J. Synchrotron Rad. (1994). **1**, 12–18

Target Specifications and Performance of the ESRF Source

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(Received 19 April 1994; accepted 7 June 1994)

Construction of the ESRF source started in 1988 as a joint project of 12 European countries. 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 nearing the end of the construction phase (scheduled for July 1994), and is expecting its first external users from September 1994 onwards. All source design-goal specifications had been reached by mid-1992. This article reviews these specifications and associated basic source parameters, then discusses the actual peak performances recorded, many of them such as intensity and lifetime being well in excess of the original targets (175 mA compared with 100 mA, 42 h compared with 8 h). Current plans for upgrading, which should lead to a considerable gain in brilliance by 1995, include increasing the current to 200 mA, lowering the emittance and decreasing the coupling, improving the beam-position stability, introducing mini-gap undulators and using innovative undulator-spectrum shimming techniques.

Keywords: undulators; beam-position stability; insertion devices.

1. Introduction

The ESRF was created following the signature of an international convention dated 16 December 1988 by 12 European countries (France, Germany, Italy, United Kingdom, Spain, Denmark, Finland, Norway, Sweden, Belgium, the Netherlands and Switzerland).

In the convention, the main objectives (ESRF Team, 1988) were to design, construct, operate and develop a third-generation synchrotron radiation source in the hard X-ray domain, together with the associated experimental instruments, for the use of the scientific community of the contracting parties. These objectives had to be met within a period of 11 years split into two phases:

Phase I, the construction phase, covers the first $6\frac{1}{2}$ years, ending with the completion of the commissioning of the first set of at least seven beamlines in July 1994. An important intermediate milestone was to reach the source design-goal performance, which was achieved by July 1993.

Phase II covers the remaining $4\frac{1}{2}$ years, with the completion of the experimental facility, 30 beamlines in total, by December 1998.

This article describes the status of the ESRF source as per March 1994, a few months before the end of phase I.

2. Review of the specifications and associated basic source parameters

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

(*a*) Priority to be given to insertion devices (IDs).

(*b*) High flexibility of the lattice at the ID location.

(*c*) Brilliance from undulators in the range 10^{18}–10^{19} photons s^{-1} (0.1% bandwidth)$^{-1}$ mrad^{-2} mm^{-2}.

(*d*) Brilliance larger than 1×10^{18} in the fundamental of an undulator at 14.4 keV.

(*e*) Bending magnet sources with critical energies at 10 and 20 keV.

(*f*) Stability of the X-ray beam better than one tenth of the r.m.s. beam dimensions.

(*g*) Beam lifetime longer than 8 h.

The essential target specification [(*c*) and (*d*)] is expressed in terms of the brilliance of undulator beams in the fundamental of the photon-energy spectrum. To obtain such a performance, optimal combination is necessary of the energy of the stored electron beam, its current, the smallest achievable emittance, and the gap, the field and the period of the insertion devices.

For the storage ring, the following basic parameters were targeted: an energy of 6 GeV, a current of 100 mA and an expanded Chasman–Green lattice which can be tuned to obtain emittances in the low nanometer range ($6.2 \times 10^{-9} \times 2\pi$ m rad horizontally or 6.2 nm in short, and a small fraction of that, 10% for instance, in the vertical plane).

The requirement for highest priority to be given to insertion devices – 29 of them can be accommodated – was satisfied by adopting a structure with 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 small size in the adjacent section (preferred location for wigglers), leading to 16-fold symmetry optical functions as shown in Fig. 1.

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

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, *etc.*). It is expected to reach 15 kW. The spectrum is white and therefore the brilliance is typically two orders of magnitude below that of the undulators.

