Internal Report
DESY F41-78/07
November 1978

VUV MONOCHROMATORS AT SYNCHROTRON RADIATION SOURCES

by

Volker Saile

VUV MONOCHROMATORS AT SYNCHROTRON RADIATION SOURCES

Volker Saile

Sektion Physik, Universität München, D-8000 München 40, Germany

Lectures presented at NATO Advanced Study Institute
"Synchrotron Radiation Applied to Biophysical, Biochemical
and Biomedical Research", Frascati, Italy, August 21 to September 1 (1978);
to be published by Plenum Press

VUV MONOCHROMATORS AT SYNCHROTRON RADIATION SOURCES

Volker Saile

Sektion Physik, Universität München, D-8000 München 40, Germany

I. INTRODUCTION

Synchrotron Radiation (SR) with its intense continuum from the infrared up to photon energies of some ten keV is an extremely versatile tool for various kinds of spectroscopy, structure analysis and a number of other applications in physics, chemistry, biology and technology[1,2]. Interest in synchrotron radiation sources has led to a rapid increase in the number of radiation laboratories and to a worldwide demand for storage rings dedicated exclusively to the generation of synchrotron radiation[3,4].

In spite of all unquestionable advantages of SR, access to it is not a trivial task. Experimentalists intending to work at a synchrotron radiation source have to consider some inconveniences and unusual factors which range from the immobility of the source to special and often expensive experimental equipment, e.g. for obtaining monochromatized light. In the past this might have been a barrier for many scientists to use this source - mostly those who are not specialists in monochromator design and operation and who refrain from handling rather heavy and complicated set ups. It is the aim of this paper to introduce into the principles and to describe examples for monochromator instrumentation at SR sources for the spectral range extending from 2000 Å to 20 Å (photon energies between 6 eV and 1000 eV). This is quite a natural short wavelength limit: For higher photon energies the instrumentation is quite different changing from grating monochromators to crystal monochromators and from ultra high vacuum conditions to operation with Be-windows and set ups under He atmosphere or even air. While in some cases the vacuum ultraviolet region was defined[5] for photon energies up to 6000 eV the limit lies at about 1000 eV from an experimental point of view. Above this energy typical X-ray experimental equipment is used.

In the VUV the dominant scientific interest is to investigate the electronic properties of atoms, molecules and solids[1,2]. Experimental methods are absorption and reflection spectroscopy and the study of secondary processes like photoelectron spectroscopy, luminescence and photofragmentation. More recently great efforts have been made to exploit short wavelengths in the order of some ten Å for microscopy[6] and lithography[7]. Calibration of light sources and detectors[8] are examples for applied research. Others are the determination of optical constants[9] and development and tests of high efficiency mirrors and gratings[10].

In a number of articles SR instrumentation is discussed. The basic ideas can be found in Ref. 5 while more special articles appeared recently[1,2,11,12]. The aim of the present review is to give an introductory survey for the existing monochromators and to outline some new developments.

2. SOURCE CHARACTERISTICS AND ITS IMPLICATIONS

Synchrotron Radiation is emitted by electrons (or positrons) radially accelerated in a synchrotron or storage ring. The highly relativistic velocities of the particles result in a characteristic radiation pattern sketched in Fig. 1. At each point of the orbit light is emitted in a very narrow cone. While horizontally the angular extension is 2π as a result of a superposition of these cones, the angular spread is vertically (ψ in Fig. 1) confined to about 1 mrad[13].

The often noted outstanding features of SR are

- a continous spectrum from the infrared to x-rays (see Fig. 2)
- linear polarization of the light in the orbit plane; outside elliptical or circular polarization (see Fig. 3)
- time structure of the radiation with pulses as short as 100 psec (see Fig. 4)
- the already mentioned azimuthal collimation of about 1 mrad
- the small size of the source with several 0.1 mm^2 to several mm^2
- stable operation with respect to beam position and intensity for many hours
- the clean environment – SR is emitted under high or ultrahigh vacuum conditions
- the exact calculability of its properties (spectral and angular distribution as well as polarization) (as examples see Figs. 2,3).

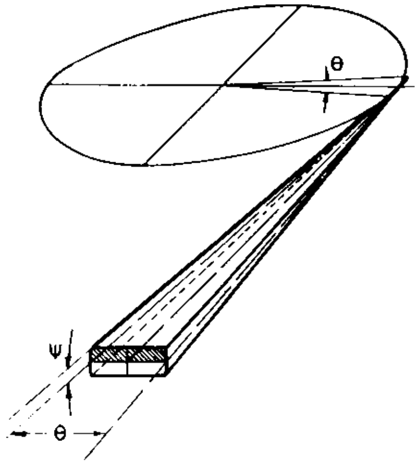

Fig. 1: Geometry at a SR-source (from Ref. 13)

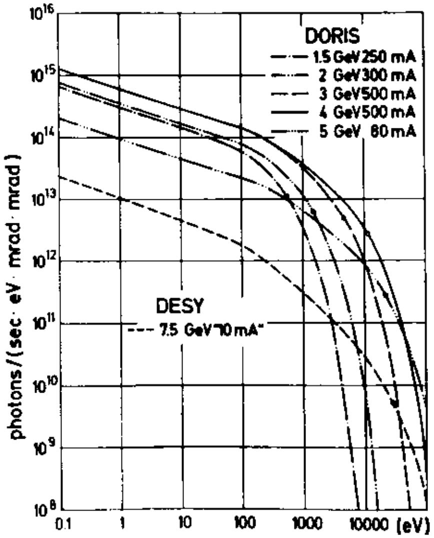

Fig. 2:

Spectral distribution of SR into a solid angle for the DORIS storage ring at different operating conditions and for the DESY synchrotron (from Ref. 14)

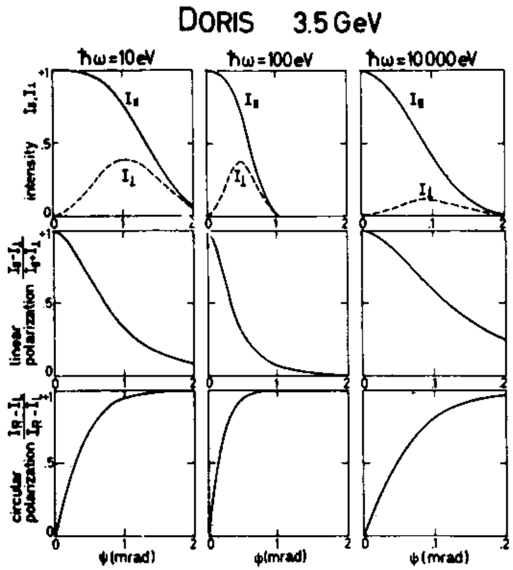

Fig. 3: Angular distribution of intensity components with E-vector parallel ($I_\parallel$) and normal ($I_\perp$) to the plane of the DORIS storage ring. (I_L) and (I_R) denote left and right hand circularly polarized components (from Ref. 15). ψ is defined in Fig. 1

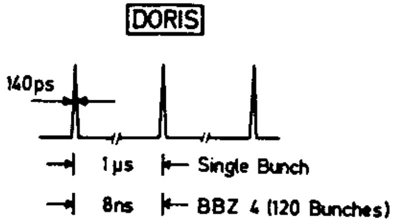

Fig. 4: Time structure at the DORIS storage ring for two operating conditions with one electron bunch and with 120 bunches in the ring

For photon energies $\hbar\omega << \varepsilon_c$, the characteristic energy of a SR source (these energies are marked in Fig. 2 by circles), the intensity in a slit with infinite extension vertical to the orbit plane (this is a good approximation because of the collimation of SR) is given[16] by:

$$N(\text{photons}/(\text{sec eV})) \gtrsim 4.5\times10^{12} \times \Theta(\text{mrad}) \times R^{1/3}(\text{m}) \times j(\text{mA})/\varepsilon^{2/3}(\text{eV})$$

where Θ is the angle accepted by the slit (see Fig. 1), R the radius of the electron orbit, j the beam current and ε the photon energy.

