DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY SR-76/02
February 1976

The New Synchrotron Radiation Laboratory at the DESY Storage Ring DORIS

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The New Synchrotron Radiation Laboratory at the DESY Storage Ring DORIS*

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The synchrotron radiation laboratory at the DORIS storage rings in Hamburg is now in full operation as a facility utilizing the intense vacuum ultraviolet and soft x-rays from the storage ring for atomic, molecular and solid state spectroscopy. The characteristics of the light source, the layout of the laboratory and the performance of the beam line arrangement are described. A short account of the experiments performed and planned in this laboratory is given.

Das Synchrotronstrahlungs-Labor an den DORIS Speicherringen in Hamburg ist jetzt voll in Betrieb. In dem Labor wird die intensive Vakuum-Ultraviolett- und weiche Röntgenstrahlung vom Speicherring für Atom-, Molekül- und Festkörperspektroskopie ausgenutzt. Die Eigenschaften der Strahlungsquelle, die Anlage des Labors und die Wirkungsweise der Strahlteilung werden beschrieben. Es wird ein kurzer Überblick gegeben über die Experimente, die in diesem Laboratorium durchgeführt werden oder geplant sind.

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*Work supported by Deutsches Elektronen-Synchrotron DESY, the Bundesministerium für Forschung und Technologie BMFT and Deutsche Forschungsgemeinschaft DFG

To be published in Optik

1. Introduction

The use of electron synchrotrons and storage rings as spectroscopic light sources for the vacuum ultraviolet (VUV) 2000 Å - 2 Å and x-ray region has lately gained considerable interest. Ten years ago the 7.5 GeV electron synchrotron DESY was among the first machines of this kind where a laboratory especially devoted to spectroscopic experiments was installed[1,2]. Thirteen groups of investigators are presently performing experiments at different grating monochromators and at other instruments such as x-ray crystal monochromators or set ups for calibration in this laboratory[3]. For the double storage rings DORIS, which were first proposed in 1966 a laboratory for utilizing synchrotron radiation was included into the building plans right from the beginning. The task of providing a beam of radiation extending from the visible to the x-ray region to spectroscopists was considerably more difficult than with the synchrotron. An enormous power of synchrotron light (up to 1 MWatt over the whole circumference) is provided by these storage rings. It is necessary to equip the whole beam pipe, the mirror boxes and the monochromators with ultrahigh vacuum (UHV) components. The project drew great benefit from the experience gained with the set up and use of the laboratory at the synchrotron. In the laboratory at DORIS there are presently three instruments in operation, one soft x-ray fluorescence experiment which started in mid 1974 and two normal incidence monochromators for the photon energy range 5-40 eV, one of them a high resolution 3m normal incidence instrument. Additionally two monochromators for the energy range 20 to 350 eV and an x-ray port are under construction.

It is interesting to note that while this laboratory is primarily devoted to experiments in physics and chemical physics another laboratory at the storage ring DORIS nears completion which will serve the community of molecular biologists as an outpost of the newly founded European Molecular Biology Laboratory (EMBL) with headquarters in Heidelberg. This laboratory will mainly use the x-ray part of the spectrum for low angle x-ray diffraction and EXAFS (extended absorption fine structure) experiments. Finally in view of the present debate on dedicated synchrotron radiation facilities[4], it is worth noting that both laboratories are operated in a parasitic mode.[5]

2. Properties of Synchrotron Radiation from DORIS

2.1 General Remarks

Synchrotron radiation is primarily produced when a fast charged particle with an energy $E \gg m_o \cdot c^2$ (m_o = rest mass of electron, c = velocity of light) is deflected in a strong magnetic field. Circular electron and positron accelerators and storage rings have been used as sources of this radiation. The properties of synchrotron radiation which are most interesting for spectroscopic applications can be summarized as follows:

1. intense continuous spectral distribution from the infrared to x-ray wavelengths,
2. highly collimated radiation confined near the orbital plane of the circulating electrons,
3. highly polarized radiation with the electric field vector in the orbital plane,
4. pulsed light source with puls length in the nanosecond range ,
5. absolute calculability of intensity and spectral distribution from well defined parameters,
6. stable, low noise,chemically clean UHV-light source.

There are several recent[6-12] reviews available on synchrotron radiation, which describe in detail these properties and the impact synchrotron radiation has made as a new powerful spectroscopic tool on atomic, molecular and solid state spectroscopy. The theory of synchrotron radiation based on the work by Schwinger[13] has been developed in detail during recent years[14,15].

In the following only expressions are given which are useful for practical estimates. They are discussed with the specific example of the storage ring DORIS in mind. Derivations and more general discussions are given in Refs. 14,15.

2.2 DORIS as a Source of Synchrotron Radiation

The electron-positron double storage rings DORIS are now in their second year of operation. They were specifically designed for high energy colliding beam experiments. As a high energy storage ring DORIS has, however, specific characteristics which make it an outstanding source of synchrotron radiation.

Spectral distribution, intensity

In Fig. 1 the spectral distribution of intensity of synchrotron radiation into a solid angle of 1 mrad x 1 mrad is shown for various energies of the electron beam and realistic beam currents. A curve for the DESY synchrotron is shown for comparison. With higher particle energies E the spectrum extends further into the x-ray region. Note that for higher beam energies of $E = 3$ and $E = 4$ GeV higher beam currents j can be obtained than at lower energies. The main reason for this is that the influence of beam-beam interactions is smaller for higher energies. At even higher energies the available high frequency power to compensate for the synchrotron radiation losses becomes the limiting factor for the circulating current.

The spectrum can roughly be devided into a low energy region where the number of photons in an infinitely high slice of one mrad horizontal width is given by

$$N\left(\frac{\text{photons}}{\text{sec}\cdot\text{eV}\cdot\text{mA}\cdot\text{mrad}}\right) = 4.5\cdot 10^{12}\ j(\text{mA})\cdot(R(\text{m}))^{1/3}\ (\varepsilon(\text{eV}))^{-2/3} \qquad (1)$$

where j is the particle current in the accelerator, R the bending radius of the beam and ε the photon energy.

The high-energy region of the spectrum begins at the cut-off energy ε_c above which the intensity drops rapidly:

$$\varepsilon_c(\text{eV}) = 2.22\cdot 10^3\ (E(\text{GeV}))^3\ \ (R(\text{m}))^{-1} \qquad (2)$$

These cut-off energies have been marked in Fig. 1.

