OVERVIEW OF THE EUROPEAN SYNCHROTRON LIGHT SOURCE

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Introduction

In order to further consolidate Europe's position in research and to intensify scientific cooperation across disciplinary and national boundaries, the governments of France, the Federal Republic of Germany, Great Britain, Italy and Spain have signed a Memorandum of Understanding with the object of preparing the construction of the European Synchrotron Radiation Facility in Grenoble (France).

Under the framework of this agreement, signed on December 10th 1985, an international team of 43 people, mainly accelerator experts and synchrotron radiation users, has been gathered in Grenoble with the following task :

- to finalize the project,
- to choose the machine site,
- to review construction, operation and personnel costs.

The conclusions of the team were presented in the Foundation Phase Report [1] that has recently been submitted to the ESRF Provisional Council for approval. The Construction Phase is expected to start by October this year with the following time schedule :

- August 1988 : Ground Breaking
- February 1993 : Running in with beam
- February 1994 : Routine Operation with the first 15 beam lines
- August 1998 : Routine Operation with 30 beam lines

Synchrotron light source specifications

Solid guidelines for the design of a low emittance storage ring with a large number of straight sections to be used as a dedicated Synchrotron Radiation Source in the hard X-ray domain were already established in the 1984 Report of the ESRP [2]. The design goal specifications were reconfirmed at a workshop held in September 1986 in Grenoble :

- First priority to Insertion Devices (undulators, wavelength shifters, wigglers);
- Capacity to produce an intense photon beam in the fundamental of an undulator at 14.4 keV;
- Possibility of varying the number and the position of a given type of device;
- Stability of the beam ≤1/10 of rms dimensions;
- Beam lifetime ≥ 10 hours;
- Capability of providing bending magnet sources in the 10 keV region.

General description

The facility will be built in Grenoble, on the 27 ha Peninsula site at the confluence of the Isere and Drac rivers. The 6 GeV positron (electron) storage ring has a circumference of 844 m. It is surrounded by an experimental area into which more than 50 beam lines with a maximum length of 75 m can be built. There are 32 dispersion-free straight sections, 29 of which are available for Insertion Devices. In addition, 26 beam ports will be open to radiation from bending magnets. The users will have the choice of selecting either the 20 keV radiation emitted by the main dipoles at 0.8 Tesla , or softer X-rays at 10 keV from 16 weaker bending magnets. The site can also accommodate about 8 extra long (up to 500 m) beam lines. The injector will be built in the inner ring area. It will consist of a full-energy 10 Hz synchrotron fed by a two stage linear accelerator: 200 Mev electron linac, converter e-/e+, 400 MeV positron linac. Main parameters are summarized hereunder.

STORAGE RING

Energy	6	GeV
Current (multi-bunch mode)	≥100	mA
Current (single-bunch mode)	7.5	mA
Filling Time (e+ multi-bunch mode)	6	mn
Filling Time (e+ single-bunch mode)	20	mn
Circumference	844	m
Radio Frequency	352	MHz
Maximum Number of Insertion Devices	29	
Free-length of Straight Sections	6	m
Beam Emittance	$6.8\ 10^{-9}\ \pi$	m x rad
Number of Bending Magnet Ports	26 at 20	keV
Number of "Soft" Bending Magnet Ports	16 at 10	keV

SYNCHROTRON INJECTOR

Repetition rate	10	Hz
Energy	6	GeV
Circumference	300	m
Beam Emittance at 6 GeV	$1.2\ 10^{-7}\ \pi$	m x rad

PREINJECTOR 200MeV e^-/400 MeV e^+

Repetition rate	10	Hz
Pulse length	1000/2	ns
Electron Current	25/2500	mA
Positron Current	0.12/12	mA

Energy

In principle, the design goal performances, and in particular the production of an intense beam at 14.4 keV in the fundamental mode of an undulator, could be achieved with a Storage Ring energy of 5 GeV, as earlier proposed [2]. However, at 5 GeV, the goal can only be reached with a 10 mm undulator vertical gap, which raises a number of technical problems; furthermore, the safety margin is rather small. A beam energy of 6 GeV, associated with a 20 mm gap is more realistic, and allows a more conservative initial design. Furthermore, it provides the potential for reaching higher photon energies with smaller undulator gaps, if required at a later stage. On the other hand, increasing the energy has some disadvantages. It requires doubling RF power and makes the standard bending dipole radiation at 20 keV harder than necessary. Sixteen "Soft" dipoles adjacent to the main dipoles and emitting at 10 keV are used to solve the latter problem.