SR sources can be roughly divided into two groups

- low energy machines ($E \lesssim 2$ GeV) and
- large machines ($E > 2$ GeV)

as illustrated in Table 1 [17]:

Table 1: Some characteristics of small and large storage rings

type of machine	small	large
magnet radius	< 5 m	> 5 m
particle energy	< 2 GeV	> 2 GeV
distance experiment - source	< 10 m	> 10 m
charact. energy ε_c	< 2000 eV	> 2000 eV
advantages	no radiation hazard and damage, much cheaper operation	x-rays available, better time structure

In addition to the "good" characteristics of SR one should keep in mind several restrictions and disadvantages if compared to conventional laboratory sources. Some of them are summarized in Table 2.

Table 2: Properties of SR, some applications and constraints

Properties	Useful applications	Constraints and Difficulties
collimation	simple monochromator design	
intense continuum	absorption, reflection, secondary effects	monochromators necessary, problems with higher orders, radiation damage by x-rays
polarization	optical anisotropy, ellipsometry, photoemission	optical components should only be used in s-polarizing geometry
time structure	time resolved fluorescence, coincidence experiments, time of flight analysers	simple counting techniques are limited to rates below the repetition frequency of the light pulses
calculability	radiation standards	
clean source	surface physics	at storage rings ultrahigh vacuum requirements for beam lines and monochromators
big machines		immobility of the source, large SR sources are often optimized for high energy physics and not for SR, beam times dictate sometimes the progress of the experiments instead of physical arguments, expensive light sources

3. MATCHING THE EXPERIMENT TO THE SOURCE

Let us assume an experiment at a SR source aimed at the investigation of processes in atoms, molecules or solids by means of VUV photons with variable wavelength λ and spectral width $\Delta\lambda$. Such a typical experiment can be sketched by the block diagram in Fig. 5.

Fig. 5: Typical set up for an experiment at a SR source

Unlike in conventional spectroscopy at SR facilities the source, beam line with optical components, monochromator and experiment have to be treated as a whole. What are the constraints for such a set up?

The basic requirement is to maximize the photon flux $N_E(\lambda)$ at the sample within the bandwidth $\Delta\lambda$. For many experiments, e.g. photoelectron spectroscopy not only the number of photons per second but the illumination of the sample $N_E(\lambda)$ per target area is the relevant quantity. In that case the sample has to be very close to the exit slit, or the monochromatic light has to be focussed by an appropriate mirror.

A word of caution regarding detectors should be mentioned here: The particles detected (photons, electrons, ions) arrive at the detector with the time structure of the SR source (see Sec. 2). The short pulses are beyond the time resolution of most detectors available. That implies that counting techniques are limited to count rates lower than the repetition frequency of the SR pulses. Otherwise it is possible that one pulse contains more than one particle to be detected. In most cases this is no serious restriction since the repetition frequencies are so high (e.g. for DORIS 1 MHz) that analog measurements can be performed easily; but it can become crucial in coincidence experiments where only a few pulses of those available are detected. For such experiments charge sensitive detectors and adequate electronics have to be used.

Considering the geometry of the set up[18] we may characterize the SR source by the horizontal and vertical dimensions x_o and y_o of the beam, the photon flux $N_o(\hbar\omega)$ for a photon energy $\hbar\omega$ with a bandwidth $\Delta\hbar\omega$, and the angular spread ψ in azimuthal direction which is depended on photon energy but a very small quantity in the order of 1 mrad for VUV-energies. Therefore we can integrate over the y-direction as explained in Section 2 and get $N(\hbar\omega)$ in photons/(sec·eV·mrad). Radiation from the source is accepted by the beamline which may contain optical elements like mirrors with an aperture Θ (see Fig. 1). The beamline transfers the emittances of the source into those of the beamline at the entrance slit of the monochromator: $\Theta \cdot x_o \rightarrow \Theta_1 \cdot x_1$; $\psi y_o \rightarrow \psi_1 \cdot y_1$ with image dimensions x_1, y_1 and a transmission coefficient $T_B \leq 1$. As for any optical device, the brightness (measured in photons/(sec·mrad·mrad·area) of the image cannot exceed that of the source. A monochromator with slits of dimensions x_M, y_M, apertures Θ_M, ψ_M and a transmission coefficient T_M

disperses the incoming radiation. The photon flux at the exit slit is given[18] by:

$$N_E(\hbar\omega) = N(\hbar\omega) \cdot T_B \cdot T_M \cdot \Theta \cdot (\Theta_M \cdot x_M / \Theta_1 \cdot x_1) \cdot (\psi_M \cdot y_M / \psi_1 \cdot y_1)$$

with $(\Theta_M \cdot x_M / \Theta_1 \cdot x_1) \leq 1$ and $(\psi_M \cdot y_M / \psi_1 \cdot y_1) \leq 1$. If these two factors exceed 1 they have to be set identically to 1 in that equation.

For a given monochromator the photon flux is mainly determined by the angle Θ accepted horizontally and beam emittances have to be carefully matched to monochromator acceptances.

4. MIRRORS AND COATINGS

Due to the lack of transmitting materials, mirrors are essential components for focussing and deflecting VUV beams. In the design of VUV monochromators mirrors are incorporated

- as beam splitters which deflect the incoming beam or part of it into a given experiment
- as a device to focus the SR, e.g. onto the entrance slit of a monochromator or onto the sample

Apart from these obvious applicationsmirrors offer further advantages:

- The polarization of the light can be enhanced as a result of the different reflectivities for the E-vector of the light being parallel (R_p) or perpendicular (R_s) to the plane of incidence (see Fig. 6). As can be seen s-polarizing reflection is the preferable geometry for mirrors and gratings.
- The reflectivity of mirrors in the VUV is strongly dependent on photon energy and angle of incidence as shown in Fig. 7. By an appropriate choice of the coating material and angle of incidence one is able to suppress short wavelengths in the reflected beam. This filter-like behaviour is extremely important at large storage rings where hard x-rays would otherwise destroy gratings and expensive mirrors with complicated shapes.

Figures 6 and 7 demonstrate that reflectivities of 30 % or more can only be obtained under grazing incidence and the angle of incidence has to be increased with photon energies. This fact implicates serious difficulties for the fabrication of mirrors. The grazing angles result in large reflecting areas, the importance of surface roughness increases dramatically for shorter wavelengths[21]. Focussing mirrors under grazing incidence have complicated shapes - in the ideal case ellipsoids which are approximated by paraboloids, toroids or two cylindrical mirrors for separate horizontal and vertical imaging.

