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ESRF-EBS: IMPLEMENTATION, PERFORMANCE AND RESTART OF USER OPERATION

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Abstract

The European Synchrotron Radiation Facility - Extremely Brilliant Source (ESRF-EBS) is a facility upgrade allowing its scientific users to take advantage of the first high-energy 4th generation light source. In December 2018, after 30 years of operation, the beam stopped for a 12-month shutdown to dismantle the old storage ring and to install the new X-ray source. In December 2019, first beam was stored and accumulated in the storage ring, allowing the vacuum conditioning and tuning to be started. Beam was delivered to beamlines in March 2020 for their commissioning. On 25 August, the user programme was restarted with beam parameters very close to nominal values.

In this report the milestones and key aspects of the return to user-mode operation are presented and discussed.

INTRODUCTION

The ESRF, located in Grenoble France, is a facility supported and shared by 22 partner nations. This light source, in operation since 1994 [1, 2], has been delivering 5500 hours of beam time per year on up to 42 beamlines. The chain of accelerators consists of a 200 MeV linac, a 4 Hz full-energy booster synchrotron and a 6 GeV storage ring (SR) 844 m in circumference. A large variety of insertion devices (in-air, in-vacuum and cryo-in-vacuum undulators, as well as wigglers) are installed in the 28 available straight sections. Bending-magnet synchrotron radiation is used by 12 beamlines [3].

Since 2009, the ESRF has embarked on an upgrade programme of infrastructure, beamlines and accelerators. The second phase (2015-2022: EBS), saw the design and the installation of a new storage ring (Fig. 1) based on a hybrid 7-bend achromat (HMBA) replacing the double-bend lattice [4-6]. Reducing the horizontal emittance from 4 nm rad down to 133 pm.rad (Table 1) allows a dramatic increase in brilliance and coherence.

Table 1: Main Parameters of the Old and New SR

	Units	ESRF	ESRF-EBS
Energy	*GeV*	6	6
Circumference	*m*	844.4	844
Lattice		DBA	HMBA
Current	*mA*	200	200
Lifetime	*h*	50	25
Emittance H	*pm.rad*	4000	133
Emittance V	*pm.rad*	4	10*

* Vertical emittance artificially increased from 1 to 10 pm rad.

IMPLEMENTATION

A white paper published in 2012 presented the first baseline of both the EBS design and of its implementation. The whole design study, further developed and detailed in the following two years, was then approved as an official project in 2015 (see planning in Table 2). The procurement phase was immediately launched allowing the assembly of 129 complete girders already starting from October 2017. In the meantime the logistics was prepared and substantial preparative work took place. Beam delivery from the old storage ring ended on 10th December 2018 [7].

Table 2: Master Planning

	Milestones and phases
01/2015	Approval of the project
2015-2017	Final Design & procurement
2017-2018	Delivery of components
10/17 to 10/18	Assembly phase
10/12/2018	**End of Service**. Start dismantling
03/2018	Start installation
28/11/2019	SR beam commissioning
02/03/2020	Beamline commissioning
25/08/2020	**Back to User Service Mode**

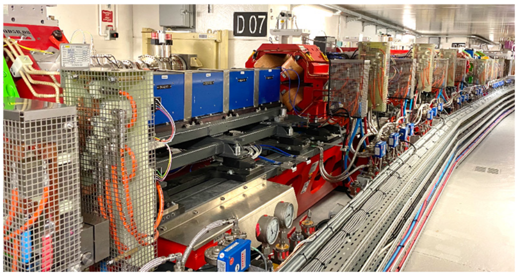


Figure 1: Inside the storage ring.

Installation

In 2019, activities concentrated on the installation of the new storage ring. During the first three months, all components of the old machine inside the tunnel were removed and checked for radio protection. In the meantime the technical gallery was prepared. After some civil work in the tunnel, the installation of girders with magnets and vacuum chambers already embedded and pre-aligned promptly took place. The cooling network, preassembled and cleaned at the factory, was mounted shortly afterwards. Cabling followed and required a significant amount of time. Installation of straight sections (for the injection, RF and insertion devices) and of the front ends came next. As soon the hardware in each cell was installed and cabled, it was immediately connected to the control system for tests. The modification of the chain of injectors was limited to a full realignment and the exchange of a few components. Indeed, the injectors had already undergone a sizeable upgrade in the first phase of the upgrade.

