Review of the Status of Synchrotron Radiation Storage Rings

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Abstract

A survey is made of all known storage rings used as sources of synchrotron radiation, categorised according to their use as Lithography, Vacuum Ultra Violet (VUV), VUV/Soft X-ray (SXR), X-ray and Hard X-ray sources. The status, structure and major parameters of each source are listed and a review is made of the several types of structure employed. The minimum attainable emittance for each structure is described and an emittance figure of merit is defined. This figure of merit is evaluated for each source and plotted according to type of structure. The relative emittances attained in practice between different structures is discussed.

1. Introduction

The dramatic growth in the use of synchrotron radiation as a scientific tool which has taken place since the mid 1960's is evidence of the special qualities of this source of radiation. Although initially parasitic use was made of radiation generated as a by-product of the operation of electron accelerators built for other purposes, principally for high energy particle physics, the increasing sophistication of synchrotron radiation experiments has stimulated the design of dedicated sources. The design of these sources has continually evolved as more exacting specifications are demanded, with the result that there is apparent a great diversity amongst the design of present day synchrotron radiation facilities. It is the intention of this review to examine the various themes which exist in the design of the principal source of synchrotron radiation throughout the world today: the electron storage ring.

2. Lattices for SR Sources

Table 1 lists all the electron storage rings in the world which are known to have a programme for the use of synchrotron radiation. The majority are in operation now, either wholly as dedicated radiation sources or on a shared arrangement in conjunction with particle physics experiments. A number of listed sources are at the planning stage only, but are sufficiently developed to be well described in the literature. A few sources have been closed but are included both for the sake of completeness and because of their important contribution to storage ring design and operation.

For each listed source a number of references to the literature are given, from where other technical details may be obtained. Table 1 does include some technical parameters which will be relevant to the discussion of lattice design. These are the beam energy, the number of dipoles, their fields and bend angles, and the designed horizontal beam emittance. Also given is the type of lattice structure used for each ring, using wherever possible the type definitions shown in fig 1 below. For some compact Lithography sources the structures are described in terrms of F or D (focussing and defocussing quadrupoles) and d (defocussing gradient dipoles).

Amongst the 73 different storage rings listed in table 1 it is apparent that there are a wide range of designs in use. There are several possible reasons for this, including the requirement for a given source to produce a specific geometry to suit local site conditions, the nature of the insertion devices to be catered for by the source, and the degree of importance attached to the beam source properties within the dipoles. There is also the question of the required beam brilliance since this can be strongly influenced by the lattice structure.

The lattices finding most frequent application as storage rings for synchrotron radiation are shown in fig 1. Other variations are found, especially ones which combine a gradient field within the dipole magnets, but an essential feature used in all sources is separate control of the bending and focussing elements. A type not shown in the diagram but met in a small number of examples is the weak focussing lattice with a single 360 degree magnet.

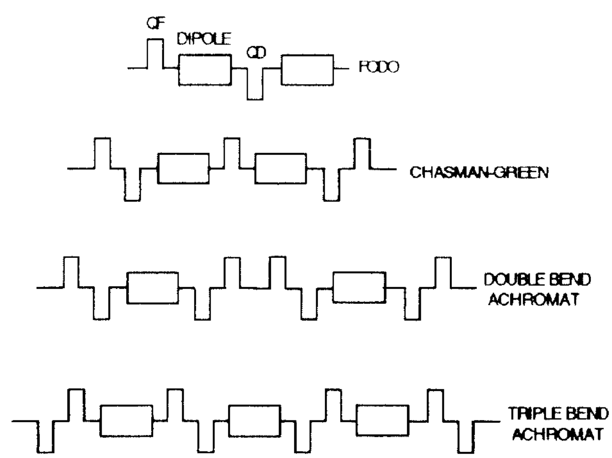

Figure 1. Lattice structures used for SR storage rings

The FODO lattice, in which quadrupoles of alternating polarity are separated by uniform field bending magnets, is the classic separated function structure. It was not used for the earliest e^+e^- storage rings because it does not have the reflection symmetry required for colliding beams and because zero dispersion cannot be obtained within a normal cell. The reflection symmetric version of the FODO cell is the Triplet and is used in both DORIS and SPEAR. Zero dispersion can, however, be matched by special cells into arc sections

