Commissioning and Performance of the ESRF

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Abstract

The ESRF (European Synchrotron Radiation Facility) is a fundamental research institute based in Grenoble, France. Construction of the ESRF source [1], [2], [3] started in 1988 as a joint project of 12 European countries (Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom). 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 optimized to produce high brilliance X-rays from insertion devices. The project is now well advanced. The electron linac delivered its first beam in May 1991 and reached design performance in the 1 μs pulse operation during the following one month commissioning period. Commissioning of the booster started in September 1991, with the operational energy of 6 GeV being reached in November 1991. Storage Ring commissioning began in February 1992, and progress was extremely fast and promising since, less than 4 months later, the target intensity of 100 mA in the multibunch mode was reached. In July 1992 the first undulator was operated without any effect on the beam and the machine diagnostics beamline was run at the full nominal current with a record brilliance in the 10^{17} range. The focusing of X-rays using a bent crystal has also been carried out to a record-breaking level for the spot size (22.7 μm). Components of three user beamlines have already been tested with beam and several more beamlines will be built and commissioned in 1993. The first external users for routine operation are expected for the beginning of 1994.

I. INTRODUCTION

The ESRF was created as a private company under French law following the signature of an international convention on December 16th 1988 by 12 European countries (France, Germany, Italy, United Kingdom, Spain, Denmark, Finland, Norway, Sweden, Belgium, Netherlands, Switzerland).

The main objectives were set as follows : To design, construct, operate and develop a synchrotron radiation source and associated 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 1 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 June 1994. An important intermediate milestone was to be the reaching of the source design goal performances by July 1993.

◊ Phase 2 is to cover the remaining 4 1/2 years with the completion of the experimental facility, 30 beamlines in total, by December 98.

The means provided to meet these objectives were as follows :

◊ 2,2 GFF in Phase 1
◊ 1,6 GFF in Phase 2
◊ and a total staff of 450 people.

This paper reflects the status of the ESRF in May 1993.

II. REVIEW OF THE SPECIFICATIONS AND ASSOCIATED TECHNICAL OPTIONS

The institute is built around a synchrotron radiation source. It consists of :

◊ an 850 m long Storage Ring for 6 GeV electrons or positrons
◊ a 300 m long 6 GeV booster synchrotron functioning at 10 Hz
◊ a linac preinjector.

The source had to fulfill a series of detailed target specifications.

I Priority was given to insertion devices.
II High flexibility of the lattice at the ID location.
III Brilliance from undulators in the range of 10^{18} to 10^{19} photons/sec/mm^2/mrad^2/0.1% bandwidth.
IV In particular brilliance larger than 1. 10^{18} in the fundamental of an undulator at 14.4 keV.
V Bending magnet sources at 10 and 20 keV
VI Stability of the X-ray beam greater than one tenth of the rms dimensions.
VII Beam lifetime longer than 8 hours.

These could only be satisfied by adopting a storage ring lattice with a high periodicity, 32 periods, with a 6 m long straight section in every period. We opted for an expended Chasman-Green lattice.

In Figure 1, the optical functions are shown. The straight sections which accommodate the Insertion Devices are equipped with triplets at both ends.

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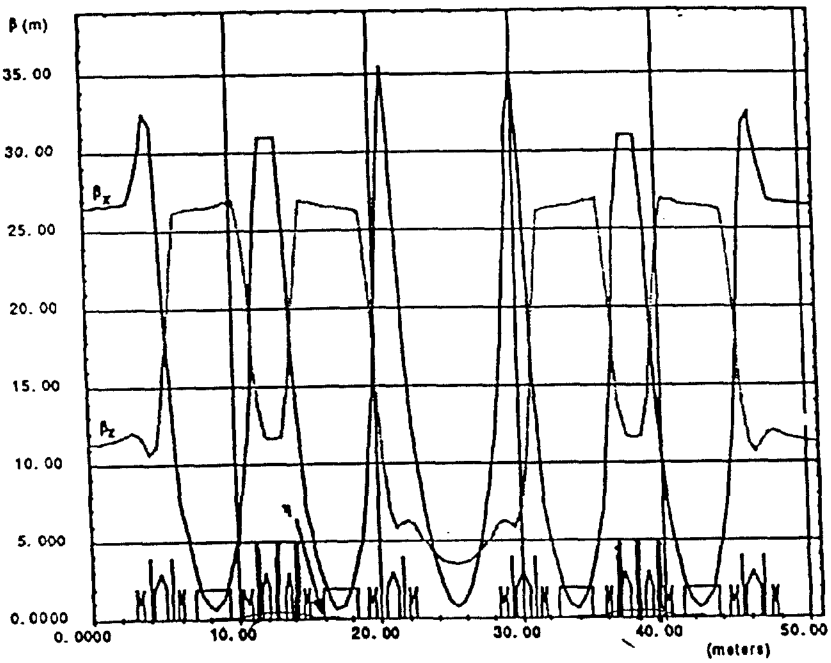
Figure 1
Optical Functions



