PERFORMANCE AND UPGRADE OF THE ESRF LIGHT SOURCE

Jean-Luc Revol, Jean-Claude Biasci, Jean-François Bouteille, Joel Chavanne, Friederike Ewald, Laurent Farvacque, Andrea Franchi, Georges Gautier, Loys Goirand, Michael Hahn, Laurent Hardy, Jörn Jacob, Jean Marc Koch, Michel Langlois, Gael Lebec, Jean-Maurice Mercier, Thomas Perron, Eric Plouviez, Kees Bertus Scheidt, Vincent Serriere, ESRF, Grenoble, France

Abstract

The European Synchrotron Radiation Facility (ESRF) is now fully engaged in a large Upgrade Programme of its infrastructure, beamlines and X-ray source. In this context, a first set of 10 insertion device straight sections are being lengthened from five to six metres; a number of them will be operated with canted undulators. The insertion devices are themselves subject to an ambitious development programme to fulfil the scientific requirements. The Radio Frequency system upgrade has started with the replacement of the booster klystron-based transmitter by high power solid state amplifiers, and the development of HOM-damped cavities operating at room temperature. A completely new DC-AC orbit stabilization system using 224 BPMs and 96 orbit steerers is currently being commissioned. The upgrade is conducted while keeping, and even improving, routine performance for the user service. In particular, the recent installation of new skew quadrupole power supplies allows routine operation with ultra low vertical emittance. This paper reports on the present operation performance of the source, highlighting recent developments and those still to come.

THE EUROPEAN SYNCHROTRON LIGHT SOURCE (ESRF)

The ESRF, located in Grenoble, France, is a user facility shared and supported by 19 countries. Since its opening in 1994, this third generation storage ring light source produces bright X-rays which are used in many different scientific areas including biology, medicine, pharmacology, physics, material science, chemistry, archaeology. In 2010, 6300 researchers came to conduct 974 experiments using the 42 specialised beamlines, producing 1798 publications. The ESRF is now embarked on an ambitious Upgrade Programme (2009 to 2015)[1]. Phase 1 includes the extension of the experimental hall, the refurbishment of a number of beamlines and a number of accelerator system upgrades.

ACCELERATOR AND X RAY SOURCE OPERATION

The ESRF accelerator complex consists of a 200 MeV electron linac, a 10 Hz full energy booster synchrotron and a 6 GeV Storage Ring of 844 m circumference with a 32 cell Double Bend Achromat (DBA) lattice. A large variety of Insertion Devices (ID) are installed in the 28 available straight sections. 72 ID segments distributed as follows: 55 in-air undulators, 6 wigglers, 11 in-vacuum undulators, including 1 cryogenic in-vacuum undulator. Bending magnet radiation is used by 15 beamlines.

Table 1: ESRF storage ring main parameters

Energy	6.04	GeV
Multibunch Nominal Current	**200**	mA
Horizontal emittance	**4**	nm
Vertical emittance	**3.5**	pm

The X-ray beam is delivered with different time structures (optimised for beamline scientific applications) corresponding to different filling patterns of the electron beam along the ring circumference (see Fig 1). The 7/8+1 mode, which offers the highest quality beam in terms of brilliance and stability, is the most demanded. This mode includes a pure single bunch in the middle of an empty gap. Since 2010, the current of the single bunch has been routinely delivered at 4 mA instead of 2 mA, using the vertical transverse bunch by bunch feedback. This feedback is also operational in uniform filing mode to reduce the vertical blow-up created by ion induced instabilities, from an emittance larger than 50 pm (depending on the vacuum conditioning after intervention) to a value close to 5 pm.

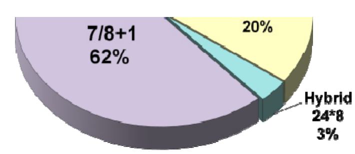

Figure 1: Filling modes in 2011, 91% of the beam time will be available for timing experiments.

In 2010, 5538 hours were effectively delivered to the beamline users, including 48.5 hours for the 599 top up. The 83 failures resulted in 68.5 hours lost. Thus, the total beam availability was 98.78 %. The first half of 2011 has been affected by only 22 trips, giving an excellent mean time between failures for that period.

Table 2: Machine Statistics for 2009-2011

	2009	**2010**	**2011** *To 27 July*
Availability (%)	99.04	98.78	99.03
Mean time between failures (hrs)	75.8	67.50	148.5
Mean duration of a failure (hrs)	0.73	0.82	1.44

On March 16, after five consecutive weeks of 100% beam availability, the ESRF broke its previous record of nonstop delivery dating from 2 years ago. Figure 2 illustrates the 795.5 hours of storage ring operation without failures. The 33 day period ended with the start of the scheduled March shutdown. The delivery was only interrupted by the machine dedicated time which occurs one day a week.

