DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY SR-74/15
September 1974

Perspectives of Synchrotron Radiation

Report on a Panel Discussion

by

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Perspectives of Synchrotron Radiation

Report on a Panel Discussion

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ABSTRACT

Synchrotron radiation is emitted by circular electron accelerators and storage rings. With present day high-energy accelerators the intense continuous spectrum extends from the infrared far into the x-ray region. With the exception of lasers synchrotron radiation is the brightest source available. In addition, the radiation is linearly polarized, calculable in absolute terms, well collimated, and has a time structure with pulses down to 100 psec long. The discussion served the purpose of instructing the audience on the properties of synchrotron radiation and considering new applications of this radiation. The interest was focussed on the comparison with other sources, applications in the x-ray regime, and use of time structure. Finally, the development from a symbiosis with high-energy physics towards storage rings dedicated to synchrotron radiation work was discussed in detail. The conclusion was reached that the installation of dedicated storage rings with typical particle energies of 2 GeV, radius of curvature about 6 m, yielding synchrotron radiation emission up to photon energies of 10 keV would be highly desirable. Costs for such a synchrotron radiation center, including buildings, would be in the order of US $ 3 million.

(To be published in: Proceedings of the IV. International Conference on Vacuum-Ultraviolet Radiation Physics, Hamburg July 22-26, 1974 (Pergamon/Vieweg, Braunschweig 1974) Edts. R. Haensel, E.E. Koch, C. Kunz, paper no. 10.1)

1. INTRODUCTION

The panel was organized and chaired by R. Haensel (Kiel), participants were the following experts on different aspects of the application of synchrotron radiation, all of them active workers in the field: S. Doniach (Stanford), P. Eisenberger (Murray Hill), I.M. Munro (Manchester), T. Sasaki (Tokyo), G.A. Voss (Hamburg), F. Wuilleumier (Orsay), and, in addition, several others from the floor. The selection of the panel members was not intended to imply a well balanced representation of the leading laboratories. It was rather hoped that the participants would cover non-overlapping subfields.

The intention of the panel discussion was twofold: (1) to provide those participants of the conference not familiar with synchrotron radiation with information on its properties and possible applications, (2) to discuss future development of synchrotron radiation sources, dedicated storage rings and experiments not yet conceived. After the discussion was over a useful and up to date review had been given. Since almost everything that was reported is to be found in one place or another in the literature[1-15] or in proposals in circulation[16] the author takes the liberty of presenting the material as a personal account of what was said rather than as a verbal transcription of the discussion. Some material had to be supplemented some deleted for the sake of clarity and balance. After roughly correlating specific topics with specific members of the panel no further references to speakers on the panel will be given. It is hoped that this method will contribute to the readability of the article.

In particular: S. Doniach gave a survey on the physical processes to be investigated, P. Eisenberger was especially concerned with the x-ray region, Y. Farge (from the floor) gave an account of possible applications in the infrared (Chapter 3). I. Munro and P. Eisenberger reported on the application of time structure (Chapter 4). I. Munro, E. Rowe (from the floor), T. Sasaki and F. Wuilleumier were especially concerned with the question of symbiotic or dedicated usage of storage rings, while G.A. Voss gave a survey on future developments of accelerators and storage rings due to the needs of high-energy physics; he further stresses the advantages of using a multipole wiggler (Chapter 5).

2. BASIC PROPERTIES OF SYNCHROTRON RADIATION

Synchrotron radiation[1-14] is emitted by circular electron and positron accelerators and storage rings with a very special characteristic as demonstrated in Fig. 1. When the particles reach relativistic energies the radiation is emitted into a very small angular cone around their instantaneous direction of flight. At a photon energy $\varepsilon = \varepsilon_c$, where ε_c is a characteristic cut-off energy as given by Eq. 2 below, the angular width $\langle\psi\rangle$ is $1/\gamma$ with $\gamma = E/mc^2$, E = particle energy. Further $\langle\psi\rangle$ varies roughly like $\langle\psi\rangle \propto (\frac{\varepsilon_c}{\varepsilon})^{1/3}$ for $\varepsilon < \varepsilon_c$ (see also Fig. 7 below). Thus the plane of the accelerator is filled with radiation, while emission in the off-plane direction is confined to a wedge of only about one milliradian angular spread. The dependence of the angular spread on the photon wavelength is illustrated in Fig. 2. (The graphs showing properties of the ACO storage ring are qualitatively also typical for other machines.)

Figure 3 gives a schematic presentation of the spectrum of synchrotron radiation as a function of the particle energy for a typical large synchrotron or storage ring (DESY, DORIS, CEA, SPEAR). With higher particle energies the spectrum extends further and further into the x-ray region. The spectrum can roughly be divided into a low-energy region where the number of photons in an infinitely high slice of one mrad horizontal width is given by

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

j = particle current in the accelerator, R = bending radius of beam. Note that intensities from different sources of synchrotron radiation can roughly be compared in this region by comparing the mean particle current. In comparing storage rings with synchrotrons it has to be remembered that there is a convention to give the current of synchrotrons during the period of acceleration (not the average current). Together with the fact that light emission sets in only some time after injection when the particles reach a sufficiently high energy (see Fig. 3) this is roughly taken into account by taking one third of the current given as an effective current.

The high-energy region of the spectrum begins at the cut-off energy ε_c after which the intensity drops rapidly. Synchrotron radiation has been used up to photon energies of about $8 \times \varepsilon_c$.

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

Table 1 gives a list of relevant parameters for most of the accelerators and storage rings under consideration.

The maximum brightness (photons/(sterad · sec · cm^2 · eV)) of the source (which is obtained in the synchrotron plane, see also Fig. 7 below) depends also on the size of the source. This is typically 2 mm high x 10 mm wide. Small storage rings at low current have beam heights as small as 0.1 mm. This can be a considerable advantage.

The intensity and the brightness of synchrotron radiation can thus be calculated in absolute numbers which allows for the use of it as a standard of radiation and which further plays an important role in the planning of new applications.

The horizontal angular segment of radiation which can be accommodated by an actual experiment depends on the distance of the laboratory from the tangential point. Where small distances are permissible and instruments are used which can accommodate more divergence of the beam a smaller accelerator can compensate for the difference in current compared to a more powerful machine. This is demonstrated in Fig. 4 where intensity into a 2 cm x 2 cm wide window is plotted at laboratory distances d as given. Where future machines are included it has to be proved that the distances given can be realized.

Another aspect of synchrotron radiation is its high degree of polarization. Figure 5 shows the degree of linear polarization as a function of angular distance from the plane of the storage ring for different wavelengths. It should be noted that radiation off the plane of the synchrotron is not an irregular superposition of parallel and perpendicularily polarized components but elliptically polarized and can be decomposed into left and right hand circularily polarized radiation with a degree of circular polarization according to Fig. 6. This could have useful applications in the future in connection with natural and magnetic field induced dichroism.

Synchrotron light sources are very unusual with respect to their time structure which is a copy of the time structure of the orbiting particles. Radiation is emitted in bunches of 0.1 - 1 nsec length depending on the accelerator or storage ring. This gives rise to a peak intensity of up to 10^4 times the average photon density. Moreover, the time arrangement of bunches can cause periodic structures of 2 nsec - 1 μsec (repetition frequency of bunches), 30 nsec - 1 μsec (period of revolution), 20 msec (period of injection into accelerators). Use is made of this time structure for measuring time dependent phenomena (see Chapter 4) but also for the reduction of background noise by using gated electronics. Further, the time structure allows for a time-of-flight photoelectron spectroscopy[18,19].

3. COMPARISON WITH OTHER SOURCES, EXPERIMENTS

3.1 Infrared and visible

An example of infrared intensities of synchrotron radiation is given for ACO at 100 mA circulating electron current in Table 2. Intensities into a solid angle of 0.1 rad x 0.1 rad, and in a band of 10^{-2} $(\Delta\lambda/\lambda)$ are listed. An angular cone of this width could be extracted with the help of an internal focussing reflector. These intensities can be compared with those obtained in a conventional Fourier spectrometer illuminated by a high pressure Hg lamp. A Fourier spectrometer would be operated with white radiation in the range 100 μm - 1 mm. Typically the total intensity into the interferometer is 0.1 μW. Since this is about equal to the mean intensity into a 10^{-2} $(\Delta\lambda/\lambda)$ band pass window with synchrotron radiation (Table 2) the intensity of synchrotron radiation is higher by two orders of magnitude than that of the conventional Hg source. This agrees in principle with considerations by other authors[20].

Since a Golay cell can detect about 10^{-10} W and a cooled bolometer about 10^{-12} W this opens up the possibility of using double beam spectrometers with very high resolution instead of Fourier spectroscopy. There are numerous applications in molecular and solid state physics.

Tunable lasers, however, once they cover the whole infrared region, will be superior to synchrotron radiation. This competing development is obviously the reason why not much effort has been invested in exploiting the infrared region of the spectrum up to now.

No interest exists in the visible part of the synchrotron radiation spectrum since ordinary sources and tunable lasers govern the field.

In this context a comparison of synchrotron radiation with radiation from other sources on the basis of brightness (photons/sec-eV-sterad-cm^2) is very illustrating. A high current storage ring like e.g. DORIS, with a current of 500 mA and a size of the source of 1 mm x 10 mm is brighter in the plane or the orbit than a 3000 ^{o}K black-body radiator, even brighter than a 6000 ^{o}K black-body source (the sun). These brightnesses are, however, small compared to those of lasers! The high brightness of a synchrotron radiation source is restricted to a small vertical angle, as shown in the lower part of Fig. 7. Many instruments in this spectral range have an acceptance which cannot be filled with synchrotron radiation because of the small size and the small angular spread of the source. In these cases the constant brightness in the full half-space of a black-body radiator can easily compensate for the difference in peak brightnesses. Each possible application, however, needs a careful analysis, before making a justified judgement. This will become especially clear in the discussion of the x-ray region below.

3.2 Vacuum Ultraviolet (VUV)

Below 2000 Å (definitely below 1000 Å) synchrotron radiation is superior to any conventional source because of the high intensity, polarization and tunability. Only the 21.2 eV He resonance line, as emitted from He capillary discharges[21], has an intensity comparable to synchrotron radiation and is, as is well known, widely applied for photoemission studies. Ordinary gas discharge sources exhibit an irregular line structure superimposed onto a weak continuum background with much less intensity than synchrotron radiation even in the lines. At the lower end of the VUV, where it boarders the x-ray region (in the 10 Å - 100 Å range), x-ray tubes are the classical sources for comparison. Their intensity is still much weaker than that of synchrotron radiation since self-absorption in the anti-cathode material diminishes the intensity of fluorescence radiation and that of bremsstrahlung.

It was mentioned (Connerade) that the BRV uranium rod source is in principle, capable of a considerable peak intensity. Two shots with a BRV source gave a spectrum which was equivalent to a two second illumination at the Bonn synchrotron. The repetition rate of the BRV source is, however, only 1 to 2 shots/minute.

