ESRF OPERATION AND UPGRADE STATUS

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Abstract

The European Synchrotron Radiation Facility (ESRF) is undergoing the first phase (2009-2015) of an Upgrade Programme which concerns its infrastructure, beamlines and X-ray source. This paper reports on the present operational source performance, highlighting the most recent developments; eight insertion-device (ID) straight sections have been lengthened from five to six metres, two of which operate with canted undulators. The lattice of two cells has been modified to create a 7 metre straight section, with the aim of testing a double vertical mini-beta optic, prior to the installation of new HOM-damped RF cavities. A second cryogenic permanent magnet undulator has been completed. High-power solid-state amplifiers have replaced the booster klystron-based radio frequency transmitter. Two normal-conducting HOM-damped ESRF designed cavities have been commissioned with beam. Thanks to the upgrade of the beam position monitoring system, a new fast orbit feedback has greatly reduced the orbit distortions induced by ID gap motions.

OPERATION

The ESRF complex of accelerators 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. 28 beamlines use the intense X-ray beams produced by various types of IDs, whereas 12 beamlines exploit bending magnet radiation.

Table 1: ESRF storage ring main parameters

Energy	**6.04**	**GeV**
Multibunch nominal current	**200**	mA
Horizontal emittance	**4**	nm.rad
Vertical emittance	**4**	pm.rad

The X-ray beam is delivered with different time structures optimised for beamline scientific applications. The average photon flux and the pulse rate are functions of the filling patterns of the electron beam along the ring circumference (Fig. 1). The 7/8+1 mode, which combines the interests of multibunch and time-structure user communities, offers the highest quality beam in terms of brilliance and stability. This mode provides a bunch train along 7/8 of the circumference and a pure single bunch in the middle of the 1/8 empty gap. The vertical transverse bunch-by-bunch feedback (BBF) is used to go up to 4 mA for a signle bunch (2 mA is the instability threshold). It is also used in uniform filling mode to reduce the ion-induced vertical blow-up, from a vertical émittance (ε_y) larger than 50 pm.rad down to 5 pm.rad. The system is also active with a smaller gain on the 7/8 multibunch train, to achieve the lowest vertical emittance, since the 1/8 gap is not sufficient to fully cure ion instabilities. The BBF system has been upgraded in order to provide a strong gated excitation that removes parasitic (low-populated) bunches, to the benefit of users requiring a high level of bunch purity (10^{-9}). With this method, the vertical blow-up of the main beam has been reduced from 2 nm.rad to a few pm during the 20 second cleaning sweep performed just after each refill, in hybrid (24*8+1) and 16 bunch modes. The drastically reduced perturbations will make the implementation of frequent refills in 16 bunch operation possible. Within the UP phase I, the reduction of the electron beam vertical emittance from 25 pm to less than 7 pm (rms) [1] led to an increase in the brilliance of some undulator-based sources by a factor of up to 3.

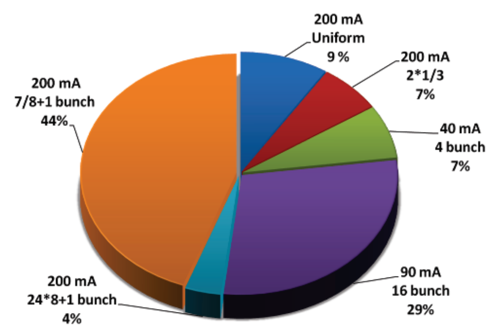

Figure 1: Filling modes in 2012.

In 2012 operations were stopped for five months due to the extensive building works underway on site. This shutdown has provided an opportunity for the renewal and maintenance of the accelerator subsystems, including fluids and electricity networks. Substantial ground movement linked to earth removal and building works have misaligned the Storage Ring. Consequently two weeks have been dedicated to an intermediate restart of the accelerators, mainly for troubleshooting. During the May restart, several days were devoted to radiation and alignment checks for all the beamlines. Three runs were scheduled in 2012 instead of the usual five. Just 3540 hours of beam time were scheduled for the users instead of the standard 5600 hours. 3459 were effectively delivered (including 31.2 hours for the refills), which represents a beam availability of 98.58 %. With 60 failures, the Mean Time Between Failures (MTBF) for this year has been 60 hours, a lower figure compared to recent years. The lower MTBF is mainly due to commissioning of new hardware.

