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A Source Design Strategy Providing 5 eV–100 keV Photons

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The future requirements for synchrotron radiation facilities in the UK have been surveyed by consulting the large user community. Some of the results of this survey are presented and it is shown that all requirements could be satisfied by access to three synchrotron radiation sources covering the spectral range from 5 eV to 100 keV. These sources are the 6 GeV ESRF, MES (a new 3 GeV replacement for the SRS) and LES (a new low-energy source at 700 MeV). Outline plans for LES and MES and their optimization to generate the requisite radiation quality and spectral range are discussed.

Keywords: source design; research programme; undulators; wigglers; free-electron lasers.

1. Introduction

Synchrotron radiation for research use has been provided in the UK since the early 1970s, first by the use of parasitic sources, and since 1981 by the dedicated 2 GeV SRS storage ring (Worgan, 1982). A large community of researchers has grown which makes use of this synchrotron radiation for a wide range of research using a diverse range of techniques (Daresbury Laboratory, 1993*a*). To monitor the scientific health of this research and to ensure that its requirements for facilities are properly met, it is the practice in the UK to conduct a review of the synchrotron radiation programme every six years.

A recent review was conducted by the Science Board of the UK SERC in 1992/1993 (Woolfson, 1993). A major part of the review was devoted to considering what new or upgraded facilities might be required over at least the next ten years, taking account of the international provision of synchrotron radiation facilities and the UK's membership of the ESRF. This paper describes the results of a survey of synchrotron radiation research requirements and a feasibility study of sources which could meet those needs.

2. Synchrotron radiation in the UK

The size of the synchrotron radiation research community in the UK is approximately 1500 individuals, although at any one time the active number is slightly lower. For example, in October 1991 the active number, defined as those with extant beamtime scheduled on the SRS, comprised 1200 researchers. The spectral range over which the SRS, together with its insertion devices, generates a useful source of photons lies between the far infra-red at $\sim 10^{-3}$ eV and hard X-rays at 50 keV. More than 40 experimental stations are provided at the SRS. They are listed in Table 1 according to the principal techniques which they support.

Table 1
Analysis of SRS experimental stations.

Technique		No. of stations
Photoemission		6
Spectroscopy		9
X-ray diffraction		11
EXAFS		7
Crystallography		5
Other		3
	Total	41
VUV		5
Soft X-ray		11
X-ray		22
Other		3
	Total	41

It is apparent, however, from the photon energies associated with these techniques that utilization of the SRS spectrum is not uniform, with the greatest exploitation being in the X-ray region from 1 keV upwards. In order that the future needs of synchrotron radiation science in the UK could be most accurately assessed, it was essential to discover from the active community their predictions for the likely directions in which their specialized areas would develop. This was carried out by conducting a survey of UK synchrotron radiation users. Approximately 1500 researchers were sent questionnaires about the scientific areas in which their future work would be carried out, the techniques and the range of photon energy which they would employ, and the physical size of a typical sample which would be researched. 27% of the questionnaires were returned by the required deadline and the replies are summarized in Table 2.

From Table 2 it is apparent that the greatest use of the synchrotron radiation spectrum in the UK is expected to occur in the X-ray region from 4 to 30 keV. Although the next largest community is in the soft X-ray region (0.1–4 keV), the VUV community below 0.1 keV is actually the second most demanding in terms of beamtime, because of the lower data rates in their typical experiments. Although no lower limit to the photon energy can be precisely

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Table 2
Survey of future research requirements (shown as percentages of individuals responding).

