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An Introduction

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Optical Components and Systems for Synchrotron Radiation: An Introduction*

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Abstract

A brief description of the nature and origins of synchrotron radiation is given with special reference to its geometrical optical properties and the use of storage rings as light sources. The geographical distribution of SR sources in the world is reviewed and some discussion of the level of experimental activity is given. Estimates of future levels of experimental activity are also made both for existing storage rings and those planned for the future. Calculations of the approximate number of mirrors and gratings that will be required are offered. Some general considerations are outlined showing how synchrotron radiation optical systems couple to the light source and indicating which parameters need to be maximized for best overall performance.

Introduction

Synchrotron Radiation (SR) is now used sufficiently widely to create a significant worldwide demand for special optics. It is the purpose of this meeting to discuss the nature of these components and the problems involved in manufacturing them. In this paper, we address some more limited questions:

1. What is the general nature of SR and how is it produced?
2. What is the worldwide capability for generating SR and what quantity of special optics is needed?
3. What are the design goals of SR optical systems and how should such systems be evaluated?

The Nature of Synchrotron Radiation

SR is emitted when electrons travel around curved paths. In storage rings, electrons are kept essentially permanently in a circular orbit and so synchrotron radiation is emitted continuously. The radiation is directed along the tangent to the electron trajectory and since the tangents to a circle completely fill the plane of the circle the radiation is emitted as a flat horizontal sheet in the plane of the electron orbit.

Fig. 1 - Universal synchrotron radiation spectrum which is applicable to all storage rings. Note that the wavelength of the light is expressed in units of λ_c the critical wavelength of the storage ring which is defined in the text.

The spectral content of the radiation depends on the nature of the storage ring, but the spectrum always has the same SHAPE. This is shown in Fig. 1. We see that the spectrum has a broad continuum at long wavelengths with a peak close to $\lambda = \lambda_c$ where λ_c is the so-called 'critical wavelength' and then a rapid fall to zero at short wavelengths (high energies). The value of λ_c is related to the storage ring parameters by the equation:

$$\lambda_c(\text{\AA}) = \frac{5.59 R(\text{m})}{E(\text{GeV})^3} \quad (1)$$

where R is the storage ring radius and E its energy. We see that the wavelengths emitted are strongly dependent on the energy of the storage ring. For high energy storage rings λ_c is short and wavelengths in the X-ray range can be produced e.g. for the SPEAR storage ring at Stanford $R = 12.7\text{m}$, $E = 3\text{GeV}$ and so $\lambda_c = 2.6\text{\AA}$. An alternative way to specify the position of the peak of the spectrum is to give the critical energy E_c instead of the critical wavelength λ_c . E_c is given by:

$$E_c(\text{eV}) = 12398/\lambda_c(\text{\AA}) \quad (2)$$

For lower energy storage rings, λ_c may be such that X-rays are not produced and the spectrum peaks in the ultra-violet. This is also useful for many applications.

The sheet of emitted radiation is not of zero thickness. The radiation has a finite opening angle in the vertical direction. The vertical angular distribution is, in fact, a Gaussian with standard deviation given by:

$$\sigma_{\text{SR}} = \frac{570}{\gamma} \left(\frac{\lambda}{\lambda_c} \right)^{0.43} \text{ milliradians (mr)} \quad (3)$$

where γ is the electron energy expressed in units of the electron rest energy $m_0 c^2$ (0.511 MeV).

We are now in a position to make a simple characterization of the electron storage ring as our optical source. The spatial extent of the source is the size of the electron beam which is very small, often on the order of 1mm^2 . The angular extent is given by (2) for the vertical direction. For the horizontal, the amount of radiation collected is determined by the size of the pipework used. Normally for ultra-violet work 10-50 mr are collected and for x-ray work about 2-10 mr.

The broad picture is that SR provides very large fluxes of photons from a very small source area and confined within a small solid angle. In other words, electron storage rings are sources of uniquely high BRIGHTNESS.

Geographical Distribution of Synchrotron Radiation Sources

The unique properties of SR and its universal appeal to scientists and technologists from a wide range of disciplines has brought about a large investment in SR sources around the world. Fig. 2 shows the distribution of sources presently existing or under construction. Sources which are planned and funded or close to being funded are shown in quotation marks. Additional information about the various sources is given in Tables I and II. Table I refers to the sources presently existing or under construction. Table II lists some which are currently planned for the future.

Optical Requirements at Synchrotron Radiation Sources

The detailed nature of the needs for optical components vary so much between different facilities that no simple definition can be given. The overall problem is addressed in the present meeting proceedings taken as a whole and by the proceedings of a previous meeting⁽¹⁾. What we do attempt to address here is the quantity of optics required. Tables I and II give information on the number of ports used for conveying SR out of the storage rings and into optical systems leading to experimental stations. The figures for the number of ports in use now and the number of experimental stations now are fairly accurate. The ratio # stations/# ports indicates the degree to which ports tend to be subdivided at that facility. The estimates of future numbers of ports and stations assume a similar subdivision ratio unless some reasonable argument indicates otherwise. The future estimates naturally involve a certain amount of guesswork. The data on numbers of ports and stations are omitted for the SR sources in the USSR. This is partly due to lack of good information and partly because the sale of some optical components to the USSR is subject to restriction.