Table 2: Machine Statistics (records in bold)

	2009	2010	2011	2012
Availability (%)	**99.04**	98.78	98.91	98.58
Mean time between failures (hrs)	75.8	67.50	**107.8**	60
Mean duration of a failure (hrs)	0.73	0.82	1.18	0.85

UPGRADE PHASE 1 STATUS

6 Metre Long ID Straight Sections

The two quadrupoles at the sides of the straight sections are not used anymore. Therefore eight ID straights have been lengthened from 5 to 6 metres [2]. Two of them (ID24, ID20) are now operational and equipped with four insertion devices, including revolver-type undulators. A third one (ID1) will be fully operational by December 2013. The canting scheme adopted for ID16 (± 2.7 mrad) and ID30 (±2.2 mrad) has been completed. The radiation axes from two sets of insertion devices are angularly separated by means of a small permanent magnet [3]. All the ID16 elements have been installed (Fig. 2). The upstream branch is equipped with a 2.5 m long in-vacuum undulator while two revolver undulators in tandem occupy the second branch. In ID30, two in-air undulators of the first branch have been in operation since March. The second branch will be completed in summer 2013.

7 Metre Long Straight Section

A local modification of the optics is required to further lengthen an ID straight section. The ID23 straight section, the first to be lengthened from 5 to 7 metres, was modified during the 2012 winter shutdown. Two shorter girders supporting two high-gradient quadrupoles (25 T/m) and two sextupoles were pre-assembled, magnetically measured and adjusted in the autumn. These magnets are equipped with independent power supplies to match the (modified) local optics. New NEG-coated vacuum chambers, mechanical supports and chicane magnets have also been installed. The machine restarted without difficulty and user service resumed on schedule. Conditioning was carried out over four days and beam parameters rapidly reached nominal values. The beam quality parameters (vertical emittance and lifetime with different beam modes) are substantially identical to those prior to the installation.

Two 1.6 metre-long undulators have been re-installed for the ID23 beamline (in a canted configuration). In the summer of 2013, three single-cell RF cavities (Fig. 2) will be installed in the space between the two undulators. In the meantime, a high-gradient quadrupole, has been installed in this location. This will allow us to test the possibility of creating two minima for the vertical β function of about 1m instead of 3 m. This mini-beta configuration exploits the possibility of reducing the in-vacuum undulator gaps down to 4mm (6mm today). Machine studies validated these special optics and assessed the detriment to machine performance: a small drop in the injection efficiency and a 10% reduction in lifetime.

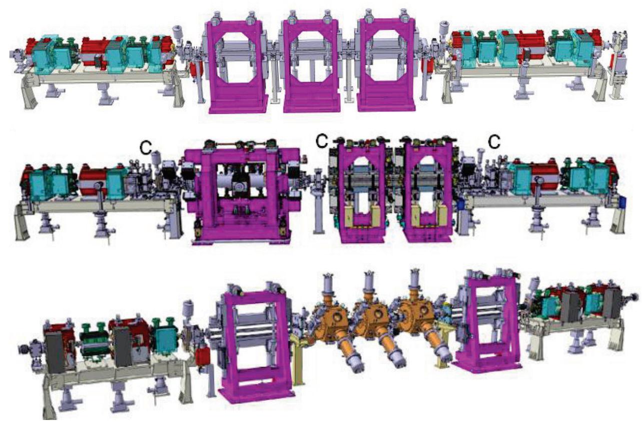

Figure 2: Standard 5 metre [Top], 6 metre ID16 [middle], 7 metre ID23 [bottom] straight sections.

Cryogenic Permanent Magnet Undulators

Cryogenic permanent magnet undulators (CPMUs), an evolution from the conventional technology of in-vacuum undulators operating at cryogenic temperature (80°K to 140°K), provide higher peak field and a better resistance to radiation-induced demagnetization [4]. Based on experience gained from a first prototype installed in 2008, a second device operating at 145°K has recently been installed on the ID11 straight section. This undulator has a period of 18 mm and a total magnetic length of 2 m. Since its installation the operation of the new CPMU has been smooth and without any specific difficulties. In the ESRF context, the use of CPMUs is primarily efficient for improving the brilliance at photon energies above 50 keV. A further development, combining a smaller magnetic gap and better performing permanent magnet materials is presently under study. This involves a very short period device (14 mm) with a K value of 1.65 at a gap of 4 mm.

Fast Orbit Correction System

Experiments can only take advantage of the extremely low vertical emittance and the resulting small spot size on the sample if the orbit of the electrons in the storage ring is stable compared to the photon beam size [5]. The orbit correction system comprises 96 corrector magnets and 224 Beam Position Monitors (BPMs), equipped in 2009 with Libera Brilliance electronics and providing a position resolution of a fraction of µm (this used to be several µm with the old system).

