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FIRST YEAR OF OPERATION OF THE ESRF-EBS LIGHT SOURCE

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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 storage ring 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. On 25th August 2020, the user programme restarted with beam parameters very close to nominal values.

This paper reports on the present operation performance of the source, highlighting the ongoing and planned developments.

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 - 3], 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 along the 28 available straight sections. Bending-magnet radiation, now produced by short bends and wigglers, is used by 12 beamlines.

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

Started in 2015, the project was conducted in four years for the design, procurement and assembly. The down time for the installation was slightly less than one year. After 6 months of commissioning, the beam was back for the users on 25th August 2020, the target date [8 - 13].

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	23
Emittance H	*pm rad*	4000	133
Emittance V	*pm rad*	4	10*

(*) Vertical emittance increased from 1 to 10 pm rad.

USER-MODE OPERATION

Despite the restrictions due to the Covid-19 pandemic, most beamlines were able to take beam on August 2020. The main beam parameters, chiefly beam intensity, lifetime and emittances, were already reached [9]. Since that date, the beam was continuously delivered to the users. During the second and third confinements in France, USM delivery was reduced to three and four days/week, respectively.

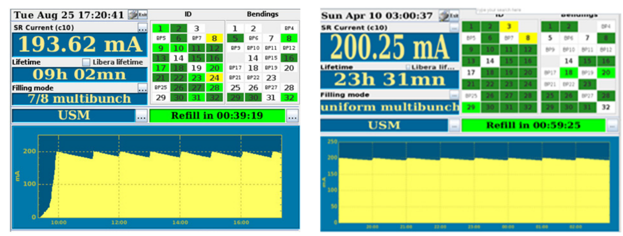

Figure 1: First USM Day on 25th August 2020 and delivery in April 2022.

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. Tests performed with the most sensitive beamlines indicated that 10 pm rad was an acceptable vertical emittance. Vacuum conditioning and optics tuning [14] led to a stable operational lifetime longer than 20 hours with the emittance artificially kept at 10 pm rad by a dedicated feedback loop (see Fig. 1).

Most of the electron beam losses are localized at the two shielded collimators for radioprotection safety and to protect insertion devices from demagnetisation [15]. The efficiency of the relocation is around 50% instead of the planned 80%. The closure of the collimators is tuned so as to reduce losses on the undulators as much as possible, with a maximum accepted reduction of the total beam lifetime of 8%, with ID gap open. Beam loss references just after the insertion devices were taken in 2018. The objective is to maintain the same level of losses with undulators closed.

Beam Stability and Top-up

Despite the reduction of the horizontal emittance, the beam stability fulfils today the beamline requirement. Associated to the 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. A task force has been established to monitor and further improve the beam orbit against different sources of perturbation. Those occurring during top-up injections are disturbing and even preventing some beamlines from acquiring data during these (short) periods. Off-axis injection

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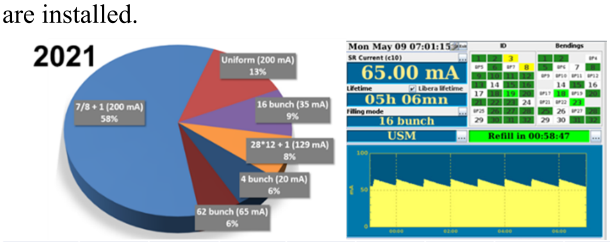
similar to the one of the old machine has been implemented for EBS. Dedicated tests have been performed with the most sensitive beamlines to characterize all injection-related sources of perturbation. Tuning of the injection perturbation damping system was a main priority during the last months [16, 17]. For the septum, a feedforward compensation is very effective, correcting most of the orbit distortion with more than one order of magnitude. The disturbances induced by kickers in the horizontal plane (and vertical by either coupling or tilted magnets) benefited from the implementation of a slow ramping injection kicker power supplies (70 µs instead of 1 µs). The damping system is operational and drastically improve beam motion and blow-up. Nevertheless, it still requires at least a factor two in the reduction to make it acceptable for the most demanding beamlines. Improvements are still on going, but the system is very close to its limit. 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, seven different modes have been delivered (see Fig. 2). In mutibunch, (7/8+1 and uniform modes), nominal parameters have been 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 in 16 bunch filling mode, one of the kicker ceramic chambers broke down due to overheating and mechanical weakness. As the increase of temperature is a direct consequence of the intensity per bunch and the number of bunches, the delivery of time-structured modes took place at a reduced current. The current was limited to the equivalent power deposit in the 7/8+1 delivery (196+4 mA). The new slow power supplies of the injection kickers, allowed to exchange the kicker ceramic chambers by existing spares with same design but coated with an increased layer, in order to decrease the power deposit. The current in 16 bunches could be increased from 35 to 75 mA during machine time and delivered at 65mA. However, issues with damaged RF fingers at the ends of one cryo-in-vacuum undulator imposed yet another limit on the total current in this filling mode until newly designed RF fingers are installed.