Accelerator Commissioning

As soon as the tunnel could be closed during the last weeks of the shutdown, interlocks, power and global control tests took place, along with the restart of the chain of injectors [8]. The first 3 turns in the new storage ring (SR) were obtained on 28th November 2019, the very first day of the SR commissioning and less than 1 year after the beam stop [9]. Beam was stored for the first time on 6th December and accumulated on 15th December. Beam current could then be increased and injection efficiency improved. Three physical obstacles on the beam path and poor vacuum in a few ID NEG coated chambers slowed down the overall commissioning. Nominal 200 mA was reached on 28th February 2020. Beam commissioning greatly benefited from first-turn diagnostics (beam position monitor, beam loss monitor, striplines,..) and from the test of commissioning tools and of part of the control system on the machine simulator [10]. In parallel to beam commissioning, the PS control software was finalized and the diagnostics further optimized.

COVID-19 Impact and Control Room Expertise

The commissioning of the storage ring was mostly completed when the first lockdown was declared in France. Thus the two-month restrictions mostly impacted the beamline commissioning. During the second and third lockdowns, the service to users was reduced and the number of shifts dedicated to machine development and tuning slightly increased. The limited access to the site was an opportunity to implement new tools for remote control and also improve procedures. Development shifts or interventions were often performed via video-conferencing tools. Today, operators are fully trained to operate the machine and an on-call support by experts has been put in place.

Beamline Commissioning

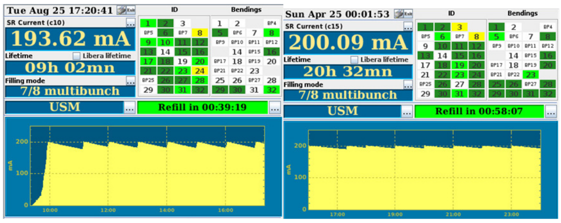
A first test was already performed on 30 January 2020 to infer preliminary information on the X-ray beam position. Fortunately, 26 out of the 27 Beamlines could see light. These beamlines were able to sequentially restart their commissioning from March 2nd for precise alignment and radioprotection validation. During the evenings and nights, RF cavities were tuned and conditioned allowing more beamlines to close the gaps of their insertion devices. 45 beamlines were validated for the start of user service mode (USM). The dedicated bending-magnet (BM) sources were progressively installed and the optics adjusted accordingly during machine-dedicated time and shutdowns [11]. A total of 17 BM beamlines are equipped with their sources of radiation. Five beamlines were already operational as of May for COVID-19 research.

USER-MODE OPERATION

8.00 am on Tuesday 25th August 2020 was the target date to resume operation with users, as defined from the start of the project. Despite the restrictions and logistic issues related to the Covid-19 pandemic, most insertion device and bending magnet beamlines were able to take beam and start experiments. The main beam parameters, chiefly beam intensity, lifetime and emittances, were already reached well ahead of schedule [9].

Beam Lifetime

Even though a vertical emittance of about 1 pm.rad could be achieved after coupling correction, the electron beam is voluntarily blown up vertically in order to reach an operational lifetime. An early lifetime of about 10 hours, led to fixing the vertical emittance at 20 pm.rad. Tests performed with the most sensitive beamlines indicated that the optimum value was around 10 pm.rad. Further vacuum conditioning and optics tuning, led to a stable operational lifetime of about 20 hours with the emittance artificially kept at 10 pm.rad by a dedicated feedback loop (see Fig. 2).



Tue Aug 25 17:20:41
SR Current (c10): 193.62 mA
Lifetime: 09h 02mn
Filling mode: 7/8 multibunch
USM
Refill in 00:39:19

Sun Apr 25 00:01:53
SR Current (c15): 200.09 mA
Lifetime: 20h 32mn
Filling mode: 7/8 multibunch
USM
Refill in 00:58:07

Figure 2: First USM Day on 25th August 2021 and delivery in April 2021.

Today the vacuum lifetime is close to 120 hours and Touscheck lifetime in excess of 40 hours (10 pm.rad) in multibunch. Most of the electron beam losses are localized at two shielded collimators for radioprotection safety and to protect insertion devices from demagnetisation [12]. The efficiency of the relocation is in the order of 50% instead of the 80% of the design. The closure of the collimators is tuned so as to reduce losses on the in-vacuum undulator as much as possible, with a maximum accepted reduction of beam lifetime by 5-10%. Beam loss references just after the insertion devices were taken in 2018. Today, the level of losses, when the undulators are closed, is the range of the values recorded on the old machine.

Beam Stability and Top-up

Both the engineering of the new storage ring and the prealignment of the initial components on the girders provided excellent initial alignment conditions of less than 50 μm in both planes. In addition to the standard slow orbit correction, a fast orbit feedback stabilizes the orbit up to 100 Hz motion to a residual motion of 0.8% and 2.8% of the horizontal and vertical beam size.