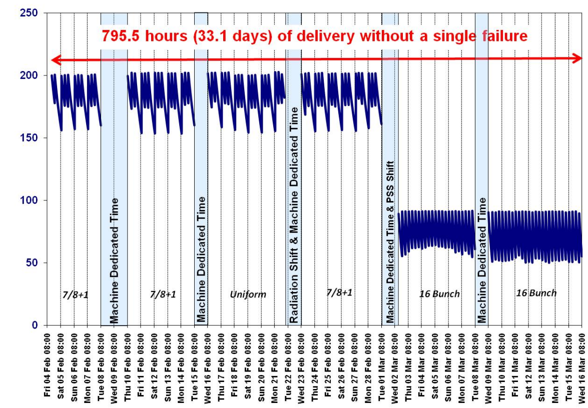

Figure 2: ESRF record delivery without a failure.

The operation schedule for 2011-2012 will be reduced with an extended winter shutdown of five months until May 3, 2012, when user operation will resume. This long interruption is necessary at the start of the civil construction work for the experimental hall extension.

RECORD BRILLIANCE

Within the Upgrade Programme, the brilliance and coherence of the undulator-generated photon beams has been increased by a factor of ten, through the reduction of the electron beam vertical emittance [2]. Values of 3.5 picometers (rms) are now reachable in User Service Mode, making possible photon beam brilliance values extended to the 10^{21} region (see Fig. 3).

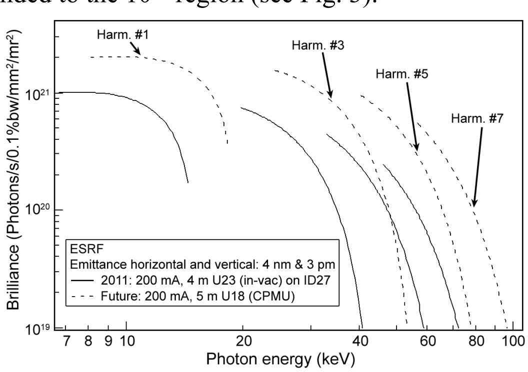

Figure 3: Brilliance of the X-ray beam emitted from the two in-vacuum undulators installed on ID27 (High Pressure beamline). Each undulator segment has a period of 23 mm, a length of 2 m and is operated with a minimum gap of 6 mm. Dashed curve: Extrapolation with two 2.5 m cryogenic in-vacuum undulators.

Since 2009, the 224 electron beam position monitors in the storage ring have been upgraded to Libera Brilliance digital electronics. This provides improved resolution in the orbit measurement which makes it possible to measure the lattice beta functions with higher accuracy. The higher precision combined with an improved algorithm for coupling correction and the increased number of skew quadrupole correctors from 32 to 64 has allowed ultra low vertical emittances to be reached. Unfortunately, some of the present 72 undulator segments have residual skew quadrupole errors which vary with the magnetic gap. As a result, when the beamline users vary the gap, the coupling correction degrades and the vertical emittance changes with time. An automatic correction is implemented to adjust the strengths of the skew quadrupole correctors to correct the difference in the coupling resonance. In addition, local skew quadrupole correctors at both ends of some straight sections are powered using look-up tables, for the compensation of the most perturbing ID's.

Reducing the vertical emittance from 30 to 3.5 pm reduces the lifetime of the stored beam due to higher intra-bunch scattering between electrons (Touschek effect). In multibunch mode, an additional injection has been added to compensate for shorter beam lifetime (injection at 9h, 15h, and 21h, with a long decay during the night). However, thanks to the improved correction of the lattice, the lifetime reduction due to the reduction of the vertical emittance was finally less than 10 hours (see Fig. 4). With such a lifetime of 45 hours at 200 mA, the number of injections is now back to twice a day. Ultra low vertical emittance is achieved in the 7/8+1 filling mode, thanks to the gap in the pattern which prevents transverse instabilities. Nevertheless, at such low vertical emittance, a slight blow-up in the range of a few tenths of picometers is still observed. This blow-up is reduced by the bunch by bunch feedback. Activating the global position feedback gives another reduction of 0.5 pm.

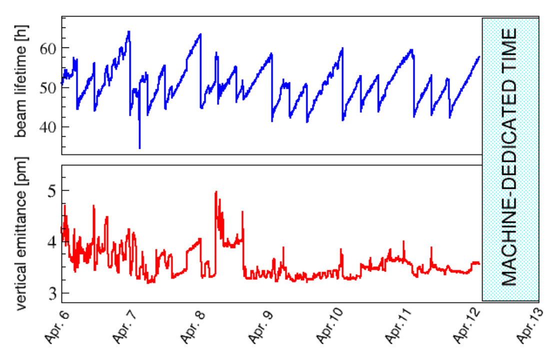

Figure 4: Typical delivery at ultra low vertical emittance (200mA with 7/8+1 filling mode). (Values during refills are not displayed).

