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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CAS CERN ACCELERATOR SCHOOL

Eighth John Adams Memorial Lecture

THE STATUS OF THE ESRF

Lecture delivered at CERN on 20 November 1992

J.L. Laclare
ESRF, Grenoble, France

GENEVA
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ABSTRACT

The ESRF (European Synchrotron Radiation Facility) is a fundamental research institute based in Grenoble. Construction of the ESRF Source started in 1988 as a joint project of 12 European countries (France, Germany, Italy, the United Kingdom, Spain, Denmark, Finland, Norway, Sweden, Belgium, the Netherlands and Switzerland). 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 mode of operation during the one-month commissioning period. Commissioning of the booster started in September 1991 with the target beam extracted at 6 GeV being reached in November 1991. Storage ring commissioning began in February 1992, and progress has been extremely fast and promising, since less than four months later the target intensity of 100 mA in the multibunch mode was reached for the first time. In July 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 commissioning of some Phase I beamlines has just started and the first external users are expected at the beginning of 1994.

CONTENTS

1. INTRODUCTION

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

The main objectives were 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 two phases:

- **Phase 1** or the construction phase covers the first 6½ 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 have obtained the source design goal performances by July 1993.
- **Phase 2** is to cover the remaining 4½ years with the completion of the experimental facility, 30 beamlines in total, by December 1998.

The means provided to meet these objectives were as follows :

- 2.2 GFrF in phase 1
- 1.6 GFrF in phase 2
- and a total staff of 450 people.

This paper reflects the status of the ESRF as at November 1992.

2. REVIEW OF THE SPECIFICATIONS AND ASSOCIATED TECHNICAL OPTIONS

The institute is built around a synchrotron radiation source. As shown in Plate 1, it consists of:

- a 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 pre-injector.

The storage ring is encased in a concrete tunnel with a saw-tooth outer wall from which the experimental beamlines emerge. The lead-protected hutches are installed along and at the end of the beam lines. The ring occupies the inner part of the annular-shaped experimental hall. The beamlines have a total length of up to 75 m from the source point in one of the machine straight sections to the outer edge of the experimental hall. Long beamlines of up to 500 m can be accommodated on the site.

2.1 Specifications Nos. 1 and 2

The source has been designed to deliver beams of X-rays around 10 keV from undulators and wigglers. It had to fulfill a series of detailed target specifications.

Priority was given to the Insertion Devices (IDs). This 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.

