HIGHER BRILLIANCE AT THE ESRF

Jean-Marie Lefebvre, ESRF, Grenoble, France
on behalf of staff involved with the Machine Programme

ABSTRACT

The ESRF is the first of the third generation synchrotron radiation light sources. The target specifications were met almost immediately. Since having reached these targets, a series of improvements in the stored beam emittance, coupling, current and the quality of the insertion devices have dramatically enhanced the performance. As a result of a first upgrade, a gain of a factor of 100 in brilliance has been achieved and a significantly wider photon energy range has been made available. A second upgrade is in preparation to further gain a factor 5-10 as a medium term objective.

1 COMPARISON OF PRESENT PERFORMANCES WITH THE FOUNDATION PHASE REPORT (FPR) TARGET PERFORMANCES

Parameters	Units	FPR Design goal	Routinely served in USM	Best achieved Performances	Medium term objectives
Current	mA	100	200	205	200
Associated lifetime	hours	8	46	35	48
Lifetime @ 100mA	hours	8	70	72	95
Horizontal emittance ε_H	nm	7	4	3.8	3
Vertical emittance ε_v	nm	0.7	0.025	0.016	0.006
X-ray beam centre stability (over a week	% of ε_H % of ε_v	20 20	5 20	5 10	5 20
Brilliance @ 1Å 1.6m undulator	ph/s/mm² mrad²/0.1%Bw	$6\ 10^{17}$	$1\ 10^{19}$	$4\ 10^{19}$	$2\ 10^{20}$
Brilliance @ 1Å 5 m undulator	ph/s/mm² mrad²/0.1%Bw	$2\ 10^{18}$ 20 mm gap		10^{20} not all parameters simultaneously	10^{21} with 10mm gaps & matched β_z

Table 1 compares the Foundation Phase Report target performances specified in 1987 with the values presently obtained and with those expected in the medium term.

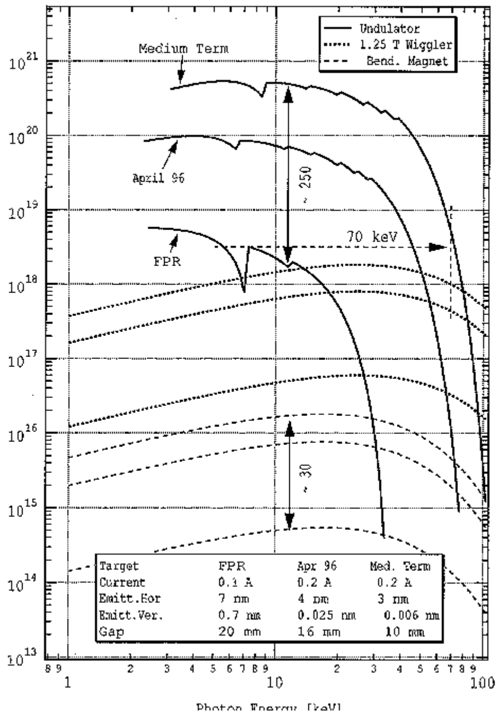


Figure 1: Comparison between original FPR design goal, the present performances as per April 1996, and the medium term objectives showing gains ranging between 30 and 250 in terms of brilliances from dipoles, wigglers and undulators

2 WHY IS IT IMPORTANT TO INCREASE BRILLIANCE ?

The brilliance and beam stability obtained at ESRF open the possibility for scientists to focus the beam to a few µm² and to use coherent and polarisation properties in the range of x-ray energy 10 to 100 keV.

Coherence obtained from lasers in the visible light range is now matched by x-ray beams produced at the ESRF. Coherent properties of the x-ray beam are currently used to obtain speckle patterns. A 1Å beam of 10^8 photons/sec with a transverse coherence length of 10µm and a longitudinal coherence length of 1µm has been used to study the dynamics of spatial arrangement of disorders. Up till now, speckle spectroscopy has been performed with extremely coherent light from lasers with the smallest visible details of the order of 1µm. By using hard x-rays (λ = 1Å) an Intensity Fluctuation Spectroscopy measurement can study the dynamics of processes down to the atomic length scale.