The above expressions allow for a rough comparison of various accelerators and storage rings. Relevant parameters for a selected number of synchrotron radiation light sources are given in Table 1. Since some of the parameters such as the stored electron current, or the length of the bunches (see below) depend critically on the actual mode of operation the references given should be consulted for details.

Collimation

Synchrotron radiation from particles with relativistic energies is emitted into a very small angular cone around their instantaneous direction of flight. At the cut-off energy ε_c the angular width $<\psi>$ is $1/\gamma$ with $\gamma = E/m_oc^2$. Further $<\psi>$ varies roughly like $<\psi> \propto (\varepsilon_c/\varepsilon)^{1/3}$ for $\varepsilon < \varepsilon_c$. The intensity of the radiation as a function of the elevation angle ψ against the orbital plane is shown for DORIS for three photon energies at the top of Fig. 2. Thus the plane of the accelerator is filled with radiation, while the emission in the off-plane direction is confined to a wedge of only about one milliradian angular spread.

Polarization

Synchrotron radiation is linearily polarized, its plane of polarization being that of the orbit. The degree of linear polarization parallel ($I_{\parallel}$) and perpendicular ($I_{\perp}$) to the orbital plane as a function of angular distance from the plane is shown in Fig. 2 for DORIS operating at 3.5 GeV. The radiation off the plane of the orbit is not an irregular superposition of parallel and perpendicularly polarized components but is elleptically polarized. It can be decomposed into left and right hand circularily polarized radiation as shown in the lower part of Fig. 2. This high degree of polarization should be kept in mind when making feasibility studies for experiments. It can for example be exploited in measurements of the optical properties of anisotropic crystals and it has interesting possible applications in photoemission work.

Time structure

The time structure of the light pulses from a storage ring is determined by the time structure of the orbiting particles. The particles are accelerated and stored in bunches. At DORIS the number of bunches on the circumference is 480 while the length of each bunch is only 2 - 3 cm[28]. Thus, as far as the time structure is concerned, the storage ring has outstanding properties; the radiation is emitted in short flashes of 140 psec duration (see Fig. 3). For spectroscopic experiments the repetition frequency is a further important parameter. It is determined by the repetition frequency of the filled bunches. Maximum separation between two pulses is obtained in the single bunch mode when only one bunch is filled. In this case the period of revolution determines the repetition frequency which is 1 μsec at DORIS. In Fig. 3 the experimentally determined pulse shape is shown for DORIS[28] and ACO[29]. Only for the SPEAR storage ring the time structure with a pulse duration of 100 to 240 psec and a repetition frequency of 780 nsec is comparable to the conditions encountered at DORIS in the single bunch mode. This time structure of synchrotron radiation offers considerable advantages for measurements of time dependent phenomena with a very good resolution in time. Furthermore the high stability of the repetition frequency may be exploited in the analysis of time dependent phenomena.

Calculability, stability and generation in a clean UHV environment
Since the intensity and brightness of synchrotron radiation can be calculated in absolute numbers, it can be used as a standard of radiation. Further this property plays an important role in the planning of new experiments and the assessment of the performance of monochromators.

At DORIS the lifetimes of the stored beam are in the order of 10 hours and the continuous decrease in intensity of the stored beam over this period from e.g. 300 to 100 mA can easily be corrected for.

The vacuum within the DORIS storage ring is kept in the low 10^{-9} Torr range. Thus the synchrotron radiation originates from a UHV environment. This property is preserved by the all metal beam pipe system (see section 4). It is of particular advantage when surface sensitive techniques like photoemission are employed where surface contamination plays a crucial role.

3. General Description of the Laboratory

The synchrotron radiation laboratory is connected with the DORIS storage ring building by a 16 m long tunnel (see Fig. 4). The total distance from the source point to the laboratory is 32 m. The beam line system consists of three major sections:

1. The extraction chamber and part of the beam pipe are located within the storage ring building. Close to the ring a water cooled copper absorber (A) can be moved into the beam in order to prevent the following valves from permanent exposure to synchrotron radiation, which might result in unwanted heat load for the components. Further important parts in this section are a fast closing valve (FCV) with a closing time of 30 μsec as a protection of the ring against vacuum hazards and a strong permanent 1.9 K Oersted-Magnet (M) which , when electrons are lost during injection into the machine prevents them from reaching the beam shutter. A much weaker secondary γ-beam at the event of a hazard would be sufficiently absorbed by the beam stop. After injection is terminated the beam-shutter can be opened. In this case a total loss of the stored electron beam would be a single event which even in the worst case could not give rise to more than the tolerable dose in the accessible region of the laboratory.

2. The next major section of the beam line system is located within the tunnel. Here the water cooled beam shutter (BS) is installed. The first mirror (S) is located at the end of the tunnel. Apertures along the beam pipe help to avoid reflections from the walls under grazing incidence.

3. Finally the mirror chambers (S) and four independent beam lines (R, D, L1 and L2) as well as the individual experimental set-ups in the laboratory constitute the third major section (see Fig. 5,6).

In order to preserve the advantages of a clean source where the radiation originates from an ultra high vacuum (UHV) environment all-metal UHV-components and metal seals are installed throughout the system. Vacuum is obtained by turbomolecular roughing pumps and ion getter pumps. Thus the vacuum in the whole beam pipe system is in the low 10^{-9} Torr range and any interference with the vacuum in the storage ring is minimized. UHV, free of hydrocarbons, is also essential to avoid surface contaminations on the optical components (see below).

There is free access to all experiments except to those on the direct beam line (D), where exposure to the hard x-ray component of the synchrotron radiation may cause hazards. It is anticipated that additional lead shielding will have to be provided as soon as the presently usual operating energy of the storage ring at or below 2 GeV will be raised above 3 GeV. This shielding will have to surround the central beam line D.