The essential target specification is expressed in terms of brilliance of undulator beams in the fundamental of the photon energy spectrum. To obtain such performances, one has to combine in an optimal way:

◊ the energy of the stored beam,
◊ its intensity,
◊ the smallest achievable emittance,
◊ the gap, the field and the period of the Insertion Devices.

The resulting main accelerator parameters adopted for the ESRF are summarized in Figure 2

Figure 2
A. Preinjector 200 MeV e- / 400 MeV e+

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

B. Synchrotron injector

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

C. Storage Ring

Energy	6 GeV
Current (Multi Bunch Mode)	≥ 100 mA
Current (Single Bunch Mode)	≥ 5 mA
Filling time (e-/e+ Multi Bunch Mode)	0.2 / 6 min
Filling time (e-/e+ Single Bunch Mode)	0.9 / 20 min
Circumference	844 m
Radio Frequency	352 MHz
Horizontal beam emittance	$6.2\ 10^{-9}\ \pi$ m x rad
Vertical beam emittance	$< 6.2\ 10^{-10}\ \pi$ m x 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	26 at 10 - 20 keV

We have adopted an energy of 6 GeV, a current of 100 mA, a lattice which can be tuned to obtain emittances in the few nanometer range : $6.2\ 10^{-9}\ \pi$ m rad horizontally, a small fraction of that, 10% for instance, in the vertical plane; a minimum Insertion device gap of 20 mm.

Our choice could appear a little conservative when compared to our competitors, the APS and Spring 8. Both of them have based their project on higher energy, higher current and smaller gap.

A few of the target specifications required the adoption of unconventional techniques. This is the case for beam position stability and reproducibility.

Table 1
Beam sizes at source points

	Bending Magnet Source	High Beta	Low Beta
βx (m)	2.2	26.6	0.8
βz (m)	26.8	11.3	3.5
σx (mm)	0.16	0.41	0.069
σz (mm)	0.129	0.084	0.047
$\sigma x'$ (mrad)	0.137	0.015	0.089
$\sigma z'$ (mrad)	0.005	0.007	0.013

Combined with beta values ranging between 0.8 and 27, the target emittances lead to rms beam sizes at source points significantly smaller than 100 µm vertically, a few hundreds µm horizontally. The unit for angles is the µrad.

The storage ring optics is hypersensitive to orbit distortion and therefore to magnetic errors and alignment. To work well, the closed orbit has to be perfect within the 0.1 mm range in rms.

Obviously we had to implement a series of unusual measures to combat this machine's hypersensitivity to imperfections and limit beam center of mass displacements to the specified 1/10 of the beam size, that is to say a few µm. Long term settlement is treated by means of the Hydrostatic Leveling System (HLS) detectors sensitive to variations of altitude in the µm range. The HLS [4] is a series of pots filled with liquid and interconnected by pipes. On the top of each pot a capacitive sensor detects the level of the liquid in the pot. These detectors constitute the input to a system of remotely controlled jacks equipping every girder of the quadrupoles and sextupoles. The horizontality of the machine can be restored within a couple of hours.

