of electron spin polarization
Ann. Phys. **2** (1993), 465

18) N.A.Cherepkov, G.Schönhense
Linear dichroism in photoemission from oriented molecules
Europhys.Lett. **24** (1993) 79

19) Getzlaff, J. Bansmann und G. Schönhense
Magnetic interactions in different oxidation states of thin cobalt films
J. Magn. Magn. Mat. **131** (1994), 304

20) S.Corvers, G.H.Fecher, K.Bange, O.Anderson, W.Gutmannsbauer, H.Haefke
Thin oxide films: An AFM and TEM study
Glastech.Ber. Glass Sci.Technol **67 C** (1994) 484

21) G.H.Fecher, J.Bansmann, Ch.Grünewald, A.Oelsner, Ch.Ostertag, G.Schönhense
Oxidation of rubidium at platinum (111)
Surf.Sci. **307-309** (1994) 70

22) C.Westphal, F.Fegel, J.Bansmann, M.Getzlaff, G.Schönhense, J.A.Stephens, V.McKoy
Orientation and substrate interaction of adsorbed CO and NO molecules probed by circular dichroism in the angular distribution of photoelectrons
Phys Rev. B **50** (1994) 17534

23) M.Getzlaff, Ch.Ostertag, G.H.Fecher, N.A.Cherepkov, G.Schönhense
Magnetic dichroism in photoemission with unpolarized light
Phys.Rev.Lett. **73** (1994) 3030

24) Getzlaff, J. Bansmann und G. Schönhense
A study of the oxidation states of Co(0001)
J. Magn. Magn. Mat. **140-144** (1995), 729

25) Getzlaff, J. Bansmann und G. Schönhense
Photoemission from Fe/W(110)
J. Magn. Magn. Mat. **140-144** (1995), 669

26) Getzlaff, J. Bansmann und G. Schönhense
The electronic structure of benzene adsorbed on thin Fe(110) and Co(0001) films
Surf. Sci. 323 (1995), 118

27) Getzlaff und G. Schönhense
Magnetic exchange effects of adsorbates on thin Fe(110) films
Surf. Sci. 331-333 (1995)

28) G.H.Fecher
The solid surface as origin of circular dichroism in the angular distribution of photoelectrons from spherical states of adsorbates
Europhys.Lett. 29 (1995) 605

29) J.Bansmann, Ch.Ostertag, G.Schönhense, N.A.Cherepkov, V.V.Kuznetsov, A.A.Pavlychev
Circular dichroism in X-ray photoemission from Pd(111) and CO/Pd(111)
Z.Phys. D 33 (1995) 257

30) M.Getzlaff, J.Bansmann, G.Schönhense
Photoemission from from Fe/W (110)
Journal of Magnetism and Magnetic Materials, 140-144 (1995) 669

31) J.Bansmann, M.Getzlaff, G.Schönhense
Photoemission from Co/W(110) with unpolarized and circularly polarized radiation
J.Magn.Magn.Mat. 148 (1995) 60

32) A.Oelsner, G.H.Fecher, Ch.Ostertag, Th.Jentzsch, G.Schönhense
Dichroic effects in photoemission from pure and oxidised Rubidium and Potassium monolayers on Platinum(111)
Surf.Sci. 331-333 (1995) 349

33) Ch.Ostertag, J.Bansmann, Ch.Grünewald, Th.Jentzsch, A.Oelsner, G.H.Fecher, G.Schönhense
The influence of a linear photon polarisation on measurements of the circular dichroism in photoemission
Surf.Sci. 331-333 (1995) 1197

34) G.H.Fecher, A.Oelsner, Ch.Ostertag, G.Schönhense
Enhancement of circular dichroism in photoemission from adsorbates by photoelectron diffraction
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