Table 1. World List of Synchrotron Radiation Storage Rings

RING NAME	LOCATION	COUNTRY	ENERGY GeV	LATTICE	DIPOLES N x Angle	FIELD Tesla	EMITTNCE nm.rad	FIG-MERIT	STATUS	REFERENCES
Lithography Rings										
COSY	Berlin	GERMANY	0.6	FDd	2x180	4.5	2600		Closed	[2]p237,[1]p1523
HELIOS	E Fishkill, NY	USA	0.7	FdF	2x180	4.5	950		Operational	[2]p295,[4]p707
SXLS	Brookhaven, NY	USA	0.7	FdF	2x180	3.87	720		Construction	[5]p1107,[2]p1828
SIBERIA-SM	Novosibirsk	RUSSIA	0.6	DB(NA)	8x45	6.0	85	7.2E-2	Planned	[3]p1767,[24]p386
SIBERIA-AS	Novosibirsk	RUSSIA	0.6	Weak Focus	1x360	3.8	1450		Planned	[3]p1767,[4]p774
NAR	Atsugi (NTT)	JAPAN	0.8	CG	8x45	1.5	147	7.0E-2	Operational	[3]p1779,[4]p781
SUPER ALIS	Atsugi (NTT)	JAPAN	0.6	DFD	2x180	3.0			Operational	[3]p1783,[4]p781
AURORA	Tokyo (SHI)	JAPAN	0.65	Weak Focus	1x360	4.33	2800		Operational	[4]p722,[23]p425
LUNA	Tsukuba (IHI)	JAPAN	0.8	FODO	4x90	1.33			Operational	[4]p767
NIJI 2	Tsukuba (ETL)	JAPAN	0.6	CG	4x90	1.43	3770	1.4E-2	Operational	[4]p722,[29]p33
NIJI 3	Tsukuba (ETL)	JAPAN	0.62	CG	4x90	4.1	250	2.6E-1	Operational	[4]p753,[5]p2655
SORTEC	Tsukuba (ETL)	JAPAN	1.0	FODO	8x45	1.2	500	3.2E-2	Operational	[1]p409,[1]p475
MELCO 2	Amagasaki (MEC)	JAPAN	0.8	Fd	2x180	4.5	1200		Construction	[4]p722,[5]p2694
VUV Rings										
HESYRL	Hefei	CHINA	0.8	TBA	12x30	1.2	27	1.1E-1	Dedicated	[20]p19,[28]p155
ASTRID	Aarhus	DENMARK	0.6	DBA	8x45	1.6	160	3.6E-2	Part Ded'ctd	[5]p2811,[2]p112
ACO	Orsay	FRANCE	0.54	DBA	8x45	1.61	192	2.4E-2	Closed	[16]p127,[28]p114
INDUS 1	Indore	INDIA	0.45	FDdDF	4x90	1.5	71	4.3E-1	Construction	[27]p16
UVSOR	Okasaki	JAPAN	0.6	DB(NA)	8x45	1.14	80	7.2E-2	Dedicated	[10]p3175,[8]p3409
SOR-Ring	Tokyo	JAPAN	0.38	DB(NA)	8x45	1.15	320	7.3E-3	Dedicated	[26]p163,[28]p103
TERAS	Tsukuba	JAPAN	0.8	DB(NA)	8x45	1.33	550	1.9E-2	Dedicated	[8]p3403,[9]p3133
NIJI 4	Tsukuba (ETL)	JAPAN	0.5	TBA	6x60	1.4	135	7.3E-2	Operational	[4]p722,[29]p54
AmPS	Amsterdam	NETHERLANDS	0.9	8BA	32x11.25	0.9	160	1.2E-3	Construction	[1]p1488,[4]p1621
EUTERPE	Eindhoven	NETHERLANDS	0.4	TBA	12x30	1.4	7.5	9.9E-2	Construction	[4]p1569,[7]p488