Lattice

A Chasman-Green (CG) lattice has been retained for the ESRF. The triplets at both ends of every straight section make it easy to match the beam size at each Insertion Device location to specific experimental requirements. The structure produces a horizontal beam emittance of 6.8 $10^{-9}\ \pi$ m x rad. Optical

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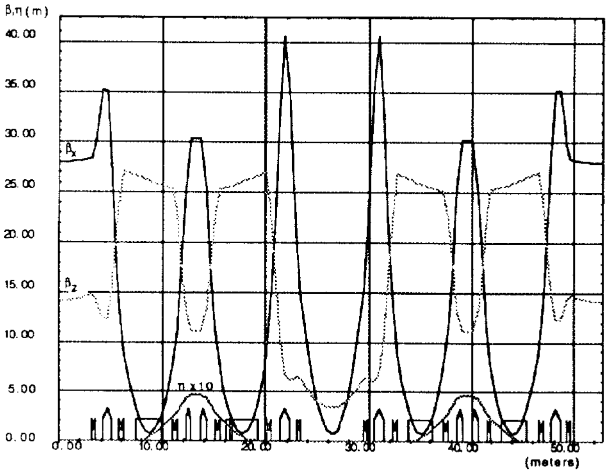

Fig. 1 Optical functions - 1/16 of the storage ring

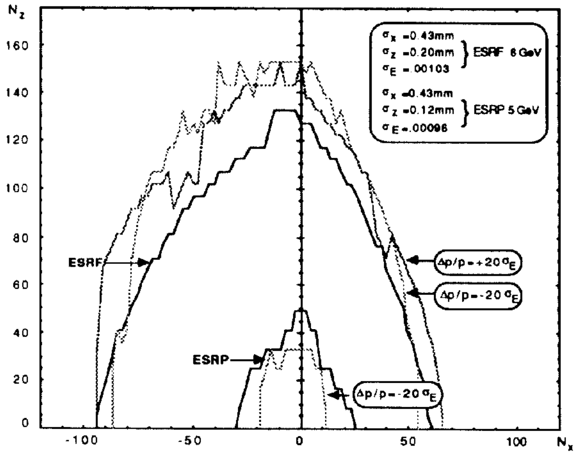

Fig.2 Comparison between the dynamic apertures of ESRP and ESRF lattices

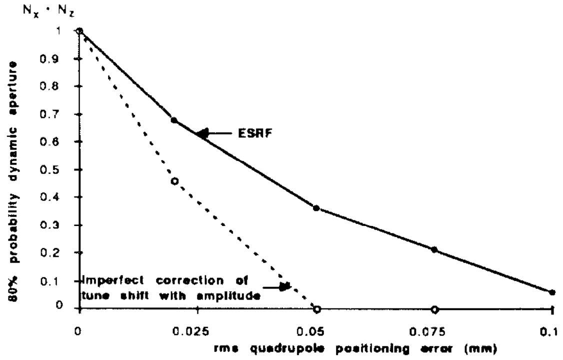

Fig.3 Sensitivity of CG lattice to quadrupole positioning errors

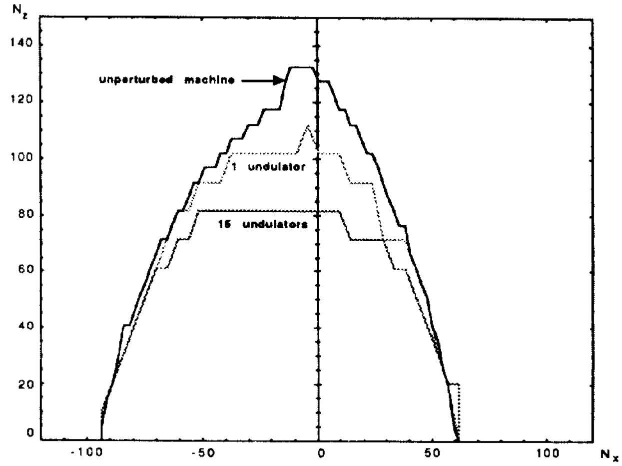

Fig.4 Effects of generic undulators on ESRF dynamic aperture

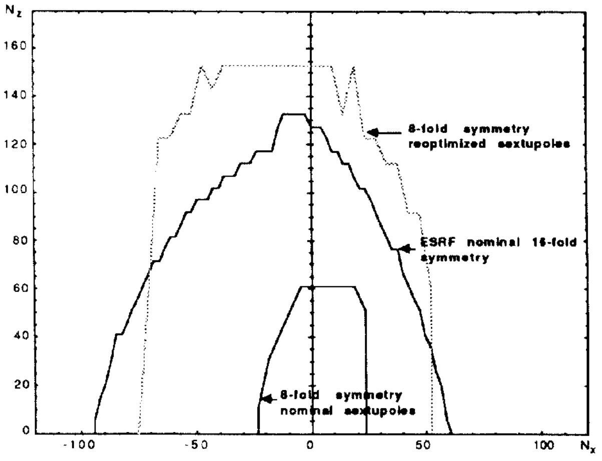

Fig.5 Dynamic aperture with 24 high β and 8 low β (8-fold symmetry)

functions are shown in Figure 1, when maximum symmetry is assumed by alternating high (undulator) and low (wiggler) betas in the straight sections sixteen times around the ring . This type of structure has already been considered for a high energy machine of large size, in 1979 by the first ESRF study group [3], in 1984 by the ESRP group [2], in 1985 by the Argonne group [4]. It was reputed to be sensitive to errors and to have a rather small dynamic aperture, when compared to the alternative lattices proposed in 1985 [5-6-7] (FODO and Triple Bend Achromat (TBA)). However, considerable improvement has been achieved during the last year by optimizing the lattice in two directions :

* choosing the working point to be well away from systematic third integer resonances, which are driven by chromaticity correcting sextupoles ;
* selecting the position of the sextupoles and tuning them to compensate the third order resonance driving terms and the tune shift with amplitude.

A comparison between the dynamic apertures of the original ESRP lattice [2] and the present ESRF lattice is shown in Figure 2. It demonstrates that the result is flat over a large range of energy spread. The improvement is remarkable. Nevertheless, before finalizing our choice, it was necessary to investigate alternatives, namely the FODO and TBA structures. With the same boundary conditions applied to all designs (32 six meter long straight sections for a storage ring circumference of 850 m), the following conclusions were reached. In terms of dynamic aperture, all lattices could be brought to comparable performances. The FODO lattice requires the most elements, some of which are close to the technical feasibility limit. It is also extremely sensitive to field and alignment errors. At this point an important remark must be made : it is useless to