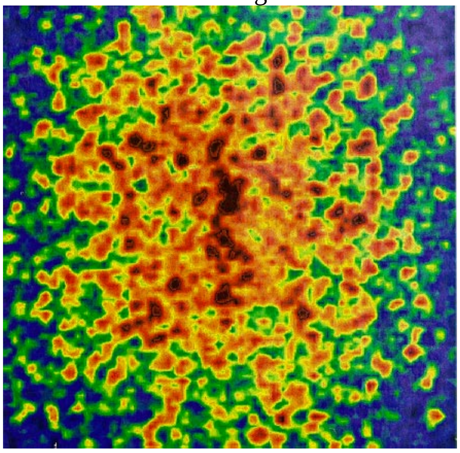


Figure 2: Speckle pattern from Fe3Al[1]

If pictures of the speckle pattern are taken at regular time intervals, one can follow the time evolution of the pattern.

Another very interesting illustration of the possibility of studying dynamic properties is the obtention of a Laue diffraction pattern from a lysozyme sample with a 60 ps, 4mA single bunch and an intensity of 5 10^{10} ph/pulse in 0.1% bandwidth in the energy range 7 to 28 keV. 5000 usable reflections can be recorded by the image plate detector.

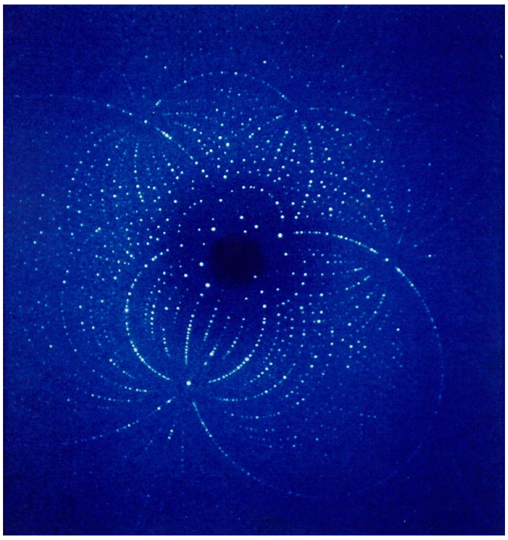


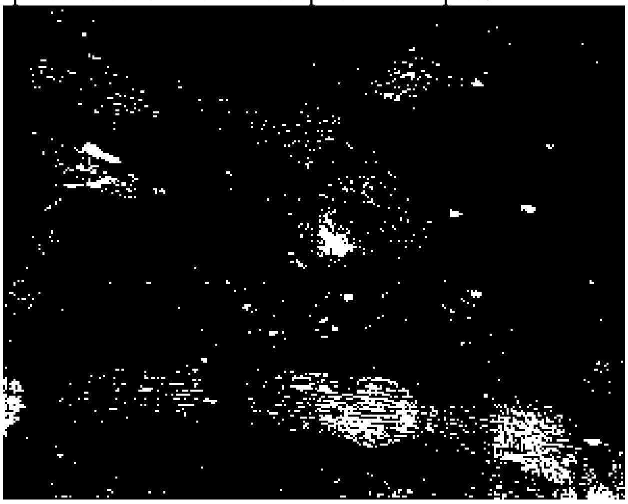
Figure 3: Laue diffraction pattern from a lysozyme sample[2]

This ultrafast diffraction technique opens the possibility of studying kinematic changes in living molecules in which the speed of nuclear displacements is in the 10^{-14} to 10^{-11} s range.

Excellent scientific applications exist for very short bunches in the sub picosecond range.

A third experiment provides a striking example of what can be achieved with bright transversely coherent x-ray beams: phase contrast imaging.

Imaging is no longer obtained from x-ray absorption, as is the case for conventional radiography techniques, but from phase contrast. A parallel x-ray beam impinging on a low density sample will deviate from rectiline propagation: different parts of the impinging wave will be deflected differently due to refraction at the sample/air interface and inside the sample. The superposition of deflected and non deflected waves produces an interference pattern depending on the distance between the sample and the detector; a deflection of 5 to 10 microns of the beam are observed at a distance of one meter. The following figure shows the advantage of this phase contrast imaging technique for low density material compared to conventional absorption techniques.