4. Optical Layout

The distance of the laboratory from the storage ring given, a maximum of 3.8 mrad horizontal beam is accepted with usual size 6" vacuum components in a single beam line. This allows for the installation of three independent beams, each about 1 mrad (40 mm at 40 m distance) wide. The outer beams (see Fig. 5) are deflected by two plane mirrors S_1 and S_2 at grazing angles of incidence of 7.5 degrees. The left beam line L_1 (total angle of deflection 15 degrees) feeds a 3m normal-incidence high resolution monochromator (HONORMI)[30]. The right beam line R feeds a 1m normal incidence monochromator without entrance slit which is of the modified Wadsworth type[31] (HIGITI).[32] The direct beam D can be partly or fully deflected by the plane mirror S_3 at a grazing angle of incidence of 4 degrees into the inner left 8 degrees beam line L_2, which will feed a fixed exit slit grazing incidence monochromator for the 20 - 350 eV range (FLIPPER). This instrument is a modified version of the DESY-monochromator[33] successfully in operation at the DESY laboratory. When the mirror S_3 is withdrawn, the direct beam can either partly or fully continue to illuminate a sample which is excited for soft x-ray fluorescence investigated by a secondary monochromator FLEUR (FL).[34] If the sample in this experiment is removed the direct beam either penetrates through a beryllium window in order to become used by one of several different x-ray experiments alternatively or is focussed into the entrance slit of a Rowland monochromator. These instruments will be installed at the marked position "X-RAY/ROW" alternatively.

Special attention has to be given to the mirrors. Mirrors which have a high reflectivity down to 40 Å in wavelength and at the same time withstand the intense synchrotron radiation without distortion are not readily available. In the initial period of planning the only information came from the experience obtained at the DESY synchrotron laboratory. There polished glass mirrors (supplied by Halle, Berlin) both with and without gold coating showed satisfactory reflection properties at grazing incidence. At DESY the intensity of synchrotron light is much less than at the storage rings DORIS and no problems are caused by heating. Nevertheless two types of deteriorations develop in the mirrors with time. The glass material discolorates internally and finally becomes black (probably due to the development of internal defects like color centers etc.). Further, cracked hydrocarbons are building up a carbon layer at the surfaces of the mirrors. The carbon layer leads to a considerable reduction in intensity of the reflected light with time, while the internal deterioration appears to be harmless. Within months the intensity is reduced by more than one order of magnitude. The reduction depends on the initial surface properties (pure glass or gold coating) and on the wavelength region under investigation. The effect is especially drastic in the wavelength region around 500 Å and at the carbon K-edge around 44 Å. At 44 Å intensity drops off within days by one order of magnitude.

Although this was never investigated quantitatively it is assumed that the rate of surface deterioration is both proportional to the intensity of synchrotron radiation and the partial pressure of hydrocarbons under the conditions found at DESY. Therefore the maintenance of the mirrors at DORIS in an UHV environment appeared to be mandatory. The increase in light intensity at DORIS by two orders of magnitude could only be compensated by a reduction of pressure by the same amount. Since the exchange of mirrors in UHV vacuum chambers is not so readily achieved as in ordinary vacuum systems, it was aimed at an increase in the life time of the mirror surfaces. A vacuum of 10^{-9} - 10^{-10} Torr with an especially reduced content of hydrocarbons after baking and strict monitoring of eventual gas streams generated by experiments investigating organic vapours by mass spectrometers should fulfil these requirements. Deterioration of the mirror reflectance as monitored by two monochromators operating presently in the wavelength region above 400 Å (HONORMI and HIGITI) was less than ≈20 % during the period of 4 months of the first running period.

Heating of the mirrors, especially since it occurs in a very shallow surface region, could be another source of problems. At 4 GeV approximately 0.2 Watts/mA stored current are hitting each of the mirrors S_1-S_3 in the beam line (Fig. 5). This could result in a total load of 100 Watts at 500 mA beam current. Such considerations led Stanford et al.[35] to the use of cooled copper mirrors at SPEAR which, however, is a material difficult to polish. At DORIS Zerodur mirrors are successfully used, a glass ceramic material which has a low thermal expansion coefficient. Up to now DORIS was only run in the region of up to 2.0 GeV and 300 mA for experiments. With these parameters the thermal load on each mirror did not exceed 5 Watts. Provisions are being made to use eventually also water cooled metal mirrors if this proves to become necessary. Dimensions of the mirrors used are given in Table 2.

For the adjustment and positioning of those mirrors and instruments which are not accessible when the beam shutter is open a laser beam simulation system is planned and almost completed.[36] An expanded laser beam is reflected into the direction of synchrotron light by a removable large 45 degree mirror which can be inserted in front of mirror S_1 into the beam line without breaking the vacuum. This mirror and a laser expansion telescope will be adjusted to match the direction and the divergency of synchrotron radiation. Three holes in the mirror mark the centers of the three 40 mm wide portions of the beam.

All of the mirrors are mounted on a bed which is supported by two strong rods which are coupled through the wall of the UHV vacuum chamber by flexible bellows. The rods are supported outside the vacuum chamber on a parallel sled which allows for a parallel reproducible motion of the mirrors. This enables one to remove all of the mirrors S_1 - S_3 from the beam in order to protect them from irradiation if not in use. The mirror S_3 is moved in such a way that different portions of the beam can be deflected into the direction of the L_2 beam line. This necessitates a motion along a path which is parallel to the direction of the L_2 beam. In this case either the direct beam D or portions of the L_1 beam (in case of withdrawn mirror S_2) can be used.

Other optical components belong to the individual monochromators. Thus in the beam line L_1 a torroidal focussing mirror FM focusses radiation stigmatically onto the entrance slit of the 3m monochromator. Stigmatic focussing in this case has the advantage of providing an almost stigmatic image at the exit slit. In the beam line L_2 a plane mirror S_4 deflects the beam downwards at such an angle (8 degrees) that the monochromatic beam which emerges after reflection from one of a series of plane mirror M_i, a plane grating G and a focussing paraboloid FM leaves the monochromator in the convenient horizontal direction. With the Wadsworth monochromator in beam line R the deflection of the exiting beam to a horizontal direction is achieved by an elliptically focussing mirror FM which images the exit slit onto a sample in the experimental chamber.

With all the monochromators an arrangement with vertical dispersion was realized. The reason is twofold. Firstly the source of radiation (the electron beam in the storage ring) has a horizontal extension of ideally 1 mm height and 10 mm length. A horizontal arrangement therefore would result in a factor of 10 loss in intensity for monochromators with entrance slits and a factor of 10 loss in resolution for the monochromators without entrance slits. The second important factor is the linear polarization of synchrotron radiation which is almost 100 % in the horizontal direction. According to Fresnel's equation s-polarization always gives higher reflectivities than p-polarization. With a vertically dispersing instrument p-polarized reflections are avoided with the exception of the reflections at mirrors S_1 - S_3. This arrangement improves both, intensities and linear degree of polarization.

5. Experiments

Despite the fact that the laboratory is in operation for only a year now several investigations have been already completed. Further experiments are in active preparation. Table 3 gives a survey on these activities.