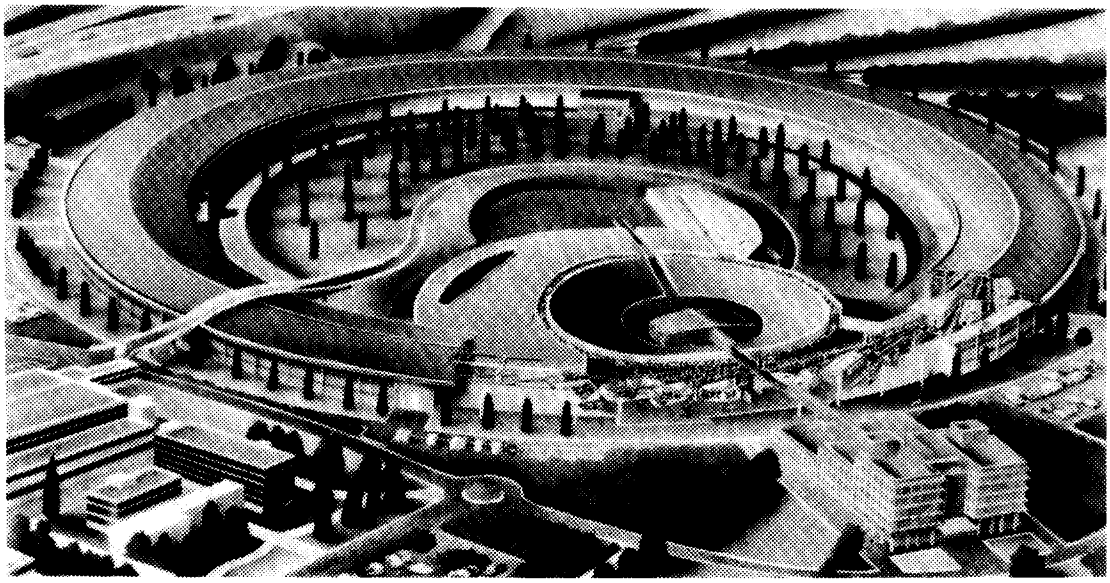
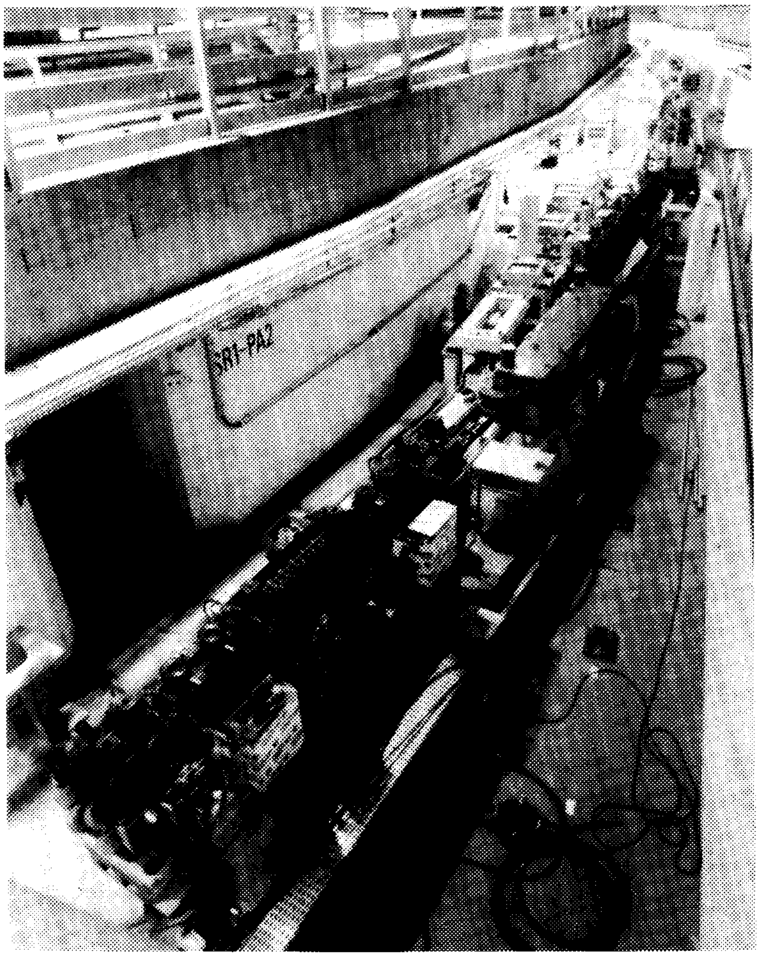


Plate 1 The Synchrotron Radiation Source

Plate 2 Injection zone



In Fig. 1, the optical functions of the lattice are shown. The straight sections which accommodate the IDs are equipped with triplets at both ends. These triplets permit the beam to be tuned, in the ID in the high beta or small divergence mode, which is preferable for undulators, and in the low beta or small size mode, which is preferable for wigglers. The straight sections are dispersion-free. The dispersion is different from zero in the achromat between the two dipoles in which the chromaticity sextupoles are located. Only three of the 32 straight sections are used to accommodate machine utilities.

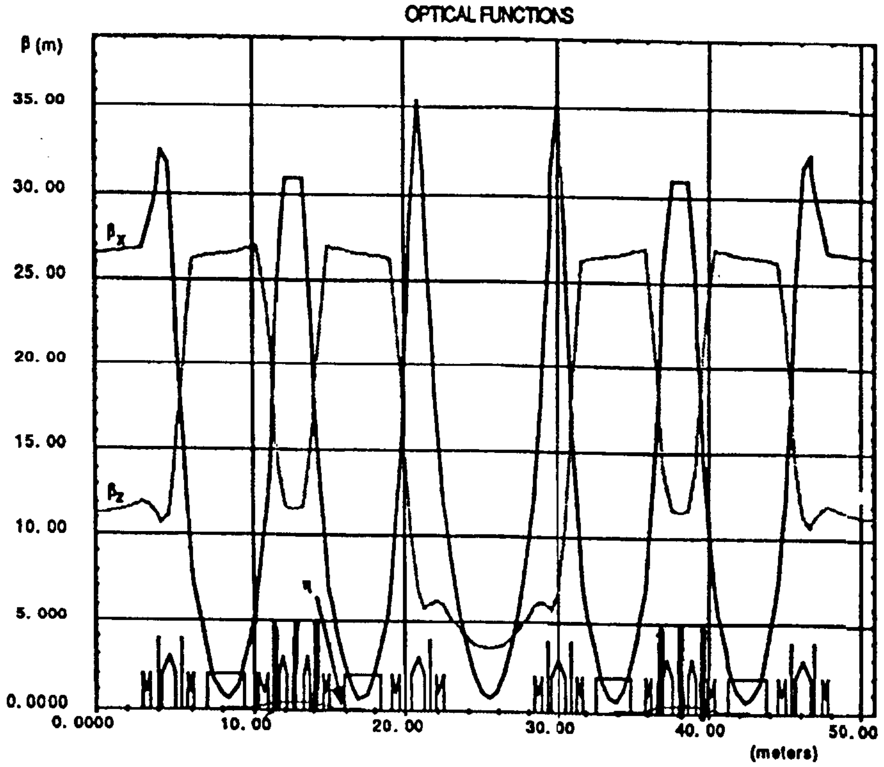


Fig. 1 Optical functions

Plate 2, shows the injection zone. The magnets of the transfer line between the booster, which is just upstream of the top background of the photo, and the storage ring, had not been installed when the picture was taken.