Table 3 lists the experimental techniques applied in the VUV using synchrotron radiation. Absorption and reflection spectroscopy is now so widely applied for locating optical transitions and for determining optical constants that no references need be given. The investigation of secondary processes is developing rapidly especially with the higher fluxes from storage rings which are becoming available now.

The calibration of rocket spectrometers and secondary light sources[33,34] needs very careful consideration and diligent measurements. One of the problems arises from the polarization of synchrotron radiation, another from the deterioration of optical components due to the very high energy contributions of synchrotron radiation. Also the long distance from the synchrotron together with the narrow cone of emission causes trouble in the comparison with classical sources.

3.3 X-Ray Range

In the region below 10 Å synchrotron radiation has to be compared with an x-ray tube. An x-ray tube is characterized by an isotropic brightness (number of photons/mm - apparent area - unit solid angle - unit energy interval - unit time). The characteristic lines emitted by an x-ray tube have about 10^3 times more intensity than the bremsstrahlung background. Its emission in time is continuous. In all these respects it differs markedly with respect to synchrotron radiation (see Fig. 8). In its narrow angular range synchrotron radiation has several orders brightness more, Fig. 7.

One or the other source could be of advantage for a certain type of application depending on whether e.g. a small cone of radiation can be accommodated (synchrotron) or a wide cone is tolerable (x-ray tube). Figure 9 demonstrates by means of the parameters of SPEAR and those of a 60 kW x-ray tube how the relative intensities depend on the width of the cone of radiation used.

In addition to spatial brightness, brightness in time, namely the question whether the photons are evenly distributed or concentrated in small intervals, is of importance in applications on non-linear effects and mixing with laser light.

Table 4 gives an account of the different experiments to be considered for the x-ray regime of synchrotron radiation. Unless a detailed experiment having a well defined goal is discussed only a very general evaluation is possible. Controversies exist on the importance of several properties of synchrotron radiation for specific experiments. One of the surprises is that for XPS no advantage in intensity is obtained using synchrotron light. Here only the tunability might be of importance. It is especially difficult to draw conclusions for experiments which have been proposed but with which no one has really identified himself yet and tried to prove the feasibility experimentally. These are, to our knowledge, Compton scattering, attack of the phase problem, x-ray holography (which was mentioned frequently but to our knowledge was never discussed in detail), and non-linear effects in the x-ray range. It is surprising, as demonstrated in Table 4, that the polarization of synchrotron radiation is not a decisive factor for a single experiment under discussion so far. A few further remarks are given on those experiments for which no information is available elsewhere in this volume.

In Compton and Raman scattering, in addition to energy transfer of photons, momentum transfer is the important measured quantity (see also 45). A good momentum resolution is achieved among other means by using a narrow incident bundle of radiation. Calculations for actual problems show, however, that the width of the synchrotron radiation cone is by far too narrow, much wider bundles are permissible, and the advantage of higher brightness (see Figs. 7 and 9) does not come into play.

Interferometry[39,40] near 1 Å is now on the program at the DESY synchrotron. In this experiment the beam is monochromatized, split and brought to interference again by successive diffraction in plane single crystals. Only a very narrow bundle can fulfill the Bragg condition and the full advantage of the high brightness can be exploited. Since the goal of these experiments is to follow the change of the index of refraction over the wavelength region in the neighbourhood of absorption edges tunability is the other advantage. The brightness of synchrotron radiation as given in Fig. 7 has to be compared with the brightness of the x-ray continuum of an ordinary x-ray tube. Once accurate measurements of the variation of the index of refraction exist, diffraction of biological samples or complicated crystals of other materials at different wavelengths around the absorption edges of prominent constituent elements provides a means to attack the phase problem.

In x-ray topography[41] single crystals are illuminated by a wide parallel beam of x-rays which do not need to be monochromatic. The Laue pattern shows in each diffraction "spot" a picture of the crystal with all its imperfections (dislocations etc.). Since several Laue peaks in different directions can be obtained in one picture stereoscopic information on the defects in a crystal is obtained. Moreover, the high brightness of synchrotron radiation allows for the future possibility of taking movie pictures of the motion of dislocations under strain.

A scanning x-ray microscope was tested[44] at the CEA synchrotron (storage ring). The principle used was to focus and collimate the beam down to a spot in the order of one micron width. The samples were moved in a scanning fashion relative to this beam and fluorescence radiation was detected by a selective detector around the sample. The high brightness of synchrotron radiation is again the decisive factor here.

Iodography in biological objects (human bodies e.g.) was proposed by the SLAC group. High contrast with moderate concentrations of iodine in blood vessels could be obtained by wavelength modulation around the Iodine K edge at 32.5 keV. This could be achieved by using a rocking monochromator crystal.

It was stated (Eisenberger) that instantaneous brightness of synchrotron radiation together with present day accuracy in obtaining data is sufficient to observe non-linear phenomena in the transition of x-rays through matter and also to see two photon effects by mixing x-rays with laser beams. No details of an experiment have yet been proposed.

4. TIME STRUCTURE OF SYNCHROTRON RADIATION

Special attention is now given to applications of synchrotron radiation making use of its peculiar time structure. The pulses, down to 100 psec wide, in principle allow for measurements of time dependent phenomena with a very good resolution in time. This fact was already mentioned in Tables 3 and 4 for several experiments. An important factor for successful experimenting can only be fulfilled when synchrotron radiation physicists are the main users of a storage ring, namely the filling of only one bunch with particles which occurs at ACO naturally and gives 73 nsec separation of pulses and would give 1000 nsec separation at DORIS.

4.1 Radiative decay studies

It is possible to excite single vibronic levels in low pressure vapours and to follow their deday in time. Figure 10 gives the fluorescence of pyrazine as an example[28]. The measured decay time was 0.5 nsec. The time-structure of the light pulse as measured is not free from distortions from the electronic equipment used.

One can further study non-exponential decay profiles in liquids and solids. Further reactivity of excited molecules can be studied by tuning on the wavelengths of reaction prodcuts. Correspondingly the decay of photofragments can be studied. Measurements on time resolved emission spectra are capable of resolving two or more superimposed components in ordinary emission spectra and can serve to clarify the origin of these components.

4.2 Transient phenomena

The time development of structural and other changes could be well investigated be it by diffraction, absorption or other techniques. One example given is that of obtaining a Laue picture with one pulse of synchrotron light. In case wire chambers are used instead of photographic film several pictures could be taken at different stages of an event. Diffraction on shock waves was one example mentioned (Vodar).

Stroboscopic repetition and accumulation of count rates is feasible when the process under investigation can be repeated and triggered. Preparations for observing the structural changes of muscular contraction are under way.[43] This will need a time resolution in the order of only one millisecond.

It was mentioned (Nagel) that a laser induced plasma source gives off considerable x-ray intensity in a very short period and a comparison with synchrotron radiation for these applications is recommended once the number of photons from the plasma source is established. Also the high peak emission from the BRV source, as mentioned above, should be seen in this context and a comparison with synchrotron rediation is needed on the basis of absolute measurements of the BRV souce. One requirement for the measurement of lifetime is, however, that the counting rate must not exceed 1/40 th of the exciting-pulse repetition rate.[28] This is necessary in order to avoid double photon pulse effects (saturation). The total flux of the exciting light and the repetition rate must, therefore, be at a maximum. The second condition will not be fulfilled (by orders of magnitude) so well by the above mentioned sources as by synchrotron radiation.

One of the other major practical difficulties encountered when using discharge sources is the necessity of shielding the detection system against electronic noise from the source. This does not occur with synchrotron radiation. Still another problem is the exponential "tail" of pulses from discharges due to afterglow which underlies the exponential lifetime decay to be measured. No light is emitted between synchrotron pulses. The next step will definitely be to use the .1 nsec pulses from DORIS and SPEAR for even better resolution in time and shorter decay times.

5. SYMBIOTIC OR DEDICATED SOURCES OF SYNCHROTRON RADIATION

Most of the accelerators and storage rings in Table 1 are machines designed only for the needs of high-energy physics. One of them is now operated for synchrotron radiation experiments only[46] (TANTALUS I at Stoughton), SURF II at the NBS near Washington will be in the same situation very soon[47]. There is one storage ring (INS-SOR II in Tokyo) near completion which will be the first source dedicated, from the beginning, only to the use of synchrotron radiation. Its characteristics are given in Table 1. This storage ring will have several advantages over present sources. However, the project suffers from too low a budget (Sasaki) which cannot be completely compensated for by the enthusiasm of its builders (the storage ring is constructed and set up by its later users). Especially ε_c = 60 eV is not sufficiently large to satisfactorily cover the whole VUV range. Its range will be comparable to that of Tantalus I.

Which dimensions are reasonable for a dedicated source? If critical energies above ε_c = 3 keV are demanded the costs start to rise rapidly as a function of ε_c (Fig. 11). Therefore, a storage ring with 2 GeV and about 6 m magnet radius like e.g. TANTALUS II[48], appears to be appropriate. For roughly US $ 3 million the machine, including a laboratory building with several beam ports, could be financed. Beam current would depend on the quality and energy of the injector. Very high currents could probably be achieved when sharing a high energy linac with high-energy installations which could otherwise not be financed from this budget. Not much of the flexibility ought to be lost with this type of a symbiosis.

The possibility exists of obtaining even shorter wavelengths from such a machine by applying a superconducting wavelength shifter which would give the beam a local strong curvature in an otherwise low curvature machine. ε_c is proportional to 1/R (Eq. 2), therefore proportional to the magnetic field. A 3 - 4 times larger ε_c could possibly be obtained this way. This would make the dedicated storage ring even more useful.

The best conditions in the far x-ray region will furtheron be found at the 4 - 5 GeV storage rings which are presently being put into operation for the purpose of high-energy physics (Table 1).

Table 5 lists the problemsmore or less encountered when using synchrotron radiation from a machine installed for the purpose of high-energy physics. Many of the disadvantages can be avoided with a dedicated machine. The table also lists some additional advantages of a dedicated machine. One of them is the multipole wiggler[49] which would allow for a multiplication of intensity by the number of poles (Fig. 12).

Several participants in this discussion stated that existing machines are offering main-user shifts for synchrotron radiation purpose. In this case those machines bear out all or several of the advantages of dedicated machines. At ACO e.g. 300 mA can be obtained at 240 MeV (only 2 mA with colliding beams) and 100 mA at 500 MeV (only 30 mA otherwise). Moreover, it should not be forgotten that the present state of the art of building accelerators and storage rings would not have been reached without the necessity of developing them for high-energy physics.

What are the future developments of storage rings for high-energy physics? Is it attractive for synchrotron radiation users to work at the even bigger machines? The spectacular recent results of SPEAR show that the cross-section for e^-e^+ collisions is not falling off as fast as expected. This makes it both feasible and interesting to build storage rings with much higher energies than the present ones. Table 1 gives the parameters of the planned machines PEP, PETRA, EPIC, and SUPER-ADONE. They have in common very large radii which make the installation of synchrotron radiation beam pipes complicated and expensive. Large distances being necessary would result in small horizontal apertures. Moreover, the current would go down compared to the present generation of storage rings because of the increasing overall microwave consumption of synchrotron radiation. Only the increase in ε_c could be of advantage for experiments with very high photon energies. Probably synchrotron radiation from these instruments will be of interest only for a few selected x-ray experiments (compton scattering).

