Status of the ESRF

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Abstract

The ESRF (European Synchrotron Radiation Facility) is a fundamental research institute based in Grenoble, France which was founded in 1988 by 12 European countries. Five years after the start of the construction, the commissioning of the Storage Ring was successfully completed, with the achievement of performances far beyond the target specifications. Since the beginning of 1993, the X-ray source has been operated at nominal conditions for the commissioning of the X-ray Beamlines ran for 3000 hours in User Service Mode over the full year 1993.

As expected, after the very fast progress achieved during the commissioning phase (the target intensity of 100 mA was reached in multibunch within only 4 months), the performances of the machine are excellent both in terms of source characteristics and availability for the Users. Following the improvements made this year to the vacuum system, the lifetime at 100 mA has gone past 50 hours (i.e. more than 6 times the target specification). The X-ray beam position stability, provided by a permanent control of the reproducibility of the closed orbit, is situated within a few % of the electron beam sizes. Record brilliances larger than 10^{18} have been produced by the undulators made from permanent magnets. Purity in the few 10^{-6} range at the design intensity of 5 mA is routinely achieved in the single bunch mode. As from September 1994, seven ESRF-funded beamlines (receiving X-rays from insertion devices) and four bending magnet beamlines (funded by Collaboration Research Groups) will be at the disposal of the Users. During the next 4 to 5 years, the number of public beamlines will be increased to 30.

1. INTRODUCTION

The ESRF was created following the signature of an international convention dated December 16th 1988 by 12 European countries (France, Germany, Italy, United Kingdom, Spain, Denmark, Finland, Norway, Sweden, Belgium, Netherlands, Switzerland). In the convention, the main objectives were set as follows : to design, construct, operate and develop a synchrotron radiation source of the third generation in the hard X-ray domain and the associated experimental instruments for the use of the scientific community of the contracting parties. These objectives had to be met within a certain time schedule. The international convention covers a period of 11 years split into 2 phases :

◊ Phase I or construction phase covers the first 6 1/2 years, ending with the completion of the commissioning of the first set of at least 7 beamlines in July 1994.

◊ Phase II is to cover the remaining 4 1/2 years with the completion of the experimental facility, 30 beamlines in total, by December 1998.

The project is now nearing the end of Phase I or construction phase, due in July 1994, and is expecting its first external Users as from September 1994 onwards. All source design goal specifications had been reached by mid 1992 (one year ahead of schedule) and the machine has been running in the User Service Mode (USM) since January 1993.

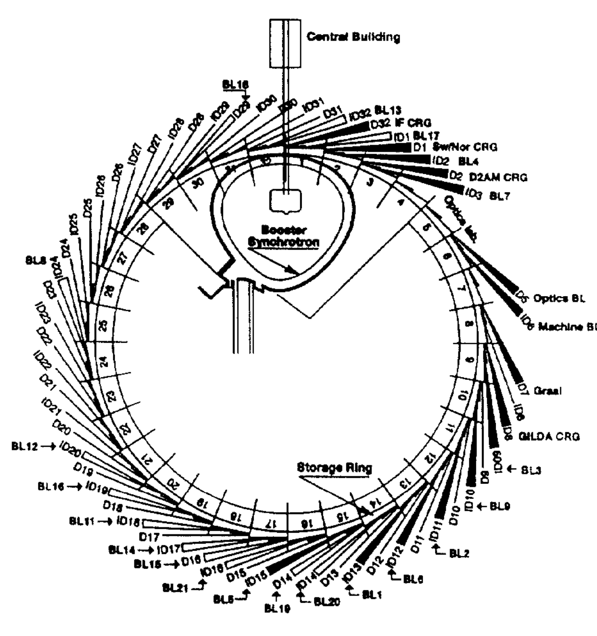
This article reflects the status of the ESRF source as per June 1994, one month before the end of Phase I.

2. TARGET SPECIFICATIONS

The general specifications set in the ESRF convention were : Priority to Insertion Devices (ID), high flexibility of the lattice at the ID location, brilliance from undulators in the range of 10^{18} to 10^{19} photons/sec/mm^2/mrad^2/0.1% band-width (in particular brilliance larger than 10^{18} in the fundamental of an undulator at 14.4 keV), bending magnet sources at 10 and 20 keV, stability of the X-ray beam better than one tenth of the rms beam dimensions, beam lifetime longer than 8 hours. To obtain such performances, one has to combine, in an optimal way, the energy of the stored electron beam, its intensity, the smallest achievable emittance, together with the gap, the field and the period of the Insertion Devices.