The storage ring sequence of structure is as follows:

- straight section
- triplet with quadrupoles and sextupoles
- first bending magnet of the achromat
- straight part of the achromat with four quadrupoles and three sextupoles
- second bending magnet
- final triplet just upstream the injection straight section.

In this injection zone, some CERN staff members would feel somewhat familiar with the hardware since there is so much equipment that has been produced in collaboration with CERN. This is the case for the thick septum and the thin septum magnets of an eddy current type, and also the case for the four kickers and the ceramic vacuum chambers.

Two other straight sections are taken up with RF cavities. Thanks to CERN's development of 5-cell copper cavities, made for LEP, we were able to buy identical reproductions for the ESRF from the same supplier. Four 5-cell cavities are necessary in our case. They are grouped by pairs in 2 low-beta sections.

It goes without saying that our transmitter specifications were also greatly influenced by CERN's experience with the 1 MW klystrons and their necessary environment. We have also copied the rotating coil bench of LEP for quadrupole and sextupole measurements.

2.2 Specifications Nos. 3, 4, 5 and 6

The next 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 IDs.

The main storage ring parameters are summarized in Fig. 2.

Storage Ring	
Energy	6 GeV
Current (multibunch mode)	≥ 100 mA
Current (single-bunch mode)	≥ 5mA
Filling time (e^-/e^+ multibunch 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} π mrad
Vertical beam emittance	$< 6.2 \times 10^{-10}$ π mrad
Natural r.m.s. bunch length	6 mm
Maximum no. of insertion devices	29
Free length of straight sections	6 m
Bending magnet ports	26 at 10–20 keV

Synchrotron Injector	
Repetition rate	10 Hz
Energy	6 GeV
Circumference	300 m
Emittance at 6 GeV	1.2×10^{-7} π mrad
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

Fig. 2 Main parameters of the Storage Ring and the Synchrotron Injector

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} π mrad horizontally, a small fraction of that, 10% for instance, in the vertical plane.

Table 1

	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

With beta values ranging between 0.8 and 27, this leads to r.m.s. beam size at source points significantly smaller than 100 µm vertically, and a few hundred µm horizontally. The unit for the angles is µrad.

The storage ring optics are 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 r.m.s. In addition, if we want to fully benefit from the small emittance, we have to limit the electron beam centre-of-mass fluctuation to say 1/10 of the beam size, that is to say a few µm.

Obviously we had to implement a series of unusual measures to combat this machine's hypersensitivity to imperfections, and limit beam centre-of-mass displacements. 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 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.

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 m. There is no rigid connection of pipes or cables to the ground or to the magnet supports.

We are permanently fighting the problem of vibrations. Figure 3 shows one of the usual vibration spectra recorded on site with typical r.m.s. amplitudes in the few 0.1 µm range. The brilliance calculation is based on a vertical beam size of a few tens of µm. We therefore have to stabilize the beam centre of mass to less than one tenth of the beam size, i.e. a few µms.