Fig. 2 - Geographical distribution of synchrotron light sources in the world. Sources which are planned, but not yet funded or not yet started are shown with quotation marks.

Table I - Present Synchrotron Light Sources

Country	City	Ring	Stge Ring	E GeV	E KeV	# Ports Now	# Exp. Stas. Now	Psble. Future Ports	Psble. Future Stas.
France	Orsay	ACO	*	0.55	0.33	4	12		
		DCI	*	1.8	3.39	2	10	2	10
Germany	Braunschweig	PTB		0.14	0.013	2	2		
	Bonn	BONN I		0.5	0.163	1	1		
	Bonn	BONN II		2.5	4.53	4	4		
	Hamburg	DESY		7.5	25.5	3	9		
	Hamburg	DORIS	*	5.0	22.9	10	29		
	Hamburg	PETRA	*	19.0	75.0	-	-	1	1
	Berlin	BESSIE	*	0.8	0.63	11	11	13	61
Italy	Frascati	ADONE	*	1.5	1.5	2	6	2	4
Japan	Tokyo	INS-SOR I		1.3	1.22	1	1		
	Tokyo	INS-SOR II		0.3	0.054	4	6	2	2
	Tsukuba	Photon Fac	*	2.5	4.3	6	27	14	56
	Tsukuba		*	0.6	0.3	4	4	12	36
Sweden	Lund	LUSY		1.2	1.05	1	2		
U.K.	Daresbury	SRS	*	2.0	3.2	2	8	10	40
USA	Stoughton	ALADDIN	*	1.0	1.06	20	20	16	16
	Stoughton	TANTALUS I	*	0.24	0.048	7	9		
	Washington	SURF II	*	0.24	0.037	6	9	1	2
	Stanford	SPEAR	*	4.0	11.2	5	14	8	10
	Stanford	PEP	*	15.0	44	-	-	1	1
	Upton	BRKHN I	*	0.7	0.40	9	11	7	3
	Upton	BRKHN II	*	2.5	4.25	18	34	10	20
	Cornell	CESR	*	8.0	35.0	3	3	-	-
USSR	Moscow	C60		0.68	0.35				
	Moscow	PACHRA		1.3	1.22				
	Yerevan	ARUS		6.0	19.5				
	Tomsk	SIRIUS		1.3	11.6				
	Novosibirsk	VEPP-2M	*	0.67	0.35				
	Novosibirsk	VEPP-3	*	2.2	3.8				
	Novosibirsk	VEPP-4	*	6	14.5				

Table II - Planned Synchrotron Light Sources

Country	City	Ring	Strge. Ring	E GeV	E _c keV	# Ports Now	# Exp. Stas. Now	Psble. Add'l. Ports	Psble. Add'l. Stas.
Australasia				.5				16	48
Europe	?	ESF	*	5.0	12.5			48	144
France	Orsay	Super ACO	*	0.8				16	48
India	Poona	-	*	0.7	0.4			16	48
Japan	Okasaki	UV-SOR	*	0.6				16	48
Japan	Tsukuba	UV Photon Factory	*	.5				16	48
P.R.C.	Hofei		*	0.8				16	48

In order to arrive at some estimate of the quantity of optics involved in SR let us make the crude assumption that for each experimental station there are 4 mirrors and 0.5 gratings. Totalling the 'Possible Future Stations' columns of Tables I and II we find:

Table I: Existing Facilities.

Possible Future Stations	286
# Mirrors	1144
# Gratings	143

Table II: New Facilities.

Possible Future Stations	432
# Mirrors	1728
# Gratings	216

We may conclude from these very rough estimates that there is a useful volume of business involved. In the opinion of this writer, it would be mutually beneficial if a few small companies were to develop a special interest in the synchrotron radiation market.

Design Goals for Synchrotron Radiation Optical Systems

The spectrum of SR is continuous and although this is one of the advantages of SR it is not generally desirable to deliver the full spectrum to an experimental sample. Normally one wishes to select a narrow band of wavelengths ($\Delta\lambda$) for application to the sample. This selection is carried out by an instrument known as a monochromator. Usually, the monochromator is designed so that the selected band of wavelengths can be tuned across a fairly wide range.

The design goals for these systems can now be stated. They are, firstly, that the selected bandwidth, $\Delta\lambda$, shall be narrow enough for the application on hand and secondly, to deliver the maximum flux within that bandpass to the sample. We are glossing over certain issues here in the interest of clarity. For simplicity, let us also neglect for the moment the coupling of the radiation emerging from the monochromator onto the sample. We are, therefore, looking for a formalism that will help us see how we can maximize the flux of radiation in $\Delta\lambda$ emerging from the monochromator.