Technique	
Crystallography	36
Diffraction/scattering	19
X-ray spectroscopy	17
Spectroscopy (other)	16
Imaging	6
Infra-red spectroscopy	5
Other	1
Photon energy	
Less than 100 eV	17
100–4000 eV	19
4–30 keV	57
Above 30 keV	7
Sample size	
Greater than 1×1 mm^2	57
Less than 1×1 mm^2	32
Less than 50×60 μm^2	11

defined for the VUV community, it is clear that there exists a strong demand for research in the chemically important region around 10 eV and it would be very desirable to provide a region that is complementary with the upper limit of conventional lasers at about 5 eV. The extent to which high-brightness radiation is required is indicated by the proportion of users in the survey working with small samples, *i.e.* $< 50 \times 50$ μm^2. With roughly 10% of users in this category, the remaining research may be well served by sources of moderate brightness.

The review thus concluded that there is a strong need in the UK for the synchrotron radiation spectrum over the range 10 eV–100 keV and that this could be matched in the following manner.

(*a*) The 6 GeV ESRF would give access to high-brightness X-rays in the range 1–20 keV and to hard X-rays of lower brightness above 20 keV. Furthermore, the scale of interest in the UK community in this region of the spectrum is well matched to the fraction of the ESRF facility which is available for the UK.

(*b*) A medium-energy source (MES), for example the DIAMOND proposal (Poole *et al.*, 1993), as it is known by the accelerator community, could supply moderate-brightness radiation from undulators in the range 0.2–2 keV and high-flux radiation from multipole wigglers spanning 1–30 keV.

(*c*) A low-energy source (LES), for example the SINBAD proposal (Daresbury Laboratory, 1993*b*), would be able to generate high brightness radiation in the range 10 000–200 eV, and certainly provide an overlap with lasers down to 5 eV, and with the lower end of the range of the MES.

3. Outline design of the sources

The outline designs of the future MES and LES, in particular the electron-beam energy, can be decided quite easily from considerations of their insertion devices and their output radiation.

The multipole wigglers in MES must provide a good flux of photons between 1 and 30 keV. In practice this implies that the critical photon energy which characterizes the spectrum needs to be around 10 keV. Although high magnetic fields can be generated by superconducting wigglers, the main emphasis in a multipole wiggler is to produce a compact engineering design which maximizes the number of poles. These need only a moderately high magnetic field. Successful examples have been constructed with permanent magnets (Sasaki, Yamamoto, Shioya & Kitamura, 1989) and can be expected to produce fields of at least 1.5 T. For MES to produce the required radiation spectrum with this field implies that the electron-beam energy should be approximately 3 GeV.

Permanent magnet technology is also the established technique for constructing undulators (Halbach, 1981; Poole, 1989), but for this type of insertion device the emphasis is directed towards producing fields with a specific spatial periodicity. Although an undulator is a source of quasi-monochromatic radiation, whose energy may be adjusted by controlling the magnetic field strength to cover a suitably broad range of the spectrum in a given source, a range of devices with differing periodicities is required. This range is limited at the short-period end by the minimum gap which operation of the storage ring will allow, and at the long-period end by the reduction of performance which occurs when a smaller number of periods are contained in a device of given dimensions.

For the MES and LES, representative undulators will have periodicities in the range 30–100 mm. For MES at 3 GeV, these undulators will provide radiation in their first harmonic from 150 to 2400 eV and third harmonics over 450 to 5000 eV.

The energy of the LES is derived by consideration of the requirement that its undulators, which will have approximately the same periodicities as those in the MES, produce optimized spectra which extend from 10 eV up to an overlap with MES. This can be achieved with an electron-beam energy of 700 MeV, although it will be necessary to use third-harmonic radiation to obtain full overlap. The photon energies available extend to 5 eV, albeit with a non-optimized flux. The coverage in this region of the spectrum could be improved by using a lower electron-beam energy, although this is likely to decrease the quality of the electron beam through inter-electron scattering phenomena (Bruck & LeDuff, 1965). The LES undulators will provide radiation in their first harmonics from 9 to 130 eV with third harmonics over 26 to 270 eV.

4. Detailed design of LES

Having decided on 700 MeV as the electron-beam energy for LES, the next stage is to establish the overall scale of the storage ring. This is derived from the size of the research programme which is projected to use the VUV spectrum between 10 and 200 eV. User meetings in the UK produced a list of scientific areas of interest which are

Table 3
Anticipated science programme for LES.

