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AN X-RAY SYNCHROTRON SOURCE FOR EUROPE

Members of the Machine Sub-Group of the ESF ad hoc Committee for Synchrotron Radiation*

Abstract

A design study is being carried out for the European Science Foundation of an electron storage ring which will, if built, be an extremely intense dedicated source of x-radiation. The objective is to provide many ports from bending magnets, with a characteristic wavelength (λ_c) of 1 Å; a few hard x-ray ports from wigglers, with $\lambda_c \lesssim 1/4$ Å, and six tunable undulators providing quasi-monochromatic radiation from 1 Å to 25 Å. A very high brightness is required.

The paper describes a well-behaved magnet lattice giving a very low emittance coupled with appropriate beam parameters in different regions of the lattice. A preliminary outline of some of the other main features of the proposed storage ring is included.

Introduction and Objectives

The European Science Foundation ad hoc Committee for synchrotron radiation has set up a "machine subgroup" to carry out a feasibility study (including cost estimates) of an electron storage ring which would, if built, be an extremely intense and bright dedicated source of x-radiation.

The objectives of the storage ring design are to provide the following basic facilities:-

a) Many ports giving synchrotron radiation with high intensity and high brightness with a normal spectrum and a characteristic wavelength of 1 Å (12.4 keV). These are the normal bending magnet ports.

b) Several ports using short wigglers to produce higher energy radiation, with a characteristic wavelength of 0.25 Å (50 keV).

c) A variety of undulators (wigglers with a large number of periods which produce quasi-monochromatic radiation) to provide very high brightness sources over a restricted wavelength range - the range of particular interest being 1 to 25 Å (12.4 to 0.5 keV).

d) A total aperture, summed over all the beam ports, of at least 500 mrad.

The requirement for 1 Å radiation from the bending magnets can be met with an electron energy of less than 4 GeV, but to allow a possibility of achieving 1 Å radiation from an undulator, an energy of 5 GeV has been chosen.

The features of the beams considered to be most important have been put in order of priority as:-

a) large number of photons/second;
b) small divergence and small beam size in the vertical plane (for many experiments, the small divergence is the more important);
c) small beam size in the horizontal plane;
d) high angular stability;
e) high position stability;
f) short bunch length (< 200 ps);
g) good beam lifetime (8-10 hours).

In accelerator terms, this means a machine with a low emittance, a small coupling, a high current, an adequate amount of straight section space for wigglers and undulators, and appropriate amplitude functions (β-functions) in both planes. It was decided to include 3 m straight sections for wigglers, and 6.8 m straights for undulators. The β-function should be high in the undulator straights, and low in the wiggler straights. The dispersion should be zero in these regions. In the bending magnets, the horizontal β-value should be low, but the vertical should not be too low, because of the importance of a small vertical divergence.

Another important factor in the design has been the desire for a well-behaved and flexible magnet lattice. There is a very close link between the optics of the circulating beam and the experimental instruments (e.g. monochromators) and detectors. It is impossible to predict with certainty the optimum beam optics for the storage ring or even simultaneously to optimise the machine for all possible users. It is therefore highly desirable to be able to adjust the β-functions from time to time and to have a lattice which is flexible in this respect.

Magnet Lattice Design

A lattice which matches the requirements fairly well(1) is shown in Fig.1, which also shows the dispersion and β-functions. Table 1 lists the magnet parameters and the resulting beam parameters.

TABLE 1

Lattice Parameters

Energy	5 GeV			
Circumference	604 m			
Number of cells	12			
Bending radius	22.36 m			
No. of dipoles per cell	4			
Length of dipole	2.93 m			
Field in dipole	0.74 T			
Quadrupoles:-	Length (m)	gradient (m^{-2})		
D1A	1.0	0.62		
F1	1.0	0.89		
D1B	1.0	0.51		
D2	0.7	0.49		
F2	0.7	0.63		
D3	0.7	0.57		
F3	0.7	0.68		
Horizontal emittance	1.1×10^{-8} m.rad			
Beam sizes at centre:-	σ_x(mm)	σ'_x(mrad)	σ_z(mm)	σ'_z(mrad)
6.8 m straight	0.50	0.02	0.07	0.007
3.0 m straight	0.11	0.10	0.03	0.019
dipole magnet 1	0.18	0.05	0.08	0.007
dipole magnet 2	0.18	0.05	0.11	0.005
(for 5% emittance coupled into vertical plane)				