SIBERIA 1	Moscow	RUSSIA	0.45	Weak Focus	4x90	1.5	880	3.5E-2	Dedicated	[3]p1789,[22]p18
MAX	Lund	SWEDEN	0.55	CG	8x45	1.53	30	1.6E-1	Dedicated	[19]p331
H-100	Kharkov	UKRAINE	0.1						Dedicated	[22]p1
SURF 2	Gaithersburg MD	USA	0.28	Weak Focus	1x360	1.2	350		Dedicated	[4]p1594,[6]p461
TANTALUS	Stoughton, WI	USA	0.24	Triplet	8x45	1.23	230	4.1E-3	Closed	[25]p211,[22]p9
NSLS-VUV	Brookhaven, NY	USA	0.744	CG	8x45	1.30	88	1.0E-1	Dedicated	[14]p232,[11]p3842
VUV/SXR Rings										
UVX2	Campinas	BRAZIL	1.15	DBA	12x30	1.4	65	9.4E-2	Construction	[4]p1573,[5]p2781
SRRC	Taiwan	CHINA	1.3	TBA	18x20	1.25	20	1.1E-1	Construction	[5]p2670,[4]p1580
DAPS	Daresbury	ENGLAND	0.5-1.2	DBA	20x18	1.3(1.2GeV)	15	9.5E-2	Planned	[4]p1599,[37]
SUPER ACO	Orsay	FRANCE	0.8	DBA	8x45	1.57	37	2.8E-1	Dedicated	[8]p3371,[3]p1373
BESSY	Berlin	GERMANY	0.8	TBA	12x30	1.5	20	1.5E-1	Dedicated	[18]p55,[8]p3368
DELTA	Dortmund	GERMANY	1.5	Triplet	16x20	1.52	11	2.8E-1	Construction	[6]p780,[5]p2859
					+4x10					
BESSY 2	Berlin?	GERMANY	1.7	TBA	30x12	1.35	6.2	1.4E-1	Planned	[1]p1420,[6]p1265
ADONE	Frascati	ITALY	1.5	DBA	12x30	1.00	240	4.3E-2	Part Ded'ctd	[17]p703,[28]p75
ELETTRA	Trieste	ITALY	1.5	DBA	24x15	0.91	4.2	3.1E-1	Construction	[2]p210,[4]p1615
TSSR	Sendai	JAPAN	1.5	DBA	12x30	1.25	81	1.3E-1	Planned	[27]p131
HISOR	Hiroshima	JAPAN	1.5	CG	12x30	1.2	83	1.2E-1	Planned	[27]p107,[3]p1713
SOR	Kyushu	JAPAN	1.5	TBA	18x20	1.2	19	1.6E-1	Planned	[27]p148,[3]p1709
VEPP 2M	Novosibirsk	RUSSIA	0.7	DB(NA)	8x45	1.9	205	3.8E-2	Part Ded'ctd	[13]p756,[21]p874
TNK	Zelenograd	RUSSIA	1.6	4BA	24x15	1.09,0.27	31	4.7E-2	Construction	[4]p761
MAX 2	Lund	SWEDEN	1.5	DBA	20x18	1.5	8.6	2.6E-1	Construction	[30],[31]
SLS	Villigen	SWITZERLAND	1.5	6BA	48x7.5	0.8	1	1.6E-1	Planned	[4]p1606
CAMD	Baton Rouge, LA	USA	1.2	CG	8x45	1.37	210	1.1E-1	Construction	[4]p1561,[5]p822
ALADDIN	Stoughton, WI	USA	1.0	FODO	12x30	1.60	110	4.2E-2	Dedicated	[5]p2643,[10]p3145
ALS	Berkeley, CA	USA	1.5	TBA	36x10	1.02	3.4	1.1E-1	Construction	[2]p359,[7]p476
X-Ray Rings										
BEPC	Beijing	CHINA	1.5-2.8	FODO	40x9	0.9(2.8GeV)	190	5.1E-3	Part Ded'ctd	[2]p175,[28]p126