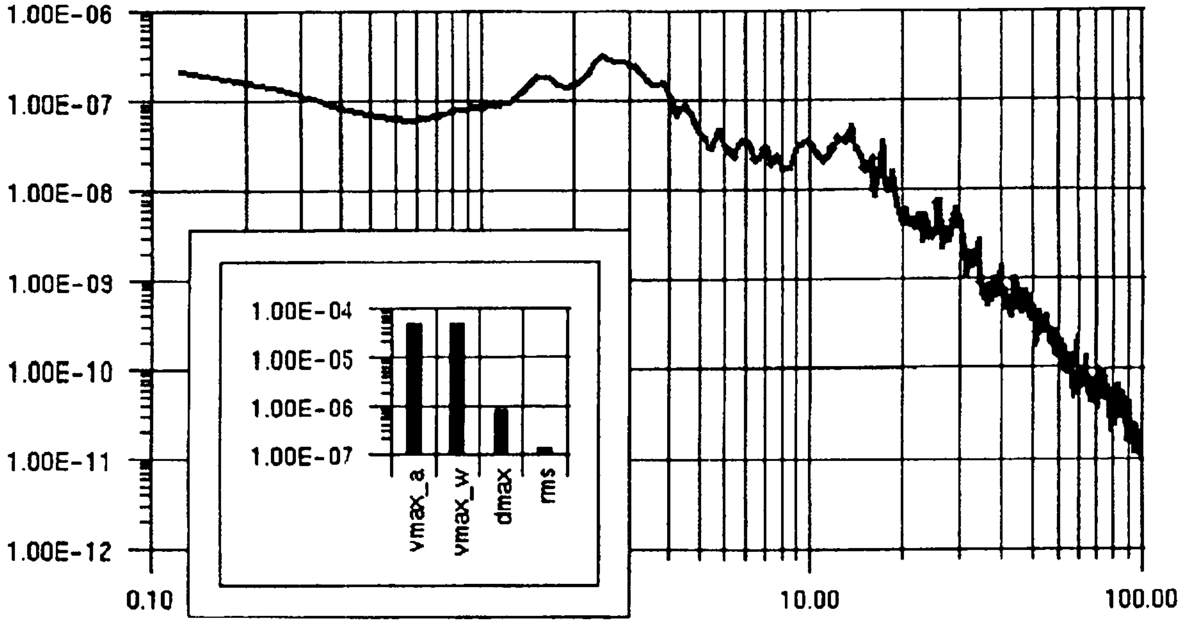


Fig. 3 Vibration spectra recorded on site with typical r.m.s. amplitudes in the few 0.1 µm range

Every insertion device is surrounded by feedback systems which use X-ray beam position monitors to feed correctors that act locally on the stored particle beam position. Needless to say, 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.

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 several 10^{18} (see Fig. 4).

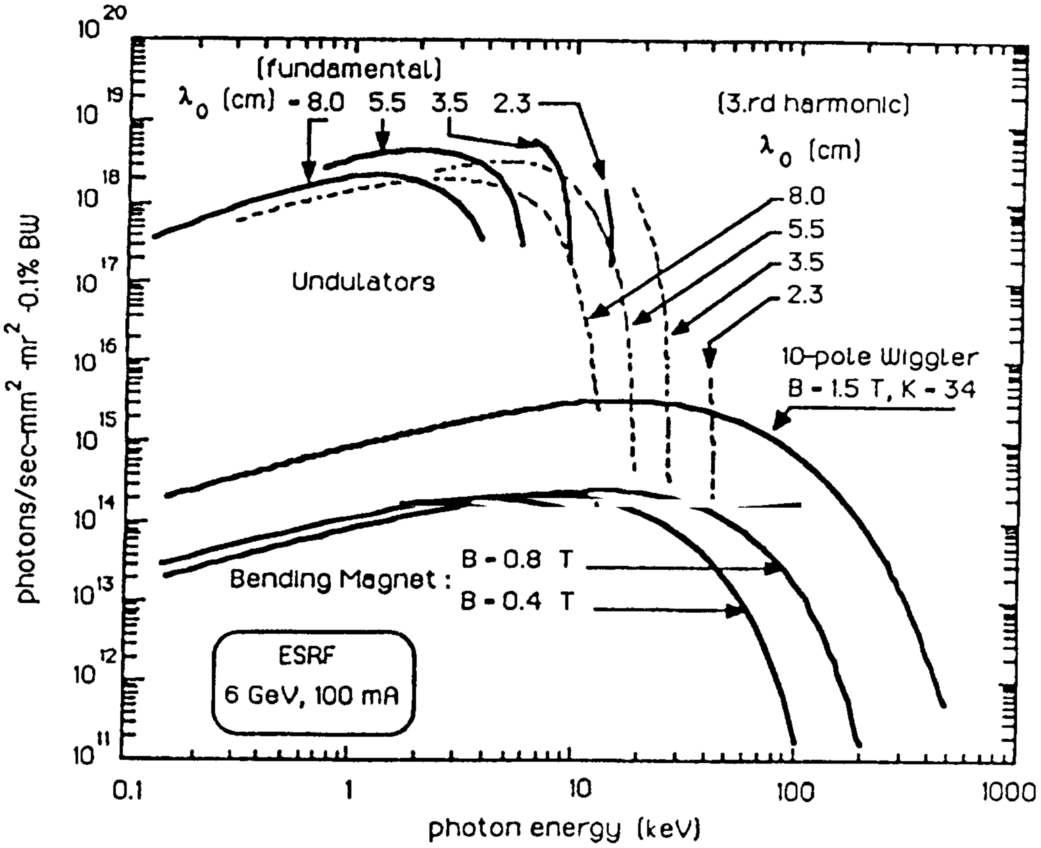


Fig. 4 Brilliance from the ESRF light source

The power density from IDs is extremely high. It can reach about 1.5 kW/mm² for the most powerful undulators at 10 m 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 three to four 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 that the fringing field has a flat intermediate step at 0.4 T, half of the full field value, 0.8 T (see Fig. 5).