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*D.J. Thompson (Daresbury Laboratory, Warrington WA4 4AD, U.K.) (Chairman)
W.H. Backer (Technical University, Eindhoven, Netherlands)
M. Bassetti (LNF-INFN, Frascati, Italy)
R. Coisson (Universita, Parma, Italy)
D. Degele (DESY, Hamburg, Germany)
J. Le Duff (Universite Paris-Sud, Orsay, France)
F. Dupont (Universite Paris-Sud, Orsay, France)
A. Hofmann (CERN, Geneva, Switzerland)
D. Husmann (Physikalisches Institut der Universitat, Bonn, F.R. Germany)
G. Mulhaupt (BESSY, Berlin, F.R. Germany)
J. Perot (CEN, Saclay, France)
M. Renard (Universite Paris-Sud, Orsay, France)
M. Sommer (Universite Paris-Sud, Orsay, France)
V.P. Suller (Daresbury Laboratory, Warrington, U.K.)
S. Tazzari (LNF-INFN, Frascati, Italy).

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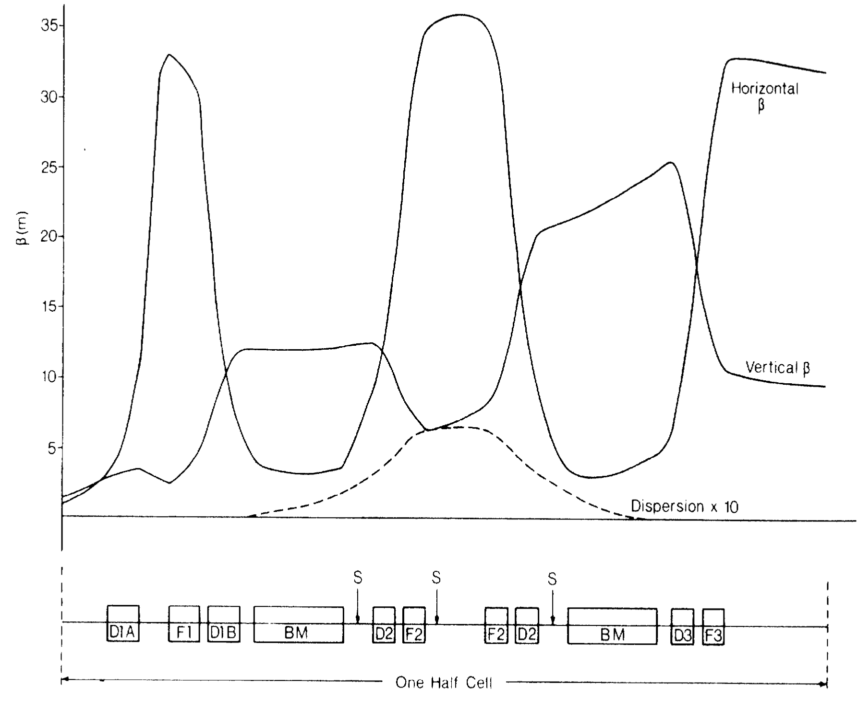

Fig.1

The lattice design is based on an achromatic arc. For a small emittance, the quantity $\mathcal{H}$ defined by Sands(2) as

$$\mathcal{H} = \frac{1}{\beta}\left[\eta^2 + (\beta\eta' - \frac{1}{2}\beta'\eta)^2\right]$$

must be small, and to achieve this the dispersion η in the bending magnets must be low. Because η increases along the length of the bending magnets, they must therefore be short. To achieve flexibility the "symmetry quadrupole" has been split; this also enables chromaticity correction sextupoles to be inserted more easily. The cell is thus fairly long, with rather a large number of magnets, between which are inserted the necessary straight sections for wigglers and undulators.

Turning to the β-function, we note that the vertical beam size depends only on the coupling and on the horizontal β-value. The vertical β is not important so long as it is not too large. The horizontal β should be fairly high for undulators and fairly low for wigglers.

It can be seen from Table 1 that a very low emittance is achieved. The price paid is that the lattice has a large circumference and a large number of magnets.

Chromaticity correction has been studied(3) and can be achieved satisfactorily with a set of three sextupoles in each half cell. The location of the sextupoles is shown in Fig.1.

Computations using the PETROS(4) program indicate(5) that the lattice is well-behaved and stable. Different lattice optics with considerably different β-functions are certainly possible though they have not yet been explored in detail.

Storage Ring Parameters

A preliminary list of the main storage ring parameters is given in Table 2. The current has been chosen to give a linear radiation density in the bending magnets of 10 kW/m, which is thought to be a practical upper limit allowing for the higher local density which will occur in the "crotch" region of the extraction ports.