SRS	Daresbury	ENGLAND	2.0	FODO	16x22.5	1.2	110	7.0E-2	Dedicated	[2]p418,[15]p680
DCI	Orsay	FRANCE	1.8	Misc	12x30	1.571	1300	1.1E-2	Dedicated	[15]p49,[28]p114
SOLEIL	Orsay	FRANCE	2.15	DBA	16x22.5	1.6	36	2.5E-1	Planned	[32]
ELSA	Bonn	GERMANY	3.5	FODO	24x15	1.08	760	9.2E-3	Part Ded'ctd	[9]p3252,[2]p356
INDUS 2	Indore	INDIA	2.0	DBA	20x18	1.2	50	7.9E-2	Planned	[27]p16
KANSAI-SR	Osaka	JAPAN	2.0	DBA	12x30	1.2	120	1.5E-1	Planned	[27]p168
KEK-PF	Tsukuba	JAPAN	2.5(3.0)	FODO	28x12.9	0.96(2.5GeV)	130	1.7E-2	Dedicated	[11]p3848,[3]p1382
KEK-VUV	Tsukuba	JAPAN	3.0	CG	48x7.5	1.0	7	9.1E-2	Planned	[4]p371
VEPP 3	Novosibirsk	RUSSIA	2.0	Comb Func	14x22.5	1.1	290	2.7E-2	Part Ded'ctd	[13]p756,[21]p845
					+4x11.25	1.1				
SIBERIA 2	Moscow	RUSSIA	2.5	4BA	24x15	1.70,0.43	78	4.6E-2	Construction	[2]p380,[4]p1603
PLS	Pohang	S KOREA	2.0	TBA	36x10	1.06	13.5	5.0E-2	Construction	[5]p2673,[6]p821
PSR 2000	Kharkov	UKRAINE	2.0	4BA	32x11.25	0.75	150	6.4E-3	Planned	[3]p1722,[4]p385
SPEAR	Stanford, CA	USA	3.0	Triplet	32x10.6	0.79	105	1.7E-2	Dedicated	[5]p1104,[16]p145
					+4x5.2	0.79				
NSLS-XRAY	Brookhaven, NY	USA	2.5	CG	16x22.5	1.22	80	1.5E-1	Dedicated	[11]p3806,[14]p232
Hard X-Ray Rings										
ESRF	Grenoble	FRANCE	6.0	DBA	64x5.63	0.86,0.4	7	1.5E-1	Construction	[2]p845,[1]p65
DORIS 3	Hamburg	GERMANY	4.5-5.3	Triplet	24x15	1.24(4.5GeV)	405	2.8E-2	Part Ded'ctd	[2]p389,[14]p315
PETRA	Hamburg	GERMANY	6.0-13.0	FODO	232x1.55	0.22(13GeV)	79	1.3E-3	Planned	[12]p1842,[5]p2793
TRISTAN-AR	Tsukuba	JAPAN	6.5	FODO	56x6.4	0.93	168	1.1E-2	Part Ded'ctd	[4]p404,[9]p1983
TRISTAN	Tsukuba	JAPAN	10.0	FODO	288x1.25	0.15	1.5	2.2E-2	Planned	[14]p144,[3]p1407
SPRING 8	Nishi Harima	JAPAN	8.0	DBA	88x4.1	0.68	7	1.1E-1	Construction	[4]p355,[5]p2646
VEPP 4	Novosibirsk	RUSSIA	6.0	Comb Func		1.42	270		Part Ded'ctd	[13]p756,[21]p845
CESR	Ithaca, NY	USA	5.44	FODO	68x4.4	0.21	65	6.0E-3	Part Ded'ctd	[14]p26,[6]p473
					+16x3.7	0.57				
					+2x1.0	0.52				
PEP	Stanford, CA	USA	7.1	FODO	192x1.87	0.143	6.4	8.7E-3	Planned	[6]p456,[12]p1836
APS	Argonne, IL	USA	7.0	DBA	80x4.5	0.6	8	9.4E-2	Construction	[3]p1403,[5]p210