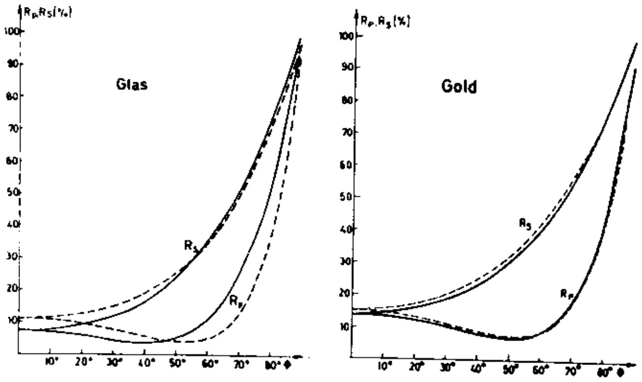

Fig. 6: Reflectivities of glass and gold vs. angle of incidence Θ. R_s and R_p denote the reflectivities for the E-vector of the light being perpendicular and parallel to the plane of incidence. The curves are calculated for two wavelengths λ = 600 Å (full line) and λ = 900 Å (dashed line). From Ref. 19.

With two mirrors it becomes possible to collect horizontally large angles and to demagnify the vertical extension of the source simultaneously[22]. With a horizontal entrance slit for the monochromator (vertical dispersion plane) this geometry can lead to high photon fluxes.

For large storage rings like SPEAR and DORIS the choice of the material for the first mirror hit by SR is of great importance. The collimation and flux of X-rays at these machines results in power densities of some 100 W/cm² at the mirror in a narrow line along the surface in the orbital plane of the machine. Heat dissipation, thermal conductivity and expansion become crucial. Several attempts have been made to solve this problem. In Stanford massive copper [23] mirrors are successfully used for some years. At DORIS glass-ceramics material (Cerodur) with negligible thermal expansion coefficient up to 300° C has proven to work up to about 2 GeV. At higher particle energies these mirrors show irreversible deformations of the surface[24]. For steel mirrors similar distortions have been found but they have beeen reversible i.e. could be observed only during illumination with synchrotron radiation[24].

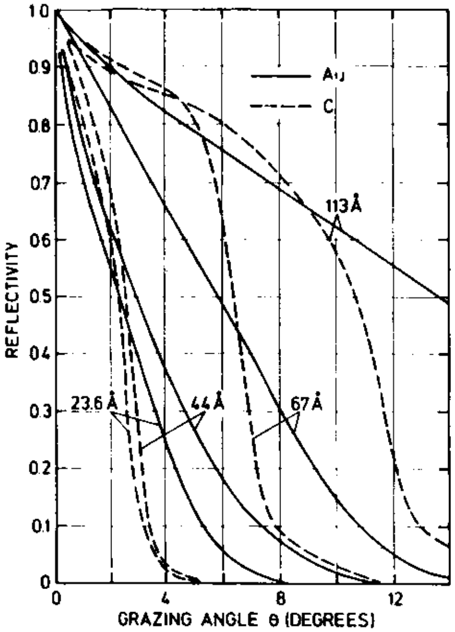

Fig. 7: Reflectivity of Au and C as a function of the grazing angle for various wavelengths. (From Ref. 20).

A promising new material - chemical vapor deposited SiC - has been carefully investigated by Rehn et al.[25]. It fulfills several conditions: extremely high reflectivity even at normal incidence (see Fig. 8), good thermal conductivity and perfectly smooth surface with about 7 Å rms roughness.

Coatings are evaporated on mirrors and gratings for increased reflectivity. In principle Fresnel's formula can be applied with known optical constants to calculate this reflectivity. In practice one has to take into account technical problems like increase of roughness with coating, sticking coefficients etc. Commonly used coating materials for photon energies below 17 eV are Al coated with MgF_2 and noble metals like Au and Pt for higher energies. Recently Haelbich and Kunz[26] made considerable progress in developing multilayer coatings for the VUV (see Fig. 9). The maximum reflectivities obtained are much higher than those for pure Au or C. Furthermore these multilayer coatings with their narrow maxima can be used as interference filters (see Fig. 9).

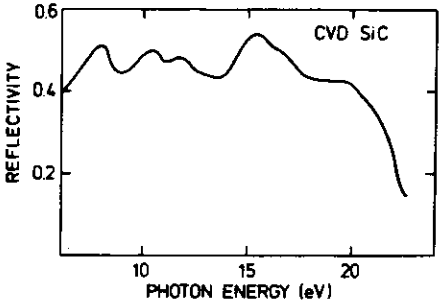

Fig. 8: Measured reflectivity of chemical vapor deposited SiC at normal incidence. (From Ref. 25).

5. MONOCHROMATORS

Powerful monochromators and spectrographs for conventional VUV sources have been developed since almost 100 years. A comprehensive description of design principles and realization is available in the literature (see Ref. 27). Basic requirements for monochromators are optimum wavelength resolution and high transmission. Due to the lack of mirrors with sufficient reflectivities in the VUV at small angles of incidence, as few reflections as possible should be applied in monochromator designs. Instruments used at SR facilities can be roughly divided into two categories.

- Normal incidence monochromators with gratings illuminated at near normal incidence. As a consequence the wavelength range is limited to about 300 Å (40 eV).
- grazing incidence instruments with gratings illuminated at grazing angles. The instruments cover the wavelengths between 600 Å (20 eV) and 10 Å (1000 eV).

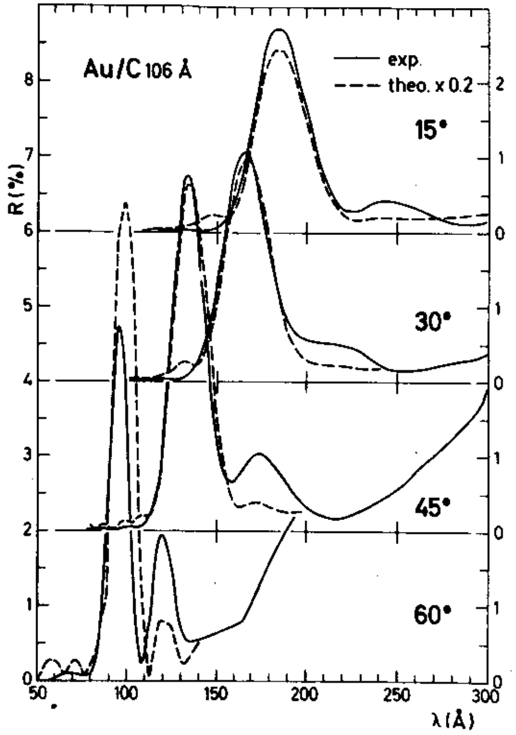

Fig. 9: Reflectivities of Au/C multilayer coatings on a glass substrate for various angles of incidence as a function of wavelengths. (From Ref. 26).

This separation is at present somewhat artificial as monochromators with widely ranging angles of incidence have been constructed (see Sec.5.3,4). Many instruments are based on the Rowland concept to combine dispersion and focussing in one optical component - the spherical grating[28] thus minimizing the number of reflecting surfaces. The optical properties of such a grating with radius R can be described by a circle tangentially to the surface of the grating.

If the entrance slit is located on that circle, the spectrum extends along the same circle. For real monochromators the spectrum is recorded either by a photographic plate bent along the circle or an exit slit where a detector is moved along the circle for photoelectric detection. Some instruments based on this concept will be discussed in Sections 5.2 and 5.3.

5.1 Gratings

Classical gratings for the VUV are reflection gratings either plane or spherically concave with mechanically ruled, equidistant grooves up to 3600 1/mm[27]. For the dispersion relation one obtains:

$$m\lambda = d\,(\sin\alpha + \sin\beta)$$

for order m of diffraction, wavelength λ, groove separation d, and angles α and β for incoming and diffracted beam. With a sawtooth profile for the grooves (blaze) it is possible to enhance the photon flux for special wavelengths in the various orders. An example for the performance of such gratings is shown in Fig. 10.