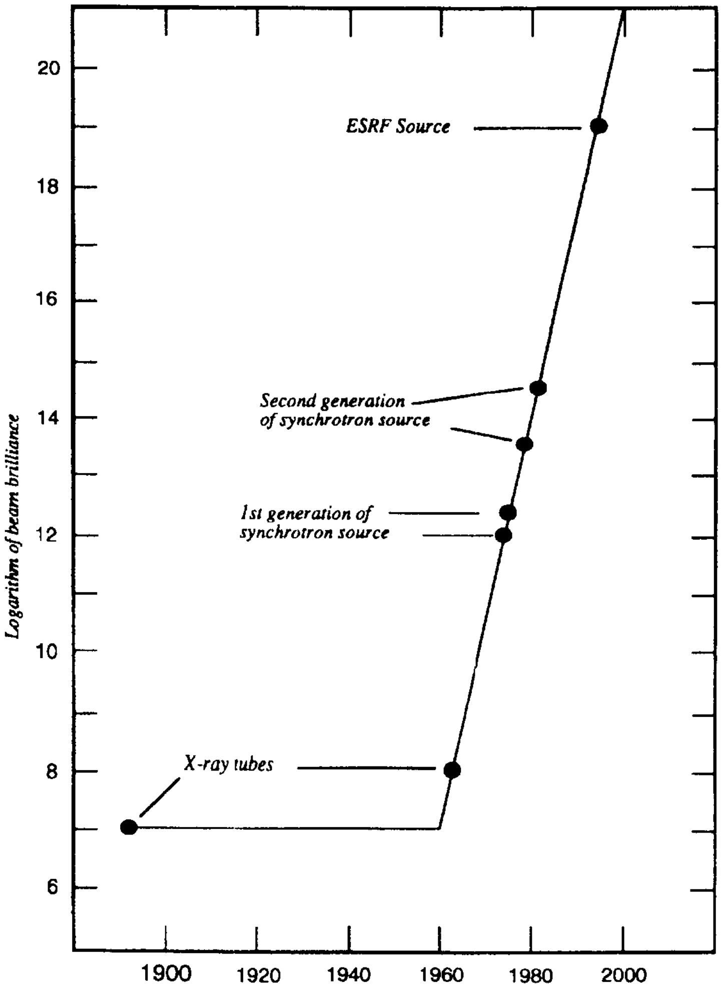


Fig. 5 Logarithm of beam brilliance

With the third generation of synchrotron radiation machines like the ESRF, the brilliance has been increased by 11 orders of magnitude when compared with the X-ray tube sources available in the 1960s.

2.3 Specification No. 7

The last requirement concerning lifetime, longer than eight hours, is standard for a synchrotron radiation storage ring. It raises the dilemma of positrons versus electrons.

3. STATUS OF PROGRESS OF THE SOURCE

Hereafter the status of progress of the source as at November 1992 is given. The construction phase started in January 1988, and the construction of the first technical buildings started in January 1990.

3.1 Pre-Injector

Fourteen months later, in February 1991, 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 1991, 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	$0.5 \times 10^{-6}\ \pi$

3.2 Booster Injector

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

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

3.3 The X-ray Source

The month of January and a part of February 1992 were used to commission the large subsystems of the infrastructure: ventilation of the experimental hall and storage ring tunnel, electricity substations, large deionized water cooling units, etc., necessary to provide utilities for the storage ring. Plate 3 shows the last view before the roof was closed.

It can be seen that the front-end parts of the photon beam lines inside the tunnel had already been installed in order to avoid repeated dead periods linked with the opening and closing of the roof.

With regard to our target specifications, progress accomplished on the storage ring commissioning has been extremely fast. 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 r.m.s. 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 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.