For periods of about one day, the machine and the experimental equipment are very sensitive to temperature variations. A temperature change of 1°C over 1 m of steel, which is the typical height of a support, gives an expansion of 10 µm. The 300 000 m^3 of the Experimental Hall are stabilized to within ± 1°, and the interior of the storage ring tunnel to better than ± 0.5°. We permanently record the temperature of the interior of the tunnel with one probe every 5 meters. There is no rigid connection of pipes or cables to the ground or to the magnet supports. Needless to say that ramping the SR magnetic field with the constraint, after the refill, of having to get back to the original position within a µm is excluded. Therefore we have a full energy injector which has to be turned off during photon beam service to avoid any vibration at 10 Hz.

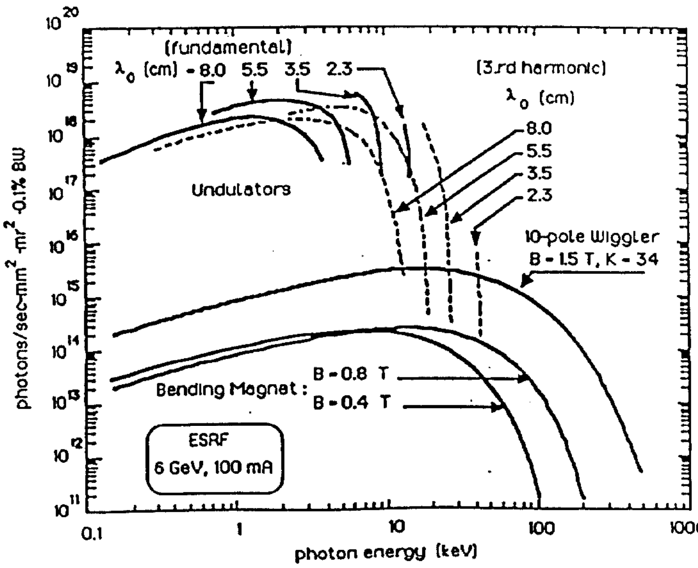
Over short periods of time, vibrations from magnets transmitted via their supports and the ground constitute the main source of instabilities. We are also permanently recording and fighting these vibrations. Every insertion device is surrounded by feedback systems which use X-ray beam position monitors to feed correctors which act locally on the stored particle beam position.

Our undulators are made of permanent magnets with longitudinal periods ranging between 8 and 2.3 cm. The full range between 0.1 and 15 keV can be covered on the fundamental with a minimum gap of 2 cm. The brilliance reaches the several 10^{18} (see Figure 3).

The power density from Insertion Devices is extremely high. It can reach about 1.5 kW per mm^2 for the most powerful undulators at 10m from the source point. In case of beam mis-steering, the storage ring can behave like a welding machine that would take 20 ms to drill a hole in the vacuum vessel. The power density from a standard wiggler is about one third of that of an undulator, although the total power in the 10 kW range is higher. However, the spectrum is white and therefore the brilliance is 3 to 4 orders of magnitude below that of undulators.

To make our unavoidable dipole sources attractive, at the request of our potential users we have designed the magnet in such a way so that the fringing field has a flat intermediate step at 0.4T, half of the full field value, 0.8T.

Figure 3
Brilliance from ESRF light source



With the third generation of synchrotron radiation machines like the ESRF, the brilliance has been increased by 11 orders of magnitude when compared to the X-ray tube sources available in the 60s.

III. STATUS OF PROGRESS OF THE SOURCE

Hereafter the status of progress of the source as per May 1993 is given. The construction phase started in January 1988 and the construction of the first technical buildings started in January 1990.

III.1 Pre-Injector

Fourteen months later, in February 91, the pre-injector building was placed at our disposal. The installation of the linac took a couple of months. This linac is based on a conventional (non-Sled) gradient of 17 MV/m. The buncher tank is followed by two 6 m long cavities, each of them producing a 100 MV acceleration. In June 91, the linac had achieved its target performances in the long pulse mode.

Table 2
June 1991
Commissioning of the Linac in the long pulse mode

Energy	200 MeV
Repetition Frequency	10 Hz
Current	25 mA
Pulse Length	1 µs
Momentum spread	± 1 %
Transverse emittances	$0.5\ 10^{-6}\ \pi$

III.2 Booster Injector

The installation of the booster started in March 91. The 300m long machine was completely installed by the end of July, that is to say less than 5 months after. After 4 months of commissioning from September to December 1991, the booster reached its nominal performances.

