IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

THE EUROPEAN SYNCHROTRON RADIATION FACILITY

S. Tazzari
European Synchrotron Radiation Project
c/o CERN, Geneva, Switzerland

Introduction

A new design study for the European Synchrotron Radiation Facility (ESRF) has been carried out in the past year by the European Synchrotron Radiation Project Group. The aim was to extend the work done in 1979 and 1982, under the auspices of the European Science Foundation, towards a very high brilliance, hard X-ray machine.

The guidelines for the design of a dedicated Synchrotron Radiation Source in the X-ray region were laid out in 1982 by the ESRF study group and confirmed at a ESRP workshop in 1983. It was concluded then that a low emittance storage ring with a large number of straight sections for wigglers and undulators, and the capability for also providing bending magnet sources in the 1 Å wavelength region should be built. The possibility of deciding on the number of a given type of device at a late stage in the project, or indeed at any time during operation, was deemed to be an important design feature. A full description of the present proposal can be found in [1].

General Description

The ESRF is an electron storage ring with a circumference of 776 m, surrounded by an experimental area into which as many as 50 beam lines can be projected, up to 30 of which may originate from wigglers or undulators. The injector is a full-energy, 10 Hz synchrotron with a race track microtron as a pre-injector. If necessary to obtain the best ultimate beam characteristics the machine can be modified to use positrons by provision of an add-on option - a linear electron accelerator, a positron converter, and an accumulation ring. The basic parameters of the ESRF are given in Table 1.

Table 1 Main parameters

Nominal electron energy	5 GeV
Nominal electron current (multibunch):	100 mA
max (with basic RF system)	~ 200 mA
Circumference	776 m
Number of wigglers and undulators	28 - 30
Free length of long straights:	
for undulators	4.0 and 5.0 m
for wigglers	2.5 m
Electron beam emittance	7×10^{-9} π·m·rad
Number of dipole magnets	
(arranged in pairs)	64
Number of quadrupole magnets	288
Energy of the injector synchrotron	5 GeV
Energy of the electron pre-injector	150 MeV

The storage ring is designed for maximum flexibility and versatility. For running-in purposes it can be operated at a larger emittance, which will still provide excellent performance but with much less stringent tolerances. Within the constraints due to the requirement of preserving some degree of symmetry and the maximum number of straight sections available, the numbers of wigglers and undulators installed or in use can be varied, and wigglers or undulators can be interchanged. The operating energy can be varied between 2.5 GeV and 5 GeV and, if required, reach 6 GeV. It is anticipated that the nature of the insertion devices may vary with time in response to experimental needs.

All questions relating to the possibility of actually achieving the low emittance afforded by the lattice in a real machine with specified positioning and field errors have been addressed. Limits to the circulating current set by interaction of the beams with the surroundings (vacuum chamber and RF cavities) and with the residual gas have been examined in detail. Other aspects, like the influence of insertion devices (wigglers, undulators, wavelength shifters) on performance, and the constraints imposed by the integration of the lattice elements with beam ports, by the large number of beam lines, and by the tight specifications on the stability of the sources, have been examined.

While it is still felt that further thought is needed in some areas to fully optimize the facility, the present stage of design has proved that the specified performance can indeed be obtained.

Performance

Energy

All the design goals can in principle be achieved with an electron energy of 5 GeV, and the machine design has been optimised for this. However, for an undulator producing an intense beam in the fundamental at 0.86 Å, the margin of feasibility is rather small and a beam energy of 6 GeV would allow a more conservative design.. Other, at present unknown, developments in the research to be carried out may require high flux or brilliance at higher photon energies than at present envisaged, and so it is demanded that the ESRF operate at 6 GeV if required. Operation at full intensity at 6 GeV will require doubling the RF installation.

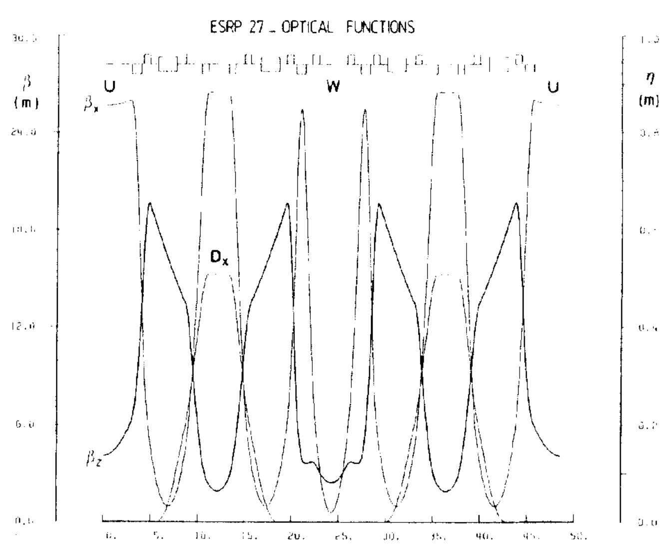

Fig. 1 The proposed ESRF lattice

Emittance

The lattice shown in Fig. 1 produces a horizontal beam emittance of $7 \cdot 10^{-9}$ $\pi \cdot$mrad. The associated dynamic aperture is shown in Fig. 2 (ESRP-27/3). By detuning the lattice a much larger aperture is obtained (ESRP-30/3 on Fig. 2) at the expense of doubling the emittance.