At the stage of the Foundation Phase Report, the following basic parameters of the Storage Ring were targeted : an energy of 6 GeV, a current of 100 mA, an expanded Chasman-Green lattice able to be tuned to obtain emittances in the few nanometer range : 6.2 10^{-9} m.rad horizontally, and a small fraction of that, 10% for instance, in the vertical plane.

Figure 1



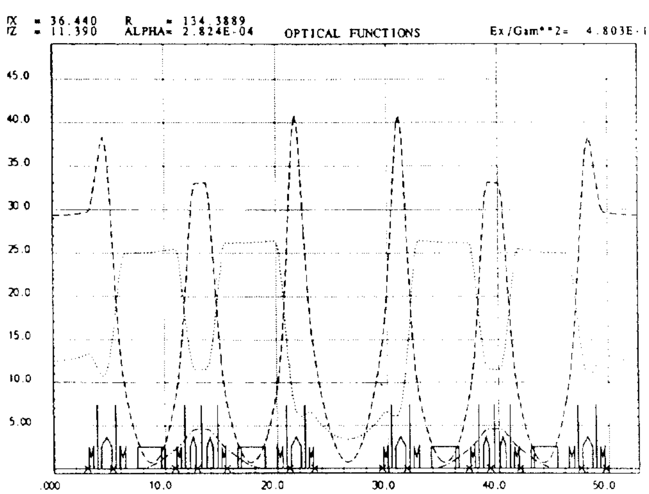
3. DESCRIPTION OF THE MACHINE

The facility consists of a 200 MeV electron linear accelerator, a 6 GeV fast cycling booster synchrotron and a 6 GeV low emittance Storage Ring optimised to produce high brilliance X-rays from insertion devices. (See Figure 1)

The requested highest priority to be given to Insertion Devices - 29 of them can be accommodated - was satisfied by adopting a structure with a high periodicity, 32 periods, and a 6 m long straight section in every period.

The straight sections which accommodate the IDs are equipped with triplets at both ends. These triplets are tuned to produce an electron beam which alternates between a small divergence in one straight section (the preferred location for undulators) and a small size in the adjacent one (the preferred location for wigglers), leading to 16-fold symmetry optical functions as shown in Figure 2.

Figure 2



The undulators are made of permanent magnets with longitudinal periods ranging from 23 to 85 mm. Depending on the undulator period and magnetic gap (20 mm minimum), the photon energy of the fundamental falls in the 2 to 15 keV range. The brilliance reaches the several times 10^{18} range. The power density from undulators is extremely high. It can reach 600 W/mm2 at a distance of 10m from the source, assuming a 5m long undulator with a 20 mm magnetic gap injected by a 100 mA current [1].

Wigglers typically present a lower power density but higher angle integrated power. The maximum power is not limited by the wiggler itself, but more by the design of the beamline front end (masks, absorbers, ...). It is expected to reach 15 kW. The spectrum is white and therefore the brilliance is typically 2 orders of magnitude below that of undulators.

To make the dipole sources as attractive as possible, the bending magnets were designed in such a way that the fringing field has a flat intermediate step at 0.4T (critical energy of 10 keV), half of the full field value, 0.85T (20 keV). In principle up to 20 dipole beam ports can be made available.

Special care was given to minimising the impedance of the stainless steel vacuum vessel (all transitions are shielded by RF fingers) which is equipped with OHFC and Glidcop absorbers.

The RF acceleration is provided by 4 LEP type RF cavities, which are fed by a single 1 MW transmitter.

The resulting main Injector and Storage Ring parameters adopted are summarised hereunder in Table 1.

Table 1

A. Electron Linac

Energy	200 MeV
Repetition rate	10 Hz
Pulse Length	1000 - 2 ns
Electron Current	25 - 250 mA

B. Booster Synchrotron

Energy	6 GeV
Repetition rate	10 Hz
Circumference	300 m
Current	5 mA - 0.1 mA
Emittance at 6 GeV	$1.2\ 10^{-7}$ m.rad

C. Storage Ring

Energy	6 GeV
Current (Multi Bunch Mode)	100 mA
Current (Single Bunch Mode)	5 mA
Filling time at 100 mA in Multibunch	1 min
Filling time at 5 mA in Single Bunch	1 min
Circumference	844 m
Radio Frequency	352 MHz
Horizontal beam emittance	$6.2\ 10^{-9}$ m.rad
Vertical beam emittance	$<6.2\ 10^{-10}$ m.rad
Natural rms Bunch Length	6 mm
Maximum number of Insertion Devices	29
Free length of straight sections	6 m
N° of Bending Magnet Ports	20 at 10 - 20 keV

4. ACHIEVED PERFORMANCES

After the successful commissioning of the Linac pre-injector in June 1991, and of the Booster injector in December 91, all target objectives for the Storage Ring were reached and even exceeded during the 10 months scheduled commissioning in 1992.