To make the dipole sources as attractive as possible, we designed the magnet in such a way that the fringe field has

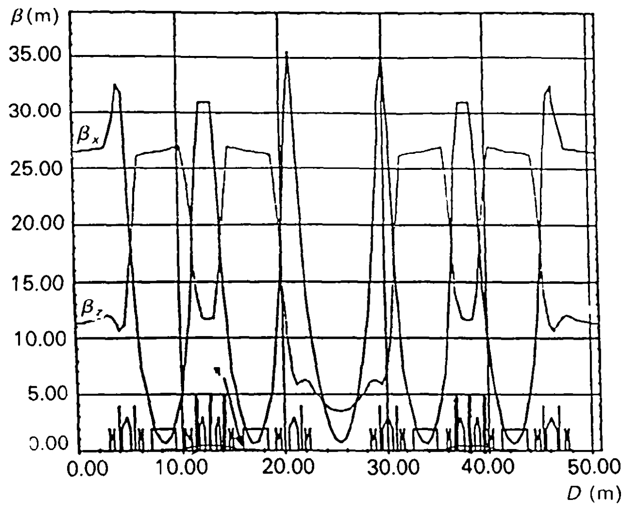

Figure 1
Beta functions of the ESRF lattice over one super-period.

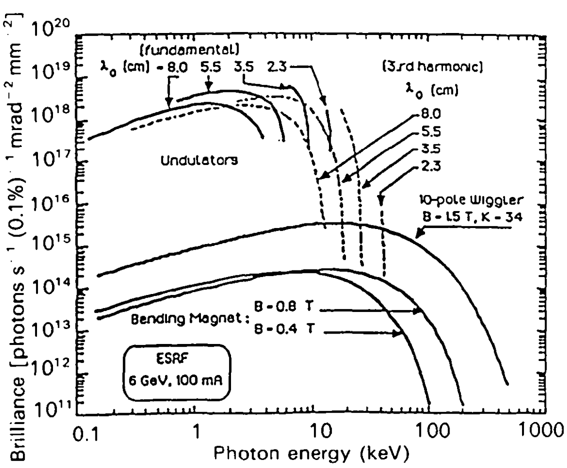

Figure 2
Performance in terms of brilliance of undulators, bending magnets and wigglers.

Table 1
Injector and storage-ring parameters.

(*a*) Preinjector 200 MeV	
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} m rad
(*c*) Storage ring	
Energy	6 GeV
Current (multibunch mode)	100 mA
Current (single bunch mode)	5 mA
Filling time at 100 mA (multibunch mode)	1 min
Filling time at 5 mA (single bunch mode)	1 min
Circumference	844 m
Radio frequency	352 MHz
Horizontal beam emittance	6.2 nm
Vertical beam emittance	< 0.6 nm
Natural r.m.s. bunch length	6 mm
Maximum number of insertion devices	29
Free length of straight sections	6 m
No. of bending magnet ports	20 at 10–20 keV

a flat intermediate step at 0.4 T (critical energy of 10 keV), half of the full field value, 0.85 T (20 keV). In principle, up to 20 dipole-beam ports can be made available.

The main injector and storage-ring parameters adopted are summarized in Table 1.

3. Experience with the operation of the source

After the successful commissioning of the pre-injector in June 1991, and of the booster injector in December 1991, all target objectives for the storage ring were reached and even exceeded during the ten months of scheduled commissioning in 1992 (Ropert, 1993).

Since the beginning of 1993, the X-ray source has been operated in user service mode (USM) to serve the commissioning of beamlines. During 1993, 24 weeks of scheduled operation (3000 h of USM and 1000 h of machine dedicated time for start-up and tests) were completed. The shutdowns were extensively used to install new front ends, new IDs and their associated straight-section chambers for the additional beamlines. The overall availability of X-ray beams during scheduled USM exceeded 90%. This is a remarkable score, particularly for a source in its first year of operation and given the fact that we were penalized by particularly stormy weather in the spring as well as autumn. We recently placed a contract for a large high-quality power supply to be installed on site by mid-1995. This will put an end to one of our major concerns in terms of beam losses, *i.e.* the stability of the mains supply. By the end of last year up to ten beamlines were being supplied with beam and since that time about one additional beamline has become available per month.

In 1994, we plan 4000 h of USM, and hence reduced installation activities for front ends and IDs. In September 1994, all the phase I beamlines will be available to the user community and scientific production will start. In 1995, a step up to the 5000 h level will be necessary before reaching the steady state of 6000 h of USM per year in 1996.