Standard x-ray image in amplitude mode

image in phase contrast mode 500µm

Figure 4: x-ray imaging of seaweed Valonia ventricose at 20 keV energy[3]

These three examples illustrate the outstanding advantages offered to scientists by bright x-ray beams with transverse and temporal coherence and time structure. More transverse coherence can be obtained from electron beams with emittances closer to the diffraction limit: the average brilliance is then the figure of merit.

3 WHAT DID WE DO TO ACHIEVE THESE PERFORMANCES?

Brilliance may be expressed as:

$$B \approx \frac{I}{K\varepsilon_x^2} f(g, E, B)$$

I = electron beam current

$K = \frac{\varepsilon_z}{\varepsilon_x}$ coupling factor

ε_x = horizontal emittance

ε_z = vertical emittance

g,B = gap and magnetic field of the insertion device.

The ESRF programme to increase brilliance acted on each of these parameters.

3.1 Stored beam intensity

Stored intensity has increased from 100mA reached in 1992 to 200mA which are now routinely delivered in the User Service Mode. The gain in intensity required the following developments:

- non uniform filling: only one third of the circumference is filled. Via beam loading, this filling pattern provides significant voltage modulation and accordingly frequency spread along the bunch train to ensure longitudinal stability with respect to Higher Order Modes.
- The single klystron RF transmitter has been replaced by two klystrons installed in parallel. At 1.3MW two klystrons are required.

3.2 Reduced horizontal emittance

The horizontal emittance has been reduced from 7nm to 4nm by adopting a new setting of the Chasman-Green lattice. The gain in emittance must be matched by a higher beam position stability: stability tolerance is 20% of emittance, or 10% of beam size.

The motion caused by beam intensity variation and sensor drift can be corrected to the tolerance level by using a global closed orbit correction scheme.

3.3 Reduced Coupling

Coupling is reduced from its 10% nominal value to 1% by correction of the two coupling resonances $\upsilon_x - \upsilon_z = 25$ and $\upsilon_x + \upsilon_z = 48$ (on working point $\upsilon_x = 36.44$ and $\upsilon_z = 11.39$). Such a reduction of coupling reduces lifetime by only a few hours in the multibunch mode. This also allows for a reduction of the undulator gap.

3.4 Reducing β_z in straight section

The β_z value in the insertion device straight section must also be reduced from 12m to 2.5m so as to get a vertical electron beam emittance matched to the diffraction ellipse. If not the brilliance would be reduced by 20%.

3.5 Development of insertion devices

$$B = 3.62\mathrm{x}10^{12}\,\mathrm{NI}\frac{Q_i}{\varepsilon_x\varepsilon_z}\,\mathrm{ph / s / mrad^2 / mm^2 / 0.1\%BW}$$

N = number of undulator periods

I = electron intensity

Q_i = function of the undulator period and gap and of electron energy

Our 1996 objectives are to obtain the following parameters:

- brilliance 10^{20}
- 4nm horizontal emittance
- 1% coupling
- 200mA
- 3 undulator segments (5 meters in length)
- 10mm gap

In April 1996, by an improved correction of the coupling (0.4%) the brilliance of 10^{20} has been obtained in a low β_z straight section with a two segment undulator (3.2m, at 16mm gap).

Multisegment phasing

The choice made at the ESRF to use one to two meter segment undulators has proved to be a flexible solution, much less constraining from a mechanical point of view than the heavy, long single piece of undulator magnet four to five meters long. However, segmentation requires phasing between the segments to ensure full brilliance on the lowest order harmonics of the spectrum: a new type of passive phasing section between undulator segments has been developed by the Insertion Device Group[4], this method is fully satisfactory.