obtain a large dynamic aperture if the tune shift within this aperture is also large. It is now realised that a large tune shift with amplitude for the unperturbed structure is more or less systematically associated with a strong sensitivity to errors. Figure 3 shows the comparative response to quadrupole positioning errors of the ESRF structure, well optimized in this respect, and a CG structure that was not brought to the same level of optimization. The TBA is comparable to the CG structure in terms of sensitivity to errors; however, as with the FODO, it also requires a larger number of stronger magnets. Accordingly the CG structure costs less, offers the advantage of not being very sensitive to insertion tuning (Figure 4) and is also versatile and flexible, performing well when the pattern of high and low betas is varied. Figure 5 illustrates the ESRF lattice behaviour when an eight-fold symmetry with 24 high betas and 8 low betas around the ring is assumed; with reoptimized sextupoles, the dynamic aperture can be totally restored. It must be pointed out that such a conclusion, in favour of the CG lattice for the ESRF, would not necessarily apply to machines of different size or energy.

Current limitation

The project objective is to achieve 100 mA in standard multibunch operation. It is planned to adopt a radio frequency of about 352 MHz, partly because of availability of suitable klystrons, and also because use could be made of cavities very similar to those developed for LEP. With two 1MW klystrons feeding four 5-cell LEP type cavities arranged in pairs in two low beta straight sections, one can accumulate more than 200 mA before the machine is RF power limited. When unmodified LEP cavities are assumed, longitudinal and transverse coupled bunch instabilities driven by higher order parasitic modes are likely to occur at a threshold current of about 50mA. For the final ESRF cavities, the impedance associated with such parasitic resonances must be reduced by a significant factor. One must also ensure that parasitic mode frequencies in different cells will be sufficiently separated so that their effects are not added. This will be one of the important items on our Research and Development programme. In parallel, it will be important to develop a feed-back system of moderate band-width (≈ 45 MHz) that could combat these instabilities when the machine is operated with one bunch every 8 buckets. Single bunch effects impose a limit at about 7.5 mA per bunch. Large uncertainties still exist on the impedance of the vacuum chamber including the effect of cross section changes, bellows, photon beam ports, antechamber, etc. This impedance must be evaluated more precisely on prototypes and with further calculations.