This is another indication that the time has come for building the E = 2 GeV, I = 1 Amp, R = 6 m, ε_c = keV dedicated sources which, with a superconducting wavelength shifter, could reach ε_c = 10 keV. These sources can serve the majority of users in an ideal manner.

Acknowledgement

The author wants to thank the participants in the panel for providing him with slides and view-graphs used by them during the discussion. He apologizes for having incorporated into this paper only a selected fraction of the material.

List of References

1. J.D. Jackson, Classical Electrodynamics, John Wiley, New York 1967, Chap. 14

2. F.C. Brown, P.L. Hartman, P.G. Kruger, B. Lax, R.A. Smith and G.M. Vineyard, Synchrotron Radiation as a Source for the Spectroscopy of Solids, N.R.C. Solid State Panel Subcommitee Rep., March 1966

3. R.P. Madden and K. Codling, Instrumental Aspects of Synchrotron XUV Spectroscopy, Applied Optics 6, 31, 1967

4. R. Haensel and C. Kunz, Experimente mit Synchrotronstrahlung, Z. für Angew. Physik, 23, 276 (1967)

5. A.A. Sokolov and J.M. Ternov, Synchrotron Radiation, Oxford, Pergamon Press, 1968, 207 p. (translated from the Russian)

6. R.P. Godwin, Synchrotron Radiation as a Light Source, Springer Tracts in Mod. Phys. 51, 1, 1969

7. C. Gähwiller, F.C. Brown and H. Fujita, Extreme Ultraviolet Spectroscopy with the Use of a Storage Ring Light Source, Rev.Sci.Instr. 41, 1275 (1970)

8. W. Hayes, Spectroscopy with a Synchrotron Light Source, Contemp.Phys. 13, 441 (1972)

9. Research Applications of Synchrotron Radiation Proceedings of a Study-Symposium held at Brookhaven National Laboratory Sept. 25-28,1972, Report BNL 50381, Edts. R.E. Watson, M.L. Perlman

10. K. Codling, Applications of Synchrotron Radiation, Rep.Progr. Phys. 36, 541 (1973)

11. G.V. Marr and I.H. Munro, Edts., International Symposium for Synchrotron Radiation Users, Daresbury Jan. 4-7, 1973, Proceedings DNPL Report No. R26

12. C. Kunz, In Proceedings on the CERN meeting on high-energy technology, April 24-26, 1974, CERN 24-9, Vol. 1, p. 155

13. M.P. Perlman, E.M. Rowe, and R.E. Watson, Physics Today p. 30 (July 1974)

14. F.C. Brown, Ultraviolet Spectroscopy of Solids with the Use of Synchrotron Radiation, in Solid State Physics, ed. by H. Ehrenreich, F. Seitz, and D. Turnbull (1974)

15. G.V. Marr, J.M. Munro, and J.C.C. Sharp, Synchrotron Radiation: A Bibliography, Daresbury, Nuclear Physics Laboratory 1972, Report DNPL/R24 and Supplement August 72 to Febr. 74, Report DL/TM 127

16. Users Handbooks and other special information can be obtained from many of the laboratories listed in Table 1 on request.

17. F. Wuilleumier, Le rayonnement synchrotron emis par les anneaux de stockage d'Orsay (ACO et DCI), LURE Report 74/03 (1974)

18. R.Z. Bachrach, S.B.M. Hagström, and F.C. Brown, this volume No. 10.11

19. G.C. Baldwin, W.A. Bryant and M.R. Gaerttner, In: Electron Spectroscopy, Ed. D.A. Shirley, North-Holland, Amsterdam, London 1972, p. 159

20. J.R. Stevenson, H. Ellis, R. Bartlett, Appl. Optics 12, 2884 (1973)

21. J.A. Kinsinger, W.L. Stebbings, R.A. Valenzi and J.W. Taylor, In: Electron Spectroscopy, Ed. D.A. Shirley, North-Holland, Amsterdam, London 1972, p. 155

22. M. Schledermann and M. Skibowski, Appl.Opt. 10, 321 (1971)

23. W.S. Heaps, D.S. Hamilton, and W.M. Yen, Opt.Comm. 9, 304 (1973)

24. W.S. Heaps, L.R. Elias, and W.M. Yen, This volume No. 4.28

25. R. Brodmann, R. Haensel, U. Hahn, U. Nielsen, and G. Zimmerer, DESY SR-74/6 Report and this volume No. 4.6

26. W. Sroka and R. Zietz, Z. Naturforsch. 28a, 794 (1973)

27. R.W. Carlson, D.L. Judge, and M. Ogawa, J.Phys. B6, 343 (1973)

28. R. Lopez-Delgado, A. Tramer, and I.H. Munro, Chemical Physics 5, 72 (1974)

29. K. Feser, J. Müller, G. Wiech, and A. Faessler, Journal de Physique, Colloque C4, Suppl. au no. 10, Tome 32, p. 331 (1971)

30. K. Feser, Phys.Rev.Lett. 29, 901 (1972)

31. A. Faessler, This volume No. 10.13

32. D. Reinke, R. Kraessig, and H. Baumgärtel, Z. Naturforsch. 28a, 1021 (1973)

33. E. Pitz, Appl.Opt. 8, 255 (1969)

34. P.J. Key, Metrologia, 6, 97 (1970)

35. P. Eisenberger, In Proc. Study Symposium on Research Applications of Synchrotron Radiation, Brookhaven National Laboratory, 25-28 Sept. 1972, Ed. R.E. Watson and M.L. Perlman, BNL Report 50 381 (1973) p. 70

36. K. Siegbahn, In: Electron Spectroscopy, Ed. D.A. Shirley North-Holland, Amsterdam, London 1972, p. 31

37. P. Eisenberger, B. Cincaid, S. Hunter, D. Sayers, E.A. Stern and F. Lytle, this volume No. 10.16

38. I. Lindau, P. Pianetta, S. Doniach, and W.R. Spicer, this volume No. 10.15

39. U. Bonse and G. Materlik, Proceedings of the Conference on Anomalous scattering, Madrid 1974, to be published

40. M. Hart and U. Bonse, Physics Today, August 1970, p. 26

41. T. Tuomi, K. Naukkarinen, E. Laurila, and P. Rabe, Acta Polytechnicy Scandinavia No. Ph-100 (1974)

42. G. Rosenbaum and K.C. Holmes, Synchrotron Radiation as a Source for X-ray Diffraction, Nature 230, 434 (1971)

43. K.C. Holmes, this volume No. 11.1

44. P. Horowitz and J.A. Howell, Science, 179, No. 4061, 608 (1972)

45. D.O. Welch, In: Proc Study Symposium on Research Applications of Synchrotron Radiation, Brookhaven National Laboratory, 25-28 Sept. 1972, Ed. R.E. Watson and M.L. Perlman, BNL Report 50 381 (1973) p. 83

46. E.M. Rowe and F.E. Mills, Particle Accelerators 4, 211 (1973)

47. R.P. Madden and D.L. Ederer, this volume No. 10.3

48. E.M. Rowe, In: Proc. Study Symposium on Research Appl. of Synchrotron Radiation, Brookhaven National Laboratory, 25-28 Sept. 1972 Ed. R.E. Watson and M.L. Perlman, BNL Report 50 381 (1973) p. 1

49. H. Winick, IEEE Trans.Nucl.Sci. NS-20 No. 3, 984 (1973)

Table 1: Synchrotrons (SY) or storage rings (ST) used (or considered) as light sources
E = particle energy, R = magnet radius, I = max. current (during acceleration for SY), ε_c = critical photon energy

Name	Location	Type	E(GeV)	R(m)	I(mA)	ε_c(eV)	Remarks
	USA						
SURF I	NBS Washington	SY	.17	.83	1	13	closed down
SURF II	NBS Washington	ST	.24	.83	50	37	dedicated, tested
TANTALUS I	PSL Stoughton/Wisc.	ST	.24	.64	20	48	dedicated
TANTALUS II	PSL Stoughton/Wisc.	ST	1.76	4.5	100	2690	proposed, dedicated
SPEAR (I)	SLAC Stanford/Calif.	ST	2.5	12.7	22	2730	} 1974 change from I to II
SPEAR (II)	SLAC Stanford/Calif.	ST	4.0	12.7	60	11200	
CEA	Cambridge/Mass.	SY/ST	6.0	26.0	30	18400	closed down
CORNELL III	Ithaca/N.Y.	SY	12	∿120	2	32000	no radiation lab.
PEP	SLAC Stanford/Calif.	ST	15	170	100	44000	proposed
	GERMANY						
BONN I	Univ. Bonn	SY	.5	1.7	30	163	
BONN II	Univ. Bonn	SY	2.5	7.65	30	4530	
DESY	DESY Hamburg	SY	7.5	31.7	30	29500	
DORIS	DESY Hamburg	ST	3.5	12.12	900	7850	tested
PETRA	DESY Hamburg	ST	25	200	5	173000	proposed
	GREAT BRITAIN						
GLASGOW	Univ. Glasgow	SY	.33	1.25	.1	64	closed down
NINA I	DNPL Daresbury	SY	5.0	20.8	50	13300	
NINA II	DNPL Daresbury	ST	2.0	5.55	1000	3200	proposed, dedicated
EPIC	Rutherford Lab. Chitt Chitton	ST	14	171.89	22	35000	proposed
	FRANCE						
ACO	Orsay	ST	.55	1.11	35	333	
DCI	Orsay	ST	1.8	3.82	400	3390	under construction
	JAPAN						
INS-SOR I	INS-Tokyo	SY	1.3	4.0	60	1220	
INS-SOR II	INS-Tokyo	ST	.3	1.1	100	54	dedicated, tested
	RUSSIA						
C-60	Lebedev Mocsow	SY	.68	2	10	349	
PACHRA	Krasnaja Pachra near Moscow	SY/ST	1.3	4	10/300	1220	under construction
ARUS	Erewan	SY	6.0	24.65	22	19500	
	ITALY						
FRASCATI	Frascati	SY	1.1	3.6	14	821	
ADONE	Frascati	ST	1.5	5.0	60	1500	no radiation lab.
SUPER-ADONE	Frascati	ST	12	64	200	60000	proposed

Table 2: Infrared emission of ACO in a solid angle 100 mrad x 100 mrad and a band pass of 10^{-2} ($\Delta\lambda/\lambda$) (after Y. Farge)

λ	wavenumber	power
1 μm	(10^4 cm^{-1})	100 μW
10 μm	(1000 cm^{-1})	5 μW
50 μm	(200 cm^{-1})	1.3 μW
100 μm	(100 cm^{-1})	0.2 μW
1 mm	(10 cm^{-1})	0.05 μW

Table 3: Application of synchrotron radiation in the VUV (2000- 10 Å)