Confocal microscopy	5–10 eV
Photo-dissociation	5–10 eV
High-resolution photo effects	5–50 eV
Circularly polarized PES	10–50 eV
Ultra-high-resolution PES	10–100 eV
Circular dichroism	5–200 eV
High-flux science	5–200 eV
High-resolution angularly resolved PES	5–200 eV
Spin-polarized PES	10–200 eV
Auger-coincidence PES	20–200 eV

shown in Table 3, and it is anticipated that the community's needs could be satisfied by 12 experimental stations centred around six undulator devices. In addition, some access to dipole sources in the same storage ring with good source brightness would be useful.

The lattice of the LES storage ring should, therefore, contain at least six cells with each including a long straight section in which an undulator may be located. Allowing for the other ancillary equipment which is essential for the operation of the electron storage ring, the result is a total number of eight straights (and cells).

The type of lattice cell which finds common application in synchrotron radiation sources is the double-bend achromat (DBA), because of its suitability, flexibility and high performance (Suller, 1992). With eight cells and an electron-beam energy of 700 MeV, the minimum theoretically attainable beam emittance is 2.8 nm rad, although a comfortable working value is more likely to be 10 nm rad. This will lead to the radiation source having reasonably high brightness.

It should not be forgotten that a synchrotron radiation source which is a national facility is likely to have a useful working life of about 20 years. During this time scientific techniques may evolve dramatically and it is very desirable that the source should have the capability to adapt to any changes. The application of VUV synchrotron radiation in research has been exploited from dipole magnet sources since the early 1960s, but it is only since the mid 1980s that undulator sources have been employed (Brennan *et al.*, 1986). It seems likely, therefore, that the field in which significant developments will occur in the VUV region of the spectrum is the technology of insertion devices.

The LES is, therefore, specifically designed to be able to accommodate new ideas for undulators. Four of its straight sections will operate with a wide range of possible undulators but these ideally need to be of proven design. Two of the remaining four straights are exceptionally long for a low-energy storage ring because of the following factors and will be able both to exploit novel undulators and to provide a test bed for their development.

(*a*) Long-period undulators for the important low-energy region of the synchrotron radiation spectrum have not yet been sufficiently explored. They will be inherently long devices needing very long straights.

(*b*) Radiation with specific but adjustable polarization can be produced from undulators with crossed magnetic fields (Kim, 1984; Elleaume, 1989). These tend to be long and require long straights.

(*c*) Very short period undulators, or those with helical fields, will have gaps which may be initially detrimental to the operation of a storage ring. To resolve such issues without having a major impact on the efficiency of the storage ring, there needs to be a rapid method, on a timescale of perhaps an hour, of switching the beam into a device under test. With very long straight sections this can