The high resolution of 0.03 Å of the 3m monochromator HONORMI[30] is used for the investigation of fine structure in the spectra of atoms like Xe, Kr and Ar and molecules like N_2, H_2O, C_2H_6. The goal is to obtain with the combination of high resolution and exact intensity measurement exact line shapes of autoionizing series and exact intensities of rotational and vibrational levels in simple molecules. Further, line shapes of excitons in solid rare gases and alkali halides should provide valuable information on the exciton phonon coupling. These investigations already showed evidence of surface excitons. The same monochromator will be used to investigate the photoemission thresholds of molecules with a zero kinetic energy electron analyzer.

Less intense secondary processes are investigated with the low resolution (1-3 Å) but high intensity monochromator HIGITI[32]. A program under way which has had already a great number of results is the investigation of luminescence of monochromatically excited rare gases in the solid liquid and gaseous state. The luminescence radiation is analyzed by a secondary UHV monochromator (Seya Namioka type). The investigation also comprises rare gas mixtures.

Two further groups are just preparing luminescence and ionization investigations of small atmospheric molecules and of small organic molecules at the HIGITI monochromator. A major technical problem with these experiments is the isolation of the investigated gas from the region of the grating by a system of differential pumping stages.

The soft x-ray emission of several oxigen compounds which were excited by the undispersed total intensity of synchrotron radiation has been investigated now for about a year with the secondary monochromator FLEUR[34]. The objective of these experiments is the investigation of valence bands of samples which are destroyed upon excitation with electron bombardement. Up to now the ordinary high vacuum in the sample chamber had to be isolated by a thin carbon window. In the near future the installation of a differential pumping stage and a UHV sample chamber will allow also for excitation at higher wavelengths and thereby investigation of other emission spectra in the whole range 30 - 600 eV photon energies.

The grazing incidence fixed exit slit monochromator FLIPPER will be used preferentially for surface photoemission experiments on clean and adsorbate covered surfaces. Since the escape depth for kinetic energies of the excited electrons around 100 eV is very low the instrument should be ideally suited for such investigations.

A high resolution Rowland monochromator supplements the equipment for the soft x-ray region. This instrument will be primarily used for the investigation of highly resolved spectra of excitations from core levels into bound states in atoms and molecules.

In the x-ray region several experiments are under active preparation. An improved version of an x-ray interferometer[37], which has been used already at DESY will soon be installed at DORIS. Further the feasibility of isolating a collimated beam with a bandwidth of less than 10^{-8} eV for Mössbauer studies will be explored.

Acknowledgement

This project profited from the generous financial support from the DFG, from BMFT and from DESY. The continuous and stimulating interest of and support from the DESY directors is gratefully acknowledged. Finally we wish to extend our thanks to the staff of DESY and to all members of the synchrotron radiation group F 41 for their cooperation and help in all phases of this project.

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Table 1 Selected list of storage rings used as light sources. For comparison parameters for the DESY and Bonn synchrotron are also given. E = particle energy, R = magnet radius, I = max current, ε_c = critical photon energy.

	E (GeV)	R (m)	I (mA)	ε_c (eV)	Remarks, References
DORIS, Hamburg Germany	4.0	12.12	300	11600	16
DESY (synchrotron) Hamburg, Germany	7.5	31.7	10-30	29500	17
BONN II (synchrotron) Bonn, Germany	2.5	7.65	30	4530	18
TANTALUS I Wisconsin, USA	0.24	0.64	60	48	dedicated 19
SURF II NBS, Washington, USA	0.24	0.83	60	37	dedicated 20, 21
SPEAR Stanford, USA	4.0	12.7	50	11200	22
ACO Orsay, France	0.55	1.11	100	333	dedicated 23
DCI Orsay, France	1.8	3.82	400	3390	23
PACHRA Moscow, USSR	1.3	4	10/300	1220	dedicated 24
VEPP-3 Novosibirsk, USSR	2.25	6.15	∿100	5600	10
INSOR II Tokyo, Japan	0.3	1.1	100	54	dedicated 18
SRS Daresbury, U.K.	2	5.55	1000	3200	dedicated to be build 25
FOT-FAC	2.5	8.33	1000	∿4300	dedicated 26
PETRA	19	194	90	78500	27

Table 2: Characteristics of the mirrors used in the beam lines (see Fig. 5)

	S_1	S_2	$S^{(c)}$	S_3	S_4
material	zerodur$^{(a)}$	zerodur$^{(b)}$	steel	zerodur$^{(b)}$	zerodur$^{(b)}$
dimensions$^{(a)}$					
length L	330±0.5	330±0.5	350±0.5	440±0.5	160±0.5
breadth B	65±0.5	65±0.5	60±0.5	20±0.5	40±0.5
height H	40±0.5	40±0.5	20±0.5	60±0.5	35±0.5
surface roughness	$\leq$10-20 Å$^{(d)}$	$\leq$10-20 Å$^{(d)}$	$\leq$10-20 Å$^{(d)}$	$\leq$10-20 Å$^{(d)}$	$\leq$10-20 Å$^{(d)}$
coating	none	none	cromium	none	platinum
supplier	Zeiss	Zeiss	Leitz	Zeiss	Zeiss

(a) all numbers in mm, L x B is the reflecting surface area

(b) registered trade name of Schott and Gen., Mainz

(c) this mirror may be used instead of S_1 or S_2

(d) increasing to the edges up to 50 Å

Table 3: List of experiments presently performed or planned in the DORIS synchrotron radiation laboratory (see also Fig. 5)

Experiment	Apparatus and Location	Institute
Molecular and solid state spectroscopy with high resolution	HONORMI L_1	Sektion Physik, Univ. München and DESY
Luminescence of rare gases and alkali halides	HIGITI R	Universität Hamburg and Universität Kiel
Soft x-ray fluorescence	FLEUR D	Sektion Physik, Univ. München
Luminescence and Ionization of small molecules (a)	HIGITI R	Universität Kaiserslautern
Photoionization and Photodissociation of small organic molecules (a)	HIGITI R	Universität Freiburg
Photoemission from molecules (a)	HONORMI L_1	Technical Univ. München
Photoemission in the soft x-ray range (a)	FLIPPER L_2	DESY
Soft x-ray absorption spectroscopy with high resolution (a)	ROW D	Universität Hamburg and Universität Kiel
X-ray interferometry (a)	X-RAY D	Universität Dortmund
Mössbauerspectroscopy (a)	D	Universität Hamburg

(a) under preparation

Figure Captions

Fig. 1 Spectral distribution of synchrotron radiation into a solid angle of 1 mrad x 1 mrad for DORIS at different operating conditions. For comparison a curve typical for the DESY synchrotron is shown.