Perturbations of the closed orbit during top-up injections are disturbing and even preventing some beamlines from acquiring data during these (short) periods. Off-axis injection similar to the one of the old machine has been implemented for EBS. As the horizontal beta-function in the standard straight section is only 6.9 m, a special injection section has been designed with β_x = 18.6 m at the septum. Conversely to the old ring, no sextupole is placed close to the two inner kickers, where the injection orbit bump is the largest and unclosed during the kicker ramp because of the feed-down fields from the sextupoles. The two sextupoles are located at the very ends of the injection bump so as to minimize those perturbation. Nevertheless the sensitivity of the beamlines is more important due to the reduced beam size of the stored beam. Dedicated tests have been performed with the most sensitive beamlines to characterize all sources of perturbation including the ramping of the booster magnets. For the septum, the feedforward compensation is very effective, correcting most of the orbit distortion within a few turns [13]. The perturbation induced by kickers in the horizontal plane is still too large. New kicker power supplies are under commissioning. While waiting for further improvement in the hardware, the top-up frequency has been reduced from one every 20 minutes to one every hour, to limit disturbance to the beamlines. Today, this problem is a limitation for the full exploitation of EBS.

Filling Modes

Since the start of USM, six different modes have been delivered. In mutibunch, (7/8+1 and uniform modes), nominal parameters have been successfully reached and delivered, namely an intensity of 200 mA for a lifetime greater than 20 hours with a stabilized vertical emittance of 10 pm.rad. However, during first tests of ramping in 16 bunch filling mode, one of the kicker ceramic chambers broke down. A thorough analysis revealed an abnormal thermal stress that cannot be withstood by these chambers. This increase of temperature is a direct consequence of the intensity per bunch and the number of bunches. New ceramic chambers have been designed and are being manufactured, with delivery expected by the end of 2021. In the meantime, a survey of the temperature of the chambers, associated with an augmented air cooling of them allowed the delivery of time-structured modes at a reduced current. The current were limited to the equivalent power deposit in the 7/8+1 already delivered (196+4 mA). Instead of 200 mA the 32*12 bunches was delivered at 150 mA and the hybrid (28*12 + 4 mA) at 129 mA. 16 bunch was served at 35 mA and 4 bunch at 20 mA instead of 90 and 40 mA respectively. All time-structured modes have been delivered with a purity of more than 10-9 between the filled and empty buckets thanks to the application of a cleaning process in the booster.

Reliability and Statistics

Despite the installation of thousands of brand new pieces of equipment and software, the reliability of the new accelerator complex is comparable to that of the old machine in its last years (see Table 3 and Fig. 3). Operation was disturbed by a few long failures, mostly from sub-systems not specifically linked to the EBS design (such as aluminium NEG coated vacuum chambers in straight sections with insufficient conditioning, failure of the RF master source and a 20 KV high voltage cable defect).

The most complex hardware to commission and develop for operation was the magnet power supply system for which we moved from family PS to individual DC-DC converters associated with a 360 V DC distribution network. Despite the increased amount of equipment (more than 1000 PS) and the complexity of the layout, the reliability of the system has been remarkable since the early days of operation. It has mostly suffered from low-level control access weakness and from interfacing with the communication network. The hot-swap function, which should even increase the reliability, is under commissioning. The 13 HOM-damped single-cell cavities fed by Klystrons and solid state amplifiers have proved extremely reliable too and were easy to condition to the nominal voltage and beam current [14].

Table 3: Machine Statistics (Until May 2021)

	2017	***2018***	**2020 EBS**	**2021 EBS**
Availability (%)	*98.3*	*98.5*	96.1	98.1
Mean time between failures (hrs)	*64.3*	*104.3*	46.0	98.7
Mean duration of a failure (hrs)	*1.11*	*1.60*	1.80	1.9

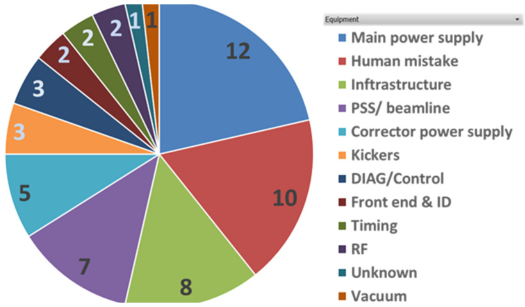


Figure 3: Distribution of failures in number.

CONCLUSION AND LESSONS LEARNED

Despite the impact of the Covid-19 pandemic, our users recovered the beam on the scheduled day and with already remarkable performances. The beamlines are now progressing and upgrading to take full benefit of the source.

The entire EBS project was completed on time and within budget. Proved engineering and technological solutions, a structured procurement, the preassembly of maximum equipment, the preparation of infrastructure and logistics ahead of the shutdown, the test of commissioning tools and software on a simulator, were all key elements for the fast start-up of the new machine. The expertise gained and the development and upgrades done on the previous machine undeniably contributed to this achievement.

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