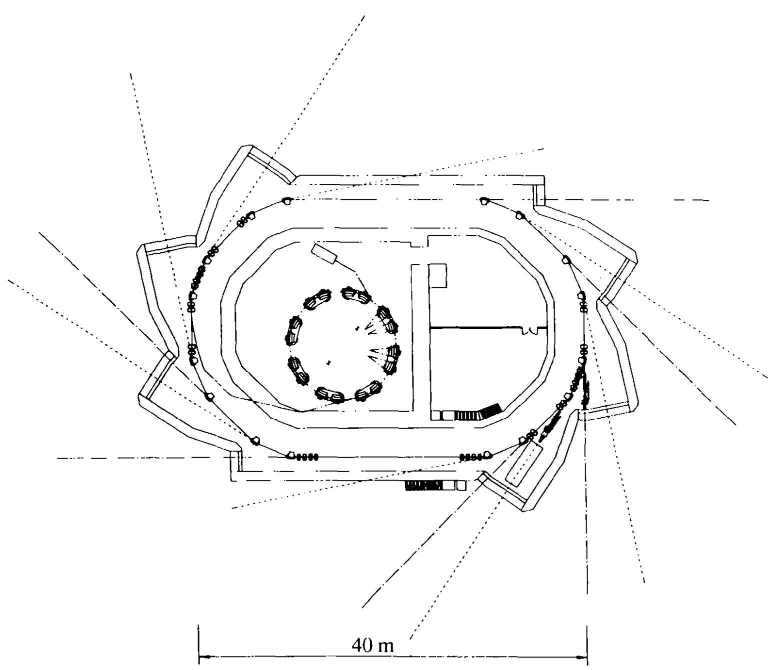

Figure 1
General view of the SINBAD storage ring.

be achieved by configuring the straight sections as bypasses.

(*d*) Free-electron lasers are a field of interest which is developing towards shorter wavelengths and higher power (Kim & Sessler, 1990) but is in need of much further experiment. A free-electron laser could be advantageously installed in one of the very long straights when it is configured as a bypass.

The general scheme of the SINBAD design proposal, which meets the specification of the LES source, is shown in Fig. 1. With its six long straights of 3.0 m and two very long straights of 15.0 m it will have a total circumference of 120 m. A relatively relaxed operating point has been selected initially, since this is most suitable for a source containing several undulators which need to be optimized and adjusted independently and with minimal restraint. The major parameters of the source for this lower-brightness mode are given in Table 4. It is undoubtedly the case that working points giving higher brightness can be developed as required. The major lattice functions are shown in Fig. 2 and indicate that the long straights can be exactly matched into the lattice functions of the standard cells by suitable adjustment of the quadrupoles within the long straights.

Table 4
Main parameters of the SINBAD design.

General		
Energy (GeV)		0.7
Magnetic bending field (T)		1.4
Circumference (m)		120
Beam emittance (nm rad)		10
Beam current (mA)		300
Lattice cell type		DBA
Number of cells		8
Length of normal dispersion free straight (m)		3.0
Length of very long dispersion free straight (m)		15.0
Lattice		
Radial, vertical tune		7.8, 2.6
Radial, vertical chromaticity		−22, −14
Momentum compaction		0.00234
Maximum beta radial, vertical		16, 32
Radio frequency		
Frequency (MHz)		500
Harmonic number		200
Energy loss per turn (keV)		12.8
Voltage (kV)		150
Number of cavities		1
Bunch length at max. energy (ps)		52
Natural beam energy spread (%)		0.046
Beam sources		
At the dipole centres	Horizontal	60 μm × 180 μr (standard deviations)
	Vertical	120 μm × 8 μr (standard deviations)
At the normal straight centres	Horizontal	280 μm × 30 μr (standard deviations)
	Vertical	65 μm × 14 μr (standard deviations)
At the long straight centres	Horizontal	260 μm × 35 μr (standard deviations)
	Vertical	85 μm × 11 μr (standard deviations)

5. Detailed design of the MES

The MES will be a larger facility than LES because it will be required to support a much larger volume of research. Representative opinions of researchers as to what techniques will be of interest in future work are summarized in Table 5. From an analysis of this programme it is concluded that the 3 GeV MES should include straights for four soft X-ray undulators and eight multipole wigglers. The accelerator itself may require a further three straights, two for acceleration cavities and one for injection. A storage ring with 16 cells can meet these requirements with one spare straight for future eventualities.