Beam lifetime

The vacuum chamber and beam ports are designed in such a way that a very large fraction of the unused radiation, which would contribute to desorption, is dumped on absorbers. The power density on crotches can reach 500 watt/mm^2. At these locations, a concentrated pumping is provided. When scattering and Bremsstrahlung on residual gas are considered, with the nominal acceptance and 200 mA in the multibunch mode, a pressure of 1 nanotorr equivalent N_2 leads to a 50 hour lifetime. In the single bunch mode, with 7.5 mA and no bunch lengthening, Touschek effect is dominant. The lifetime will still be large, with 12 hours for nominal conditions and a 20 mm undulator gap outside vacuum (vertical aperture of vacuum vessel of 16 mm). A reduction of vertical aperture to 10 mm would cause a significant reduction in the lifetime to 3 hours.

Beam stability

To obtain full benefit of the small emittance, in particular in the vertical plane, stringent tolerances must be put on the beam displacement : in phase space, the beam center of mass position must be kept within an emittance of $\approx 2\pi$ µm x µrad during one eight hour shift. In this respect, the effect of vibrations transmitted by the ground to magnetic elements via the supports was investigated. As far as cultural noise is concerned, the selected site looks perfectly adequate, provided vibrations in the 10-40 Hz range to which the machine is sensitive are not drastically amplified by the supports. The in situ infrastructure must be carefully designed in order to induce tolerable noise level. In any case, measuring such small beam displacements in the machine is impossible with standard monitors. Therefore, at every beam port, a feed-back system relying on a signal provided by the experiments and acting on local bumps will be installed. Stringent tolerances are also required for the long term stability and differential settlement must be ≈ 0.1 mm/year over a distance of 10 m. This implies unusual constraints on the building design.

Positrons or Electrons

During the early commissioning of the synchrotron and the storage ring, a high intensity beam is required and therefore an electron beam is preferable. The question of whether electrons could be considered for steady state light production is unanswered at the moment, and accordingly, the positron part of the preinjector is included in the ESRF budget. The stability of an electron beam is a fundamental problem for most Synchrotron Radiation sources in operation. The electrons ionize the residual gas and under certain conditions, the ions are trapped in the potential well of the circulating beam and accumulate along the particle path. For a machine like the ESRF storage ring, due to the combination of the small emittance and the moderately large current, the potential well is very deep which means that ions will be automatically cleared by overfocusing forces. According to our simulation model, for nominal parameters and single bunch operation, the ions would start being unstable at a threshold current well below the nominal 7.5 mA. In the multibunch mode, the current per bunch is much lower and ions are trapped. To get rid of ions a gap must be introduced in the bunch train. This gap destroys the focusing force symmetry and generate unstable mass bands similar to half integer resonances. In the worst case the required gap length would correspond to a significant part of the circumference. The decision to order the positron part of the preinjector will be slightly delayed with the hope that further experimental evidence will become available.

Magnet, Power Supply and Vacuum Vessel Technology

In the storage ring, the sixty four main dipoles will be parallel ended and assembled by stacking 1.0 mm to 1.5 mm laminations along a curve to match the beam trajectory and minimize the pole width. In order to provide the maximum space for vacuum pumping on the inside of the curve, clear of the radiation absorber, the open side of the 'C' cored magnets will be on the inside of the ring.

The designs of the quadrupole and sextupole magnets are strongly influenced by the position of emerging beam lines from both the Insertion Devices and dipoles. As in the previous design [2], the quadrupoles are split horizontally, with no ferro-magnetic return yokes between the upper and lower pole pairs. The necessary mechanical supports can then be modified at will, to accommodate beam lines without disturbing the quality of the magnet. Eight families of quadrupoles will be required, and two separate designs are envisaged; the high gradient families require diverging pole sides to prevent saturation in the pole root. Because of the poor field quality, the quadrupoles will not be used to generate dipole correction fields. The sextupole magnets will be of novel design, with the radially outer yoke removed to provide space for emerging radiation lines. To guarantee that this modification does not allow dipole and quadrupole distortions to be present in the magnet, the yoke should also be split at the two positions 120° from this opening. However, lack of space in the lattice requires that the sextupole should also be used for generating vertical and horizontal dipole correcting fields, which can be of good quality in this type of magnet. These would not be compatible with large gaps at three positions in the yoke, and hence the two gaps added for symmetry purposes will be small, of the order of 1 to 2 mm. The dipole fields will be generated by five independently powered, air cooled coils mounted on the backlegs of each sextupole; the presence of the small gaps will result in a small increase in the Ampere-turns required to generate the correction fields.