When unusually low emittances are to be obtained, particularly in the vertical plane, machine errors combined with the strong non linear elements can easily increase the nominal emittance by large factors. The behaviour of the machine (stability, emittance, closed orbit) including magnet misalignment and field errors has therefore been investigated. The program PETROC, the CERN version of PETROS, has been used to study the effect of random magnet positioning errors and strength errors.

Since even moderate closed orbit amplitudes can produce large effects it is essential to also simulate the closed orbit correction to estimate the real performance of the machine. For this study four beam position monitors and four correctors per half-cell were assumed for each plane, located near the high β_x and high β_z positions in the lattice. The random monitor and corrector inaccuracies were taken to be the same as those used in simulations of LEP, namely 0.6 mm and 0.2 G$\cdot$m respectively (standard deviations), although the monitor error is considered to be quite pessimistic and it is hoped to achieve 0.3 mm.

The final results show that if a proper tune is chosen and a proper closed orbit correction scheme is implemented, the effect of errors and imperfections on the emittance is negligible. Also, the residual closed orbit will be further reduced if the performance of beam position pick-ups can be improved.

A vertical emittance of $7 \cdot 10^{-10}$ $\pi \cdot$mrad is obtained under most conservative assumptions.

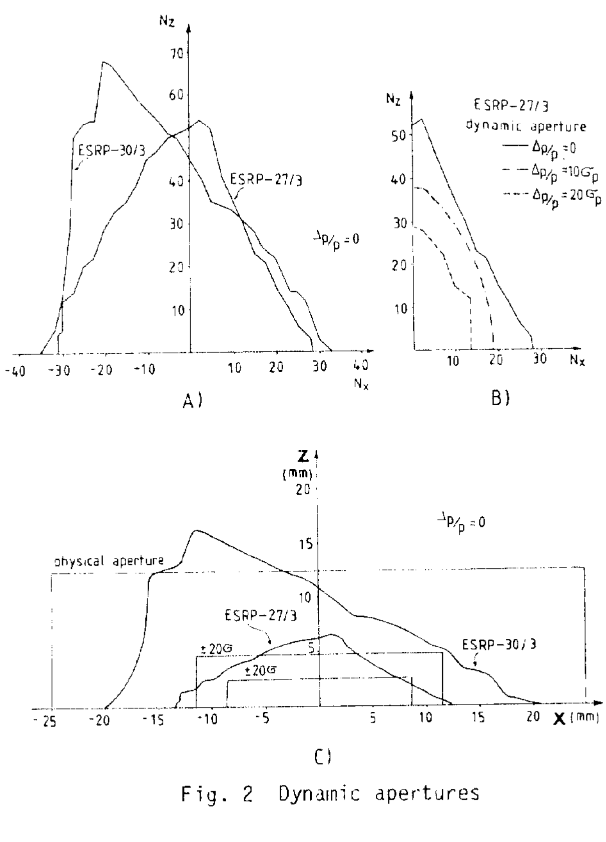

Fig. 2 Dynamic apertures

Electron current

The initial goal for normal multibunch operation is 100 mA. The machine can accommodate ~ 200 mA at 5 GeV before it is RF power-limited. Longitudinal and transverse coupled bunch instabilities could occur in multi-bunch operation of the ESRP storage ring but can be avoided at the design current levels by damping the parasitic cavity resonances which drive these instabilities and making their frequencies different in each cavity. LEP cavities are proposed for the ESRP ring. These cavities contain five cells and can provide a peak voltage of about 3 to 3.5 MV. Two such cavities are needed. The main parasitic resonances of these cavities need to be damped by about a factor of two only, for 5 GeV operation. It might be worthwhile to develop new cavities with a lower shunt impedance for the fundamental mode which are better adapted to the beam loading occuring for multi-bunch operation at the design current. This would at the same time further reduce the number and strength of the parasitic modes. A third harmonic RF system is also foreseen since practical experience at other storage rings shows that stability is improved by the addition of a higher harmonic RF.

Single bunch effects impose a limit on the maximum storable current in a single bunch because of bunch lengthening and widening and transverse turbulence. Bunch lengthening and widening calculations show that an increase of the energy spread by a factor 3 to 4 may occur for a bunch current of 5 mA at 5 GeV.

Transverse turbulence can lead to beam loss and therefore limits the storable bunch current. Thresholds depend on the bunch length and the accuracy of calculations is thus limited by the uncertainty on the bunch lengthening. It is however safe to state that currents per bunch of 3 to 6 mA at 5 GeV, and ~ 4.5 to 8.5 mA at 6 GeV can be achieved. Single bunch effects are caused mainly by the impedance of the vacuum chamber including bellows, photon beam ports, etc. This impedance will have to be evaluated more precisely on prototypes and by further calculations.