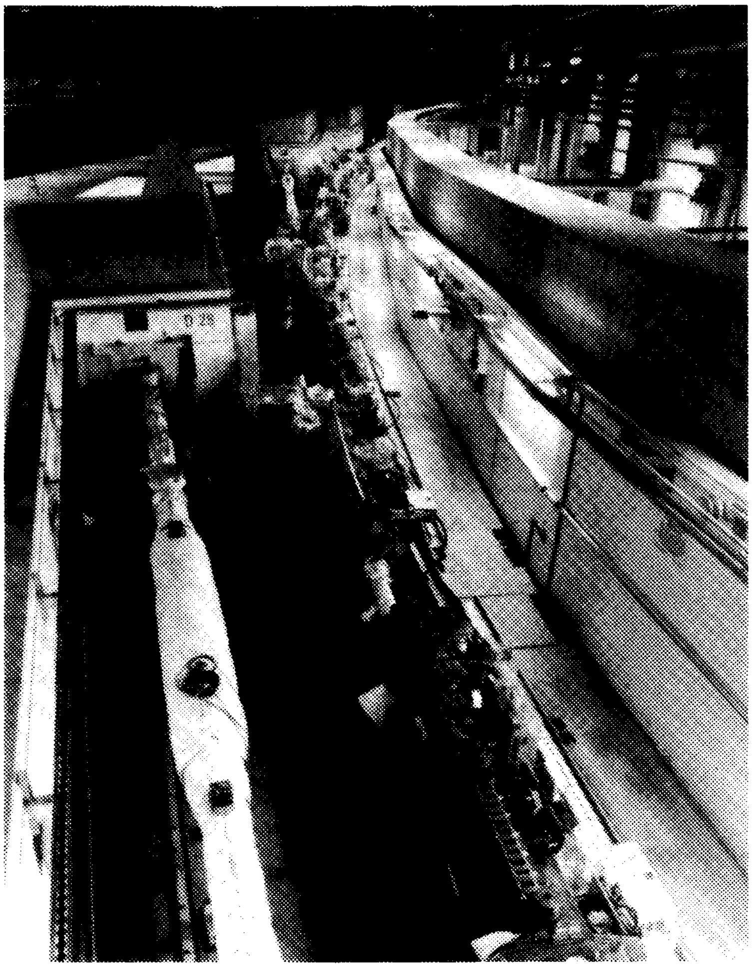


Plate 3 Last view before roof was closed

We also use the more simple scraper method which consists of reducing the physical aperture left of the beam, step by step on the horizontal axis, while we measure the lifetime of the beam along the vertical axis. The fit of the measured curve leads to the value of the r.m.s. local beam size. In the horizontal plane we obtained values of:

$$8.2 \times 10^{-9} \text{ measured lower limit} < \varepsilon_Z < 3.4 \times 10^{-8} \text{ measured upper limit}$$

to be compared with

$$\varepsilon_{z0} = 6.9 \times 10^{-9} \text{ mrad ,}$$

for the perfect machine.

In the vertical plane, error bars are larger and the result depends on coupling

$$5.0 \times 10^{-10} \text{ measured lower limit} < \varepsilon_z < 3.4 \times 10^{-9} \text{ measured upper limit}$$

to be compared with

$$\varepsilon_{z0} = 6.9 \times 10^{-10} \text{ mrad .}$$

We have therefore obtained the small target emittances in the nanometer range.

The second essential parameter entering the formula of the brilliance is the stored current. In the multibunch mode, we had reached our 100 mA target already in June. Since then, we heve extensively run the machine at maximum current to clean the vacuum vessels and lower the dynamic pressure. We have now accumulated some 30 Ah. Figure 6 shows the progressive improvement of lifetime during the commissioning.