For practical use the efficiency i.e. the intensity ratio between light of wavelength λ falling onto the grating and diffracted by it, is of great importance. While the total intensity reflected is given by the coating material, the efficiency is determined by the blaze. Recently various experimental results dealing with these efficiencies of quite different types of gratings have been reported[1,2,11].

In the last few years grating fabrication was revolutionized by the application of coherent laser beams. These so called "holographic gratings" are produced by fixing interference fringes in a photoresist on a substrate[31]. Compared to mechanically ruled gratings holographic ones offer the following advantages[32]: They are free from ghosts, low level of stray light, very large diffracting areas and high line densities (6000 1/mm) can be produced, and the blanks for the grating may have complicated shapes, e.g. toroids or ellipsoids. The most remarkable feature of holographic gratings is the possibility to introduce focussing properties by adequate interference fringes in the production process[32]. This can be achieved by a variable spacing of the grooves or curved grooves[33]. With that method it is possible to correct aberrations like astigmatism in conventional monochromators and even to produce gratings which are totally stigmatic for three wavelengths.

For VUV wavelengths two new promising components for dispersion have been introduced recently. The first one is the free standing transmission grating[34] with 1000 1/mm. It has been tested successfully with line sources[35] and at the SPEAR facility[36] and a monochro-

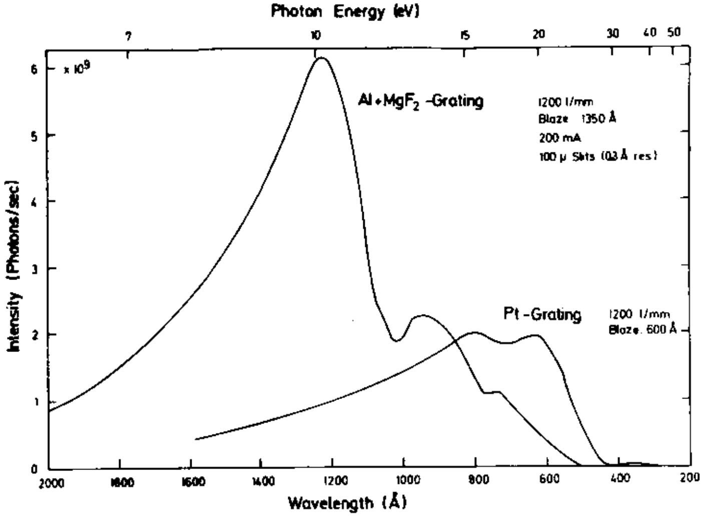

Fig. 10: Intensity available in first order at the exit slit of the 3m normal incidence monochromator at DORIS for an electron beam current of 200 mA (from Ref. 29). The distribution entering the instrument is totally flat. The absolute photon flux is measured by a double ionization chamber[30]. It should be noted that the spectra are convolutions of blaze characteristics with spectral dependence of reflection for the coating material.

mator based on it is planned for a new beam line[37]. The second is the Fresnel zone plate[31]. Holographically produced zone plates are already utilized for monochromators[31] and as lenses for x-rays at DESY[6].

5.2 Normal Incidence Monochromators

For the normal incidence range, that is the part of the spectrum extending from 2000 Å to about 300 Å conventional sources though limited in their usefulness are available. Among these alternative light sources are: Excimer lasers[38] and methods like generation of VUV frequencies by nonlinear mixing[38] cover more and more wavelengths between 1000 Å and 2000 Å. For some photon energies up to 40 eV harmonic generation of laser wavelengths has been reported[40]. Rare gas line sources[41] have been used successfully for many years but they cover only a very few wavelengths. Above 800 Å carefully developed lamps producing the He-continuum yield a photon flux comparable to that from a SR source[42]. A detailed comparison of the properties of these sources with SR appears e.g. in Ref. 12.

The availability of these sources has led to the development of a great variety of Normal Incidence Monochromators[5] and most of the designs currently in use at the various SR laboratories are obvious extensions of the existing mountings. Some examples realized at SR facilities are illustrated in Fig. 11. The first three mountings are found at most SR-facilities. Scanning of the wavelengths is performed by a rotation of a concave grating. With fixed entrance and exit slits this results in a serious defocussing which is overcome by different techniques.

For the McPherson type monochromator (Fig. 11a) the scanning mechanism performs a simultaneous rotation and translation of the grating along the bisector of the angle subtended by the slits at the grating center[5]. With such an instrument high resolution given by the focal length and angular dispersion of the grating can be obtained. At the DORIS storage ring a 3m - instrument with vertical dispersion plane provides a bandwidth of 0.03 Å with 10 µm slits and grating with 1200 l/mm. The wavelength range covered extends from 3000 Å to 300 Å (4 eV to 40 eV)[33,44]. In Fig. 10 the spectral distribution of the radiation behind the exit slit is given in absolute values for 100 µm slits (0.3 Å resolution). A toroidal mirror with a reflecting surface of 500 x 60 mm^2 focusses under a deflection angle of 15° the SR onto the entrance slit. A cone of 1 mrad × 1 mrad is accepted in a s-polarizing geometry. An example for the capabilities of this instrument is shown in Fig. 12 where the absorption of Ar gas is recorded photoelectrically up to very high quantum numbers. In the last 3 years a number of experiments in solid state physics[45], molecular physics[46] and atomic physics[44] have been performed with this instrument with great success.

The second mounting shown in Fig. 11b is the Seya-Namioka monochromator[47] with the simplest scanning mechanism of all types, i.e. a rotation of the grating about an axis through the center of the grating: To minimize the deviation from the Rowland circle, the angle between incident and diffracted beam is chosen as 70°30'. The most severe aberration of a Seya-Namioka monochromator is the astigmatism. This drawback can be corrected by appropriate mirrors[48] or specially corrected holographic gratings[49]. For the instrument at the Stanford SR facility the aberrations are reduced by astigmatic source optics and long focal length. A resolution of 0.18 Å is obtained with 20 µm slits and a 1 m grating with 1190 l/mm[22].

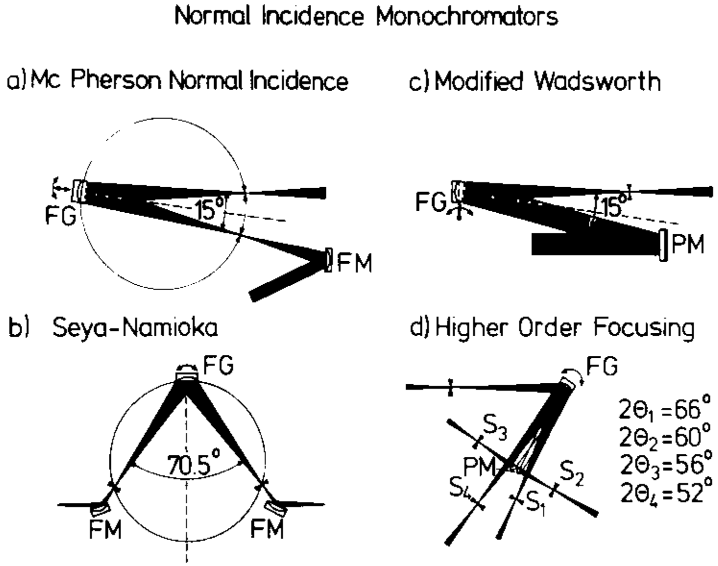

Fig. 11: Some types of normal incidence monochromators (from Ref. 43).
FM: focussing mirror, FG: spherical concave grating, PM: plane mirror, S_i: exit slits. For d) the angles $2\Theta_i$ subtended by the fixed slits are given. For references see text.