Table 3
September-December 1991
Commissioning of the Booster

Energy	6 GeV
Repetition Frequency	10 Hz
Accelerated current peak performance	5 mA
Routine Operation	3 mA accelerated / 2.5 mA extracted

III.3 The X-ray Source

The month of January and a part of February 1992 were used to commission the large sub-systems of the infrastructure : ventilation of the experimental hall and storage ring tunnel, electricity substations, large deionized water cooling units etc..., necessary to provide utilities to the Storage Ring. The front end parts of the photon beam lines inside the tunnel had already been installed with the view to avoiding repeated slack periods linked with the re-opening and closing of the roof.

With regards to our target specifications, progress accomplished on the Storage Ring commissioning has been extremely fast [5]. Several working points have been explored but for injection efficiency reasons, there is a strong tendency to prefer tunes just below the coupling resonance and the half integer. In general the closed orbit is extremely well corrected. The corresponding rms closed orbit amplitude is 0.15 mm in both the horizontal and vertical planes.

Concerning the horizontal and vertical emittances, which are two key parameters entering into the definition of the brilliance, we use several methods based on the light emitted by the beam, either the X-ray light from an undulator or the visible light from a bending magnet.

We also use the more simple scraper method which consists in reducing step by step the physical aperture left to the beam, while we measure the lifetime of the beam. The fit of the measured curve leads to the value of the rms local beam size. In the horizontal plane we measured values between $8.2\ 10^{-9}$ and $1.3\ 10^{-8}$ to be compared with $6.2\ 10^{-9}$ mrad for the perfect machine. In the vertical plane, error bars are larger and the result depends on coupling. Experimental results range between $5.0\ 10^{-10}$ and $3.4\ 10^{-9}$ to be compared with $6.2\ 10^{-10}$. We have therefore obtained the small target emittances in the nanometer range.

The second essential parameter entering into the formula for brilliance is the stored current. In the multibunch mode, we had reached our 100 mA target already in June. Since then, we have slowly but steadily increased the current up to 135 mA. To go any further, we need to replace our X-ray beam absorbers made of standard OFHC copper by the more heatload resistant glidcop absorbers. This work will be completed by the end of the year and will allow a current of up to 200 mA.

In the uniform multibunch mode of filling, strong coupled bunch instabilities can develop. Transversally, we have to face a resistive wall instability that can be damped by increasing the chromaticity. However, the more Insertion Device narrow gap chambers we install, the more we increase the impedance and the stronger the required chromaticity to damp the beam, with the consequence that the unwanted non linear effects eat up the remaining dynamic aperture more and more. The uniform multibunch mode can also excite longitudinal Higher Order Modes in the RF cavities. However, at the present current level these HOMs are not systematically excited. They can be detuned by careful control of the temperature in the cavities. Neither transverse nor longitudinal coupled bunch instabilities show when only one third of the circumference is filled with beam.

A long lifetime is essential for the quality of service offerred to users. We have now accumulated some 150 A*hours. As of today, we reach a lifetime of 17 hours at 100 mA, which is already significantly above our 8 hours target. Our objective is to reach 24 hours by the end of the year.

In the single bunch mode, the goal had been set rather low at 5 mA. We now routinely achieve 10 mA by pushing the chromaticity to high positive values. We can also apply some feedback. In that case we can go beyond 15 mA with a temporary best performance at 20 mA. Single bunch purity is essential for time of flight experiments and Mossbauer ones, for example. By means of an RFKO technique using a shaker and a scraper, we are able to clean up all lowly populated bunches and reach purities in the 10^{-6} range.

For high current needs, we anticipated several advantages in running the machine with a few (8 or 16) equally spaced and filled bunches. The long space between bunches makes it much more difficult for cross-talk to occur between them. Therefore it leaves less potential for coupled bunch instabilities and in any case the required feedback system to damp instabilities would be of moderate bandwidth. Unfortunately, we systematically found an unexpectedly high dynamic pressure and correspondingly a short lifetime (3 to 5 hours at 100 mA). The mechanism is not fully understood. However, the gap to be bridged to make the few bunch mode as attractive as the multi-bunch mode in terms of lifetime is very challenging.