The experience gained during the first year of operation at target performances indicates that the ESRF source can offer very stable X-ray beams of extremely high quality (Laclare, 1993). In addition, as discussed in detail below, there is a large potential for even higher performance.

4. Present performance of the source and plans for upgrading

All major source performance parameters are reviewed below and the status as of March 1994 is given.

4.1. *Multibunch mode: current*

The design current 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. For all third-generation machines, higher-order modes (HOMs) in RF cavities were considered as a major obstacle to reaching high currents in the uniform filling mode of operation. At the ESRF, with cavities similar to those of LEP (CERN), which are not optimized for a synchrotron radiation source, simple solutions have nevertheless been found to overcome the predicted HOM limit and go significantly beyond the design current.

For instance, we were successful in testing the detuning of the HOMs by using temperature control of the cavities. However, the preferred solution for avoiding both transverse and longitudinal coupled-bunch-mode coherent instabilities consists of adopting non-uniform filling. The beam is much more stable longitudinally and transversely, with regards to HOMs and the resistive wall, respectively, when the storage ring is filled leaving an empty gap corresponding to about two-thirds of the circumference.

The reasons why the one-third mode of filling stabilizes the beam can be sketched out as follows. In the transverse and mostly vertical plane, the coherent motion is driven by the wake field of the resistive wall impedance. This is a rather short-range wake that decays significantly over a revolution period. With a gap of empty buckets extending over two-thirds of the circumference, we impose a significant decay of the driving coherent field between the passage of the tail of the bunch train and the next passage of the head. By so doing, the possibility of transmission and build-up of the potentially destructive field is interrupted *via* cross talk between adjacent bunches that avoids the growth of the instability.

In the longitudinal plane, we are essentially dealing with very narrow resonant HOMs. Consequently, the stabilizing effect cannot come from the decay of the wake field which lasts for significantly more than one revolution period. In fact, the stabilization originates from the periodic beam loading of the cavities at every passage of the bunch train that produces a deep amplitude modulation of the RF voltage at the revolution frequency, typically 10% for 100 mA in the one-third mode of filling. The resulting spread in synchrotron frequencies of the bunches in the train (Landau damping) prevents a constructive build-up of the instability *via* cross talk between successive bunches.

Peak intensity performances have been steadily increased over the last two years:

June 1992	100 mA
April 1993	125 mA
July 1993	150 mA
March 1994	175 mA

In preparation for achieving our objective of a 200 mA beam before the end of 1994, *i.e.* twice the original target:

(*a*) we have upgraded one of our klystrons to 1.3 MW;

(*b*) at the end of every dipole and all around the storage ring, we have changed the copper absorbers, on which most of the unwanted photons are dumped, for more heat-load resistant glidcop absorbers;

(*c*) we have tested a new front-end configuration with reinforced protection of the beryllium window in module 2 to withstand the heat load of the most powerful insertion device at 200 mA current;

(*d*) we have upgraded our beam-position monitors (BPMs).

When compared with the target of 100 mA, the expected doubling in intensity in the multibunch mode will automatically provide a doubling in the source flux and brilliance.

4.2. *Lifetime*

Throughout 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 a 24 h lifetime, *i.e.* three times the target, in September 1993. The present record set in March 1994 stands at 42 h, *i.e.* five times the original target, and there is still some expected vacuum improvement to come which justifies our 48 h objective as indicated in Table 2.

With such long lifetimes, the machine can be operated with one refill per day. This way the heat load 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 phase I performance. Our results confirm the prediction that, in comparison with second-generation machines, third-generation sources with their low emittance and high current produce an unstable over-focusing of light ions. Although trapping of heavy dust particles could not be

Table 2
Source performance.