composed of FODO units, although in small rings this is an uneconomic option. It is feasible in large rings and the high energy particle physics rings PEP, CESR, PETRA and TRISTAN all use FODO lattices. The early dedicated sources SRS and KEK-PF also use FODO. In general the FODO structure is flexible and economical and in principle can attain the lowest minimum emittance as will be described later.

The Chasman-Green (CG) structure can produce zero dispersion in many straight sections and its advantages as a synchrotron radiation source were described in 1975 [33]. The basic CG cell contains a symmetric pair of dipoles with a single focussing quadrupole at the centre point between them. This quadrupole controls the dispersion function in the lattice and for one unique setting produces zero dispersion in the other straights outside the achromat. These straights contain other quadrupoles which do not affect the dispersion but which control the lattice functions in these straights. Since the straights can be made arbitrarily long they are ideally suited for the operation of insertion devices such as wigglers and undulators. The CG structure is slightly inflexible and the lattice chromaticity is not easily controllable by sextupoles in the locations available for them and although it can produce a low emittance its minimum is not as small as in a FODO. Therefore the CG structure is not as popular as its precedence might have suggested; examples are found in NSLS-VUV and NSLS-XRAY, MAX and CAMD.

The Double Bend Achromat (DBA) is sometimes called the extended or modified Chasman-Green because it replaces the the single dispersion controlling quadrupole of the CG by either a quadrupole triplet or, more usually, by a pair of quadrupole doublets. This greatly improves the flexibility for adjusting the lattice functions whilst maintaining zero dispersion in the long straights. It also provides locations for sextupoles which allow easier control of the chromaticity. The minimum emittance performance of the DBA is the same as that of the CG because the form of the lattice functions in the bending magnets is basically the same. The DBA is the most frequently encountered lattice amongst synchrotron radiation sources with all the purpose designed Hard X-ray sources, (APS, ESRF, Spring-8), using it, as also does SUPER-ACO and ELETTRA. It has also been used in a non-achromatic configuration DB(NA) in small rings such as ACO and SOR-ring and is also chosen for the recent MAX 2 design.

The Triple Bend Achromat (TBA) simply interposes a third dipole into the finite dispersion region between the dipoles of a DBA. The reason for doing this is that the lattice functions in the third dipole can be configured to generate a smaller contribution to the emittance than the other two dipoles. Therefore the minimum emittance of a TBA is lower than that of a DBA or CG. The first source to use the TBA was BESSY, and later examples can be seen in SRRC, PLS and ALS. The technique of putting additional dipoles into a DBA to reduce the minimum emittance can obviously be extended to any number of dipoles, the drawback being that the number of available dispersion free straights in the source decreases. The extension to four dipoles (4BA) can be seen in SIBERIA-2 and PSR-2000, to six dipoles (6BA) in SLS, and to eight dipoles (8BA) in AmPS.

Weak focussing rings with a single 360 degree dipole can be very compact, but with no straights for locating injection and rf systems they are inevitably limited to low energies. SURF-2 and AURORA are examples of this type. The minimum beam emittance is obtained by using a magnet n-value of 2/3.

Pure combined function structures have all the focussing combined with the dipole fields. With appropriate strengths chosen for the F and D elements such lattices can be made damping in all three axes and thus become suitable for use as synchrotron radiation sources. They are compact and economical but lack flexibility. VEPP-3 and VEPP-4 are the only examples. Several sources are partially combined function, having gradient in the dipoles in addition to separate focussing quadrupoles. This may be done to achieve compactness (HELIOS and SXLS), to achieve better optimised lattice functions in the dipoles (ALS and ELETTRA), or to achieve a lower emittance (INDUS-1). When a separated function ring is operated with an offset orbit by adjusting the radio frequency it becomes partially combined function, and this method has been used to alter the damping partition coefficients. PEP has been tested in this mode and shown thereby to produce a lower emittance.