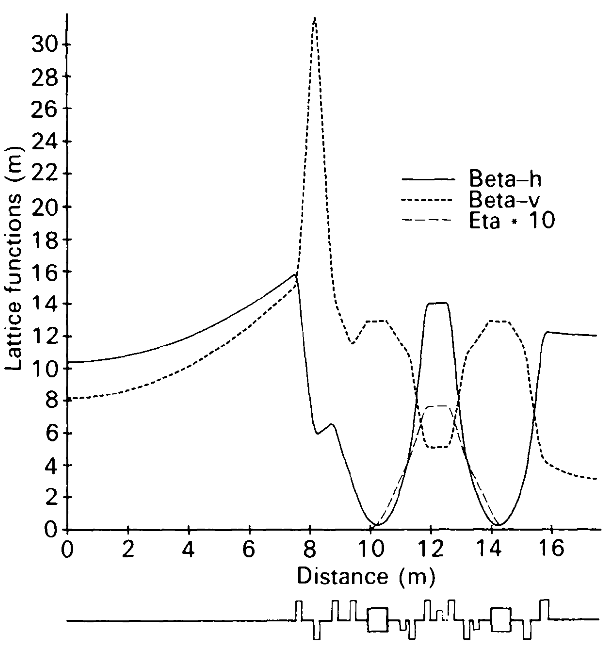

Figure 2
The lattice functions of the SINBAD source.

It is also highly important to include future development potential in the design of the MES. As with the LES, improvement in the design of insertion devices can be expected to be of interest, but it is more likely that the direction of MES evolution will be towards improved high-flux sources of hard X-rays. To allow for this possibility, the conceptual design of the MES includes the capability to replace a fraction of the normal dipole magnets with high-field superconducting magnets, as and when required. The advantage of high-field dipoles in the normal lattice compared with high-field wigglers, is that the former do not encroach on the straight sections which remain free for other insertion devices.

Various options for the lattice structure of the MES have been considered (Poole *et al.*, 1993), but a triple-bend achromat (TBA) (Suller, 1992) offers advantages of simplicity in replacing dipoles. A proposed structure of a lattice cell is shown in Fig. 3, where the central dipole can be seen as either a conventional type or a superconducting magnet. Dipoles would be replaced in pairs, diametrically opposite, to maintain the high symmetry of the storage ring. This helps to ensure conditions for the stability of the electron beam.

With the structure shown in Fig. 3, the straight sections for the insertion devices have lengths of 3.0 m, which is

Table 5
Anticipated science programme for MES.

High-brightness radiation	
Core level PES	0.2–1 keV
High-resolution Auger spectroscopy	0.2–1 keV
Dispersive NEXAFS	0.2–1 keV
NEXAFS/X-ray absorption near-edge structure (XANES)	0.2–1 keV
High-flux radiation	
Magnetic X-ray dichroism	0.2–1 keV
Chemical state imaging	0.2–1 keV
Microscopy	0.2–1 keV
Near-edge fragmentation	0.2–2 keV
Surface EXAFS	0.2–1 keV
EXAFS, XANES, magnetic EXAFS	0.2–2 keV
Surface EXAFS/X-ray standing wave	1.8–5 keV
Atomic excitation radiation effects	2–25 keV
Magnetic scattering	3–30 keV
SEXAFS/X-ray standing wave	4–12 keV
Ultra-dilute EXAFS	4–12 keV
Time-resolved EXAFS	4–12 keV
Dilute photoelectron diffraction	5–15 keV
Non-crystalline diffraction	8–12 keV
Suface X-ray diffraction	8–20 keV
Fluorescence analysis	8–20 keV
Liquid/interface X-ray diffraction	8–20 keV
Protein crystallography	8–20 keV
White-beam energy-dispersive diffraction	10–40 keV
High-Q diffraction	10–50 keV
High-pressure X-ray diffraction	10–50 keV
Microcrystal X-ray diffraction	12–20 keV
Topography/trace-element analysis	12–20 keV

Table 6
Main parameters of the DIAMOND design.