Technique	References	Remarks
1. Absorption	standard	) Determination of optical constants;
Reflection	standard	) use of polarization
Ellipsometry	22	)
2. Photoelectron spectroscopy	several papers this volume	Yield and EDC spectroscopy especially elimination of final state density; surface states; chemisorbed atoms; use of time structure
3. Luminescence	see e.g. 23-28	Excitation with white and monochromatic radiation; investigation of decay processes in insulators and molecules; use of time structure;
Fluorescence	29 - 31	soft x-ray fluorescence
4. Photoionization	see e.g. 32	
Photofragmentation		Mass spectrometry
5. Calibration of light sources and transmission of monochromators	33, 34	

Table 4: X-ray experiments performed or proposed†. Those properties of synchrotron radiation (SR) which are a decisive advantage over x-ray tubes are marked ++ other properties which could become an advantage for some special experiments of this type are marked +. (see also Ref. 35)

	Reference	TUNABILITY (vs. lines of fixed energies)	BRIGHTNESS IN SPACE (vs. total intensity)	BRIGHTNESS IN TIME (vs. CW operation)	SHORT PULSES (vs. CW operation)	POLARIZATION (vs. unpolarized)	TOTAL WHITE INTENSITY (vs. few intense lines)	Remarks
1. EXAFS (absorption)	37	++			+	+		SR very favourable
2. XPS (photoelectrons)	38	?			+	+		Al and Mg monochromatized Kα lines better than SR
3. COMPTON†, RAMAN† (momentum transfer)		+			+	?		x-tubes better than SR for usual applications
4. INTERFEROMETRY (Index of refraction)	39,40	++	++			+		SR very favourable
5. X-FLUORESCENCE (secondary excitation)	29 - 31					+	++	SR only choice in soft x-region
6. TOPOGRAPHY (dislocations in crystals)	41	++	++		+	+	++	SR very favourable
7. SMALL ANGLE SCATTERING (biolog. materials, order in crystals)	42,43	+	++		++			SR very favourable
8. PHASE PROBLEM† (variable scattering amplitude)		++	+					SR favourable depending on results of No. 4
9. X-MICROSCOPE (scanning)	44	+	++				++	SR favourable
10. IODOGRAPHY (scanning around K edge of Iodine (32.5 keV))		++	+					Application to biological matter
11. NON-LINEAR† (and mixing with lasers)		+	++	++		?		

Table 5: Symbiotic (with high energy physics) or dedicated (only for synchrotron radiation) usage of accelerators or storage rings

A. Problems of symbiotic usage

1. Waiting for useful conditions of operation depending on the high energy program
2. Radiation damage
3. Health hazards, necessity of shielding and remote control
4. Motions of source
5. Lower than possible intensity, storage times, and stability because of colliding beam restrictions at storage rings.
6. Especially low stability of current with synchrotrons
7. Improvements for high energy physics usually mean disadvantages for synchrotron radiation experiments.

B. Advantages of dedicated machines

1. Free choice of parameters:
   a) Variation of energy to vary ε_c and to check for higher order and stray-light contributions
   b) Special choice of pulse pattern for life-time measurements
   c) Control of beam position, shape and possibly size
2. Filling with low current for safe adjustments at instrument
3. High stability of beam position and intensity

C. Special features possible in dedicated machines

1. Focused beam in magnets for increase of brightness
2. Beam wigglers for multiplication of sources seen by one experiment (see Fig. 12)
3. Wavelength shifter for local extension of wavelength limit
4. Periodic motion of beam at radiation point for wavelength modulation with monochromators which use beam as entrance slit
5. Special devices built into the vacuum chamber of the machine in order to obtain more beam aperture like:
   a) mirrors to collect infrared radiation
   b) integrated monochromators which collect very wide horizontal apertures.

Figure Captions

Fig. 1 Geometry of synchrotron radiation emission (after 17)

Fig. 2 Angular distribution of synchrotron radiation (vertical and horizontal components) as a function of angle ψ against the plane of the synchrotron (after 17)

Fig. 3 Dependence of spectral distribution on particle energy (schematically, after 12)

Fig. 4 Spectral distribution of intensity into a 2 cm x 2 cm wide aperture at laboratory distance d at different accelerators and storage rings (after 17)

Fig. 5 Degree of linear polarization P as a function of angle ψ against the plane of the synchrotron (after 17)

Fig. 6 Decomposition of elliptical polarization into left hand I_L and right hand I_R contributions (after 17)

Fig. 7 Brightness of synchrotron radiation of DORIS (based on source size 1 x 10 mm^2) DESY (based on source size 3 x 10 mm^2), Cu Kα characteristic radiation and bremsstrahlung from a 60 kW x-ray tube[35] (estimated from a source size of 1 x 1 mm^2), Al Kα characteristic radiation from a 5 kW x-ray tube[36] (estimated on the basis of a 2 mm diameter spot size) and HeI (21.2 eV) resonance line[21] (estimated from a 10 mm diameter source size, 20 meV line width, and a guessed collimation of the 10^{13} photons into 0.01 sterad)

Fig. 8 Schematic comparison of synchrotron radiation with an x-ray tube with respect to their characteristics in angle, energy, and time (after P. Eisenberger)

Fig. 9 Comparison of intensity of synchrotron radiation of SPEAR with characteristic Kα radiation from a Cu 60 kW x-ray tube at different angular apertures under the assumption that because of the usually large distances from the source the spectrometer will accept only a synchrotron radiation beam of 1 mrad horizontal width, the vertical width is restricted by the natural width, see Fig. 7 (after P. Eisenberger)

Fig. 10 Time resolved emission spectrum of pyrazine at 3240 Å (after 28)

Fig. 11 Cost of a dedicated storage ring for synchrotron radiation as a function of the critical energy ε_c respectively wavelength λ_c. The price unit is approximately 1 million british pounds (after I. Munro)