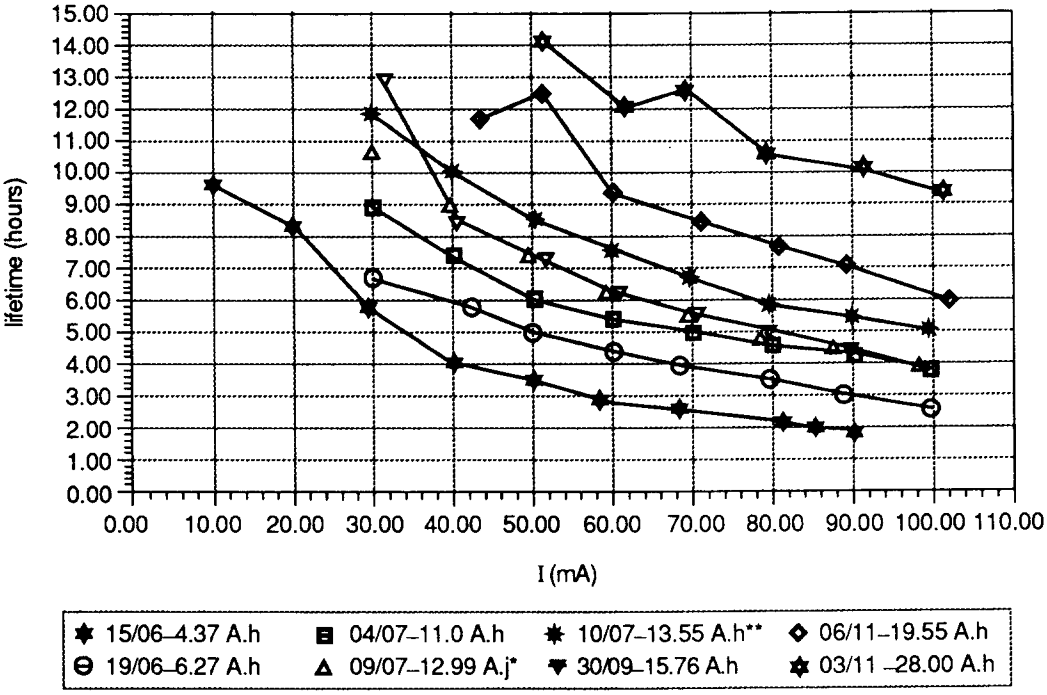


Fig. 6 Improvement of lifetime during commissioning

As of November 1992, we have 9.5 h at 100 mA which is already significantly more than our 8 h target. Although we are very attentive to problems of lifetime, until now we have had no reason to believe that the performances would be better with positrons. In the single-bunch mode, the goal had been set rather low with 5 mA. We now routinely achieve 10 mA by pushing the chromaticity to high positive values. We can also apply some feedback. In this case we can go beyond 15 mA with a temporary best performance at 18 mA.

In June we tested the first 1.6 m long undulator segment with a 2 cm minimum gap in one of the straight sections (see Plate 4).

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 was 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. Recently, an experiment on stability was performed on ID6. At low current, the photon beam could be focused vertically down to a 20 μm FWHH spot. The stability of the spot measured with slits centred at the edge of the spot where the slope is at its maximum was found to be 1 μm r.m.s. In other words, the natural stability of the photon beam is better than the target, i.e. 10% of the beam size.

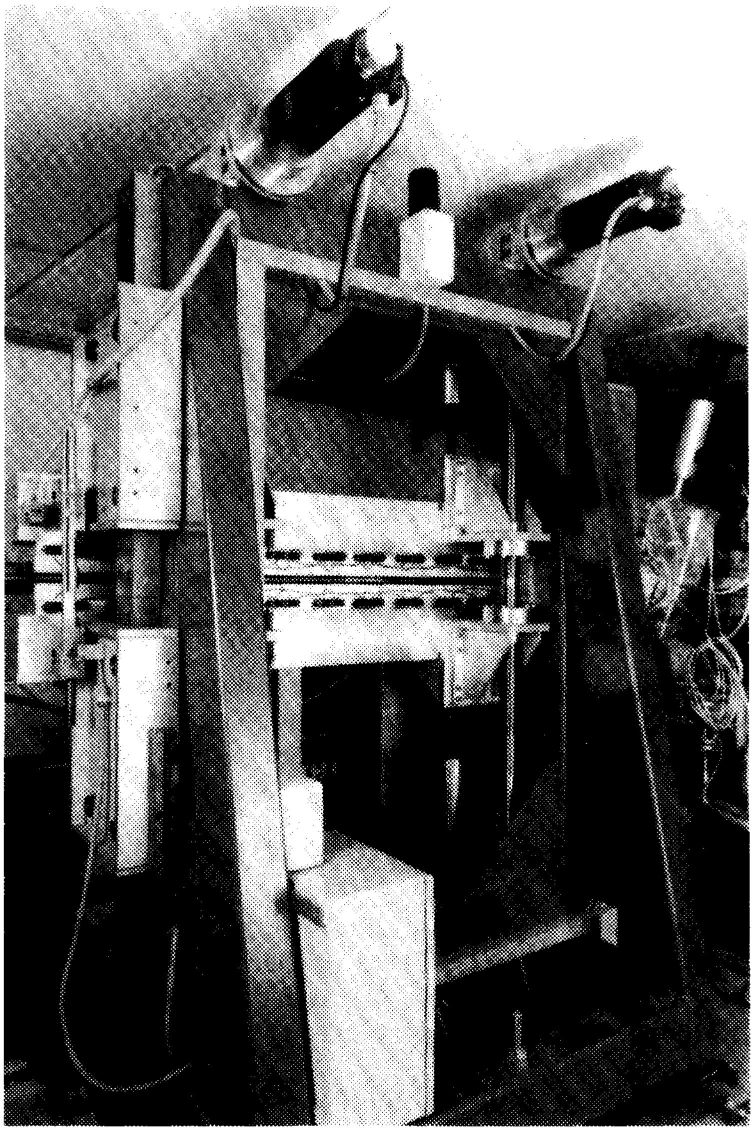


Plate 4 1.6 m long Undulator Segment with a 2 cm minimum gap in one of the straight sections

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 centre-of-mass amplitude. Therefore, at the ESRF, the brilliance of the beam will not be spoilt by the unstable position of the beam centre of mass. We hope to minimize the displacement to a few per cent of the beam size.