The third type of normal incidence monochromator (Fig. 11c) is the modified Wadsworth mount first realized by Skibowki and Steinmann[50]. This instrument works without an entrance slit thus exploiting the small divergence of the SR beam. To reduce defocussing at the exit slit an eccentric pivot for rotation of the grating is chosen. The finite size of the source which acts as a virtual entrance slit in combination with defocussing limits the resolution to 1 - 2 Å for a monochromator with a grating of 2m radius and 1200 l/mm and a source like DESY/DORIS. In a mounting with a vertical dispersion plane[51] the resolution is increased slightly. Recently a similar mount with a holographic grating corrected for astigmatism was

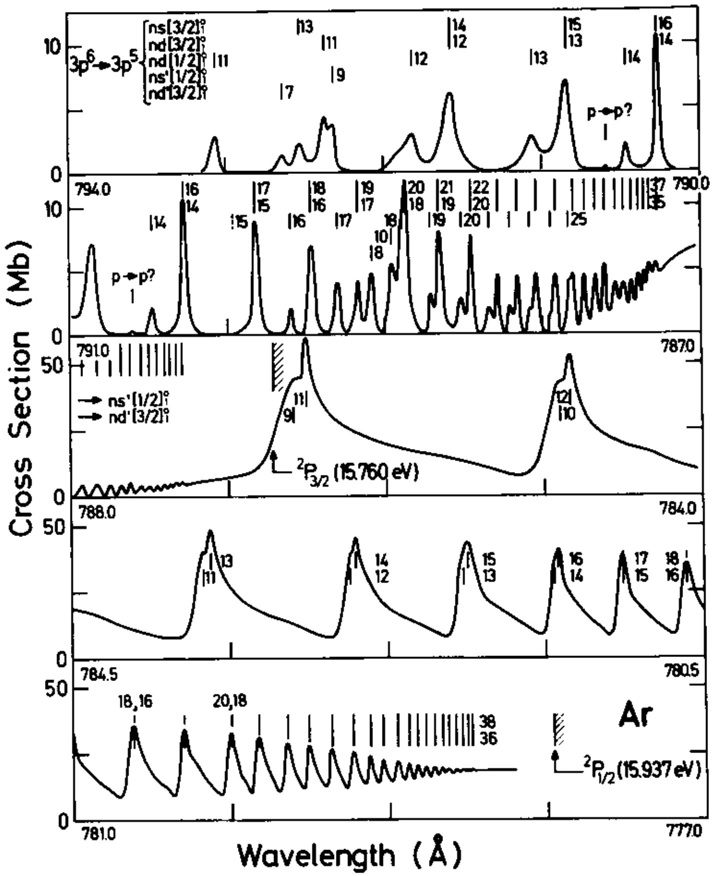

Fig. 12: Absorption spectrum for Ar near the first two ionization limits. Between the ionization limits Fano-Beutler profiles are observed. Note that the whole spectrum covers only 450 meV.

brought into operation at LURE[52]. The high transmission (only one slit, no focussing optics besides the grating) and the simplicity favor this type of instrument for experiments requiring a high photon flux. As an example a set up for time resolved luminescence measurements[53,54] is shown in Fig. 13.

The radiation monochromatized by a modified Wadsworth monochromator is focussed onto a sample. A Seya-Namioka monochromator disperses the light emitted by the sample. The lifetimes of excited states are determined by monitoring the exponential decay of emitted intensity after excitation with a light pulse from DORIS (see Fig. 14).

Based on various new theoretical treatments of imaging and diffraction with gratings[33,56-58] a number of new mountings have been suggested. One of them with 4 exit slits is shown in Fig. 11d.[59] The idea of such asymmetrical mounts is to introduce a defect in focus to balance higher order aberration terms and to maximize the product of resolution times luminosity.

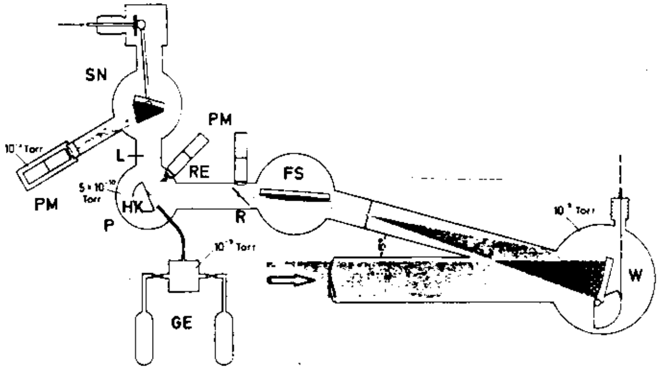

Fig. 13: Experimental set up including a modified Wadsworth and a Seya-Namioka monochromator for luminescence measurements (from Ref. 53).
W: modified Wadsworth monochromator, FS: focussing mirror, P: experimental chamber, HK: Helium flow cryostat, SN: Seya-Namioka monochromator, PM: photomultiplier, R: reference signal, RE: reflected light, L: emitted light, GE: gas handling system

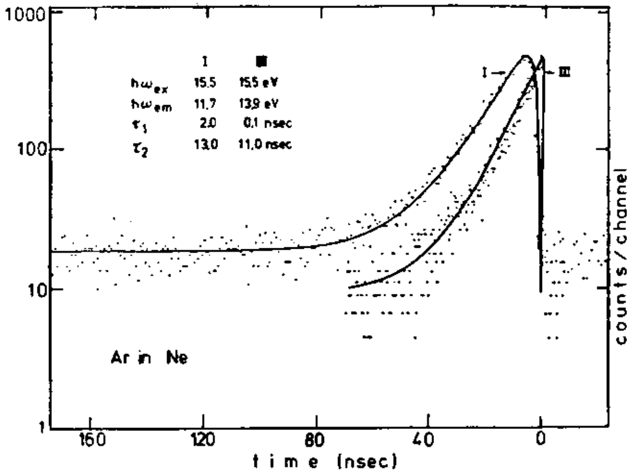

Fig. 14: Time resolved luminescence of Ar atoms in a Ne matrix (from Ref. 55).
$\hbar\omega_{ex}$ is the excitation energy, $\hbar\omega_{em}$ the emitted photon energy. τ_1 are population and τ_2 decay times extracted from these curves.

5.3 Grazing Incidence Monochromators

The grazing incidence range presents more difficult problems than the normal incidence region, e.g. superposition of higher orders and complicated imaging. As there exists no unique solution which meets all requirements simultaneously (that is high resolution, high efficiency (aperture), good order sorting capabilities, a fixed exit slit and simple scanning mechanism) quite a lot of different instruments have been designed, each of which aiming at a particular compromise concerning these requirements. A comprehensive survey on grazing incidence monochromators used at SR facilities and the problems involved for this wavelength region is given in Ref. 43, 60, 61. Some of the instruments tested and in use at SR facilities are sketched in Figs. 15 and 16.