Emittance measurements include several systems. Two X-ray pinhole cameras imaging the electron beam inside bending magnets provide both horizontal and vertical beam sizes. Eleven dipole radiation projection monitors (DRPM) are evenly distributed around the ring circumference for vertical emittance measurements. They are installed in air behind the dipoles, making use of the 170 keV X-rays that leak through the high power copper crotch absorbers. The continuous processing of all emittance diagnostics allows a precise monitoring of the vertical emittance and thereby tracks the slightest disturbance to the electron beam. The DRPM monitors are now at the limit of their resolution. A programme for the optimization of the two pinhole cameras and the installation of a new emittance monitor based on X-ray refractive lenses has been initiated with the aim of resolving vertical emittances below 2 pm.

Following the new BPM electronics and the installation of new AC power supplies which drive the 96 steerers, the fast orbit correction of the storage ring is under full reconstruction. The new system should be operational by end of 2011 and will provide improved position stability in line with new emittance performances [3].

LONGER INSERTION DEVICE STRAIGHT SECTIONS

The DBA storage ring lattice was designed with triplets of quadrupoles located on both sides of the 5 m long straight section occupied by IDs. Since 2006, the setting of the lattice has allowed the removal of one quadrupole on each side of the straight section. An increase of the ID length from 5 to 6 m is therefore possible after the modification of the hardware (such as vacuum chambers, valve, cables, piping,.....). Aluminium vacuum chambers of 6.2 metres (8 mm internal aperture) with Non-Evaporable Getter coating are now routinely produced at the ESRF [4]. Four straight sections have already been converted to 6 metres; another set of five will be done before mid 2012. ID chambers are pre-conditioned on the machine dedicated straight section. Consequently the low level of bremsstrahlung allows the beamline to take beam after only a few days of conditioning. Standard in-air ID mechanics having lengths of 1.6 metres, shorter assemblies have been built to fill the 6.2 metres of available length. In summer 2011, ID24 was the first beamline equipped with four mechanics, one of them being a revolver type. Longer in-vacuum undulators (2.5 m) are also under development [5].

A few beamlines will operate with two independent experimental stations using two canted undulators in a single 6.2 metres ID straight section, with a maximum separation angle of 5.4 mrad. The deflection is provided by a set of permanent magnets. Sextupoles of shorter length with individual power supplies will replace the existing sextupoles on each side of the ID straight section.

A further increase in the available space for IDs to 7 m is possible by replacing two quadrupoles on both ends of the straight sections with shorter ones and by displacing the adjacent sextupoles. New quadrupoles with higher gradient 26 T/m together with their individual power supplies have already been delivered. It is planned to implement the first 7 m straight section on ID23 during the winter 2012 shutdown. In summer 2013, this sector will host either a five cell copper cavity or 3 single cell cavities which will be fed by the new RF transmitter to be built in cell 23. In the future, half of the RF cavities installed in cell 7 will be dismounted allowing the creation of a new beamline after a conversion of the straight section to 7 m.

RF UPGRADE

An increase of the ESRF storage ring current from 200 to 300 mA, has been tested successfully with the existing RF system. At this current level, the HOM tuning of the existing five-cell copper cavities becomes delicate, and to ensure reliable operation in user mode, HOM-free normal conducting cavities have been under development at the ESRF since 2005. There being an option for a user operation at 300 mA in the Upgrade Programme, three operational prototypes will be built by three manufacturers [6], two having been already delivered to the ESRF. The first one has already seen RF power on the test stand and has produced 500 kV.

One of the six five-cell copper cavities has already been removed from the ring and will be replaced by the first prototype during the October shutdown, for a full test with beam during the last run preceding the long winter shutdown. Although the 300 mA option has finally not been retained for the first phase of the upgrade, the aim is to validate the new cavity design for a possible later increase in current.

Up to now, the RF power needed at the ESRF to inject and accelerate the beam has been generated by transmitters based on 1.3 MW klystrons. The analysis of the market had shown that an alternative to klystrons needed to be investigated to guarantee the long-term operation. Within the Upgrade Programme, the ESRF has ordered seven 352.2 MHz – 150 kW Solid State Amplifiers (SSA), with a design derived from the existing SSA developed by SOLEIL [7]. The first four SSAs will be commissioned by the end of 2011 and connected to the booster cavities during the long winter shutdown. The replacement of the klystron by a SSA on the booster will reduce the electrical power consumption during injection from 1200 to 400 kW. The three remaining SSAs will be received in 2012 and will feed the new RF sector to be created in cell 23. SSAs can be operated with a number of RF individual modules missing and are therefore intrinsically highly redundant, which ensures reliable operation.

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