Parameter		Design goals	Achieved during commissioning	Present peak performance	Medium-term objectives
Current (mA)	Multibunch (100 mA)	100	114	175	200
	Single bunch	5	7 (15 with feedback)	7 (15 with feedback)	
Lifetime (h)	Multibunch	8	12	42	48
	Single bunch	8	10 at 5 mA	30 at 5 mA	30 at 5mA
Electron beam emittance (m)	Horizontal	6.3×10^{-9}	8.4×10^{-9}	7×10^{-9}	3.5×10^{-9}
	Vertical	6.3×10^{-10}*	3.8×10^{-9}–6.0×10^{-10}	2×10^{-10}	3.5×10^{-11}
X-ray beam stability		10% of beam size and 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 [photons s^{-1} $(0.1\%)^{-1}$ $mrad^{-2}$ mm^{-2}] at 100 mA		6.0×10^{17}	4.0×10^{17}*	2.6×10^{18}	1.8×10^{19}

* Assuming 10% coupling.

excluded, for other reasons we are also running the machine in the one-third filling mode which constitutes an additional counter-measure against ion trapping. For the time being, despite efforts made during machine-physics runs, it has been impossible to provoke ion-related effects even in the most favourable conditions of low current and uniform filling of the circumference. Present ESRF experience confirms that in terms of beam stability, no benefit can be expected in using positrons instead of electrons for third-generation sources.

4.3. *Emittances and coupling*

The X-ray beam spot drawn from the machine diagnostics beamline ID6 enables the photon-beam emittances and hence the electron-beam emittances to be measured permanently. The 7–8 nm measured for the horizontal plane is very close to the theoretical 6.2 nm value. The machine is routinely run near the coupling resonance with a coupling of about 10%, which again corresponds to the design value. The procedures for decreasing the coupling, *i.e.* for compensating the two coupling resonances in the vicinity of the working point, have been successfully tested. During the last 1994 USM runs, the beam was delivered with a small coupling in the 1–2% range, which resulted in a slight decrease of the lifetime from 42 to 39 h. 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.

At the design stage, it was feared that these new lattices for third-generation light sources would be extremely difficult to commission. The reason was their unprecedented sensitivity to errors due to the exceptionally high focusing required to obtain a low emittance and the necessity of introducing large non-linearities *via* sextupoles to compensate for the chromaticity. The ESRF was the first machine of a growing series of third-generation light sources (SRRC, ALS, ELETTRA) to be successfully commissioned and achieve its target emittance.

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 correct 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 h at 5 mA) recorded since then.

This further reinforces confidence in this type of lattice and now the possibility of reducing the natural horizontal emittance by allowing for non-zero dispersion in the straight sections is being investigated. A diminution of the horizontal emittance from 6.2 to 3.5 nm can be expected from the simulations of new optics, hopefully by the end of 1994. The vertical emittance will follow by maintaining the coupling-factor constant. Therefore, on top of the gain associated with the small coupling, a further gain in brilliance by a factor of about 3 is likely to be obtained by lowering the horizontal emittance.

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 is routinely stored. With a strongly overcompensated chromaticity, more than 7 mA can be obtained. In addition, by means of a prototype feedback system, it was demonstrated 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 30 h with 10% nominal coupling but goes down to the 10 h range with 1–2% coupling (Table 3).

The 16-bunch mode of filling (16 highly populated and equally spaced bunches) is a hybrid mode of operation which presents the advantage of satisfying the users performing experiments using the beam time structure, while

Table 3
Performance in different bunch modes.

Bunch mode	I (mA)	Average pressure (mbar)	Lifetime (h)
Single bunch	5.0	$\sim 2 \times 10^{-9}$	30
16-Bunch	70	4.8×10^{-9}	25
Multibunch	70	3.1×10^{-9}	48

simultaneously minimizing the penalty for those requiring a high current. The upgrade of the linac hardware and timing system allowing the acceleration of five bunches 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 min.

Single bunch purity is essential for all experiments using the time structure. Our 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.

On the basis of our present experience, it is difficult to imagine that an upgraded 16-bunch mode could compete with the multibunch mode. The multibunch mode can integrate most, if not all, the planned increase in brilliance (*i.e.* increase of current, reduction of horizontal emittance and of coupling, reduction of the undulator minimum gap, *etc.*) with only a moderate reduction of lifetime. This will never be the case for the 16-bunch mode.