Fig. 12 Principle of multiplication of source by a beam wiggler

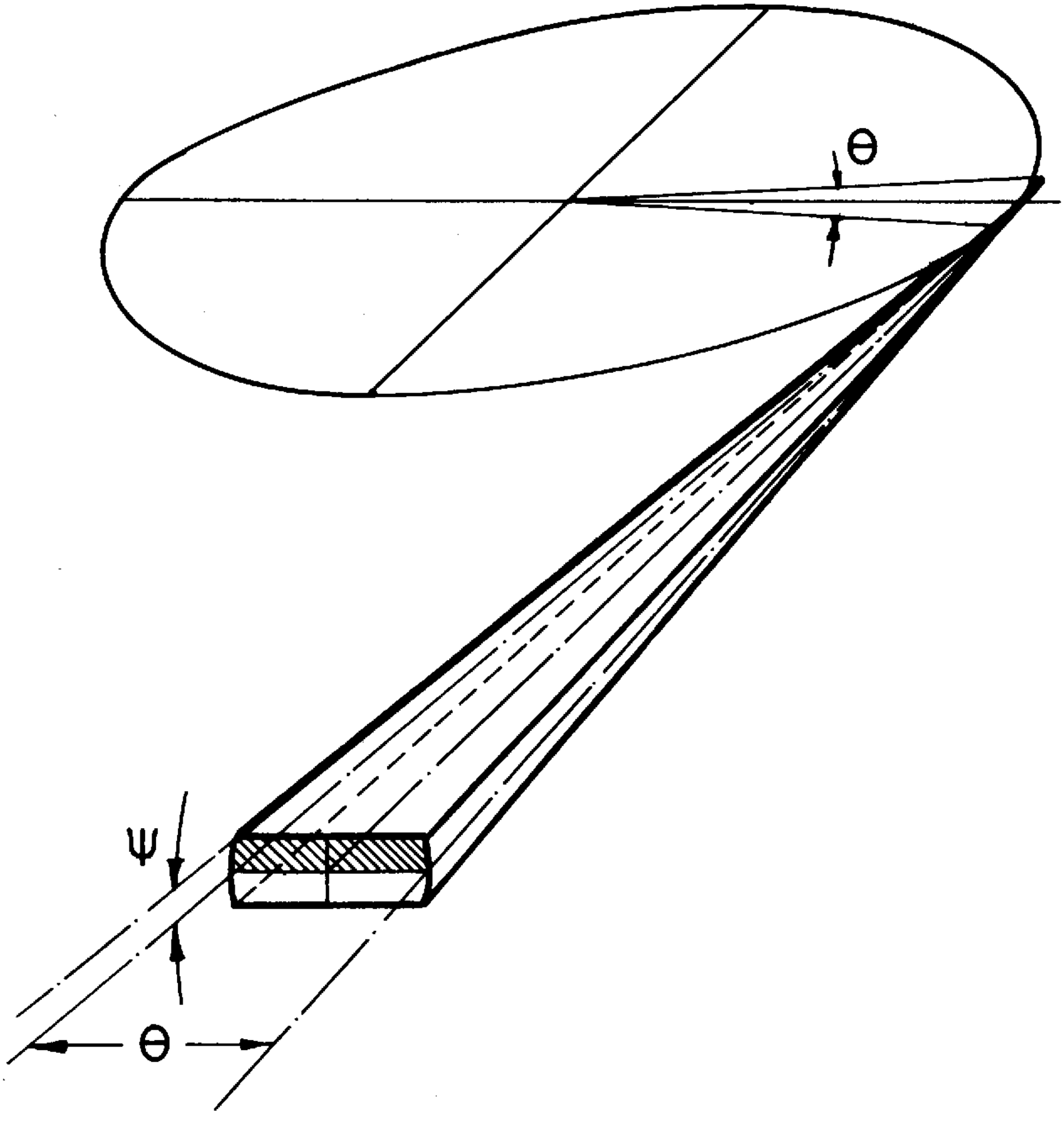


Fig. 1

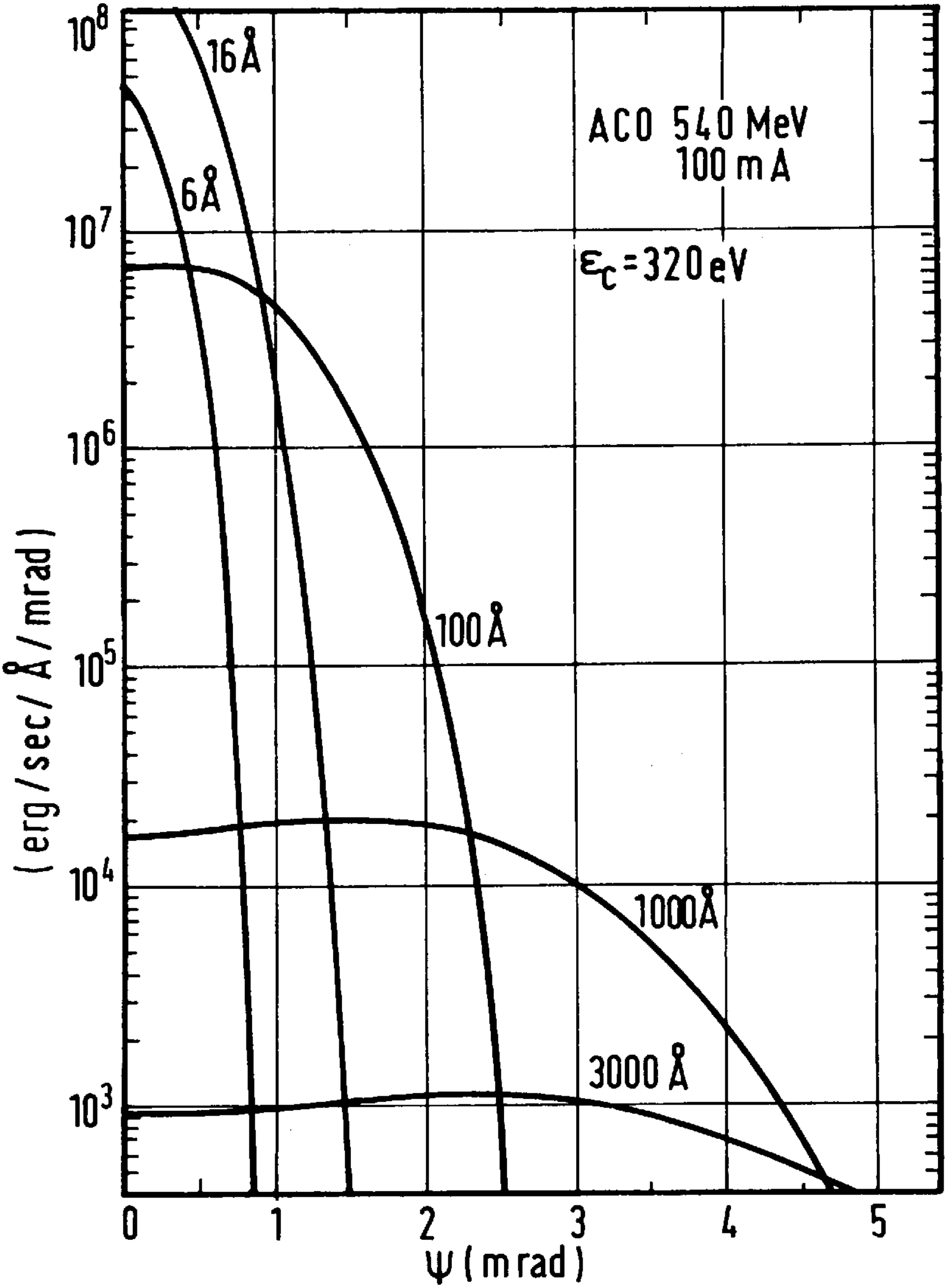

ACO 540 MeV
100 mA
ε_c = 320 eV
16 Å
6 Å
100 Å
1000 Å
3000 Å
(erg/sec/Å/mrad)
ψ (mrad)
10^8
10^7
10^6
10^5
10^4
10^3
0
1
2
3
4
5

Fig. 2

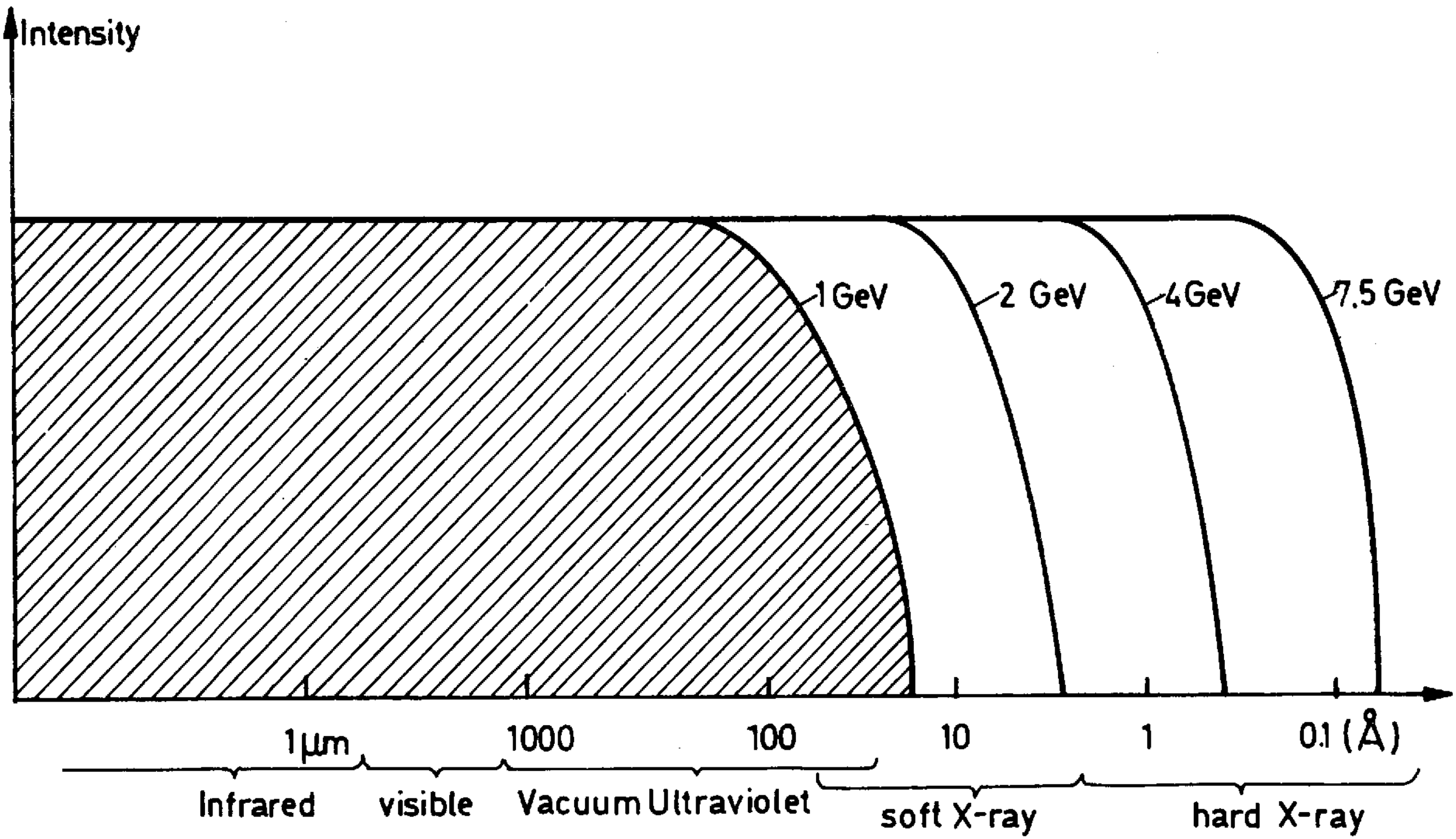

Intensity
1 GeV
2 GeV
4 GeV
7.5 GeV
1 μm
1000
100
10
1
0.1 (Å)
Infrared
visible
Vacuum Ultraviolet
soft X-ray
hard X-ray

Fig. 3

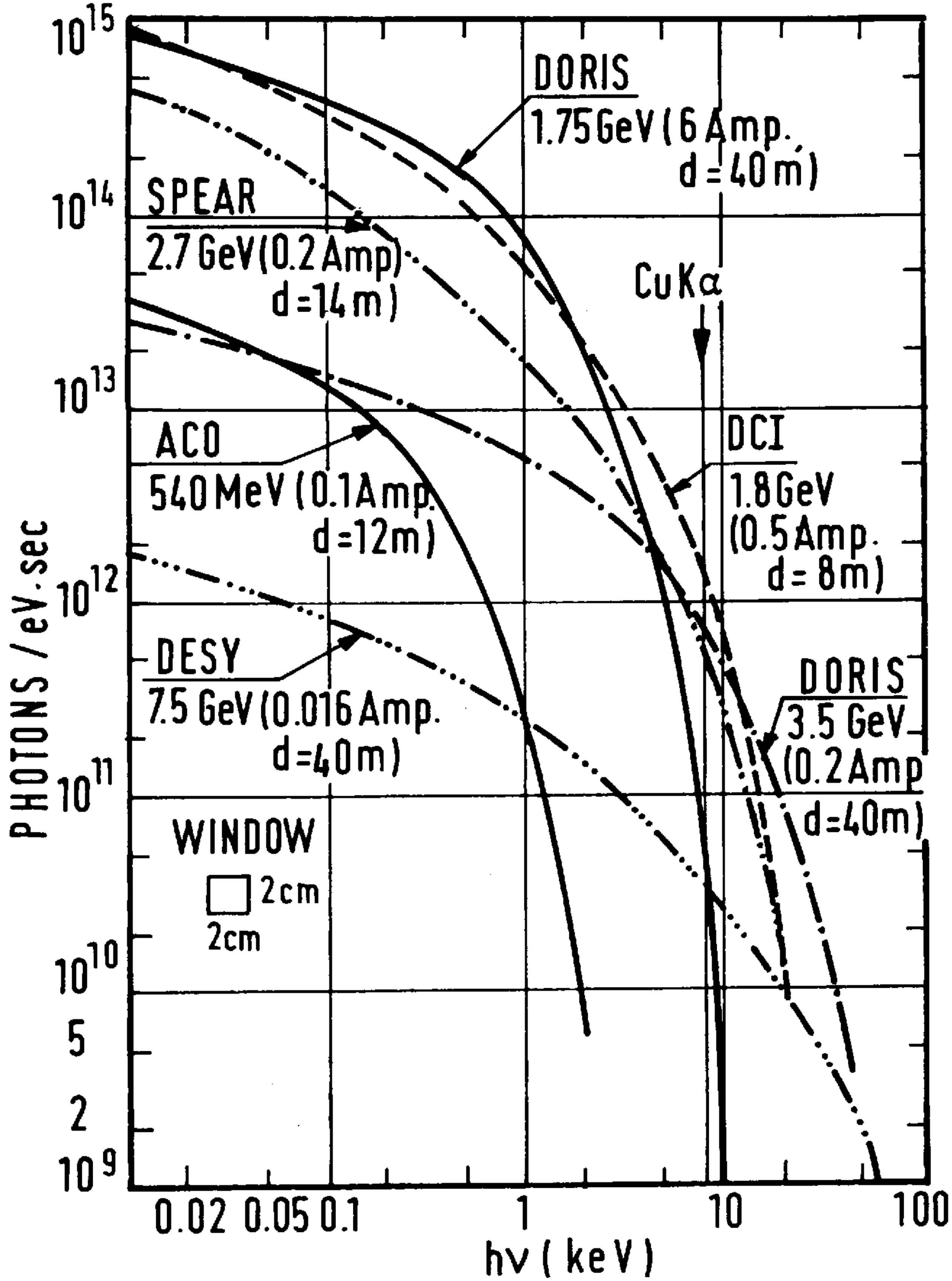

PHOTONS / eV·sec
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
5
2
10^{9}
0.02 0.05 0.1
1
10
100
hν (keV)
DORIS
1.75 GeV (6 Amp.
d = 40 m)
SPEAR
2.7 GeV (0.2 Amp)
d = 14 m)
CuKα
ACO
540 MeV (0.1 Amp.
d = 12 m)
DCI
1.8 GeV
(0.5 Amp.
d = 8 m)
DESY
7.5 GeV (0.016 Amp.
d = 40 m)
DORIS
3.5 GeV
(0.2 Amp
d = 40 m)
WINDOW
2cm
2cm