Hereafter all major Source performances are reviewed and the status as of June 1994 is given.

Table 2

		design goals	achieved during routine operation	present peak performances	medium term objectives
Intensity	Multibunch (100 mA) Single Bunch	100 mA 5 mA	105 mA 5.5 mA	175 mA 7 mA (15 mA with feedback)	200 mA
Lifetime	Multibunch Single Bunch	8 hours 8 hours	<45 hours 30 hours at 5 mA	56 hours 30 hours at 5mA	60 hours 30 hours at 5mA
e^- beam Emittances	Horizontal Vertical	$6.3\ 10^{-9}$ m.rad $6.3\ 10^{-10}$ m.rad	$8.4\ 10^{-9}$ m.rad $2.\ 10^{-10}$ m.rad	$5\ 10^{-9}$ m.rad $7\ 10^{-11}$ m.rad	$3.5\ 10^{-9}$ m.rad $3.5\ 10^{-11}$ m.rad
X-ray beam Stability		10% of beam size & divergence	a few % in both H and V planes	1 % in H 10% in V	1% in H 10% in V
Brilliance at 1 Å from a 1.6 m long undulator in phot /s/0.1 %/ $mm^2/mrad^2$		$\sim 1.\ 10^{18}$	$4.\ 10^{17}$	$8.4\ 10^{18}$	$2.1\ 10^{19}$

4.1 Intensity

The design intensity of 100 mA was achieved in June 1992. Initially, this current was considered as a challenging target since instability thresholds of the order of 60 mA had been predicted. With cavities similar to those of LEP (CERN) and not at all optimised for a synchrotron radiation source, a simple solution has been found to nevertheless overcome the predicted HOM limit and go significantly beyond the design current.

It consists in adopting a non-uniform filling. The beam is much more stable longitudinally and transversally, with regards to HOMs and the resistive wall respectively, when the Storage Ring is filled leaving an empty gap corresponding to about 2/3 of the circumference.

Peak intensity performances have been steadily increased over the last two years : 100 mA in June 92, 125 mA in April 93, 150 mA in July 93 and 175 mA were reached in March 94, thanks to the new 1.3 MW transmitter connected to the 4 cavities [2].

4.2 Lifetime

All through 1993, an extensive programme of upgrading of vacuum equipment was carried out with the replacement of absorbers, some defective vacuum chambers and RF finger springs. At the nominal 100 mA, the impact of the resulting better vacuum conditions, combined with the refined corrections of tunes, chromaticity and closed orbit, led us to the "magic" 24 hours lifetime, ie 3 times the target, in September 93. Vacuum conditioning [3] is still improving and the current record set in June 94 stands at 56 hours, i.e. 7 times the original target. There is still some expected vacuum improvement to come which justifies our 60 hours objective as indicated in Table 2.

With such long lifetimes, the machine can be operated with less than one refill per day. This way the heatload on the beamline optics remains practically constant during the period of time needed for a typical experiment.

Given the rapid, excellent and beyond target results obtained in terms of lifetime with electrons, it is easy to come to the conclusion that it was unnecessary to implement a positron option on the injector for achieving our Phase I performances. For the time being, despite all efforts made during machine physics runs, it was impossible to provoke ion-related effects even in the most favourable conditions of low current and uniform filling of the circumference.

4.3 Emittances and Coupling

The X-ray beam spot drawn from the Machine Diagnostics Beamline ID6 enables the photon beam emittances and accordingly the electron beam emittances to be permanently measured. The 7 to 8 nm.rad measured for the horizontal plane are very close to the theoretical 6.2 nm.rad value. The machine is routinely run near the coupling resonance (ν_x=36.44, ν_z=11.39) with a coupling of about 10%, which again corresponds to the design value. The procedures for decreasing the coupling, i.e. compensating the two coupling resonances in the vicinity of the working point, have been successfully tested. During the last 1994 USM runs, beam was delivered with a small coupling in the few % (1 to 2%) range, which resulted in a 3 hours reduction of the lifetime. When compared with the 10% target, this reduction of the vertical emittance gives an equivalent gain of a factor of 5 to 10 in brilliance.