Fig. 2 Angular distribution of intensity components with electrical vector parallel ($I_{\parallel}$) and normal ($I_{\perp}$) to the plane of the synchrotron, linear polarization, and circular polarization (from decomposition into left (I_L) and right (I_R) hand circularly polarized components). ψ is the elevation angle perpendicular to the orbital plane (after Ref. 3).

Fig. 3 Experimentally determined shape of the light pulses for the storage rings DORIS (from Ref. 28) and for ACO (from Ref. 29).

Fig. 4 Layout of the synchrotron radiation laboratory at DORIS. Shown are part of the storage ring DORIS, the beam line to the laboratory and the location of the different experiments on the laboratory site. For details see text.

Fig. 5 Optical layout of the synchrotron radiation beam lines at the synchrotron radiation laboratory at DORIS. The beam (from left) is split into four independent beams L_1, L_2, D and R. S_1 to S_4 plane mirrors, FM focusing mirrors, FG concave reflectance gratings, G grating, Mi flat mirrors, SL entrance and exit slits respectively, FL x-ray fluorescence experiment, X-RAY/ROW space for an X-ray experiment or a Rowland monochromator.

Fig. 6 Photograph of the synchrotron radiation laboratory at DORIS

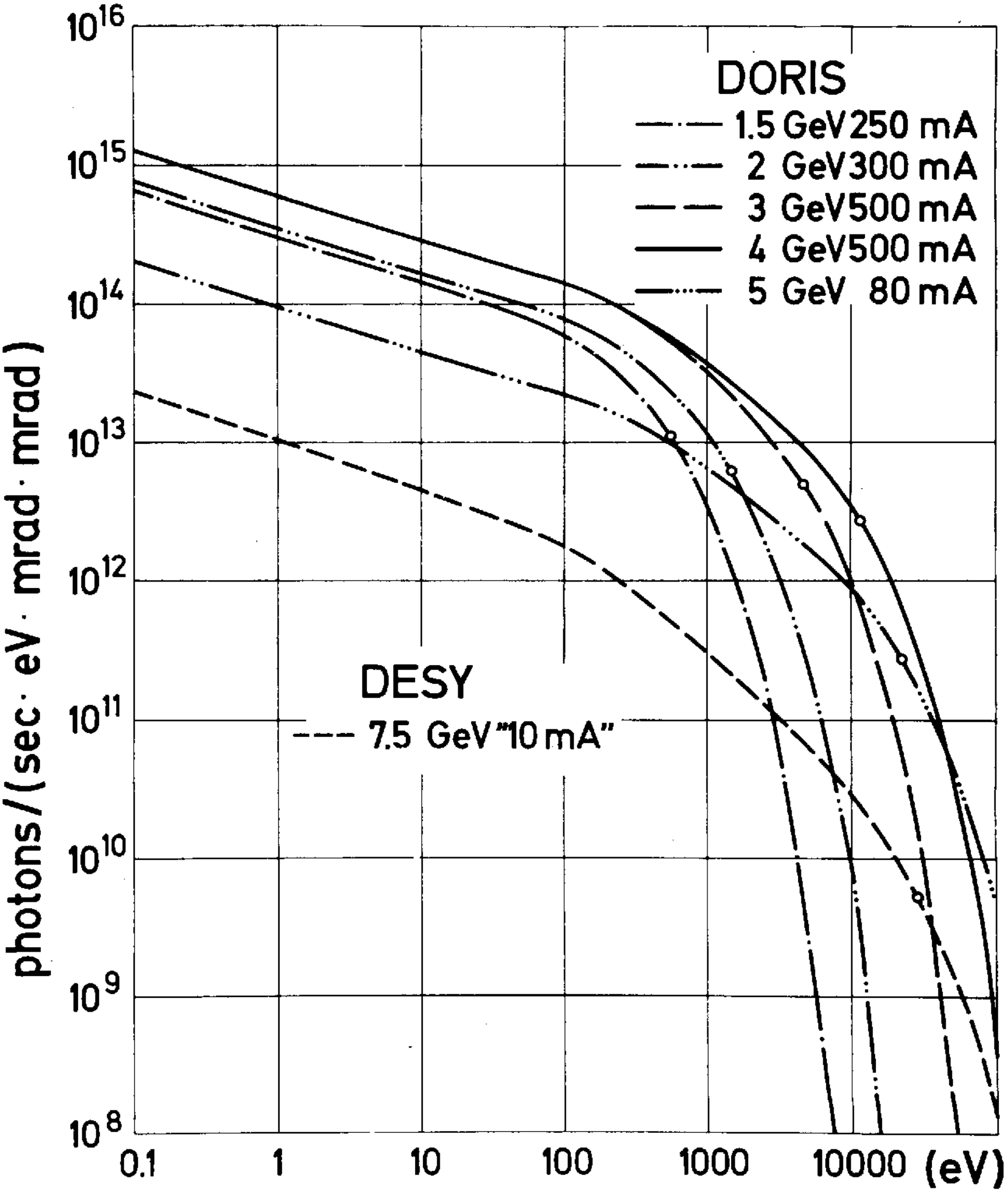

DORIS
1.5 GeV 250 mA
2 GeV 300 mA
3 GeV 500 mA
4 GeV 500 mA
5 GeV 80 mA
DESY
7.5 GeV "10 mA"
photons/(sec · eV · mrad · mrad)
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
0.1
1
10
100
1000
10000 (eV)