Performance Calculations

Returning to Fig. 1, we see that we start out with a flux of photons that we can describe as:

$$N(\lambda) \text{ photons/sec/mr/}\mu\text{A/GeV}/0.1\% \Delta\lambda/\lambda$$

'mr' refers to the horizontal angle (θ) which is collected. 'mA' refers to the storage ring current i and 'GeV' refers to the electron energy E . It is assumed that all of the vertical angular spread is collected. Our beam line thus collects from the source a flux of photons given by:

$$N(\lambda) E i \theta \frac{\Delta\lambda}{\lambda} \text{ photons/sec.}$$

Now let us suppose that we are dealing with a monochromator which has both an entrance and an exit slit and that our optical system consists of a single condensing mirror which 'images' the source onto the entrance slit. This simple system is easy to visualize but the conclusion we are working toward is applicable to a much more general class of systems. If the image of the source is smaller than the entrance slit (set for bandpass $\Delta\lambda$) and if the angular extent of the beam going into the monochromator is smaller than the angular acceptance (horizontally and vertically) of that instrument, then we have no problems. The optical system is underfilled and all of the flux within $\Delta\lambda$ collected by the beam line can be used. More normally, however, the optical system is overfilled and we now proceed to calculate the flux $F(\lambda)$ at the exit slit of the monochromator for this case. We have:

$$F(\lambda) = N(\lambda) E i \theta \frac{\Delta\lambda}{\lambda} \times \begin{pmatrix} \text{vert.} \\ \text{slit} \\ \text{width} \end{pmatrix} \begin{pmatrix} \text{horiz.} \\ \text{slit} \\ \text{width} \end{pmatrix} \begin{pmatrix} \text{vert.} \\ \text{slit} \\ \text{accept.} \end{pmatrix} \begin{pmatrix} \text{horiz.} \\ \text{slit} \\ \text{accept.} \end{pmatrix} \times \begin{matrix} \text{Efficiency} \\ \text{Factors} \end{matrix} \quad (4)$$

$$\begin{pmatrix} \text{vert.} \\ \text{spot} \\ \text{width} \end{pmatrix} \begin{pmatrix} \text{horiz.} \\ \text{spot} \\ \text{width} \end{pmatrix} \begin{pmatrix} \text{vert.} \\ \text{beam} \\ \text{diverg.} \end{pmatrix} \begin{pmatrix} \text{horiz.} \\ \text{beam} \\ \text{diverg.} \end{pmatrix}$$

The efficiency factors represent the efficiency with which photons in $\Delta\lambda$ are reflected or diffracted by optical components. We note that for the four fractions, the top lines refer to the geometry of the monochromator and the bottom lines refer to the geometry of the photon beam focal spot at the entrance slit. It is understood that each fraction has a value less than unity for overfilling or unity for underfilling. We also note that the top lines of the four fractions are equal to the étendue (or light gathering power) of the monochromator and the bottom lines are the product of the horizontal and vertical emittances of the photon beam. We thus arrive at:

$$F(\lambda) = \frac{\text{Flux from source}}{(\text{emittance})^2} \cdot \text{étendue} \times \text{efficiency factors.} \quad (5)$$

The fraction on the left is nothing more than the brightness of the source. So we write finally, noting that the monochromator étendue is a function of bandwidth:

$$F(\lambda) = \text{BRIGHTNESS} \cdot \text{ÉTENDUE} \left(\frac{\Delta\lambda}{\lambda} \right) \cdot \text{EFFICIENCY FACTORS}$$

(6)

We have thus identified the characteristics in our system which contribute to achieving a high value of $F(\lambda)$, the photon flux in $\Delta\lambda$ emerging from the monochromator. We conclude that we want a high brightness source, a high étendue monochromator (when set to $\Delta\lambda$) and highly efficient reflectors and diffractors.

We have assumed through this argument that the value of $\Delta\lambda$ is fixed by the requirements of the experiment and the monochromator is capable of achieving that value. Now, clearly, the ability to achieve high resolution is one aspect of a 'good' monochromator. A high étendue is another. So to arrive at a figure of merit for comparing monochromators, we should include both aspects. This is traditionally done using a parameter loosely called the 'resolution, luminosity product' (L) and defined by:

$$L = \frac{\lambda}{\delta\lambda} \cdot \text{étendue} \quad (7)$$

where $\frac{\lambda}{\delta\lambda}$ is the resolving power of the instrument. This is convenient when line sources are being used (or studied) but is not useful with a continuum source. This is because for continuum sources, the light gathered increases as the square of the bandpass setting instead of linearly as for line sources. Consequently, it is convenient to define a different figure of merit for the continuum case, say L' , given by:

$$L' = \left(\frac{\lambda}{\delta\lambda} \right)^2 \cdot \text{étendue} \quad (8)$$

The figure of merit is then once again independent of the slit setting.

Reference:

1. Workshop on X-ray Instrumentation for Synchrotron Radiation Research, Stanford, April, 1978 ed. Winick and Brown, SSRL report #78/04.

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