It must be mentioned that at the end of 1993, we discovered by chance that one sextupole (out of the 224) had been connected with the wrong polarity from the very beginning. This fortunately did not prevent us from commissioning and even reliably operating the machine for one year. Understandably, once the sextupole had been powered with the right polarity, the machine proved to be much more forgiving. The dynamic acceptance has significantly increased, as deduced from the dramatic gain in single bunch lifetime (from 10 to 30 hours at 5 mA) recorded since then.

4.4 Single and few bunch modes

The target performances in the single bunch mode were obtained and even surpassed during the commissioning period. As predicted, the maximum current is limited by the fast head tail instability, the threshold of which is chromaticity dependent. With standard sextupoles, 5 mA are routinely stored. With a strongly overcompensated chromaticity, more than 7 mA can be obtained. In addition, by means of a prototype transverse feedback system [4], the demonstration was made that the instability threshold could be pushed up to 15 mA. The lifetime is sensitive to the vertical beam size (Touschek effect). At 5 mA, it exceeds the 30 hours with the 10% nominal coupling but goes down to the10 hours range with the 1 to 2% coupling.

The 16-Bunch mode of filling (16 highly populated and equally spaced bunches) is a hybrid mode of operation which has the advantage of satisfying the Users performing time resolved experiments, whilst simultaneously minimising the penalty for those requiring a high current. The upgrade of the linac hardware and timing system allowing 5 bunches to be accelerated simultaneously in the injector has significantly eased the possibility of operating the machine in the 16-Bunch mode. The filling of the storage ring remains quite fast at about 3 minutes.

Single bunch purity is essential for all experiments using the time structure. The cleaning technique of lowly populated parasitic bunches, which combines a shaker with a vertical scraper, works perfectly. Purities in the low 10^{-5} to 10^{-6} range are routinely achieved in USM.

4.5 Beam position stability - Orbit correction

All attempts to minimise the emittances would be in vain if the X-ray beam stability and reproducibility in position and angle were not excellent.

First of all, given the present differential ground settlement of about 0.1 mm per month peak to peak, the storage ring is realigned twice a year, before the summer and winter shutdowns. The operation is performed on line with a weak beam of 5 mA permanently stored. It consists in moving the quadrupole girders by activating the motorised jacks which support them. The amplitude of the motion is provided by the Hydrostatic Levelling System installed on each girder [5]. It takes a few hours and is followed with the Beamline shutters open. These realignments at 6 month intervals prevent the need to correct large orbit distortions.

On a much shorter time scale, every 5 minutes during USM the closed orbit is corrected in three steps, ie : a global harmonic correction over the entire ring first, a retuning of the RF frequency if necessary, then finally a series of local re-adjustments in position and angle of the e- beam at the location of the Insertion Devices. This brings the DC rms orbit deviations with respect to the reference orbit (established for the entire 6 month period between two realignments) passing through the centre of the Beam Position Monitors (BPM) to below 5 µm in both planes. In routine USM and over periods of 2 to 3 weeks, we are accustomed to achieving DC beam centre of mass stabilities corresponding to a few percent (1 or 2%) of the target beam sizes and therefore well within the original target of 10% of the beam sizes.

For the AC part, at the design stage a large effort was put into the study of ground vibrations, design of the infrastructure, of the magnet girders, of transmission of vibration to the girders, etc... As a consequence, the beam displacement at frequencies higher than 1 Hz are naturally of the order of 5% of the beam sizes at the most and therefore within the 10% target. Nevertheless, fast feedback systems installed at both ends of every ID can locally further stabilise the AC beam displacements. For one year we have tested such a system by using X-ray Beam Position Monitors (XBPMs) located in the Front-Ends as sensors. As expected, this can significantly improve the situation down to the 1% of beam size range. However, the present generation of XBPMs, which work perfectly for wigglers or even dipole beams, has the disadvantage, when being used for undulators, of being sensitive to the tails of radiation from the upstream and downstream dipoles and therefore to gap variations (different contrast between the undulator and the parasitic dipole radiation). The solution currently being looked into is to use the e- BPMs as sensors. Preliminary results look encouraging. In parallel, we are developing a new generation of XBPMs. Obviously these feedback systems become essential if one wants to fully benefit from the increased brilliance obtained from emittance or coupling reduction.