The DC power supplies for the dipole magnets, and for the quadrupoles and sextupoles located in the achromats are conventional, and power each group of magnets in series. However, to provide maximum flexibility for adjusting the ß values at the insertions, it is highly desirable to have independent control of the strengths of the individual quadrupoles and sextupoles in these regions. This leads to economic problems, since large numbers of small independent supplies are up to three times more expensive than single high power units. A number of solutions, involving the use of high frequency invertor/rectifier systems are currently being investigated.

The beam vacuum chamber is designed with a constant beam stay clear cross section : 70 x 32 mm^2. All the necessary interruptions and cross section changes due to crotches, pumps, beam ports are rejected in the antechamber. A 9 mm wide slot connects the main chamber and the antechamber. Stainless steel will be used because of its mechanical properties and adequate fabrication techniques. Provision is made for a 300° C in-situ baking.

Radiation from Insertion Devices

Figure 6 presents the brilliance for various generic Insertion Devices to be installed in the ESRF straight sections. A brilliance in the range of 10^{18} phot/sec/mm^2/mrad^2/0.1 % bw can be reached between 0.1 and 14 keV in the fundamental for permanent magnet undulators with a 20 mm gap. For a 10 mm gap, 20 keV could be reached. High field multipole wigglers (made of permanent or electromagnets) generate a high flux and brilliance over the whole range from 0.5 to 200 keV.

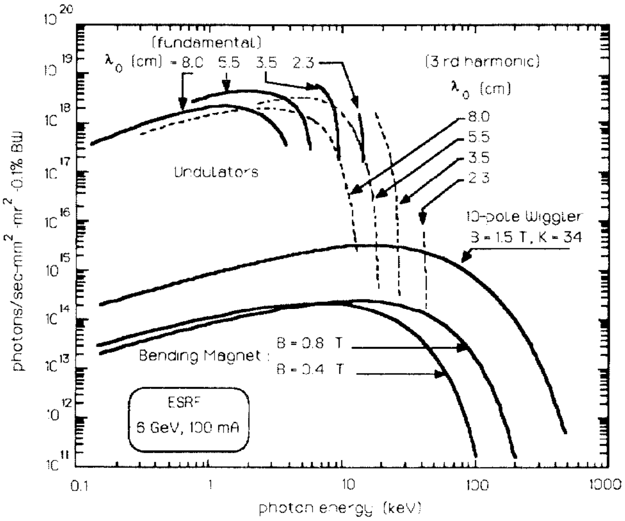

Fig. 6 Brilliance from Insertion Devices

Cost Considerations

The capital costs of the ESRF will amount to 1 690 MFF. The major part of this sum (1 438MFF) will be spent during the Phase 1. This is broken down as follows :

- 576 MFF for the machine (including Insertion Devices) ;
- 143 MFF for the first fifteen beam lines ;
- 431 MFF for the buildings ;
- 157 MFF for the laboratory and office equipment ;
- 131 MFF for a 10 % contingency.

During the first years of the Operation Phase, another 15 beam lines will be installed and the Insertion Devices of the existing beam lines will be upgraded, which leads to further capital costs expenditure of 250 MFF. Recurrent costs (electricity, maintenance, general expenditure, technical developments and in-house research) will grow during the Construction and Operation Phases to 150 MFF per year. On the long term, these recurrent costs together with personnel costs(140 MFF) and some additional capital costs (25 MFF) for the machine and experiments will finally lead to a constant budget of 315 MFF per year (in Dec. 86 FF).

The ESRF personnel will increase during the Construction Phase to a total of 434 people. This figure includes 93 people working for the operation and developments of the accelerators, 159 working for the experiments, 93 for general support, 40 for administration. The total also includes 32 students who will be responsible neither for the operation of the machine nor for experiments but who will play an important role in the upgrade of the performance of the facilities and developing the application of Synchrotron Radiation to various scientific areas.

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