Fig. 1

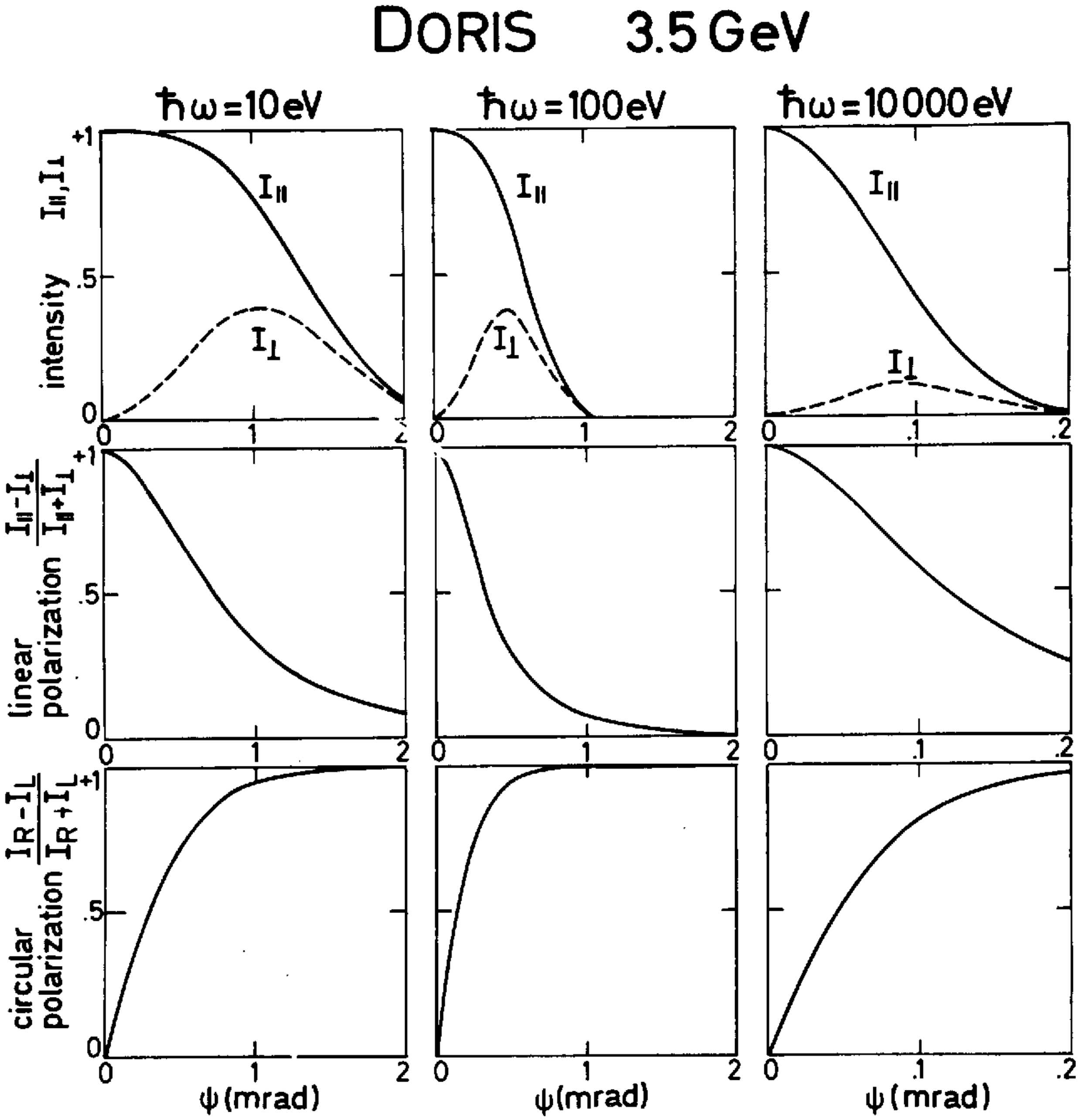

DORIS 3.5 GeV
$\hbar\omega$=10eV
$\hbar\omega$=100eV
$\hbar\omega$=10000eV
intensity $I_{\parallel}, I_{\perp}$
linear polarization $\frac{I_{\parallel}-I_{\perp}}{I_{\parallel}+I_{\perp}}$
circular polarization $\frac{I_R-I_L}{I_R+I_L}$
$I_{\parallel}$
$I_{\perp}$
+1
.5
0
1
2
.1
.2
ψ(mrad)