It must also been reported that no significant effect due to magnetic perturbation (neither on the closed orbit, nor on the tunes) can be observed on the electron beam when closing the gap of an Insertion Device which demonstrates the high magnetic quality of our IDs.

5. ROUTINE OPERATION

Most of the time, the machine is run in the multibunch mode: The beam intensity varies from 105 mA (after a refill) down to 55 mA. In that mode only 1/3 of the machine circumference is filled. A typical beam decay lasts 20 to 30 hours, and if no failure occurs, the intensity is just topped up to 105 mA during a standard refill.

In the single bunch mode of operation the beam intensity varies from 5.5 mA (after a refill) down to 3 mA. The 30 hours lifetime enables to have long beam decays.

In the 16 bunch mode of operation the beam intensity varies from 75 mA (after a refill) down to 35 mA. In that mode 16 equally spaced bunches of the machine are filled.

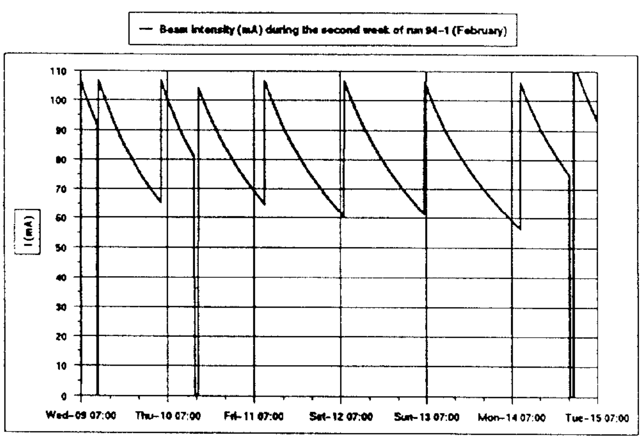
Whatever the mode of operation, the filling times are quite short and the complete refill sequence takes about 15 minutes. The linac and booster have an availability close to 100% and are straight forward switch on/switch off machines

The machine availability over the full last year and a half was excellent (close to 90%) which corresponds to 4000 hours of beam delivery to the Users. The 10 % of beam time lost was mainly due to RF problems (first with the transmitter system, then with the cavities), drops on the electrical mains (essentially due to Storms) and interlocks from the various cooling systems.

Last year, a lot of work was carried out to increase the mean time between failure which now stands at about 12 hours during USM. This work, together with the very long lifetime, resulted, in a record of 36 hours of uninterrupted beam delivery and of a period of 103 hours without any beam trips (see Figure 3).

Since April 94, 15 beamlines have been receiving X-ray beams : 10 from an insertion device (6 undulators and 4 wigglers) and 5 from a bending magnet, out of which 4 are CRG beamlines.

Figure 3



6. FUTURE IMPROVEMENTS

The major part of the machine side of the construction programme has of course been completed. There still remains the completion of the installation of Insertion Devices and Front-Ends (another 11 Beamlines will be open to the Users in September 95) and the installation of the High Quality Power Supply which will shield us against the mains drops caused by storms [6].

Two major goals have been set with regards to future machine developments :

• Improving the quality of operation at target performances (availability, stability and reproducibility)

• Bettering the performances (increasing brilliance, stability, lifetime, photon spectrum, ..). The goal will be first to increase the intensity to 200 mA, second to modify the optics in order to divide the horizontal emittance by 2 and to reduce the coupling to a few %. By doing so we expect to increase the brilliance by a factor of 10 within the year to come [7].

With a new shimming technique developed at the ESRF, considerable improvements can be made to the energy spectrum produced from the undulators, the radiation of which is in the 20-40 keV [1]. A minigap (7 mm) undulator and a superconducting wiggler [8] will also be installed soon in the ring.

7. CONCLUSION

Six and a half years after its creation, the ESRF has completely fulfilled and even surpassed the target specifications. Moreover, it has demonstrated a potential for a significant upgrading of the brilliance which will be at the disposal of the Users by next year.

It will be opened to the first external Users starting from next September 94. The USM time will be increased from 4000 hours in 1994 to 5000 hours in 1995 before reaching the 6000 hours target in 1996.

The rapid success of the ESRF, the first machine of the 3rd generation Synchrotron Light Source now enables speculation to be accelerated as to the next generation of diffraction limited machines.

8. REFERENCES

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