Spectrum shimming of undulators

The first generation of ESRF undulators was designed for a 20mm minimum gap. For the commonly used undulator with a 46mm period, radiation can be scanned between 2 and 6 keV for the fundamental, 6 and 18 keV for the third harmonic and 10 and 30 keV for the fifth harmonic. This covers the original target specification of 12keV. However, due to field errors, the brilliance decreases at higher harmonics. A magnet block shimming technique was developed in 1994 in order to maintain maximum brilliance at high harmonics, the result of this technique is shown in Figure 5, on which the undulator spectra before and after shimming is illustrated.

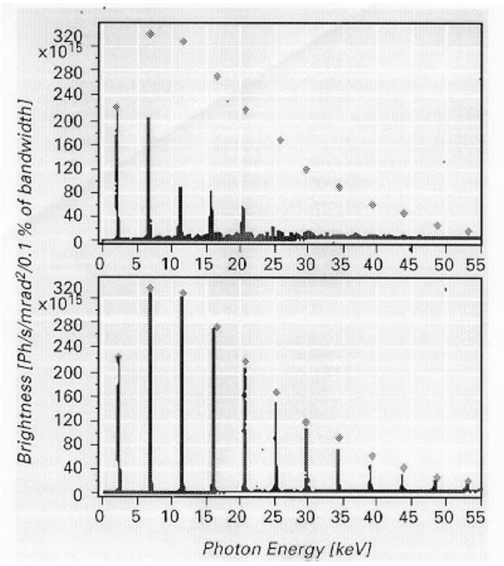


Figure 5:Comparison of undulator spectra before (a) and after (b) spectrum shimming. Spectrum shimming increases the brightness at all harmonics and removes background between peaks. The dots correspond to an ideal field. [5]

IDs in operation

At the ESRF, a record total length of 40 meters of undulators are installed.

Exotic IDs

A superconducting wavelength shifter was installed in December 1994. Its nominal field of 4 Tesla has been reached, the critical energy of the photons is 100 keV. The possibility to reduce both ID gaps and periods has been explored by producing an 80cm long, 26mm period prototype minigap allowing a variable gap down to 7mm. The expected gain is to shift the whole spectrum to higher energies (fundamental at 12 keV) with respect to a standard 20mm gap, 46mm period undulator.

Evolution of the ID gap

The minigap undulator is a very sophisticated piece of equipment, extrapolating length from 0.8 to 5 meters is rather unrealistic. The evolution at ESRF is to produce segmented 5 meter long IDs with a gap reduced to 16mm; twelve 15mm high, 5 meter long ID vacuum vessels have already been delivered. The tendency for the medium term is to reduce gaps to 10mm. A prototype for a 10mm ID vacuum vessel is presently being constructed.

A SPring 8 undulator under vacuum will be installed at the ESRF in July 1996, in the frame of our collaboration programme with SPring8.

3.6 Lifetime

Continuous upgrading of vacuum, combined with refined corrections of resonances, chromaticity and closed orbit enabled us to achieve a 70 hour lifetime iN March 1996 for a 100mA stored beam. More vacuum conditioning is still expected which justifies our 48 hour medium term objective for a 200mA stored beam.

3.7 Single - 16 bunch and hybrid modes

Single bunch

The maximum current is limited by the fast head-tail instability, the threshold is chromaticity dependent. With standard sextupole values, 5mA are routinely obtained with a 30 hour lifetime. With strongly overcompensated chromaticity, more than 15mA can be obtained for an 8 hour lifetime. In addition, the instability level may be pushed to 20mA by means of a feedback system.

Single bunch purity is essential for all experiments using time structure, our cleaning technique for lowly populated parasitic bunches combines a shaker with a vertical scraper, this method works extremely well, purity in the low 10^{-7} range is routinely delivered to Users.

16 bunch

The 16 bunch mode is a good compromise to satisfy both Users using time structure and those requiring high current. The maximum current is limited to 80mA due to overheating of the RF liners equipping the bellow section and to the presence of HOMs. Overheating is believed to appear at the RF finger contact; the ongoing research and development programme to improve RF liners is giving promising results.

Hybrid mode

In this mode, only one third of the storage ring is filled with 200mA and a single bunch (5mA) is placed in the middle of the empty space. This mode provides a good compromise between time structure and intensity requirements.