General		
Energy (GeV)		3.0
Magnetic bending field (T)		1.31, 4.36
Circumference (m)		300
Beam emittance (nm rad)		10–50
Beam current (mA)		300
Lattice cell type		TBA
Number of cells		16
Length of dispersion free straight (m)		3.0
Lattice		
Radial, vertical tune		16.74, 7.53
Radial, vertical chromaticity		20.5, −31.5
Momentum compaction		0.00158
Maximum beta radial, vertical		8.5, 28.5
Radio frequency		
Frequency (MHz)		500
Harmonic number		500
Energy loss per turn (MeV)		1.0–1.5
Voltage (MV)		3–4.5
Number of cavities		2 × 3 cell
Bunch length at max. energy (ps)		20–17
Natural beam energy spread (%)		0.095–0.13
Beam sources		
At the outer dipole centres	Horizontal	160 μm × 180 μr (standard deviations)
	Vertical	125 μm × 40 μr (standard deviations)
At the middle dipole centres	Horizontal	320 μm × 70 μr (standard deviations)
	Vertical	65 μm × 14 μr (standard deviations)
At the straight centres	Horizontal	390 μm × 45 μr (standard deviations)
	Vertical	55 μm × 16 μr (standard deviations)

a suitable value for multipole wigglers and soft X-ray undulators. The total circumference of the MES which then results is 300 m.

The major parameters of the DIAMOND proposal for the MES are shown in Table 6. As befits a radiation source which must cope with independently adjusted insertion devices, a relaxed working point has been chosen initially, which produces a beam of moderate brightness. The lattice is ultimately capable of producing significantly higher brightness and such options would be the subject of future studies. The inevitable effect of including superconducting dipoles will be to reduce the brightness and this possibly limits the number which can be replaced to eight. At this number the beam emittance has deteriorated by about a factor of 2, as shown in Fig. 4.

An overall view of the DIAMOND storage-ring design is shown in Fig. 5 and the lattice functions are shown in Fig. 6. The latter demonstrates how a cell containing a superconducting dipole can be matched into a standard cell without perturbing the lattice functions.

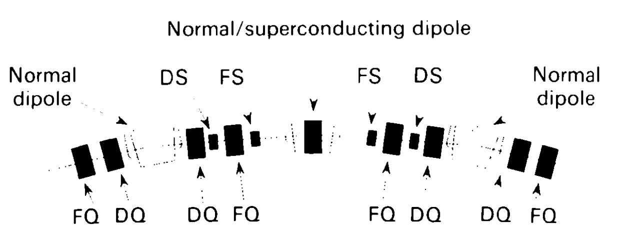

Figure 3
The arrangement of the lattice cell for DIAMOND, showing the centre dipole in its normal and superconducting alternatives.

6. Total spectrum

The overall spectra from the three facilities, ESRF, MES and LES, are shown in Fig. 7. This figure shows both the maximum flux and brightness envelopes which will be available from the whole range of insertion devices in these sources. It is assumed that the undulators will be used both for their fundamental and third-harmonic outputs. For the long-period undulators the range of deflection parameter, or K value, which will be usable is approximately 0.5–3.0 in the fundamental and 1.0–4.0 in the third harmonic. A much more restricted range, perhaps only 0.5–1.0 (European Science Foundation, 1979), will be available from the

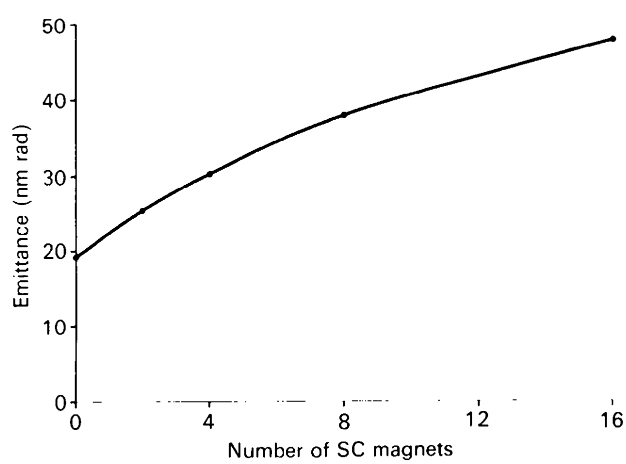

Figure 4
The increase of emittance in DIAMOND as the number of superconducting dipoles is increased.