4.5. *Beam-position stability – orbit correction*

All attempts to minimize the emittances would be in vain if 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, which is followed with beamline shutters open, takes a few hours and is performed with a weak beam of 5 mA permanently stored. These realignments at 6 month intervals prevent the need for correction of large orbit distortions.

On a much shorter timescale, during USM, the closed orbit is corrected every 5 min in three steps, *i.e.* a global harmonic correction over the entire ring first, a series of local readjustments in position and angle of the electron beam at the location of the insertion devices, then finally a retuning of the RF frequency if necessary. This brings the DC r.m.s. orbit deviations with respect to the reference orbit passing through the centre of the stored beam-position monitors (BPMs) to below 5 μm in both planes. (Note that the reference orbit is established for the entire 6 month period between two realignments.) In routine USM, and over periods of 2–3 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 displacements at frequencies higher than 1 Hz are naturally of the order of 5% of the beam sizes at most and therefore within the 10% target. Nevertheless, fast feedback systems installed at both ends of every ID can locally further stabilize 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 end as sensors. As expected, this can significantly improve the situation down to 1% of beam size. However, we found that our present generation of XBPMs, which work perfectly for wigglers or even dipole beams, have 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 radiations). The solution currently being looked into is to use the electron beam-position monitors 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 benefit fully from the increased brilliance obtained from emittance or coupling reduction.

4.6. *Mini-gap undulator*

In order to explore the potential for higher photon energy from undulators at the ESRF in the future, consideration was given to the desirability and possible characteristics of an undulator with a much smaller minimum gap than the standard 20 mm gap of the current IDs. For the sake of comparison, with a 20 mm minimum gap, the period of a standard (reasonable range of tunability) undulator is around 46 mm. With a 7 mm minimum gap, a similar tunability could be obtained with a 25 mm period. The comparison (see Fig. 3) between these two cases leads to a gain in brilliance of a factor of 2 at 5 keV, a factor of 7 at 20 keV and a factor of 10 at 30 keV for a given undulator length. The construction of two prototypes has already started. One of them could be installed and tested on a beamline before the end of 1994. From experiments made with a scraper used to simulate the expected effect of aperture limitation, we have found that in the multibunch mode the corresponding reduction of lifetime of a few hours is certainly affordable. The single or 16-bunch modes will be penalized much more.

4.7. *Spectrum shimming of undulators*

The present first generation of ESRF undulators has been designed for a minimum gap of 20 mm. For the most commonly used tunable undulator with a 46 mm period, radiation can be obtained between 2 and 6 keV on the fundamental, and between 6 and 18, and 10 and 30 keV for the third and fifth harmonics, respectively. This nicely covers the energy range around 10 keV, which constitutes our basic target specification. *A priori*, due to field errors, the effective brilliance decreases dramatically at higher harmonic numbers, being half the theoretical value for the fifth harmonic. This prevented us from speculating on the use of higher harmonics at the time of the ESRF design phase.

Very recently, in addition to the usual field integral corrections, special attention has been given to the shimming of magnet blocks when preparing a 48 mm period undulator with a view to maintaining maximum brilliance at high harmonic numbers (Chavanne & Elleaume, 1994). We were successful in pushing the 50% reduction of brilliance from the fifth to the eleventh harmonic, *i.e.* more than twice the photon energy. It is our intention to generalize this spectrum shimming technique, which contributes a significant widening of undulator usability (increased brilliance) at higher X-ray energies. For undulator radiation experts, it is worth mentioning that the adverse influence on the brilliance of the electron energy spread can only start being significant at harmonics well above the eleventh for a 1.6 m long undulator segment.

Clearly, this method of increasing brilliance at high energies, in parallel with the mini-gap, or even combined with it, can open up new frontiers and new scientific applications.

4.8. *Gain in brilliance*

Table 4 sums up the overall gain in brilliance that can be achieved for three different photon energies, once the various improvements have been incorporated. The present performance is given, based on a current of 100 mA, emittances of 8.5 nm × 0.2 nm, a gap of 20 mm and an undulator length of 1.6 m, then the accumulated performance adding on each additional gain to a parameter is shown.