In June 1992 we tested the first 1.6 m long undulator segment with a 2 cm minimum gap in one of the straight sections. The undulator was shooting in the direction of the Machine diagnostic beam line which had been thoroughly equipped to perform full tests of the emitted X-ray beam. In particular, we installed a diamond monochromator which has been submitted to the full 100 mA current and which proved to have excellent characteristics over the full intensity range.

The high quality of the undulator magnetic field resulted in a meagre 3 μm vertical displacement of the beam in one of the nearby dipoles equipped with a visible light output when the gap was opened and closed. Since then 5 IDs are routinely operated in the Storage Ring. All of them can be manipulated at will with no significant displacement of the X-ray beam in other beamlines. To check the overall stability of the beam in actual experimental conditions, at low current, the photon beam was focused vertically down to a 20 μm FWHH spot. The stability of the spot measured with slits centered at the edge of the spot where the slope is maximum was found to be 1 μm rms. In other words, the natural stability of the photon beam is better than the target, ie 10 % of the beam size.

As already mentioned, all IDs will be equipped with dynamic correctors to feed back the position and angle of the X-ray beam by acting on the electron beam. The feedback loop was closed during the experiment and we saw an appreciable difference between feedback on and feedback off. The gain was a factor of 4 reduction of the beam center of mass amplitude. Therefore, at the ESRF, the brilliance of the beam will not be spoilt by the instability in position of the beam center of mass. We hope to minimize the displacement to a few percent of the beam size.

Up till now, four shutters have been opened to allow X-rays through for the commissioning of beam lines. Another ten shutters will be opened before the end of the year. A few prototype experiments have already started. The goal is to place the beamlines, once commissioned, at the service of the European user community in less than one year from now. First results are extremely encouraging.

During the design period, it was anticipated that at design current and emittances, only ions of mass higher than 50 could be trapped due to the over-focusing of the electron beam. This did not exclude problems at lower current during ramping or with very heavy particles such as dust particles according to experience from CERN, the Photon factory at KEK, or super Aco in Orsay. We therefore started the machine with electrons and kept the option for the positron part of the preinjector open up till now. Given the results obtained, we conclude that it is obviously unnecessary to implement the e+ option in order to achieve our target performances in current lifetime, emittances and stability.

The trapping of macro particles is not presently observed.Should this be the case one day (after accidental venting for instance), we would still have resources such as leaving a gap in the bunch train in reserve.

To leave nothing to chance, we have prepared a full e+ preinjector project ready to be started. We will continue our observations and if one day the advantage of positrons becomes apparent, we will reconsider this option.

IV. OPERATION

Since the beginning of the year, we are operating the machine 50% of the time (in periods of 2 weeks on followed by 2 weeks of shutdown) to serve the commissioning of beam lines. Excellence in operation with the target performances is our primary objective and results are very promising. From January to April, we were able to really serve 91.7% of the scheduled 1000 hours of operation time. During the periods of real service, the beam was made available to beam lines for 92% of the time, the rest being used for refilling and other beam preparation.

We will operate the source 3000 hours in 1993 for X-ray production, with a plan to go to 4500 hours in 1994 and 6000 hours in 1995.

V. CONCLUSION

For several years, we considered the objectives of a 3rd generation machine to be very challenging and were anxious as to the outcome of the commissioning of the first machine of its type. The rapid success of the ESRF will now enable speculation to be accelerated as to the next generation of diffraction limited machines. In this sense the ESRF has shown that at least one order of magnitude more can be gained in the foreseeable future.

VI. REFERENCES

[1] JL Laclare, "Synchrotron light sources", *Proceedings of the 1988 European Particle Accelerator Conference.*

[2] JL Laclare, "Synchrotron radiation light sources", *Proceedings of the 1990 European Particle Accelerator Conference.*

[3] A. Ropert, "The Status of the ESRF", *Proceedings of the 1992 European Particle Accelerator conference.*

[4] D. Roux, "The Hydrostatic Levelling System (HLS) / Servo-controlled precision jacks : a new generation altimetric alignment and control system", these proceedings.

[5] A. Ropert, "Challenging issues during the ESRF storage ring commissioning", these proceedings.