	7/8 + 1	Uniform	32*12	28*12+1	62 bunch	16 bunch	16 bunch	4 bunch
First time	25/08/2020	24/11/2020	24/11/2020	04/05/2021	13/07/2021	10/03/2021	03/05/2022	11/05/2021
I_{max} (mA)	196+4 * (~~192+8~~)	200	150 * (~~200~~)	125+3* (~~200~~)	65*	35* (~~90~~)	65* (~~90~~)	20* (~~40~~)
Lifetime (hours)	> 22	> 25	> 22	> 23	~ 14	~ 8	~ 5	~ 5
ε_v (pm) *	10	10	20	20	20	20	20	20

Figure 2: Distribution of beam modes (nominal current in red, delivered current in black).

For time structure modes, the vertical emittance blow-up is fixed at 20 pm rad in order to keep a reasonable lifetime and maintain 1-hour top-up. All time-structured modes have been delivered with a purity of more than 10^{-9} between the filled and empty buckets with a cleaning process applied in the booster and occasionally in the SR.

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 2 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 during commissioning, failure of the RF master source and a damaged 20 kV high voltage cable). Two problems of copper deposits in the SR cooling system were observed during the first half of 2021. The copper clogging in the orifice of the magnet flow meters has now been drastically reduced by regular checks of the flowmeters and by improving the absolute filtration in all cells. The copper deposits in the needle valve of the absorbers is temporary solved by increasing the flow rate. Additional actions are in progress to solve both issues.

One of the most complex hardware to set up for operation was the magnet power supply (PS) system for which we moved from shared 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, which are now solved. The hot-swap function, which should even increase the reliability, has been successfully tested and should be gradually put in operation.

The 13 HOM-damped single-cell cavities fed by klystrons and solid state amplifiers (SSA) have proved extremely reliable and were easy to condition to the nominal voltage and beam current [18]. Nevertheless, during the last run of 2021, an air leak occurred on cavity 7 coupler. The coupler was first varnished and then exchanged. An air leak appeared again on this new coupler after only a few days of operation. It was varnished and the cavity put in a passive mode after a sizeable modification of the waveguide network, the first ten cavities sharing the same klystron. To prevent this type of intervention and down time, it is planned to feed each cavity with its own SSA in the upcoming years. The coupler was exchanged during winter shutdown and reconditioned during the restart. No more problems occurred since and the investigation of the ceramic did not show defects. The statistics for the two runs of 2022 are excellent with a drastic reduction of the number of failures and without long interruptions.

From January 2021 to May 2022, over the 6627 refills, only 187 were skipped (2.8%). This good result should be mitigated by the fact that with 1 hour toping up frequency, the operator is able to follow the refills and intervene on the fly to solve problems.

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Table 2: Machine Statistics (until May 2022)

	2018	*2020*	2021	2022
Availability (%)	*98.5*	*96.1*	96.4	99.5
Mean time between failures (hrs)	*104.3*	*46.0*	66.4	137.2
Mean duration of a failure (hrs)	*1.60*	*1.80*	2.42	0.63