3. MINIMUM EMITTANCE

It was realised in the 1980's [34] that for a DBA or CG lattice there is a minimum achievable horizontal emittance which is proportional to the cube of the dipole bend angle. This was soon extended to an arbitrary lattice [35] which can attain a lower minimum emittance but shows the same dependance on the dipole bend angle. A comprehensive treatment [36] demonstrated that the minimum horizontal emittance is given by

$$\varepsilon_x(\mathrm{min}) = \frac{k_i C_q \theta^3 \gamma^2}{J_x} \quad (\mathrm{m.rad}) \qquad (1)$$

where C_q = 3.83 10^{-13}, θ is the dipole bend angle, γ is the relativistic factor of the beam energy, J_x is the lattice horizontal partition coefficient, and k_i is a factor dependent on the form of the lattice structure and the constraints imposed by the lattice functions.

For example a DBA or CG lattice demands a dispersion function together with its derivative which are zero at opposite ends of the dipole pair, and this results in a value for k_i of

$$k_{DBA/CG} = \frac{1}{4\sqrt{15}} \qquad (2)$$

If there are no constraints on the dispersion function, such as might be found in a FODO or other general lattice, k_i has a value which is a factor of three lower

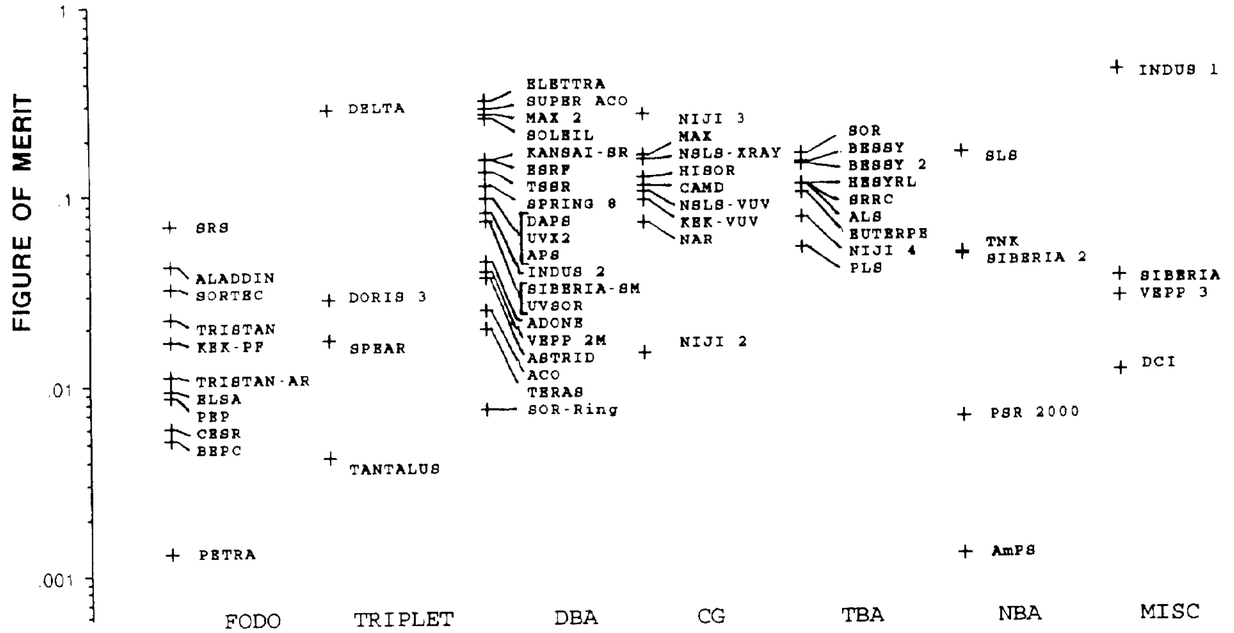

Figure 2. Emittance figure of merit versus lattice structure

$$k_{general} = \frac{1}{12\sqrt{15}} \qquad (3)$$

The minimum emittance expression above is an approximation which is strictly accurate only for small values of θ. However for a lattice with six dipoles ($\theta = 2\pi/6$) the approximation overstates the emittance by 4%, and the error grows only to 11% for a lattice with four dipoles.