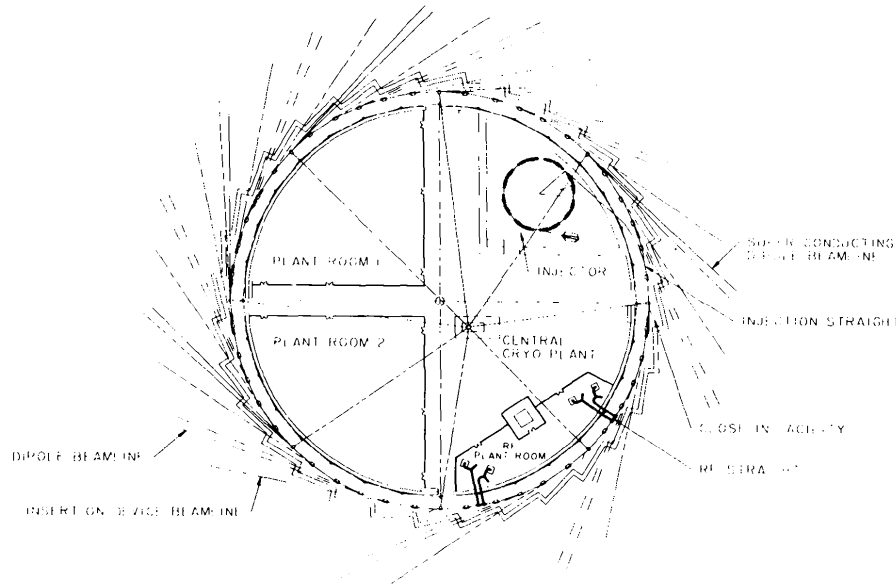

Figure 5
General view of the DIAMOND storage ring.

shortest period undulators due to the minimum gap being limited to a value approximately equal to the undulator period. The use of smaller gaps in these short-period undulators is prevented by the essential demand of a storage ring for sufficient beam aperture.

The flux spectra in Fig. 7 are presented on the assumption that the whole central radiation cone from the undulators is collected. This is a reasonable assumption due to the narrowness of typical undulator emissions. Dipole magnets and multipole wigglers emit broader radiation fans and, therefore, the amount of radiation collected by an experiment depends on its distance from the source point. This distance is determined by the thickness of the radiation shielding surrounding the storage ring and by its overall radius of curvature. The flux curves for MES and ESRF multipole wigglers are therefore shown for assumed horizontal collection angles of 6 and 2 mrad, respectively. In addition, the MES superconducting dipole output is shown for the interesting suggestion of a high-flux experiment mounted close to the source point within the shield wall and collecting 20 mrad horizontally. In this case the flux obtainable would be very similar to that from an ESRF ten-pole multipole wiggler.

Also shown in Fig. 7 as dashed curves are the spectra which would result from very long undulators in the 15 m straights of the LES. Although there are still formidable technical difficulties to be overcome before such devices can be realized, the obviously enhanced spectra which would result justify their consideration for development.

Fig. 7 makes it clear that the needs of the UK synchrotron radiation research community for radiation of specific qualities and spectral range could be well provided by access to the three sources LES, MES and ESRF.