TABLE 2
Tentative parameter list

Energy	5 GeV
Beam current	565 mA
No. of stored electrons	7.12×10^{12}
Mean radius	96.2 m
Betatron oscillations per turn (horizontal, vertical)	26.2, 13.7
Momentum compaction factor	6.6×10^{-4}
Vacuum chamber aperture	70 mm x 25 mm
Characteristic wavelength	1 Å
Photon flux at 1 Å	4.5×10^{13} photons/s/mrad/0.1% bandwidth
Wiggler characteristic wavelength	0.25 Å
Wiggler photon flux at λ_c	4.5×10^{13}
Injection energy	5 GeV
Radiation loss per turn from dipoles	2.47 MeV
Additional loss per wiggler	31 keV
Total synchrotron radiation power including 6 wigglers	1.5 MW
R.f. frequency	500 MHz (main) 1000 MHz (harmonic)
Harmonic number	1008
Peak voltage (10 hr quantum lifetime)	4.08 MV (main r.f.) 1.35 MV (harmonic)
R.f. power requirement (approx.)	2 MW (main r.f.) 100 kW (harmonic)
Natural bunch length	σ = 10 mm (main r.f. only) = 30 mm (with harmonic)

In arriving at figures for radiation loss and of power input, allowance has been made for six 3-pole wiggler magnets each long enough to give 15 mrad horizontal bend in the centre pole with λ_c = 0.25 Å.

The choice of radio frequency presents some difficulty. A low frequency (below 100 MHz) is advantageous in giving a longer bunch length and hence reduced higher order mode losses. Howver, the cavity structure will be long and the r.f. equipment expensive. From all engineering and cost considerations a high frequency is preferable, 500 MHz being the lowest frequency for which cheap efficient power sources are readily available. However the very short bunch length, whilst attractive to some users, may give problems. To counteract this, it is proposed to include a second harmonic system. The voltage and power required, though greater than for a third harmonic, are not excessive, and this choice leads to maximum bunch lengthening and the required beam aperture is possible with good shunt impedance.

The proposed injection energy is 5 GeV, the injector being a synchrotron cycling at 10 Hz so that a mettal vacuum chamber can be used. By injecting at the operating energy, many problems are avoided. In particular, as magnets will not need to be ramped, it should be possible to maintain the position and direction of the synchrotron radiation beams very stable over long periods. Also, frequent "topping-up" can be used to maintain constant intensity of radiation.

Undulators

There are various possible designs for undulators and they will no doubt be changed from time to time during the life of the machine. An output at 1 Å can be achieved either by using a linear magnet which has a very small vertical aperture, and has to be put into position after the closed orbit has been corrected; or by using a harmonic from a higher field full aperture undulator. Radiation up to about 25 Å can be obtained at 5 GeV with a 30 pole undulator in the space available, and this would tune to 100 Å at 2.5 GeV.

Two specific examples of undulators using linear periodic magnets are given below. For larger wavelengths, e.g. an undulator wavelength of 125 mm, a helical magnet is also possible.

a) Full aperture undulator. Gap height 45 mm.
Undulator wavelength 56 mm,
90 periods, maximum field 0.4 T

With B=0.08 T, E=5 GeV, the total undulator radiated power is 235 W, with the peak at 3.15 Å. The number of photons/s in a 5% bandwidth (minimum bandwidth defined by the divergence of the electron beam) is 5.2 x 10^{16}. This is the number of photons through a pinhole subtending a solid angle approximately $1/\gamma^2$ x fractional band width, i.e a solid angle approximately 5 x 10^{-4} mrad^2.

With B=0.23 T, several harmonics are obtained. The total radiated power rises to 2 kW, the first harmonic is at 5 Å, with a power of 78 W, and the fifth harmonic is at 1 Å with 26.4 W (1.32 x 10^{16} photons/s in a 5% bandwidth).

Going to B=0.31 T, the total power rises to 3.75 kW and 2 x 10^{16} photons/s in 5% bandwidth at 0.95 Å are obtained using the 7th harmonic.

b) If a small-aperture undulator is used, for instance with permanent magnets moved into position after the beam has been stacked and the closed orbit corrected, one might achieve:

Undulator wavelength 16 mm, 125 periods, field 0.21 T which gives a total power of 730 W, of which 85 W is in a 5% bandwidth centred on the fundamental wavelength at 0.875 Å (i.e. 3.75 x 10^{16} photons/s).

The intention is to publish a detailed feasibility study report on this proposed facility during 1979.

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