The classical concept for a high resolution grazing incidence monochromator is that developed by Rowland[27] as already discussed in Sec. 5.1. In the simplest version[63] the SR is focussed by a

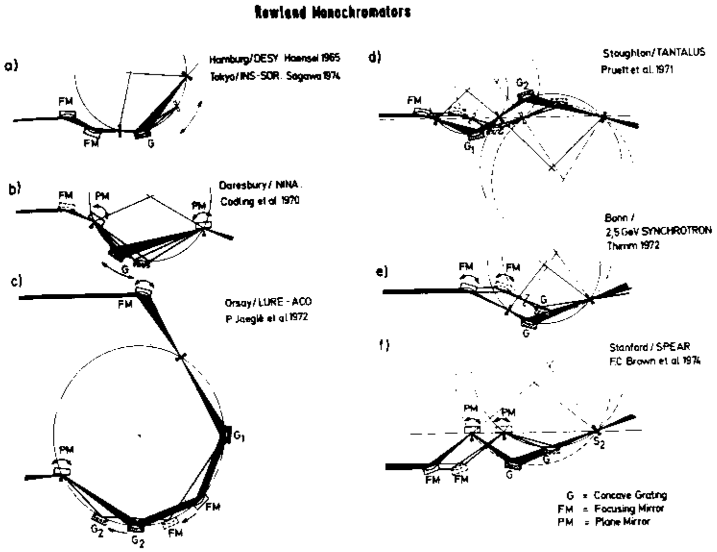

Fig. 15: Some monochromators based on the concept of a Rowland circle (from Ref. 62).

mirror onto the entrance slit. A moving exit slit allows experiments with massive equipment to be located only in front of the monochromator or spectrograph. This restricts the number of possible experiments to transmission measurements. With bent photographic plates for a simultaneous registration of the whole spectrum a Rowland monochroamtor is extremely powerful especially for very low intensities or exploitation of higher orders for increased wavelength resolution.

To overcome the limitations of a travelling exit slit, the design in Fig. 15b[64] introduces rotating mirror-slit combinations. One of the major drawbacks, the contribution of higher orders at longer wavelengths is minimized with double grating monochromators. Examples are the instruments in use at ACO[65] and at the Tantalus I storage ring[66]. Due to the number of reflecting surfaces the transmission of these systems is rather limited. This led Thimm et al.[67] to construct a monochromator (see Fig. 15e) with only two reflecting surfaces by taking into account a small variation of the exit beam direction. The so called "Grasshopper" monochromator[18,68] in use at

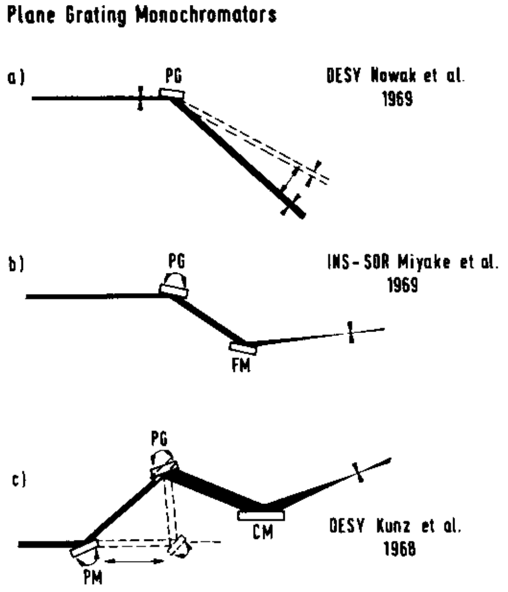

Fig. 16: Plane grating monochromators at SR facilities exploiting the small divergence of the SR beam (from Ref. 60). PG: plane grating, PM: plane mirror, FM: spherical mirror, CM: parabolic mirror

SPEAR is shown in Fig. 15f. A mounting with a fixed exit slit is achieved by rotating a 1m Rowland circle around the exit slit S_2[69,70]. Great efforts have been made to connect this instrument in an optimum way to the high power storage ring in Stanford: An ultrasmooth platinum coated copper mirror 6.5 m from the orbit and 9.7 m from the monochromator is illuminated under a grazing angle of 2° and focusses horizontally 2 mrad of SR onto the entrance slit. This mirror not shown in Fig. 15f works as a beam-splitter and a filter with a cut-off energy of about 2.5 keV. As a consequence the heat load on the following mirror is minimized. Thus this spherical mirror FM can be a quartz mirror with Pt coating. It moves parallel to the beam under a grazing angle of 2°. The entrance slit - mirror combination is similar to that developed by Codling et al.[64]. With a grazing angle between 3° (Zeroth order) and 8° (400 Å) this mirror determines the short wavelength limit to about 1 keV and rejects higher orders at longer wavelengths. With a 2m grating, 600 l/mm and 15 μm slits a bandwidth of 0.15 Å has been achieved; for 2400 l/mm a band pass of 0.25 eV at 280 eV has been reported[18]. The "Grasshopper" works up to very high photon energies of about 1 keV. Its capability even for a very critical energy region - the carbon K edge where cracked hydrocarbons reduce the reflectivity of mirrors and gratings drastically[21] is shown in Fig. 17.

Plane grating monochromators as illustrated in Fig. 16 exploit the collimation of SR to a nearly parallel beam. The simplest instrument possible[72] (Fig. 16a) is limited in resolution and order sorting capability. A design with a spatially fixed exit beam is realized at the Tokyo SR facility[73] (Fig. 16b). Modified versions have been developed at the Daresbury SR source[74]. For the third type (Fig. 16c)[75] wavelength scanning is achieved by rotating a plane mirror and grating in such a way, that they remain parallel. Additionally the plane mirror moves along the incoming beam. The dispersed light is focussed by a parabolic mirror onto a fixed exit slit. A great advantage of this instrument is the rejection of higher orders due to the fact that for longer wavelengths the angles of incidence are more normal incidence like. The finite size of the source defines as a virtual entrance slit the wavelength resolution. For the UHV requirements at the DORIS storage ring the scanning mechanism had to be simplified. The result is the "Flipper" monochroamtor[76] developed for photoelectron spectroscopy experiments (see Fig. 18). Instead of a moving premirror it is equipped with 6 mirrors which can be slided into the beam with high precision. Each mirror corresponds to a certain wavelength range. The movements are reduced to a simple rotation of the grating. The instrument accepts horizontally 0.75 mrad of SR and provides with a grating with 1200 l/mm, a parabolic mirror of 1m focal length and the DORIS source a resolution E/ΔE between 5600 and 1250 from 13 eV to 250 eV. By changing the angle of incidence over a wide range such instruments bridge the gap from 25 eV to 50 eV where neither normal incidence nor grazing incidence monochromators of the Rowland type work satisfactorily.

