

OPERATION AND UPGRADE OF THE ESRF SYNCHROTRON LIGHT SOURCE

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Abstract

After 16 years of successful continuous user operation, a seven year upgrade programme (2009-2015) of the European Synchrotron Radiation Facility (ESRF) has been approved and initiated. The accelerator complex and X-ray source will benefit from several upgrades. A number of insertion device straight sections will be lengthened from five to six meters. The number of experimental stations will be increased by operating some straight sections with canted undulators. New insertion devices will be built to fulfil the requirements of the scientific programme. The RF system will face a major reconstruction with the replacement of klystron-based transmitters with high power solid state amplifiers and the development of HOM damped cavities operating at room temperature. A modern digital orbit stabilisation system is under development. This paper reports on the present operation performance of the source, highlighting the recent developments.

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. Several thousand researchers come each year to Grenoble to conduct experiments using the 42 highly specialised beamlines.



Figure 1: Artist's view of the future experimental hall

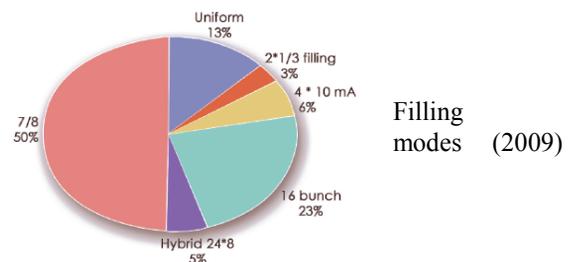
In 2008, the ESRF Council approved the launching of an ambitious upgrade programme [1]. Phase 1 of this upgrade programme (2009 to 2015) will include the extension of the experimental hall, the refurbishment of a number of beamlines and a number of accelerator system upgrades, presented in this paper.

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 (SR) of 844 m circumference. The 32 cell Double Bend Achromat (DBA) lattice of the SR produces a low emittance electron beam. A large variety of Insertion Devices (ID) are installed in the 28 available straight sections. The present configuration includes 70 segments of insertion devices distributed as follows: 53 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	GeV	6.03
Multibunch Nominal Current	mA	200
Horizontal emittance	nm	4
Vertical emittance	pm	10



In 2009, 5510 hours were delivered to the beamline users with a record beam availability of 99.04 %. Dead time due to failures accounts for the remaining 0.96 %. The number of failures is lower compared to the previous years, thus leading to an all time record Mean Time Between Failures of 75.8 hours. This excellent performance was the result of multiple actions, including an active preventive maintenance policy as well as the protection against electrical mains drops provided by a new High Quality Power Supply system in operation since July 2008.

The X-ray beam is delivered with different time structures (optimised for the beamline scientific applications) corresponding to different filling patterns of the electron beam along the ring circumference. The multibunch filling modes (7/8+1, uniform and 2x1/3) provide the highest ring current with long lifetime. and

dominate the distribution with 66% of the beam time. The 7/8 +1 mode, which includes a 2 mA pure single bunch in the middle of an empty gap is the most demanded.

ACCELERATOR AND X RAY SOURCE UPGRADE

Following intensive preparation works performed in previous years [2], the upgrade programme could be started at full speed in 2009.

New electronics for the Electron Beam Position Measurement System (BPM)

The electronics processing the weak Radio Frequency (RF) signals of all the 224 electron Beam Position Monitors (BPM) of the ESRF Storage Ring were replaced in 2009 [3]. The new Libera Brilliance electronics, manufactured by Instrumentation Technologies, are heavily based on digital processing. The installation, re-cabling and integration in the control system was spread over several shutdowns and Machine Dedicated Time (MDT) covering a period of 5 months, with the objective to maintain the same absolute position for every beamline. Following this replacement, a strongly reduced noise and a much higher resolution has been observed in the horizontal and vertical orbit measurements.

Several flows of data are simultaneously available from the Libera electronics with different sampling rates and averaging, resulting in different noise levels. The 10 Hz data flow, which provides the lowest noise and highest resolution, is used to correct the orbit every 30 seconds. Each Libera unit also provides a data stream of low latency ($<130 \mu\text{s}$) at a rate of 10kHz. This flow of data will be distributed over a dedicated fiber-optic network to fast-feedback processors which will drive 96 new steerer power supplies providing orbit corrections. This system presently under development will operate continuously from DC to a few hundred hertz. It is expected to result in a much improved DC and AC orbit stability.

Each Libera is also able to generate data turn-by-turn at the 355 kHz storage ring revolution frequency. These data are stored in buffers and synchronised for all units with a timing precision of 9.3ns, allowing beam position analysis up to 170KHz. Turn-by-turn data are used for specific beam dynamics studies like phase-advance and betatron amplitude measurements as well as for injection tuning. The data processing also includes beam position interlock functionalities and flexible buffers for data-logging.

Improving the vertical emittance

An improved method for the measurement and the correction of both focussing and coupling errors of the storage ring lattice has been implemented, based on the measurement of the orbit response matrix. The correction algorithm drives 64 quadrupolar correctors (normal and skew). With this improved method and a reduced noise from the BPM data, a vertical emittance of about 10 pm at 200 mA is routinely achieved after such correction. Unfortunately, such a low vertical emittance can only be

maintained during user service from a few hours to a few days due to the small change of residual skew quadrupole introduced by the changes of magnetic field in some undulators. Work is in progress to reduce such erratic emittance fluctuations.

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 other vertical imaging systems are installed in the air, immediately downstream of some bending magnets. They are sensitive to the very hard X-rays (centred around 170 keV) passing through the high power copper absorber (crotch absorber). The simultaneous processing of all 13 emittance diagnostics allows a monitoring of the vertical emittance with a resolution as low as 0.01 pm and thereby tracks the slightest disturbance to the electron beam.