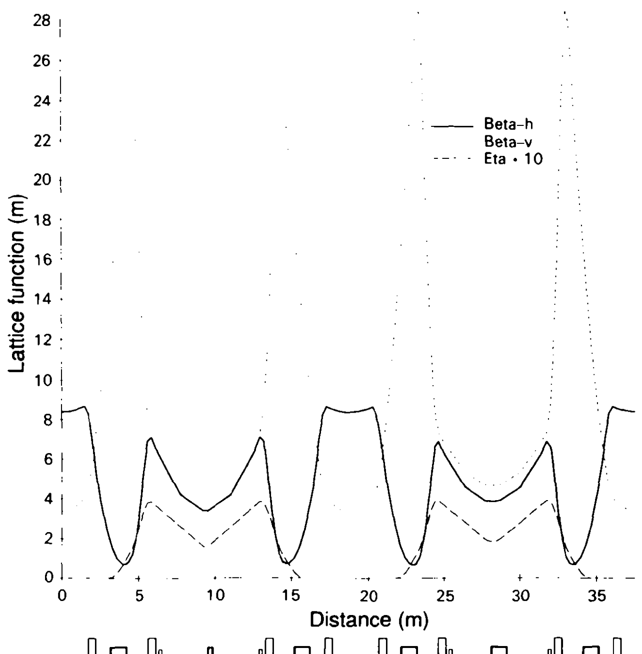

Figure 6
The lattice functions of the DIAMOND source, showing a normal cell and a cell with a superconducting dipole.

7. Conclusions

Increasing demand for synchrotron radiation in research is evident from the obvious growth in the number of sources around the world (Suller, 1992). Inevitably this demand in growth is accompanied by a refinement in application techniques, leading to more stringent beam-

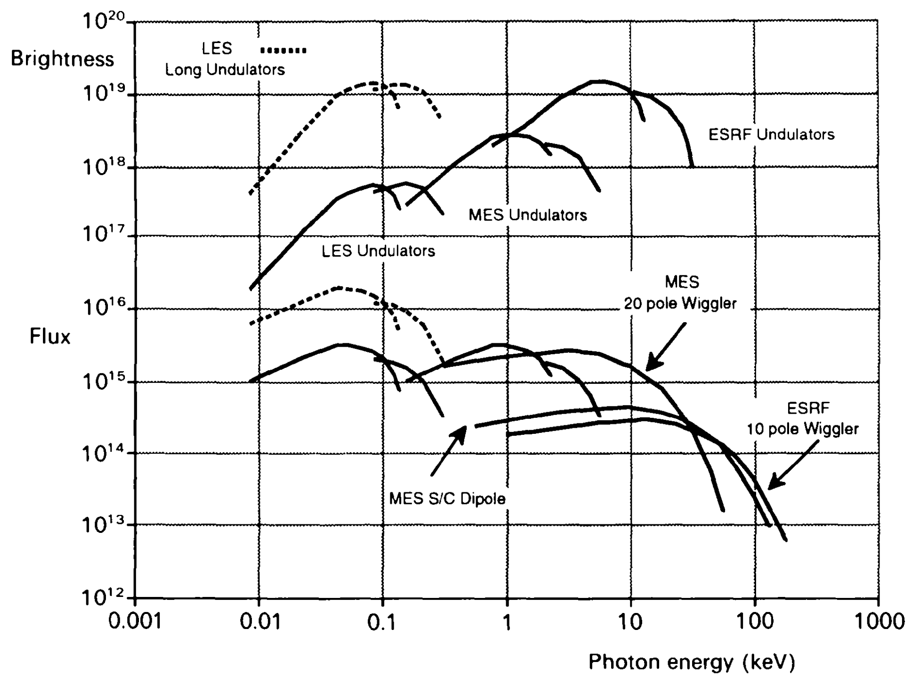

Figure 7
Total spectral ranges covered by the LES, MES and ESRF. Brightness is given in photons s^{-1} (0.1% bandwidth)$^{-1}$ mrad^{-2} and flux is given in photons s^{-1} (0.1% bandwidth)$^{-1}$.

property requirements. Modern third-generation sources are inherently designed for use with insertion devices in order to generate high-quality radiation, but additionally should have potential for development to meet the as yet unknown directions in which synchrotron radiation usage will evolve.

The work reported here was performed by a large number of individuals, both at Daresbury and within the UK synchrotron radiation research community, as part of the Woolfson review. The author acknowledges that his role has been to distil from numerous contributions the more concise presentation made here. Joan Bordas and his group prepared the analysis of the future research programme and conducted the user survey. Mike Poole and his team conducted the outline designs of the accelerators.

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