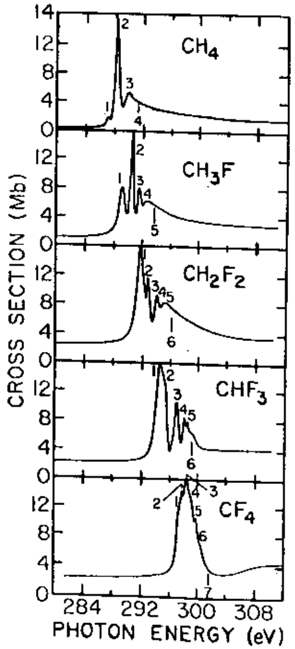

Fig. 17:
Rydberg transitions in methane vapor and fluoromethanes at the carbon K-edge (from Ref. 71)

5.4 New Developments

The remarkable progress made in the development of new dispersive optical components has been discussed already in Sec. 5.1. Studies of secondary effects like angular resolved photoemission require monochromators with a very high transmission over a wide photon energy range from approximately 10 eV to 300 eV. For such an application instruments with holographically produced and corrected gratings[32,33] on toroidal blanks[77] are very promising (see Fig. 19). A small instrument with 0.3 m focal length at ACO[78] has proven to be extremely useful: It accepts 5 mrad of SR under a grazing angle of 19° and provides a photon flux up to 4×10^{11} photons/(sec·Å) with

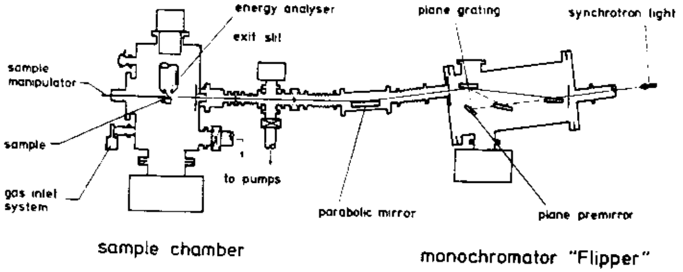

Fig. 18: Photoemission experiments at the DORIS storage ring with the "Flipper" monochromator (from Ref. 76)

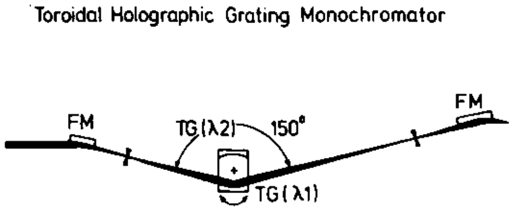
Toroidal Holographic Grating Monochromator

Fig. 19: Proposed monochromator with two switchable toroidal gratings TG(λ1) and TG(λ2). FM: focussing mirrors (from Ref. 43)

1 Å resolution (100 μm slits) for photon energies up to 110 eV. Instruments with larger focal lengths and higher resolution and for shorter wavelength are under construction[78].

The photon energy range between 300 eV and 1000 eV gains more and more interest for example for EXAFS applications. Unfortunately it is inaccessible for most of the monochromators discussed. The reasons for this are hydrocarbon contamination and roughness of optical surfaces[21] as well as the extreme grazing angles necessary. As an alternative approach to conventional instruments with reflecting components a monochromator with a free standing transmission grating has been proposed with a resolution of 1:1000 with 1000 1/mm for 10 eV to 1000 eV[37]. A second approach for a new instrument in this region is a monochromator based on zone plates[79] fabricated by X-ray lithography or holographically[31].

6. Conclusion

Selecting a monochromatized beam of photons of a given energy from the continuum of synchrotron radiation is not an easy task. While a number of mountings based on conventional concepts have been developed to a high degree of sophistication much remains to be done. We observed today very interesting developments in the area of grating technology, the manufacturing of mirrors and optical elements which may eventually lead to completely new and powerful concepts in the monochromator design for the VUV-range.

Acknowledgement

The author wishes to thank Dr. E.E. Koch for critically reading the manuscript and making many valuable suggestions. He is indebted to Drs. C. Kunz and W. Gudat for providing figures and their manuscript Ref. 43 prior to publication. Careful and skillful typing of Mrs. E. Thumann is gratefully acknowledged.

References

1. Vacuum Ultraviolet Radiation Physics, ed by E.E. Koch, R. Haensel and C. Kunz (Pergamon-Vieweg, Braunschweig, 1974)
2. Vth Int.Conf. on Vacuum Ultraviolet Radiation Physics, Extended Abstracts, ed. by M. Castex, M. Pouey and N. Pouey (Montpellier, Sept. 5-9, 1977)
3. An Assessment of the National Need for Facilities Dedicated to the Production of Synchrotron Radiation (Solid State Sciences Committee, Assembly of Mathematical and Physical Sciences, National Research Council, Washington, 1976)
4. Synchrotron Radiation a Perspective View for Europe,prepared by ESF (European Science Foundation, Strasbourg, France 1978)
5. a) J.A.R. Samson, Techniques of Vacuum Ultraviolet Spectroscopy (Wiley and Sons, New York 1976)
   b) A.N. Zaidel' and E.Ya. Shreider, Vacuum Ultraviolet Spectroscopy, (Ann Arbor-Humphrey Science Publishers, Ann Arbor, London, 1970)
6. G. Schmahl, D. Rudolph and B. Niemann in Ref. 2, Vol. III, p. 40
7. E. Spiller and R. Feder, X-Ray Lithography, in Topics in Appl. Physics. Vol. 22, ed. H.J. Queisser (Springer Verlag, Berlin, Heidelberg, New York, 1977); W. Gudat in Ref. 11, p. 279
8. D. Einfeld, D. Stuck and B. Wende in Ref. 2, Vol. III, p. 114; R.P. Madden in Ref. 2, Vol. III, p. 120; E. Pitz and A. Schulz in Ref. 11, p. 243
9. H.J. Hagemann, W. Gudat and C. Kunz, J.Opt.Soc.Am. 65, 742 (1975); R.P. Haelbich, M. Iwan and E.E. Koch, Optical Properties of Some Insulators in the Vacuum Ultraviolet Region Physik Daten, Physics Data ZAED, Karlsruhe, Germany, Vol. 8-1 (1977)
10. Several contributions in Ref. 1, 2, 11
11. Proc. Intern. Conf. on Synchrotron Radiation Instrumentation and New Developments, ed. by F. Wuilleumier and Y. Farge, Special issue of Nuclear Instruments and Methods 152 (1978)
12. Synchrotron Radiation, ed. by C. Kunz, Topics in Current Physics (Springer-Verlag, Berlin, Heidelberg, New York, in press)
13. P.M. Guyon, C. Depautex and G. Morel, Rev.Sci.Instr. 47, 1347 (1976)
14. E.E. Koch, C. Kunz and E.W. Weiner, Optik 45, 395 (1976)
15. C. Kunz, Phys. Bl. 32, 9 (1976)
16. C. Kunz in Ref. 1, p. 753
17. A more detailed dicussion is found in Chap. I of Ref. 12