Fig. 2

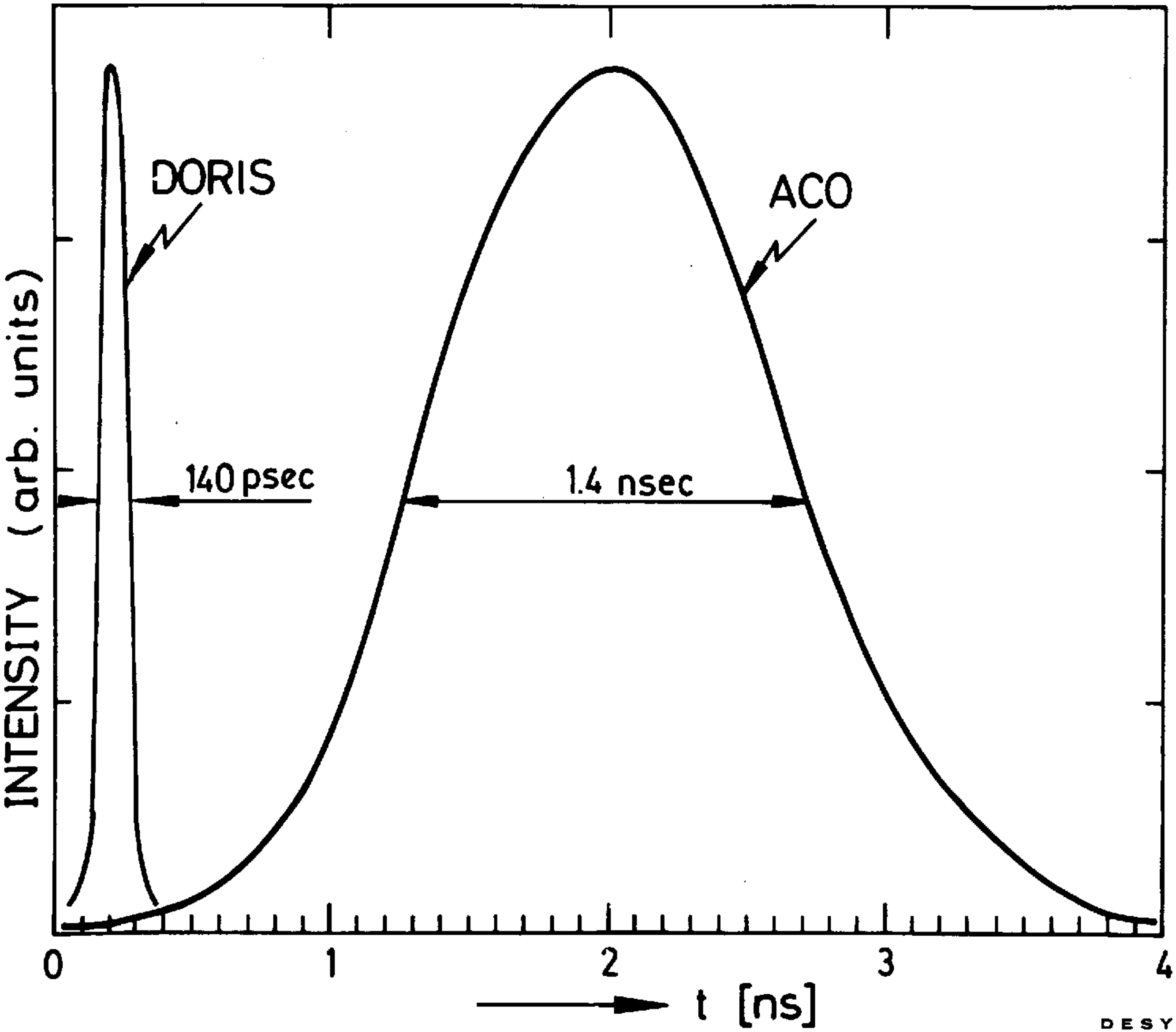
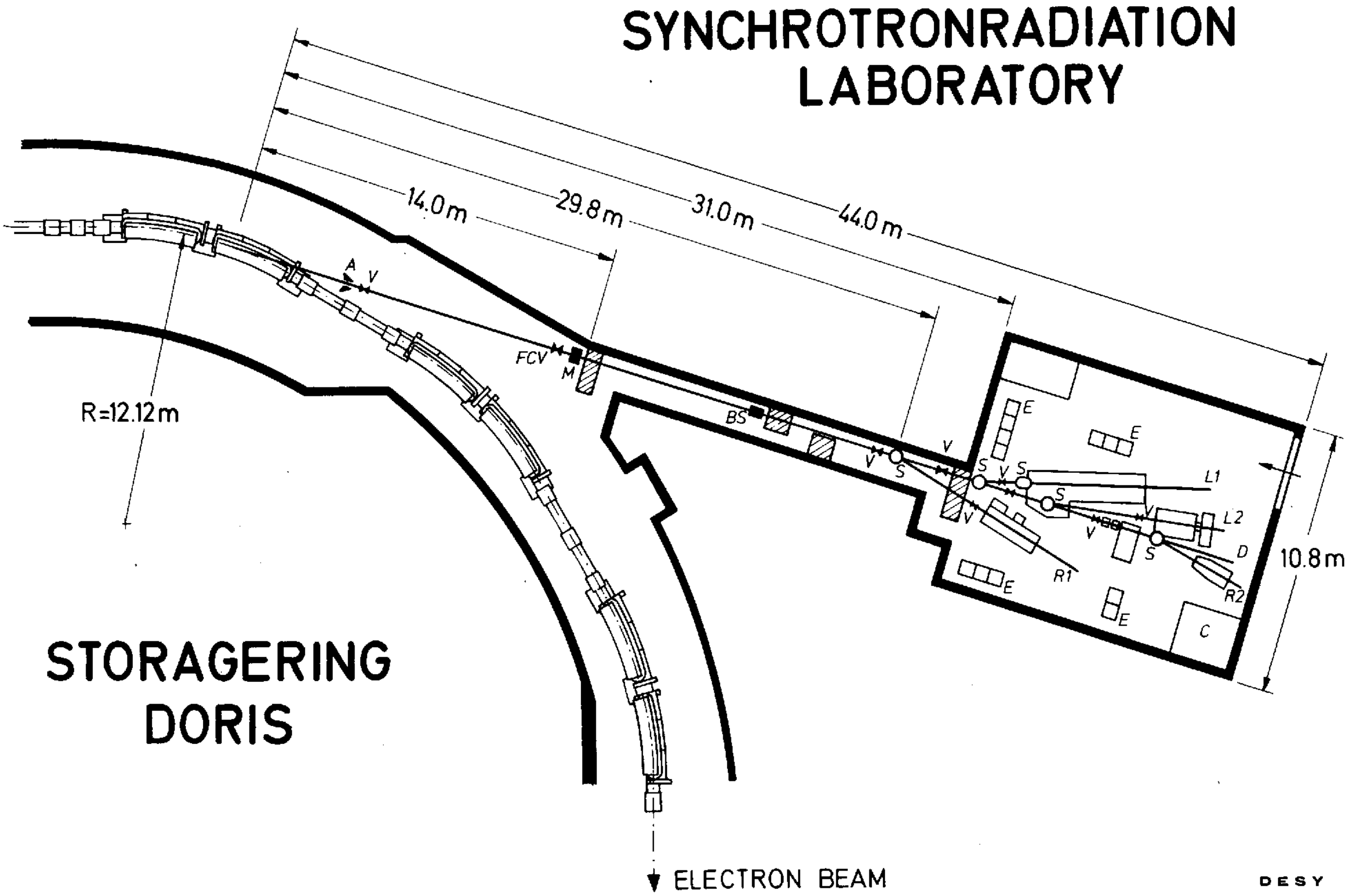