Fig. 4

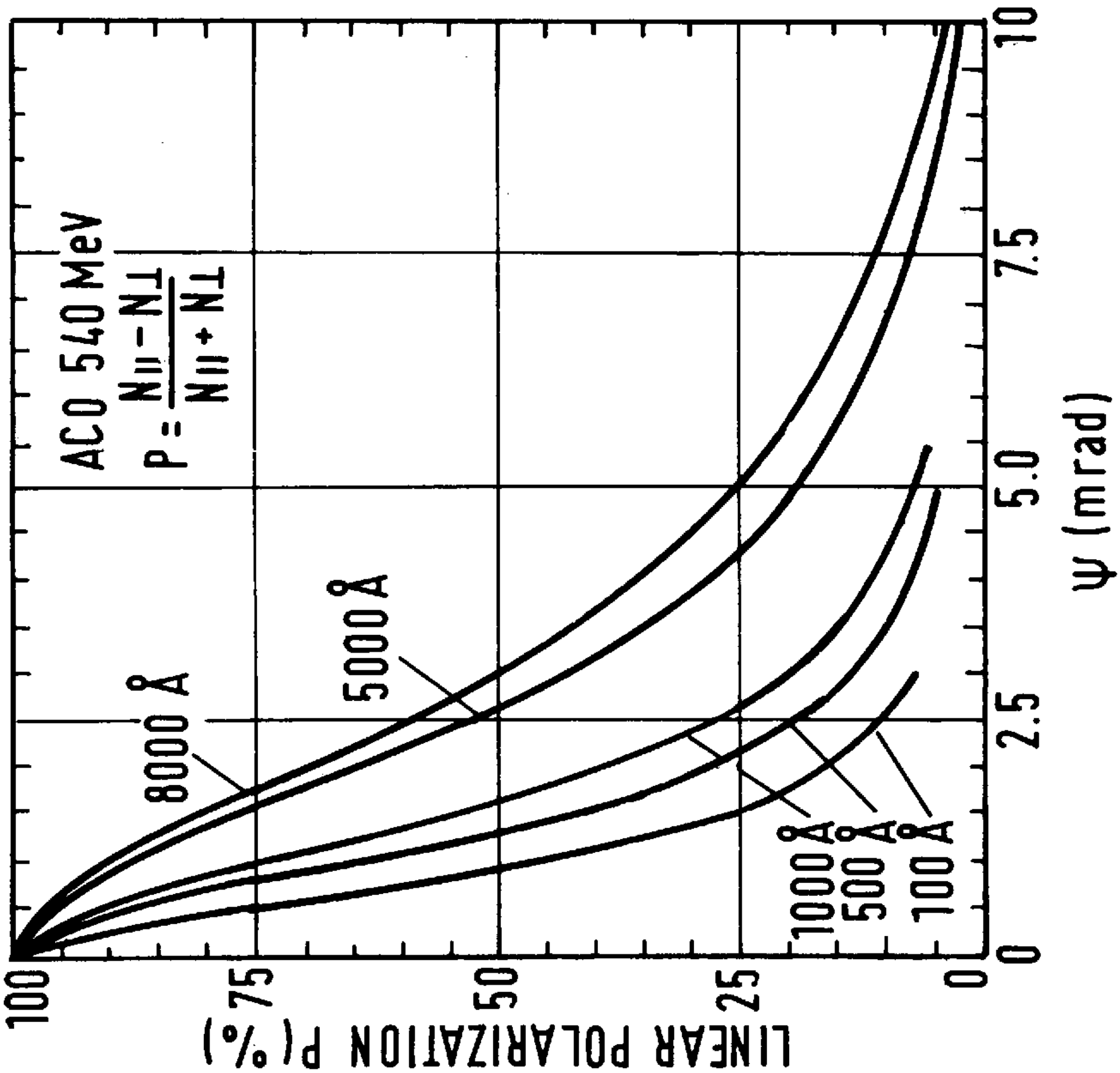
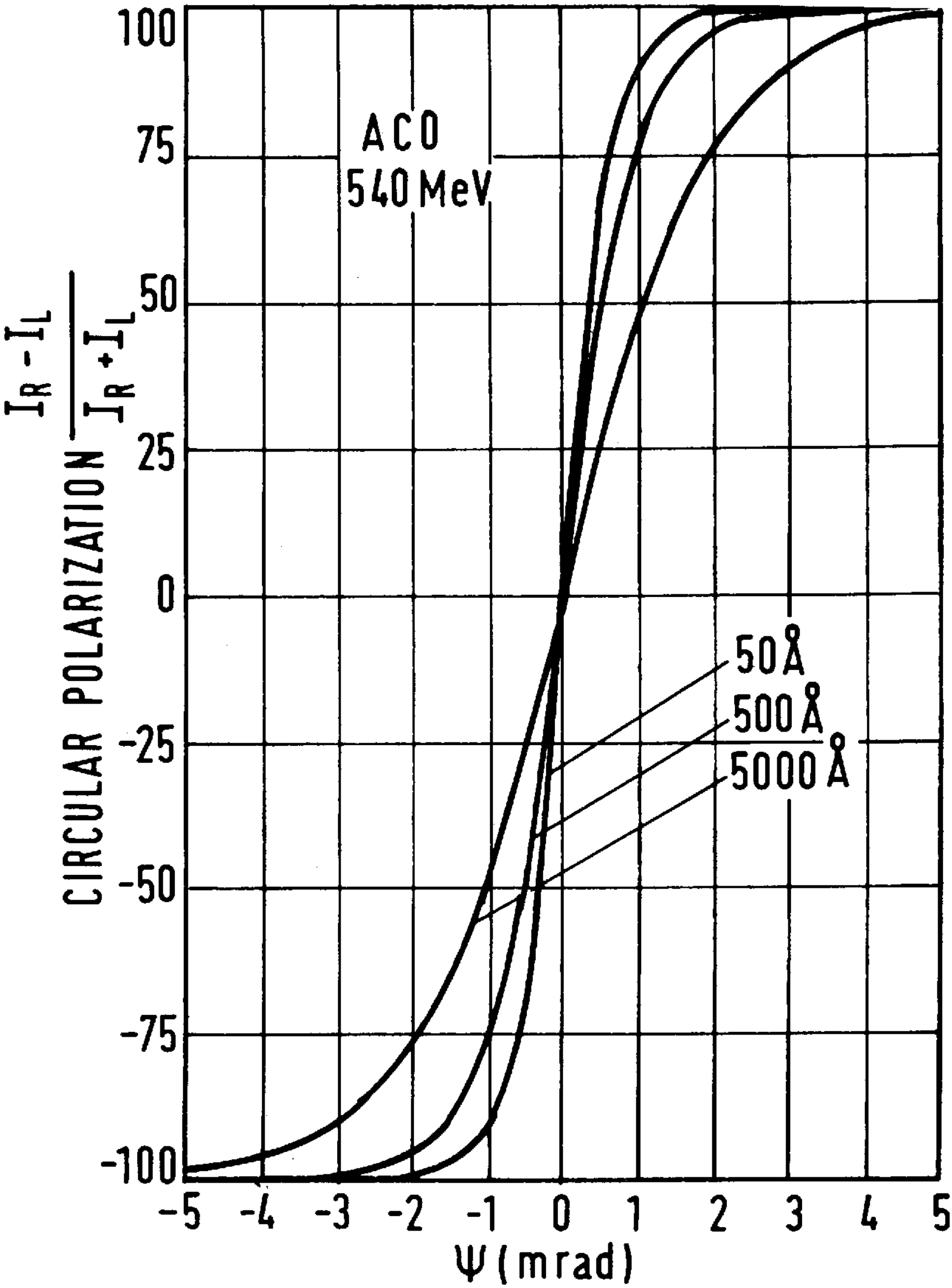
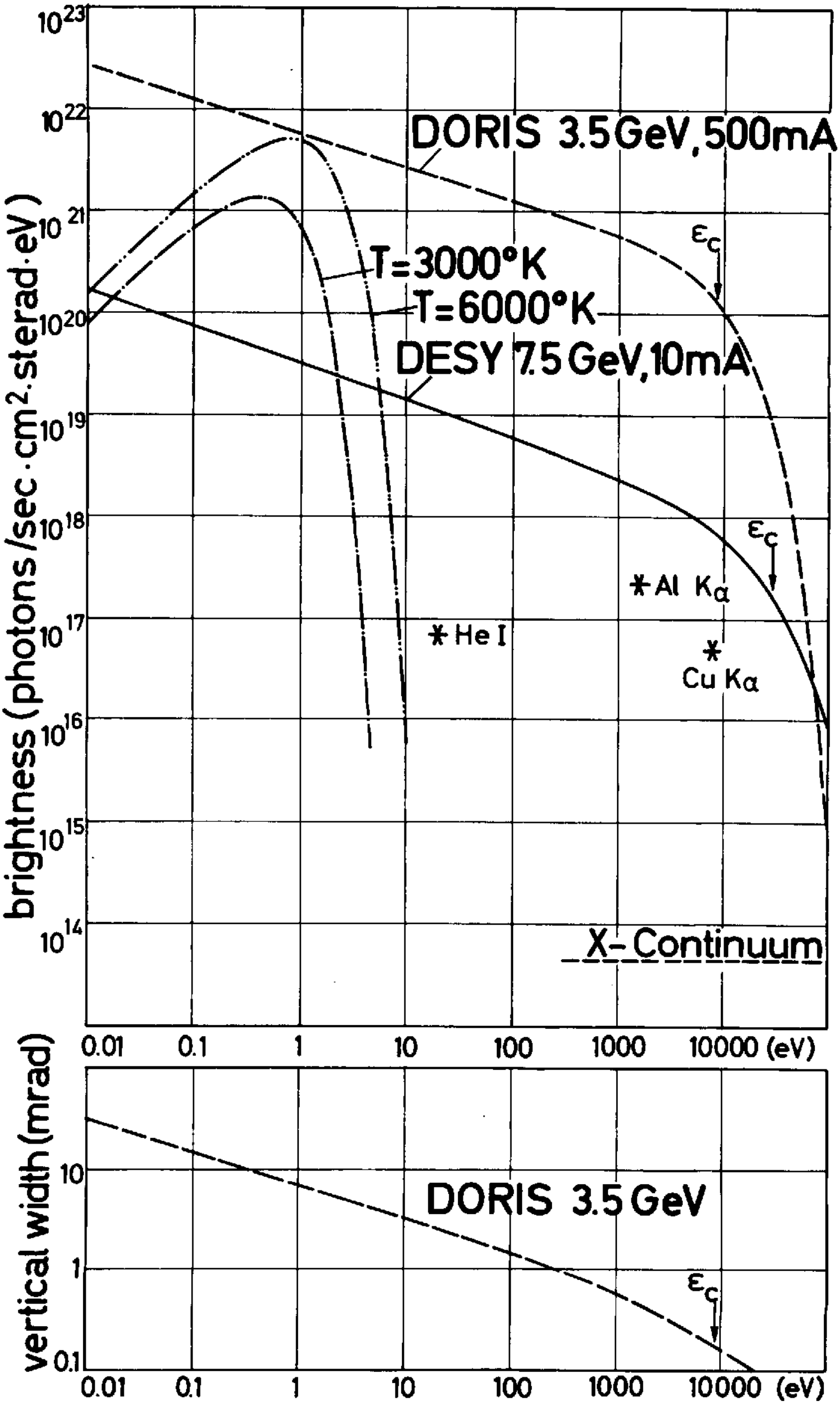