New Linac pre-injector

The 90 keV electron beam injected into the 200 MeV linac is produced by a thermoionic triode gun. The manufacture of the cathode of the gun was discontinued forcing us to develop a new gun and the associated transport system. It is based on the CLIO/SOLEIL design and was commissioned in Summer 2009. The addition of a 3 GHz pre-bunching cavity has resulted in an enhancement of the capture efficiency by a factor 2. Some beamlines, operating with time structured filling patterns, require a purity ratio of 10^{-9} between the empty and the main electron bunches. This is achieved by a so called "cleaning" process applied in the storage ring following each injection from the booster. This cleaning process operates with a vertical blow-up of the beam size for a few seconds, which is undesirable from the beamline point of view. In order to prepare a top-up mode of operation to be delivered in 4 or 16 bunch modes without such a penalty, alternative cleaning methods are under investigation in the booster and in the storage ring. Following the installation of the new gun the initial purity ratio from the injector (without cleaning) increased from 10^{-3} to 10^{-4} . Further improvement in the purity contrast was achieved by adding vertically deflecting electrodes followed by an iris installed immediately downstream of the new gun. Sending a transversely deflecting pulse of 700 V with 1.5 ns FWHM duration, improves the bunch purity by more than three orders of magnitude. Unfortunately, this improved purity contrast is limited by the field emission in the 3 GHz buncher cavity located upstream of the first accelerating cavity of the linac.

6 metre ID 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 insertion devices. Such triplets give extensive flexibility to tune locally the beta functions in the insertion devices. Nevertheless, such flexibility has never been used. A new setting of the quadrupole of the storage ring lattice was implemented in 2006. This resulted in the possibility to remove one

quadrupole on each side of the ID straight section, and therefore an increase of the ID length from 5 to 6 m [4]. The full benefit for the beamlines can only be seen once the hardware (such as chambers, valve, cables, piping, insertion devices) has been modified accordingly. Such modifications have been fully implemented on one beamline and will continue at the rhythm of two beamlines per year (imposed by the continuous operation and limited number of shutdowns). A new fixed gap aluminium vacuum chamber with 8 mm internal aperture and total length of 6.2 m has been developed with Non-Evaporable Getter (NEG) coating [5].

The creation of two independent experimental stations using two canted undulators in a single ID straight section will be applied for a few beamlines. The maximum separation angle is 5.4 mrad to account for the vacuum chambers and front end geometry. The associated deflecting magnets will be made of permanent magnets [6]. Shorter length sextupoles with individual power supplies will replace the existing sextupoles on each side of the ID straight section. New Insertion Devices optimised for the new needs of the beamline scientists as well as the extended length of the ID straight sections are under design and/or manufacture. These include a number of revolver type in-air undulators, a 2.5 m long in-vacuum undulator, a second cryogenic in-vacuum undulator [6].

7 metre straight sections

A further increase in the available space for insertion devices to 7 m is possible by replacing two quadrupoles on both sides of the insertion device with shorter ones and by displacing the adjacent sextupoles [4]. To do so, new quadrupoles with higher gradient 26 T/m together with their individual power supplies are under manufacture. It is planned to implement such 7 m straights on ID7 and ID23. Both straight sections will be shared between RF cavities and IDs.

300 mA current in the storage ring

The ESRF storage ring has been operating at 200 mA current in multibunch mode for nearly 13 years. 300 mA is of interest for an increase of spectral flux and brilliance of all insertion device and bending magnet beamlines. Another interest is to develop a deeper understanding of the limiting parameters in the storage ring operation and in the beamline optics linked to heat load. A ring current of 300 mA was already achieved in 2006. Unfortunately, high current operation had to be interrupted due to a vacuum leak in the tuner port of one of the cavities. It was resumed in April 2010. Tests to address accelerator and beamline technical issues will continue during future MDT, but delivery of 300 mA in USM is not planned before the end of Phase 1 of the Upgrade Programme.

RF cavities

A single cell HOM damped RF cavity, derived from the European-ALBA type cavity, has been numerically and mechanically designed at the ESRF. Three power prototypes have been ordered from three different

companies. The cavities will be tested on the RF power test stand and with beam on the storage ring. When validated, they will be installed in ID23, allowing then to remove one of the 5-cell cavities presently installed on ID7. This will give the possibility to create a long beamline on ID7. Further procurements are foreseen for a partial or a total replacement of the remaining 5-cell cavities. Further works include the collaboration with CERN and SOLEIL to develop higher power RF couplers using the robust window recently developed for the LHC.

High power solid state RF amplifiers

The RF power needed to inject and accelerate the beam is today generated by four transmitters based on 1.3 MW klystrons (three for the storage ring and one for the booster). This system is equipped with a waveguide switching network providing the relevant redundancy to maintain the nominal 200 mA operation in case of failure of any one of the four transmitters. In order to keep the redundancy at 300 mA and to anticipate the possible obsolescence of ESRF type klystrons, it is planned to gradually replace the klystrons with Solid State Amplifiers (SSA) similar to those developed at SOLEIL. An order has been placed in 2009 for the manufacture of four 150 kW SSA for the booster synchrotron and three 150 kW SSA for the storage ring. Each SSA unit will combine two 75 kW amplifier towers. A large number of 650 W modules, built with the most recent LD MOS-FET transistors, are combined in each 75 kW tower. The booster SSA are pulsed at 10 Hz and their common power supply is filtered with anti-flicker capacitances of 3 F. The replacement of the klystron by a SSA on the booster will reduce the electrical power consumption during injection.

CONCLUSION

The ESRF has started an Upgrade Programme, which is challenging from a technical and organisational point of view. Conducting the upgrade in parallel to full user operation and maintaining the high stability and reliability of the X-ray source will be most demanding.

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