Fig. 3

DESY

24139



DESY

Fig. 4

23841

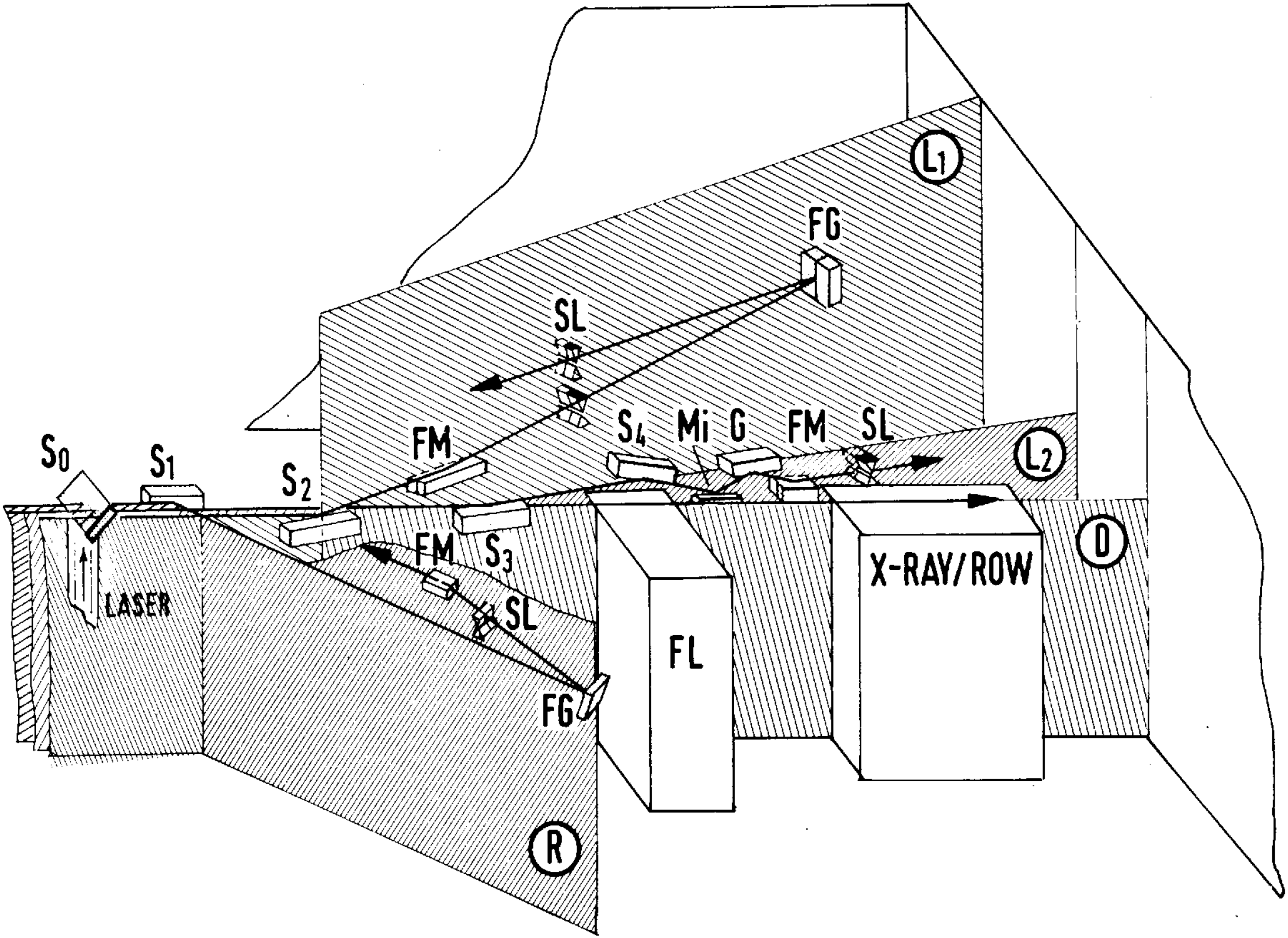


Fig. 5

DESY

24137

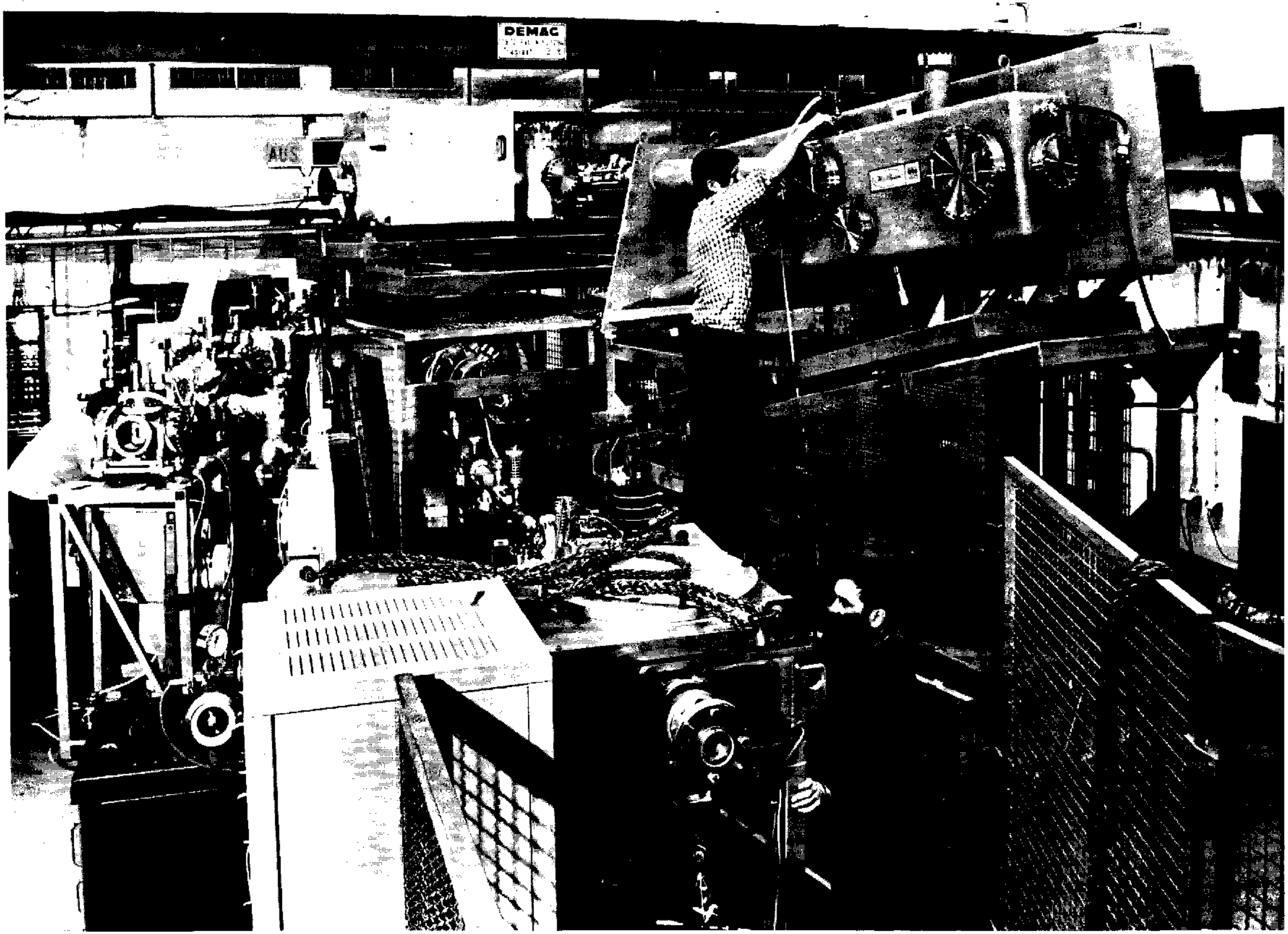


Fig. 6