It is planned to run the Source 6000 h/year for scientific production. In view of this, reliability of the chain of accelerators is essential. Figure 7 shows the evolution of the percentage of time during which beam was made available until November 1992.

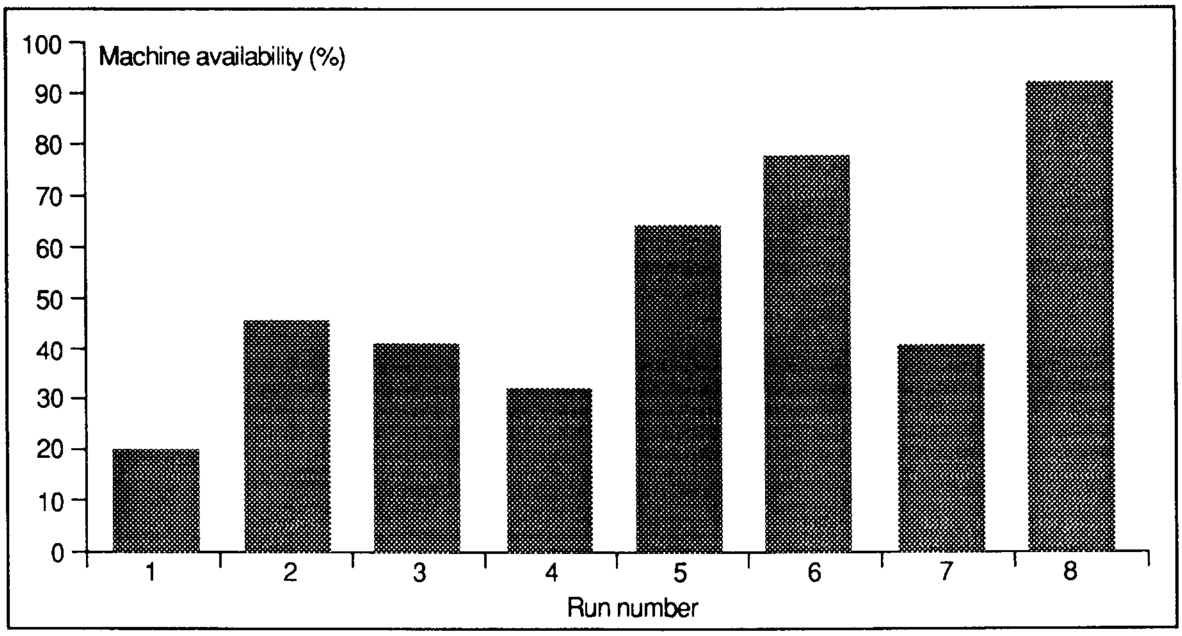


Fig. 7 Machine availability

A clear average progression culminating at 86% in the most recent runs can be observed. It is well known that such a machine should never be stopped. You can see the bad percentage obtained right after the summer shutdown during run number 7.

4. EXPERIMENTAL SLAB AND FIRST SERVICE TO BEAMLINES

Since October, three shutters have been opened to allow X-rays through for the commissioning of beam lines. Another five shutters will be opened in March. A few prototype experiments have already started, but the goal is to place the beam lines, once commissioned, at the service of the European user community in exactly one year from now.

I cannot hide the fact that we have had some difficulties with the floor of the experimental hall. The trouble has its root in the bad execution of this part of the civil engineering. Owing to excessive differential shrinkage between the upper and lower parts of the 18 cm thick concrete slab, we obtained a curling of the concrete layer with the creation of voids below the surface in the corners and at the edges. Apparently, the curling has stopped, and a large portion of the experimental hall slab has been stabilized by injecting grout below the surface to fill in the voids. In order to advance the installation of beam lines, all that remains is for us to gain confidence in the long-term durability of the repair. To leave nothing to chance, we are preparing the design of a new slab. Stopping the whole facility for several months and getting a large part of the slab demolished and reconstructed cannot be excluded.

5. COLLABORATION WITH CERN

For a long time now, CERN has had the reputation of being the world leader in high-energy physics and accelerator technology. Sir John Adams greatly contributed to this reputation of excellence, and I am proud to have been asked to deliver this memorial lecture. A significant part of the ESRF's success is linked with its extremely successful collaboration with CERN.

6. CONCLUSION

For several years, we considered the objectives of a third-generation machine to be very challenging and we were anxious about 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.