3.8 Intense short bunches

ESRF performances may be compared to those of the SLAC Linear Coherent Light Source (LCLS) as a reference. The announced peak brilliance in LCLS is in the 10^{31} range in standard units, eight orders of magnitude larger than the present 10^{23} figure. With a natural rms length of 15ps, the ultimate ESRF bunch is 100 times longer than the 130fs announced for the LCLS.

*Storage ring bunch lengths*The natural (zero current) bunch length in storage ring scales like $\sqrt{\frac{\alpha E^3}{\omega_{rf} V_{rf}}}$ in which α stands for the momentum compaction.

In order to decrease the bunch length we are left with two possibilities:

- increase the RF gradient by means of the voltage V_{rf} or increase the frequency ω_{rf}
- run the machine as an isochronous ring: $\alpha \ll 1$.

One method which seems attractive is to reduce α to a value near zero. We made an extensive study of this possibility and, the conclusion is clear: it does not work[7] [8]

It can therefore be concluded that quasi isochronous circular machines cannot produce short intense pulses.

The possibility of reducing bunch lengths from the increase in the RF gradient or to reduce the impedance of the machine were also evaluated, resulting in the conclusion that a reduction of bunch length by a factor 100 is out of range and therefore the pulse length announced by LCLS cannot be achieved by conventional storage rings.

However, if one cannot reach the fs domain for bunch length, one could imagine an ultra fast shutter to open a 100fs slot in the storage ring bunch length, this device is called a jitter free streak camera[9]. A collaboration has been started with the Centre for Ultra Fast Optical Science (CUOS) in Michigan, USA to develop and construct such a femto-second streak camera detector system over the next three years.

4 EXPECTED BRILLIANCE LIMITATIONS

Coherent x-ray radiation produced by low emittance third generation synchrotron light sources is an outstanding tool for scientific experiments.

The ESRF is already very close to the diffraction limit in the vertical plane. A second upgrade is programmed to reach:

- a horizontal emittance of the electron of 3nm
- a coupling of the order of 3.10^{-3}
- a vertical emittance of about 10^{-11} mrad at 12keV.

The forthcoming second upgrade will push the ESRF in the 10^{21} range in brilliance.

With 200mA, the ultimate brilliance for a diffraction limited source at 12keV would be around 2 10^{23}, 100 times our second upgrade objective.

Figure 6 shows the progression of brilliance over the years and the ultimate performance for hard x-ray sources.

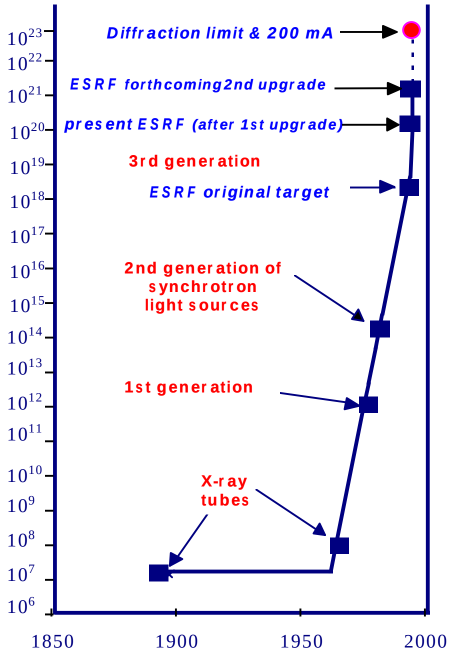


Figure 6: Logarithm of x-ray source average brilliance over the years

The 10th ICFA Workshop on 4th Generation Light Sources[10](held in Grenoble on January 22 - 25, 1996) set at about 10^{22} the average brilliance expected from storage rings of the fourth generation.

This target is only a factor of 10 with respect to the ESRF goal, however, this small difference can probably only be attained at the expense of a significant lengthening of the circumference (factor 2 to 3).

Therefore, it would appear that the time for dramatic progress of up to four orders of magnitude every ten years for storage rings in increasing brilliance, is over.

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