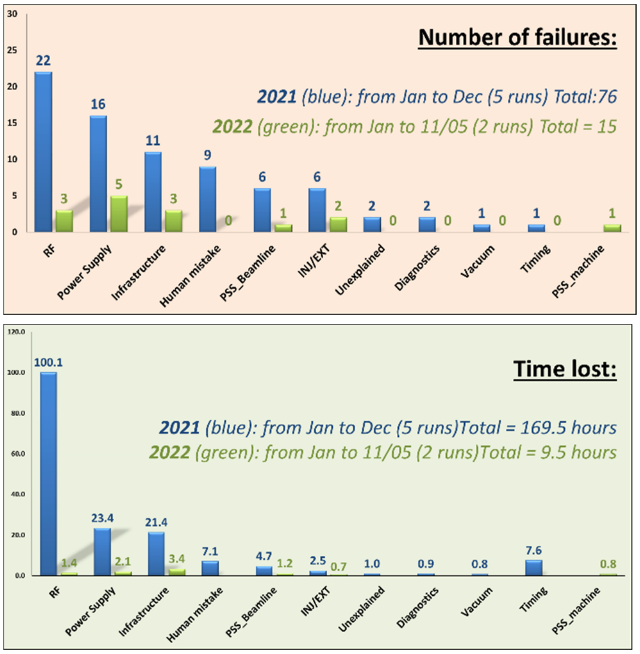

Figure 3: Distribution of failures in number and time.

OPERATION-RELATED DEVELOPMENT

The priority of the first year of operation was to consolidate the operation of the new SR. Along sizeable machine time devoted to the understanding of equipment behaviour and to correct malfunctioning, a dense development programme of insertion devices for the upgraded beamlines is taking place [19]. The accelerator division has also progressed with new projects in order to continue to improve the availability, stability and brilliance of the source.

New Ceramic Chambers

Since the start-up of EBS, the ceramic chambers of the kickers and shakers turned out to be weak points, leading to drastically limit the current in timing modes. A programme to re-design and manufacture new chambers with different production techniques is ongoing. New chambers should be available in 2023. Retrieving reliable and full performance in time structure is a priority for operation.

Solid-State Amplifiers (SSA)

Presently, the first 10 RF cavities are fed by a single klystron transmitter [18], with a spare ready to take over. Due to the obsolescence of klystrons and in order to improve the redundancy and flexibility to repair, these will be replaced by 10 SSA. The amplifiers are already in production and will be progressively put in operation until 2026.

4^{Th} Harmonic Cavities

4th harmonic RF system is being designed to lengthen bunches (up to a factor 3) in timing modes, with the goal of increasing the lifetime and maintain the top-up injection frequency at 1 hour. It will consequently minimize the radiation losses onto the insertion devices and the total injected charge, which is a strong regulation limitation. Bunch lengthening will also contribute to the brilliance increase allowing an operation without the large vertical blow-up for the same lifetime. In addition it will help in avoiding microwave instabilities, reducing the heat-load and stress of critical chambers and improve injection efficiency. The design of an active damped copper cavity is progressing well. Depending of the project priority, the system could be in operation in 2026.

Injector Upgrade

Further reducing the injection perturbation is important for the nano-focussing beamlines. In parallel to the development of the damping system, new injection schemes are under evaluation. A solution based on non-linear kickers looks promising [20]. The present injector underwent a series of upgrades during the last decade [2]. Depending of the injection scheme, a larger upgrade is envisaged and different solutions are being studied [21]. Among them, a new booster lattice using the same configuration with more quadrupole families is under study and could be implemented without large modifications. By reducing the horizontal emittance from 83 to 54 nm, it is expected to improve the injection efficiency, presently at about 70%. Spare magnets and vacuum chambers are also needed to ensure a long-term reliable operation.

Mini-Beta Optics

High-energy (i.e. high-undulator harmonics) experiments could benefit from an improved brilliance achieved with low-gap short undulators installed in the middle of a straight section, associated to reduced beta functions. This project still requires more beam dynamics study and a test bench will be installed in ID31 for this purpose.

CONCLUSION

After one and a half year of dismantling, installation and commissioning, the ESRF is back to normal and reliable operation with a largely increased brilliance. Despite the impact of the Covid-19 pandemic, users recovered the beam on the scheduled day and with remarkable performances. Since then, the operation was stabilized with downtime and machine availability similar to those of the old source. Time structure operation and the reduction of injection perturbation are the main remaining issues. Several projects are also ongoing to further push the performance.

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