ACO 540 MeV
P = (N∥ − N⊥)/(N∥ + N⊥)
8000 Å
5000 Å
1000 Å
500 Å
100 Å
0
2.5
5.0
7.5
10
ψ (mrad)
0
25
50
75
100
LINEAR POLARIZATION P (%)

Fig. 5



ACO
540 MeV
CIRCULAR POLARIZATION $\frac{I_R - I_L}{I_R + I_L}$
100
75
50
25
0
-25
-50
-75
-100
50 Å
500 Å
5000 Å
-5 -4 -3 -2 -1 0 1 2 3 4 5
Ψ (mrad)

Fig. 6



DORIS 3.5 GeV, 500mA
T=3000°K
T=6000°K
DESY 7.5 GeV, 10mA
ε_c
Al Kα
He I
Cu Kα
X-Continuum
brightness (photons/sec·cm².sterad·eV)
10^23
10^22
10^21
10^20
10^19
10^18
10^17
10^16
10^15
10^14
0.01
0.1
1
10
100
1000
10000 (eV)
DORIS 3.5 GeV
vertical width (mrad)
10
1
0.1

Fig. 7

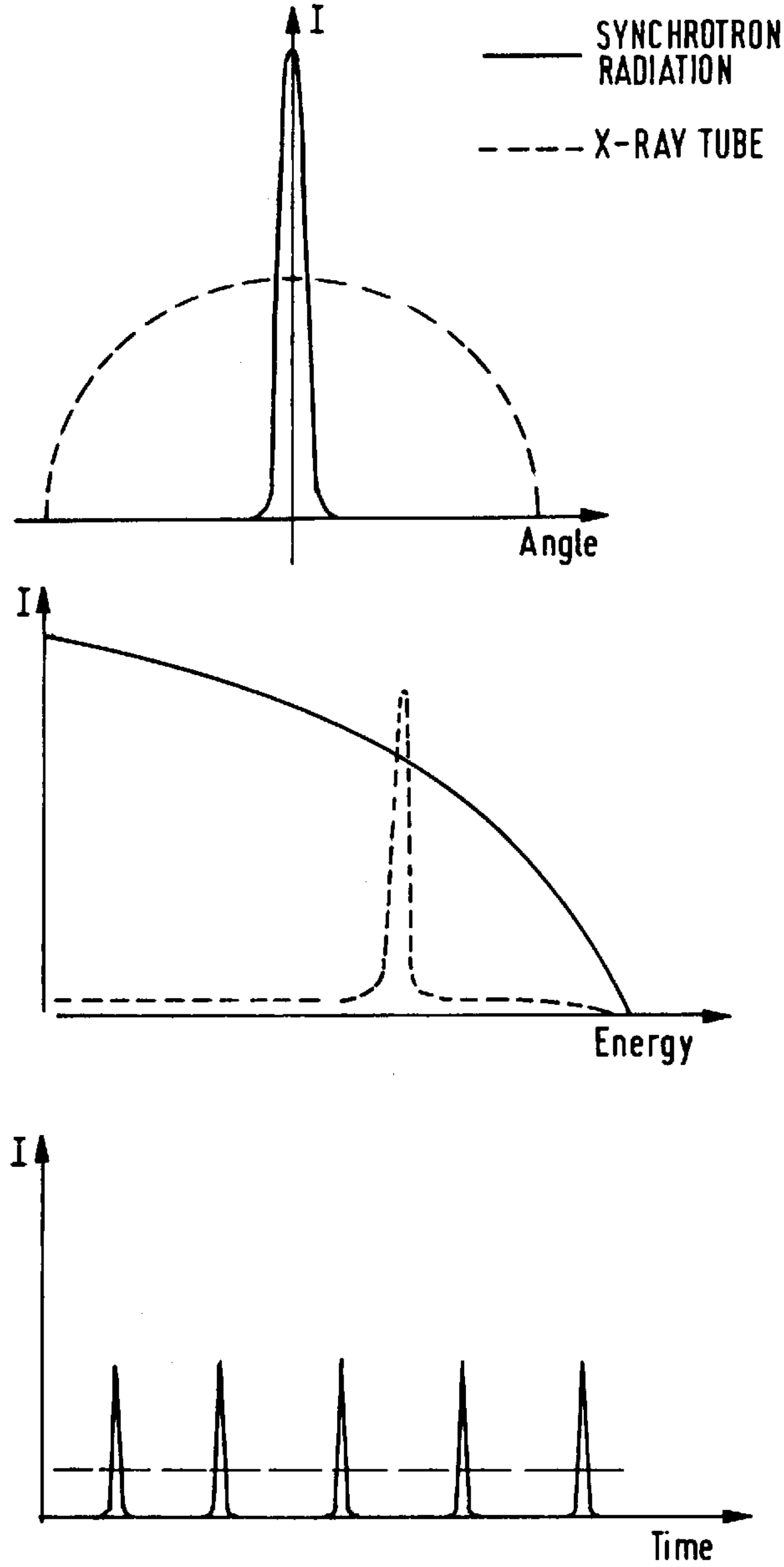
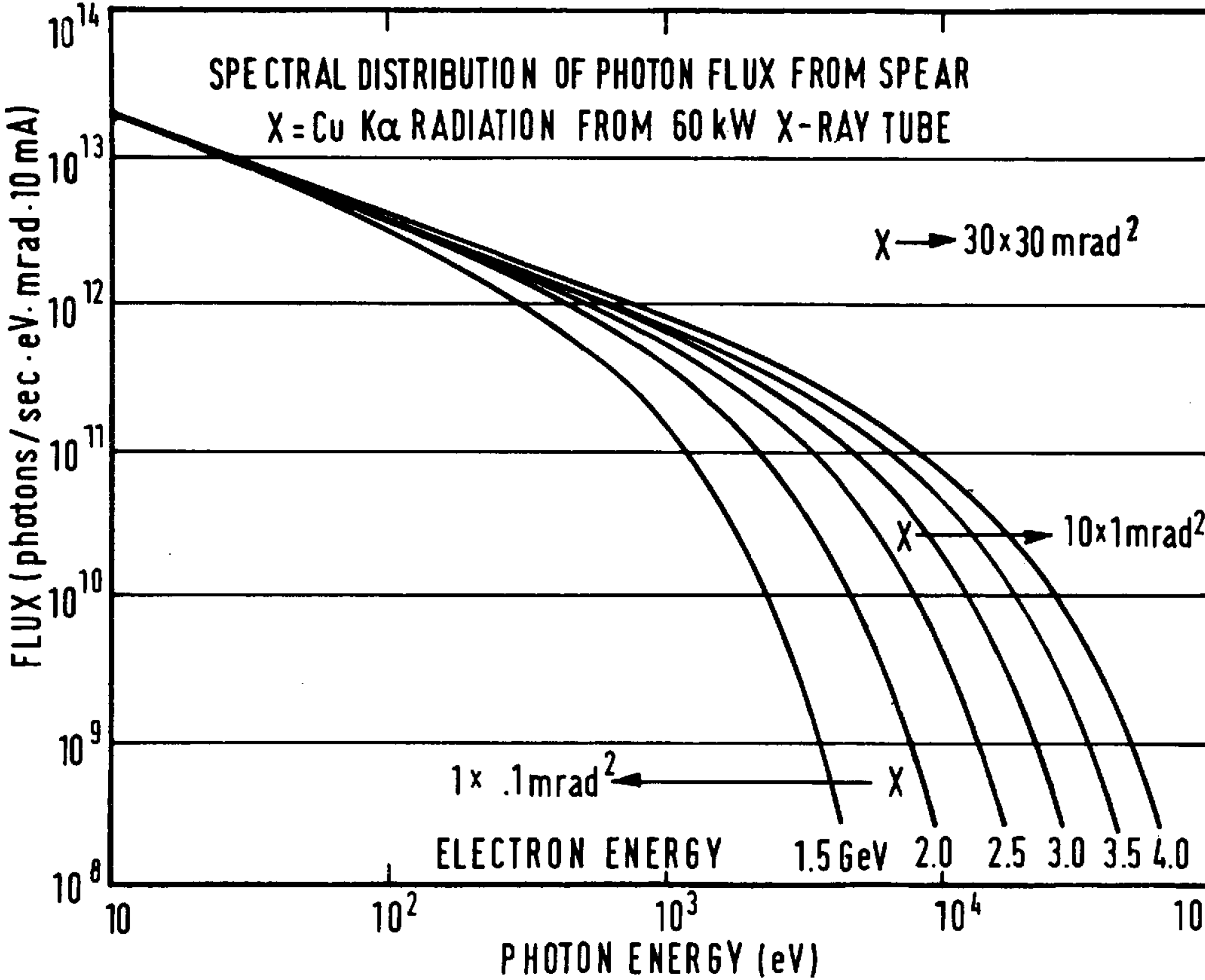