4.9. *Influence of gap changes*

There are presently ten IDs in use on the storage ring. Whatever the gap value, all magnets, undulators and wigglers are well within specifications in terms of magnetic field defects reinjected on the trajectory of the electron beam. From this point of view, gaps should be able to be varied at will by the experimenters without inducing observable beam displacement. However, we must report on two problems experienced with IDs.

First of all, during commissioning poor steering of the injection channel into the storage ring occurred on a few occasions, which resulted in significant beam losses in some of the ID straight sections. The corresponding magnets suffered from demagnetization and we had to remagnetize blocks, reassemble, measure and shim the IDs.

The second problem is linked with the imperfect cleanliness of the ID vacuum chambers which are polluted by magnetic debris, either metallic brush hairs left by the constructor or heavy dust particles freed from the non-evaporable getter material used for distributed pumping. At certain gap values, the magnetic debris form stalactite–stalagmite-type arrangements which short-circuit magnetic lines across the beam section thus acting as a target on which the stored beam is lost. Although the impact on the operation in USM is almost negligible, it is obvious that it will take all the shutdowns until the end of 1994 to replace all defective vessels.

Table 4
Gain in brilliance for different photon energies.

	12 keV	25 keV	50 keV
Present performance	1.2×10^{18}	2.6×10^{17}	1.1×10^{16}
Current = 200 mA	2.5×10^{18}	5.2×10^{17}	2.2×10^{16}
Reduced emittance: 4.5 nm × 0.1 nm	7.5×10^{18}	1.7×10^{18}	7.6×10^{16}
Gap = 7 mm	4.1×10^{19}	1.7×10^{19}	2.5×10^{18}
Length = 5 m	1.8×10^{20}	6.6×10^{19}	8.8×10^{18}

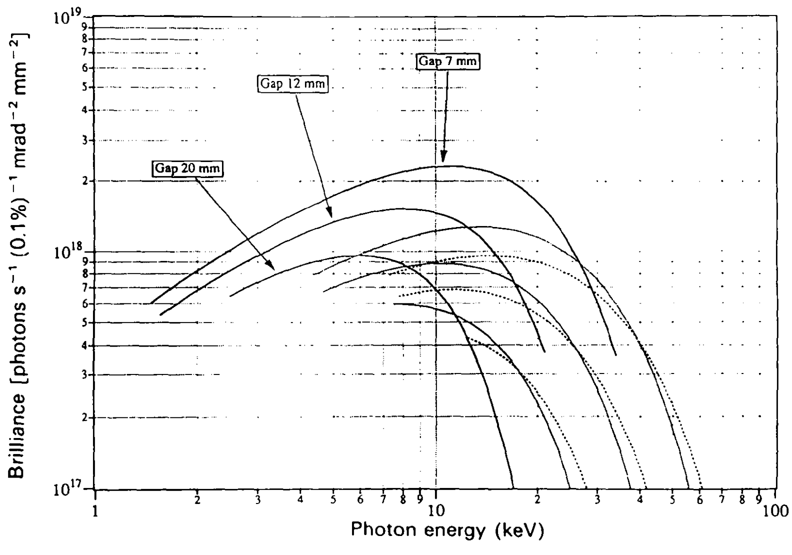

Figure 3
Expected gain in brilliance after lowering the gap from 20 to 7 mm.

5. Conclusions

For several years, we considered the objectives of third-generation synchrotron light sources to be very challenging and were anxious as to the outcome of the commissioning of the ESRF as the first machine of this type. The rapid success of the ESRF, and the conviction acquired that this machine still has potential for development of at least one order of magnitude in brilliance, will now enable speculation to be accelerated as to the next generation of diffraction-limited machines.

Perhaps before commenting on sources of the next generation, a prerequisite would be to raise the question as to whether beamline instrumentation has been developed to the point where it can fully benefit from the presently available first high-brilliance photon beams produced by third-generation light sources. Though this was not the case a few years ago, over the past two years, with the need to actually construct beamlines, great progress has been made on basic optical elements. Therefore, the ESRF answer to the question today would definitely be yes for a certain number of beamlines in their present state. Accordingly, consideration of the next generation of machines could get underway very soon.

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