18. F.C. Brown, R.Z. Bachrach and N. Lien in Ref. 11, p. 73
19. U. Backhaus, Diplomarbeit Universität Hamburg, 1973; calculated with the optical constants given by K. Platzöder, Diplomarbeit Universität München, 1967
20. A.P. Lukirskii, E.P. Savinov, O.A. Ershov, V.A. Fomichev and I.I. Zhukova, Opt. Spectrosc. 19, 237 (1965)
21. R.Z. Bachrach, S.A. Flodstrom, R.S. Bauer, V. Rehn and V.O. Jones in Ref. 11, p. 135
22. V. Rehn, A.D. Baer, J.L. Stanford, D.S. Kyser and V.O. Jones in Ref. 1, p. 780
23. J.L. Stanford, V. Rehn, D.S. Kyser and V.O. Jones in Ref. 1, p. 783
24. B. Niemann, private communication
25. V. Rehn, J.L. Stanford, V.O. Jones and W.J. Chyoke, Proc. Int. Conf. on Physics of Semiconductors, Rome, August 1976, p. 985; V. Rehn, J.L. Stanford, A.D. Baer, V.O. Jones and W.J. Chyoke, Appl.Opt. 16, 1111 (1977); feasibility of SiC for gratings is discussed in W.J. Chyoke, W.D. Partlow, E.P. Supertzi, F.J. Venskytis and G.B. Brandt, Appl.Opt. 16, 2013 (1977)
26. R.P. Haelbich and C. Kunz, Optics Commun. 17, 287 (1976)
27. G.W. Stroke, Encyclopedia of Physics, Vol. XXIX, ed. by S. Flügge (Springer-Verlag, Berlin, Heidelberg, New York, 1967), p. 426; Diffraction Grating Handbook, ed. Bausch and Lomb Inc. (Rochester, New York, II. edition 1972)
28. H.A. Rowland, Phil.Mag. 16, 197 and 210 (1883)
29. V. Saile in Ref. 11, p. 59
30. V. Saile, P. Gürtler, E.E. Koch, A. Kozevnikov, M. Skibowski and W. Steinmann, Appl.Opt. 15, 2559 (1976)
31. G. Schmahl in Ref. 1, p. 667
32. Diffraction Gratings Ruled and Holographic - Handbook, ed. Jobin-Yvon Company (Longjumeau, France, 1976)
33. H. Noda, T. Namioka and M. Seya, J.Opt.Soc.Am. 64, 1031 (1974)
34. J.A. Dijkstra and L.J. Lantwaard, Opt.Commun. 15, 300 (1975)
35. S.A. Flodstrom and R.Z. Bachrach, Rev.Sci.Instr. 47, 1464 (1976)
36. E. Källne, H.W. Schopper, J.P. Delvaille, L.P. van Speybroeck and R.Z. Bachrach in Ref. 11, p. 103
37. J. Stöhr, V. Rehn, I. Lindau and R.Z. Bachrach in Ref. 11, p. 44
38. D.J. Bradley, M.H.R. Hutchinson and C.C. Ling, Tunable Lasers and Applications, ed. by A. Mooradian, T. Jaeger and P. Stokseth, Proc. of the Loen Conf. Norway, 1976 (Springer-Verlag, Berlin, Heidelberg, New York, 1976) p. 40
39. P.P. Sorokin, J.A. Amstrong, R.W. Dreyfus, R.T. Hodgson, J.R. Lankard, L.H. Manganaro and J.J. Wynne, Laser Spectroscopy, ed. by S. Haroche, J.C. Pebay-Peyroula, T.W. Hänsch and S.E. Harris, Proc. II. Int.Conf., Megêve, 1975 (Springer-Verlag, Berlin, Heidelberg, New York (1975))
40. Physics Today, Dec. 1976, p. 17
41. E.E. Koch, Interaction of radiation with condensed matter, Vol. II, L.A. Self (editor), publication of the Trieste Center for Theoretical Physics Int.Atomic Energy Agency, Wien 1976, p. 225

42. K. Radler, private communication
43. W. Gudat and C. Kunz, Chapter 3 in Ref. 12
44. V. Saile, Thesis, Universität München, 1976
45. V. Saile, M. Skibowski, W. Steinmann, P. Gürtler, E.E. Koch and A. Kozevnikov, Phys.Rev.Lett. 37, 305 (1976)
46. W.B. Peatman, B. Gotchev, P. Gürtler, E.E. Koch and V. Saile, J.Chem.Phys. (in press)
47. M. Seya, Sci. Light 2, 8 (1952); T. Namioka, Sci. Light 3, 15 (1954), J.Opt.Soc.Am. 49, 951 (1959)
48. N. Rehfeld, U. Gerhardt and E. Dietz, Appl.Phys. 1, 229 (1973)
49. H. Noda, T. Namioka and M. Seya, J.Opt.Soc.Am. 64, 1043 (1974)
50. M. Skibowski and W. Steinmann, J.Opt.Soc.Am. 57, 112 (1967)
51. E.E. Koch, Thesis, Universität München, 1972
52. C. Depautex, M. Lavollee, G. Jezequel, J.-C. Lemonnier and J. Thomas in Ref. 11, p. 69
53. U. Hahn, N. Schwentner and G. Zimmerer in Ref. 11, p. 261
54. U. Hahn, Thesis, Universität Hamburg, 1978
55. U. Hahn and N. Schwentner, in preparation
56. M. Lavollee and S. Robin, J.Opt.Soc.Am. 64, 319 (1974)
57. C.H.F. Velzel, J.Opt.Soc.Am. 68, 38 (1978)
58. M. Pouey, Some Aspects of Vacuum Ultraviolet Radiation Physics, ed. by N. Damany, J. Romand and B. Vodar (Pergamon Press, Oxford, 1974) Chapter 9
59. M. Pouey in Ref. 1, p. 728
60. C. Kunz, Proc. Intern. Symposium for Synchrotron Radiation Users, ed. by G.V. Marr and I.H. Munro (Daresbury Nucl.Phys.Lab. Report DNPL:R26, 1973) p. 68
61. E.E. Koch, Problems of Elementary Particle Physics, Proc. of the 8th All Union School of High Energy Particle Physics (Yerevan, 1975), p. 502
62. K. Thimm, J. Electr. Spectr. Rel. Phenom. 5, 755 (1974)
63. R. Haensel and C. Kunz, Z. Angew. Physik 23, 276 (1967)
64. K. Codling and P. Mitchell, J.Phys. E3, 685 (1970)
65. P. Jaeglê, P. Dhez and F. Wuilleumier, Rev.Sci.Instrum. 48, 978 (1977); P. Dhez, P. Jaeglé, F.J. Wuilleumier, E. Källne, V. Schmidt, M. Berland and A. Carillon in Ref. 11, p. 85
66. C.H. Pruett, N.C. Lien and S.D. Steben, III. Int. Conf. on Vacuum Ultraviolet Radiation Physics, Tokyo 1971, 31a A2-5
67. G. Puester and K. Thimm in Ref. 11, p. 95; K. Thimm see Ref. 62
68. F.C. Brown, R.Z. Bachrach, S.B.M. Hagström, N. Lien and C.H. Pruett in Ref. 1, p. 785
69. M. Salle and B. Vodar, C.R. Acad.Sci. Paris 230, 380 (1950)
70. A design with the Rowland circle rotating around the grating has been realized by H. Sugawara and T. Sagawa in Ref. 1, p. 790
71. F.C. Brown, R.Z. Bachrach and A. Bianconi, Chem.Phys.Lett. 54, 425 (1978)
72. J. Römer, Diplomarbeit, Universität Hamburg, 1970
73. K.P. Miyake, R. Kato and H. Yamashita, Sci. Light 18, 39 (1969)

74. J.B. West, K. Codling and G.V. Marr, J.Phys. E7, 137 (1974); M.R. Howells, D. Norman, G.P. Williams and J.B. West, J.Phys. E11, 199 (1978)
75. C. Kunz, R. Haensel and B. Sonntag, J.Opt.Soc.Am. 58, 1415 (1968); H. Dietrich and C. Kunz, Rev.Sci.Instrum. 43, 434 (1972)
76. W. Eberhardt, G. Kalkoffen and C. Kunz in Ref. 11, p. 81; W. Eberhardt, Thesis, Universität Hamburg, 1978
77. A monochromator based on a toroidal grating ruled mechanically has been realized by R.P. Madden and D.L. Ederer, J.Opt.Soc.Am. 62, 722 (1972)
78. Y. Petroff, P. Thiry, R. Pinchaux and D. Lepere in Ref. 2, Vol. III, p. 70; D. Depautex, P. Thiry, R. Pinchaux, Y. Petroff, D. Lepere, G. Passereau and J. Flamand in Ref. 11, p. 101
79. E. Spiller, Workshop on X-Ray Instrumentation for Synchrotron Radiation Research, ed. by H. Winick and G. Brown, SSRL Report No. 78/04 (May 1978)