Beam lifetime

The machine is designed to achieve a beam lifetime of at least eight hours. Furthermore, the 5 GeV injector will permit to refill the ring regularly without ramping the magnetic fields, and, if desired, in the so-called topping-off mode.

A vacuum of a few 10^{-9} torr is sufficient to ensure that scattering and bremsstrahlung on the residual gas do not cause faster losses. A vacuum system that maintains the pressure of ~ 1 ntorr N_2 equivalent when the machine is operating in the steady state at 6 GeV with 0.2A of circulating current has been designed. Calculations are based on a thermal desorption rate of about $3 \cdot 10^{-12}$ torr$\cdot \ell \cdot s^{-1} \cdot cm^{-2}$ and a beam desorption coefficient of $2.7 \cdot 10^{-7}$ molecules/photon for a stainless steel vacuum vessel.

The geometry of the machine and of the beam ports is such that most of the unused radiation power contributing to the desorbed gas load can be captured by absorbers placed at suitable locations where a large, concentrated pumping speed can be provided.

The Touscheck effects limits the lifetime in the single bunch operation: the calculated lifetime for 5 mA in one bunch at 5 GeV without bunch lengthening, is only 2.5 hours.

Output parameters

Bending magnet sources: (up to 24)
λ_c = 0.89 Å. Useful flux to 0.2 Å or beyond.

Wiggler sources: Multipole wigglers can be provided with λ_c in the range from 0.5 Å to several Å: To produce harder X-ray radiation with a smaller value of λ_c than is achievable with a permanent magnet hybrid device on the same gap, requires the use of superconducting technology. A detailed design of a three-pole device similar to the one in use on the SRS, Daresbury, but with a much smaller radiation opening angle (~ 10 mrad) has been carried out. A peak magnetic field of 3.0 Tesla is obtained in the median plane, corresponding to $\lambda_c \geq 0.25$ Å, giving useful flux to at least 0.05 Å. (240 keV).

Undulator sources: These will be built to meet requirements. The highest energy envisaged is 14.4 keV corresponding to 0.86 Å in the fundamental. This is the lowest wavelength being considered for an undulator source; the design is therefore the most demanding and has been considered in some detail. A permanent magnet (rare earth cobalt, REC) and iron "hybrid" configuration were chosen. Calculations of the spectral brilliance including the effect of electron beam divergence have been performed for different gap settings and the results are shown in Fig. 3. Circularly polarized radiation can be obtained from specially designed undulators.

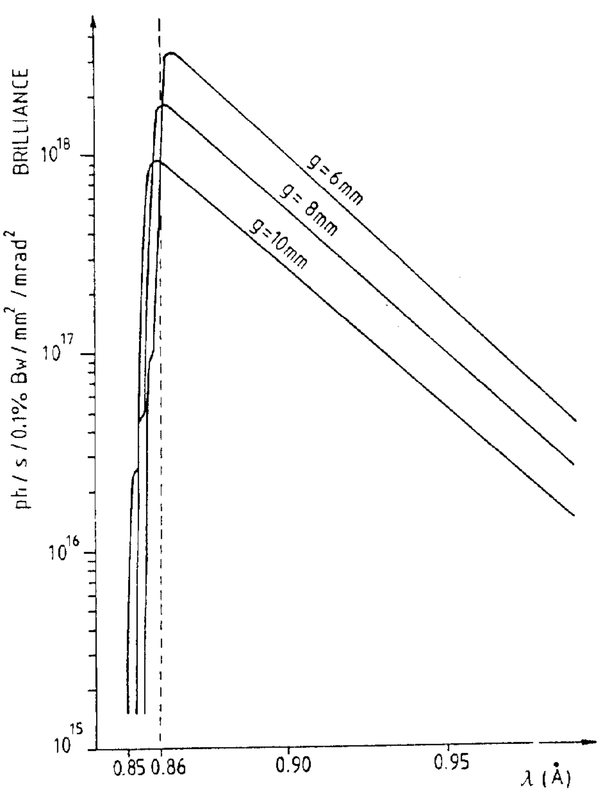

Fig. 3 Brilliance of a short wavelength undulator for the ESRF

Table 2 gives the source dimensions (electron beam cross-section and beam divergence) at the three types of source position in the lattice:
x = horizontal plane, z = vertical plane.

Table 2 Source dimensions and beam divergences

Source type	σ_x mm	σ'_x mrad	σ_z mm	σ'_z mrad
Bending magnet	0.092	0.090	0.100	0.008
Wiggler	0.062	0.106	0.040	0.016
Undulator	0.410	0.016	0.052	0.013

References

(1) Report of the ESRP, 1984, presented by B. Buras and S. Tazzari