In May 2012 the orbit correction system was restarted with the implementation of the following new items:

- A new set of wide-band power supplies to drive the corrector magnets with a bandwidth of 500 Hz.
- A fast data network able to broadcast position and correction data at a rate of 10 kHz
- Eight FPGA controllers connected to the communication controller and to the data ports of the power supplies.

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The orbit distortions are now damped in the frequency range 0-150 Hz. For the users the effect of the orbit distortions (up to 5 µm) that occur during the change of gap and phase in some Ids, is now unnoticeable. Recent tests have demonstrated the stability of the electron beam position of a few hundred nm in the vertical plane, and in the µm range in the horizontal plane (Fig. 3).

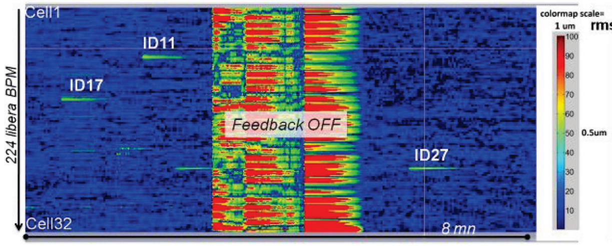

Figure 3: Orbit stability in the vertical plane.

RF Upgrade

Four 150 kW RF solid-state amplifiers (SSAs) have been in operation on the booster synchrotron for one year without any major problems (Fig. 4) [6]. A 3.2 F capacitor bank, installed on the DC power supply, to smooth out the power drawn from the mains, limits the flicker at 10 Hz. Only 366 kW AC are drawn from the mains. Under similar operation conditions, this is about one third of the power demand of the former klystron transmitter. Only one out of about one thousand RF modules failed without disturbing operation, thanks to the redundancy. Three SSAs operating in CW will be installed on the storage ring. They will be connected to the three new HOM-damped cavities in cell 23.

Three operational prototypes of the HOM-free normal conducting cavities developed at the ESRF have been built and delivered by three manufacturers [7]. The first two cavities have been validated for 800 kV accelerating voltage, i.e. slightly above the design goal of 750 kV. Both have been tested one after the other with beam on the SR. In passive mode they have seen all filling patterns without any abnormal degassing or heating, which validates the design and fabrication of the HOM dampers and their ferrite absorbers. Both cavities have also been successfully tested in active mode at full beam loading, powered up to 150 kW (Fig. 4). The ESRF design is now fully validated in its two mechanical construction versions (mainly brazing versus mainly electron beam welding). The third prototype will be tested soon. The three prototype cavities will be installed in ID23 next summer. Although eventually the 300 mA option has not been retained for the phase I of the ESRF upgrade, this development is very important for phase II [8].

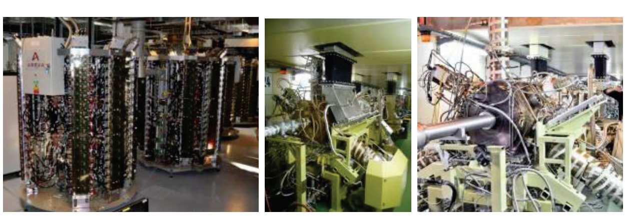
Figure 4: SSAs(left), single-cell cavities (middle, right).

TOP-UP

In order to reduce the heat load variation on the beamline optics, the implementation of top-up is under evaluation and preparation. This will be greatly beneficial for the 16 bunch mode,which has the lowest lifetime. Moreover it will also allow delivery at low ε_y, since it is now increased from 5 to about 60 pm.rad in order to increase the lifetime from 5 to 15 hours. The gated bunch cleaning previously described allows frequent injection in this mode. The development of bunch cleaning in the booster shall further improve the top-up transparency to users. The upgrade of the booster RF was a first step towards reliable and efficient operation in top-up mode. Other injector equipment is due to be renewed. Amongst these, a new power supply for the booster magnets, two extra 5-cell cavities, a spare linac modulator, two spare linac accelerating sections, a spare buncher and new booster BPM electronics will be implemented.

Top-up tests have been performed during machine dedicated time and will soon be qualified with selected users. The storage ring equipment has been validated at a constant current of 90 mA for a few hours, validating the higher heat load induced by the RF beam losses.

PERSPECTIVES

The ESRF is undergoing a major upgrade programme. Most of the accelerator-related projects of the first phase (2009-2015) reviewed in this paper are completed, while the remaining ones are on schedule. The second phase, to take place 2015-2019, has been devised to decrease the horizontal emittance of the storage ring to 150 pm by replacing the present DBA with a 7-bend lattice. The ESRF is now progressing with the Technical Design Study for this project [8, 9].

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