When the effects of gradients in the dipoles are considered it is found that the minimum emittance may be reduced by using a suitable n-value[36]. The condition for the minimum emittance to be smaller than given in the previous expression (1) is that

$$\theta\sqrt{1-n} > 1$$

where $n = -\rho . B'/B$ with ρ as the bending radius and B the magnetic field. It is clear that for lattices with large numbers of cells, ie small θ, useful emittance reduction is only obtained with large negative n-values, which implies strongly focussing magnet units. This may be difficult to include in the overall structure optimization. But for lattices with a few cells only, useful emittance reduction is produced even with weak focussing magnets,

$$0 < n < 1$$

4. PERFORMANCE COMPARISONS

There are several possible reasons why a lattice should not be operated at its minimum emittance. These include; selecting particular betatron tunes for good dynamic aperture; setting specific chromaticities; setting specific values of the beta functions in the straights and the dipoles to optimise the radiation source properties. Nevertheless it is instructive to compare the design emittance of a given synchrotron radiation source with that of a generalised low emittance lattice using plain dipoles with the same bend angle per dipole. An emittance figure of merit may be defined as

$$\text{figure of merit} = \frac{\varepsilon_x(\text{min})}{\varepsilon_x(\text{design})}$$

$$= \frac{C_q \theta^3 \gamma^2}{12\sqrt{15}\,\varepsilon_x(\text{design})J_x}$$

$$= \frac{7.85\ 10^3 E^3(\text{GeV})}{\varepsilon_x(\text{design})(\text{nm.rad})J_x N^3} \qquad (4)$$

where E is the electron energy, and N is the number of dipoles in the structure. The value of J_x to be used is that of the minimum emittance configuration. For isomagnetic structures with a large number of cells J_x is well known to tend to 1.0, but for structures with as few as only four dipoles it is necessary to use the expression

$$J_x = \frac{N}{\pi}\left(1 - \frac{\pi^2 B}{20N^2E}\right)\sin\frac{\pi}{N} \quad (\text{min emittance}) \qquad (5)$$

where B is the field in Tesla in the dipoles.

The emittance figure of merit has been evaluated for the sources listed in table 1. Those with fewer than four dipoles, mainly compact sources, have not been treated because of the limitations of expression (1). The figure of merit is plotted in fig 2 with the sources grouped according to lattice type.

When considering fig 2 it should be remembered that the maximum possible figure of merit for a CG or DBA with plain dipoles is 0.33, since these structures have a minimum emittance three times larger than the generalised lattice on which the definition of the figure of merit is based. It is seen that a number of DBAs of recent design (ELETTRA, MAX 2 and Super ACO) approach this value and are obviously highly optimised sources. There is no significant difference in emittance performance between DBAs and CGs.

TBAs and their higher derivatives (NBAs) are potentially able to exceed the 0.33 limit of DBAs, but in practice fig 2 shows that existing designs do not yet achieve this. The reason for this is not apparent, but may be simply due to the TBA being a more recent design, of which the capabilities have not yet been thoroughly explored. Although this may change in the future, at the present time there would appear to be no reason for selecting a TBA design in preference to a DBA.

Also apparent from fig 2 are the low figures of merit of the large particle physics rings. Although these achieve small emittances in absolute value, this is by virtue of the fact that these rings are large with large numbers of cells. However, if there are opportunities to reconstruct these rings as fully optimised radiation sources the exciting prospect exists of reducing further their emittances by up to two orders of magnitude.

Finally it is evident that high figures of merit can be achieved without the use of achromatic structures. DELTA is a triplet with two very long dispersion free straights which can be operated in a very low emittance mode and INDUS 1 achieves good relative emittance performance by using an additional weak focus gradient ($n = 0.5$) in its four dipoles.

5. CONCLUSIONS

There are 36 operational storage rings for synchrotron radiation throughout the world, with a further 18 in construction and at least 16 being planned. At the present time the favoured choice of lattice structure for a dedicated source, offering good emittance performance and a suitable number of dispersion free straights, would appear to be the DBA.

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