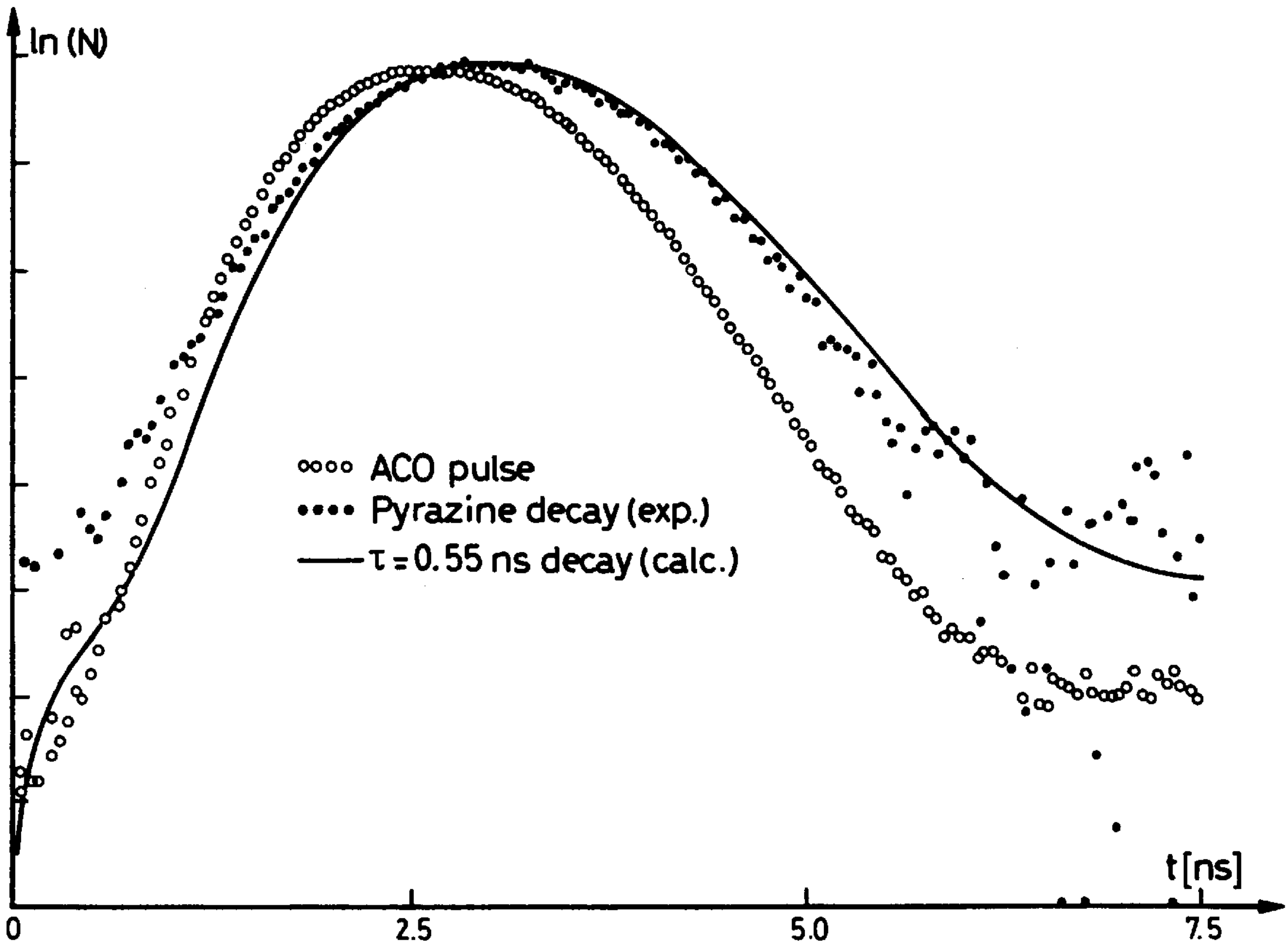
Fig. 8



SPECTRAL DISTRIBUTION OF PHOTON FLUX FROM SPEAR
X = Cu Kα RADIATION FROM 60 kW X-RAY TUBE
X → 30×30 mrad²
X → 10×1 mrad²
1× .1 mrad² ← X
ELECTRON ENERGY
1.5 GeV
2.0
2.5
3.0
3.5
4.0
FLUX (photons/sec·eV·mrad·10 mA)
10¹⁴
10¹³
10¹²
10¹¹
10¹⁰
10⁹
10⁸
10
10²
10³
10⁴
10⁵
PHOTON ENERGY (eV)

Fig. 9

Fig. 10



ln (N)
ACO pulse
Pyrazine decay (exp.)
τ = 0.55 ns decay (calc.)
t [ns]
0
2.5
5.0
7.5

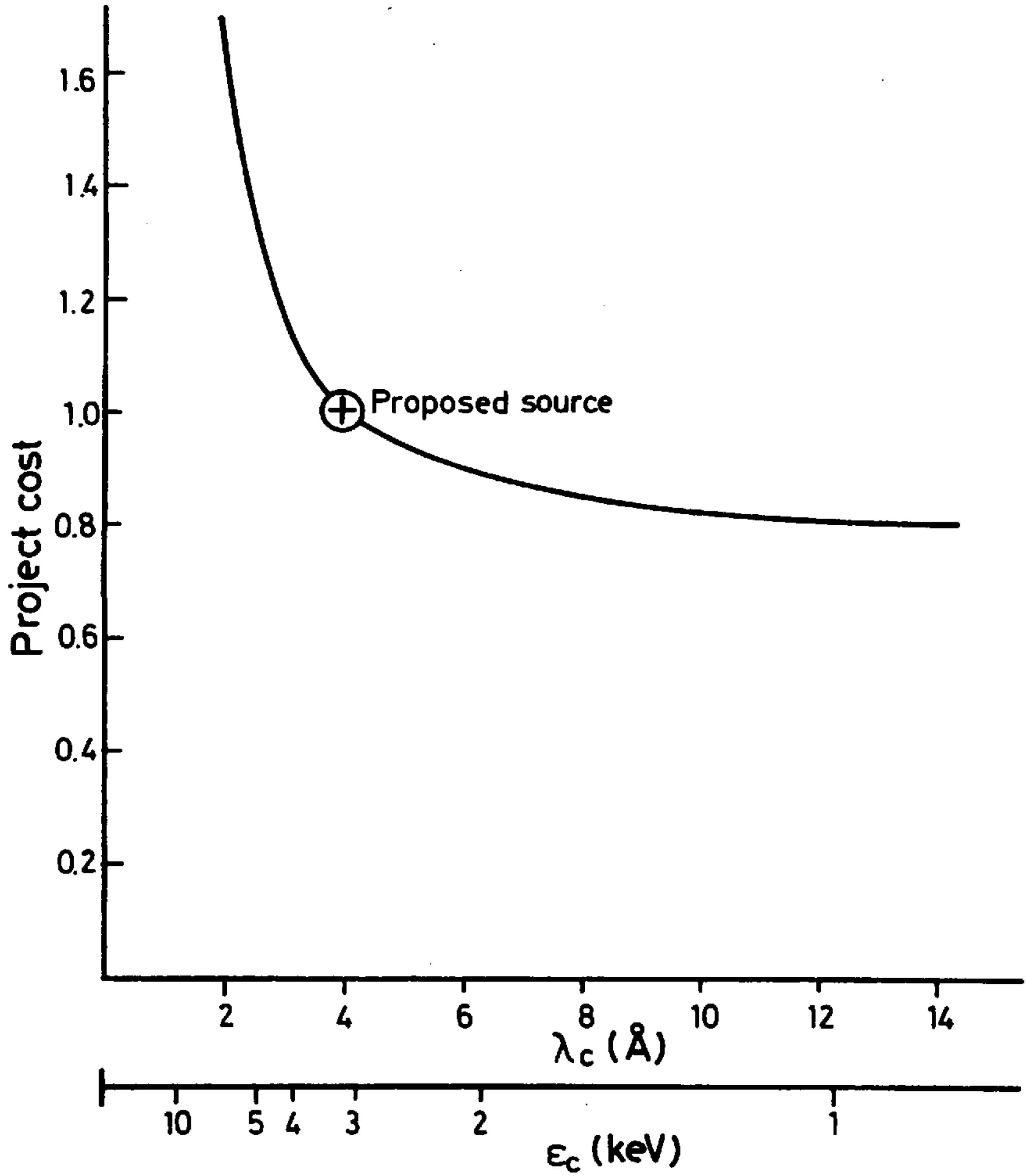

Project cost
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Proposed source
2
4
6
8
10
12
14
λc (Å)
10
5
4
3
2
1
εc (keV)

Fig. 11

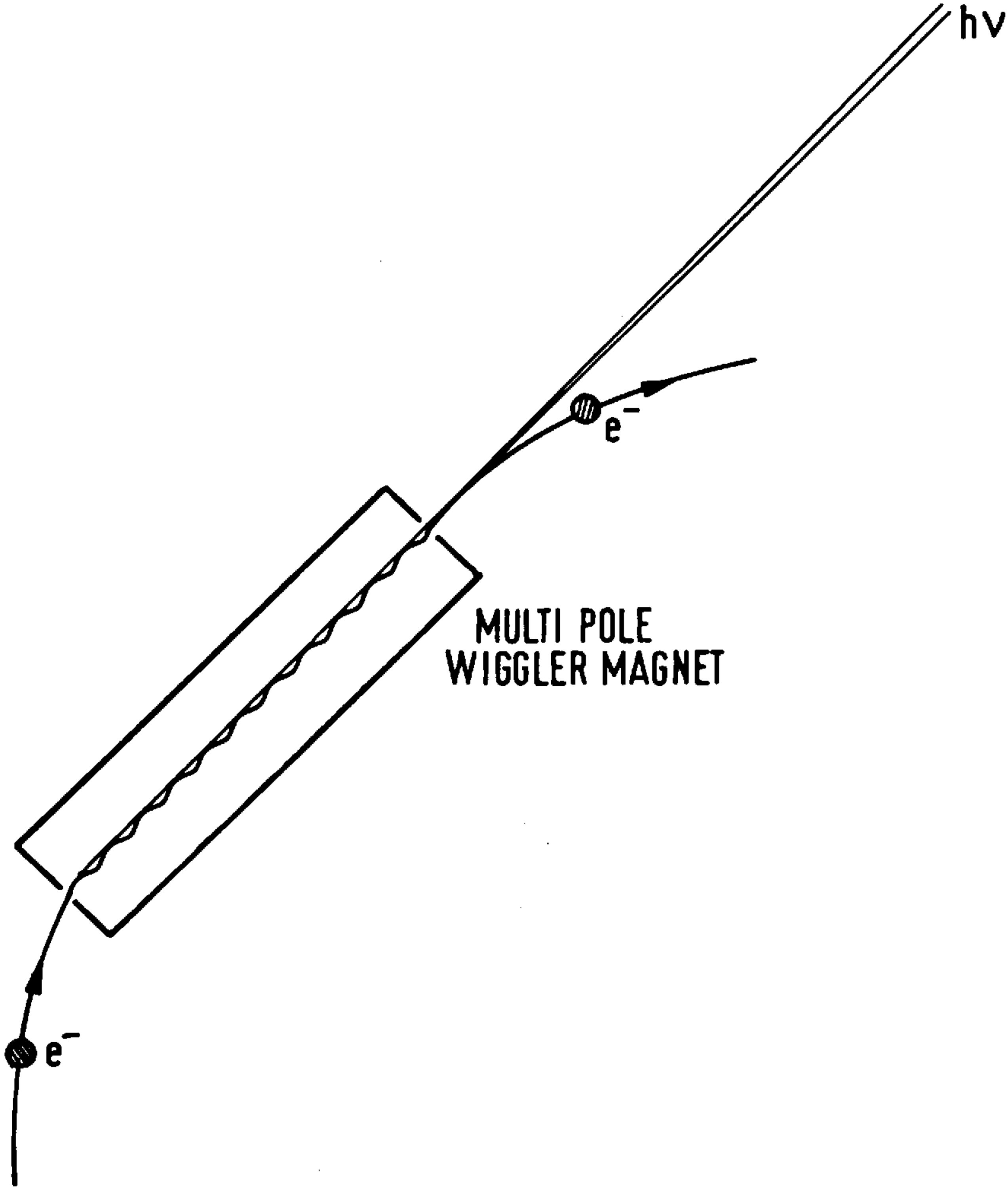


Fig. 12