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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. Since then beam is back for the users at full operation performance and with an excellent reliability. 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, 2, 3], has been delivering 5500 hours of beam time per year on up to 42 beam-lines. 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) [4] 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 [5, 6, 7, 8]. Reducing the horizontal emittance from 4 nm rad down to 133 pm rad (see 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	23
Emittance H	*pm rad*	4000	133
Emittance V	*pm rad*	4	10*

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

Started in 2015, the project was conducted in four years with one year downtime for installation. The beam has been back for the users since August 2020 at full operation with an excellent reliability [9, 10, 11, 12, 13, 14, 15]. The renewal of the infrastructure and the construction of the new storage ring was also the occasion to decrease significantly the energy consumption [16].

USER-MODE OPERATION

2022 was the first year with a standard operation schedule since the beginning of EBS, i.e. no longer dependent upon the COVID context (see Fig. 1).

Figure 1: Delivery in April 2023.

Beam Stability

The beam stability today fulfils the beamline requirement. Associated to the slow orbit correction, a fast orbit feed-back 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. Perturbation during top-up injections are disturbing and even preventing some beamlines from acquiring data during these periods. Off-axis injection similar to the one of the old machine has been implemented for EBS. For the septum, a feedforward compensation is very effective, correcting most of the orbit distortion. 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 [17, 18]. Associated to the transverse damping system, it drastically improves beam motion and blow-up. A longitudinal compensation has been also implemented to compensate the synchrotron oscillations inducing path lengthening. Even if the compensations are effective, they still require at least a factor two in the reduction to make the top-up acceptable for the most demanding beamlines. An emittance measurement, synchronized with injection, indicates an increase from 125 to 250 pm rad in the horizontal plane and up to 15 pm rad in the vertical plane. Even with the top-up frequency reduced to one every hour in order to limit disturbance to the beamlines, this problem is a limitation for the full exploitation of EBS.

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RELIABILITY AND STATISTICS

Two years after the commissioning, efforts have been made to continuously improve the EBS reliability, which are reflected in the mean time between Failures of 88.5 hours. The mean duration of a failure decreased also by nearly a factor three leading to an excellent accelerator availability of 99.06 % (see Table 2 and Fig. 2).

The longest failure of 2022 led to the understanding of the damage to the coupler of one of the RF cavities, forcing a time-consuming replacement of this device on two occasions in 2021. This failure was thoroughly analysed and it was discovered that a series of RF interlock thresholds were wrongly set and did not stop the cavity power when voltage breakdowns occurred. After adjustments, no more of these RF failures occurred.

As far as repetitive failures are concerned, we faced four mysterious failures, which occurred at the same time during consecutive evenings, with disturbance to the electrical mains on the 20 kV line. Investigation revealed that this was due to a change in voltage and frequency in the signal sent by the electricity provider to trigger a change in the price of electricity. This unusual signal distortion was interpreted by our protection system as a voltage frequency drift, which stopped several EBS and infrastructure subsystems, causing the beam trips. The electricity provider restored the original signal and the issue disappeared.

Table 2: Machine Statistics

	2018	*2020*	**2021**	**2022**
Availability (%)	98.5	96.1	96.4	99.1
Mean time between failures (hrs)	104.3	46.0	66.4	88.5
Mean duration of a failure (hrs)	1.60	1.80	2.42	0.83

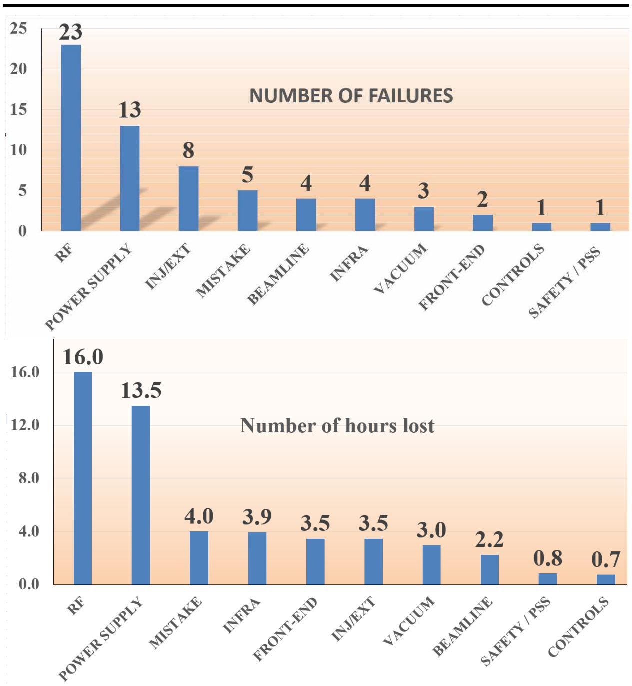

Figure 2: Distribution of failures in number and time.

OPERATION-RELATED DEVELOPMENT

Besides the efforts to increase the reliability, developments were made to improve the beam quality and performance: perturbations at injection, power supply hot swap system, in-vacuum cryogenic undulators. Reducing by 0.5 MV the RF working points without changing delivery performance made significant reductions in the electricity consumption [16].

Solid-State Amplifiers (SSA)

Today 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 as of next year until 2026.

4th Harmonic Cavities

The 4th harmonic RF system is being designed to lengthen bunches (up to a factor 2.5) in timing modes, with the goal of increasing the lifetime. Bunch lengthening will also contribute to the brilliance increase allowing an operation without the large vertical blow-up, increase microwave instabilities threshold, reduce the heat-load and stress of critical chambers [12]. The design of an active damped copper cavity is progressing well (operation in 2026).

Injection Upgrade

New injection scheme projects, to further reducing injection perturbations have been launched. First the septum will be moved closer to the stored beam in order to reduce the injection bump amplitude. This modification should provide the factor 2 required by beam lines by mid-2024. Another solution based on a fast injection kicker added downstream the existing injection acting on a single bunch should also reduce injection oscillations by factor 2. A prototype, developed in collaboration with SLS will be tested in March 2024 at ESRF. Finally, a non-linear kicker, providing full transparency is under design [20].

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 [21]. This project still requires more beam dynamics study and a test bench is already installed in ID31 for this purpose. Machine physics studies will start in the coming months.

FILLING MODES REVIEW

Overview

Timing modes optimised to the beamline needs have always been delivered at the ESRF, with a slight evolution of the distribution [2].Preserving timing mode was a strong requirement in the EBS specifications. Today, timing modes fully benefit from EBS design, lifetime is even better than proposed (see Figure 3 and 4), highlighting the ESRF potential.

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All timing modes are delivered with a purity better than 10^{-9} with cleaning in the booster. However, due to the mechanical weakness of the kicker ceramic chambers, the current is deliberately limited in 16 bunch mode [13]. New chambers in production should be available in 2024

	7/8 + 1	Uniform	28*12+1 (Hybrid)	16 bunch	4 bunch
I_{max} (mA)	192+8	200	192 + 8	75	40
Lifetime (h)	> 20	~ 25	> 16	~ 5.5	~ 5
ε_v (pm)	10	10	20	20	40
Reached	13/09/22	21/11/20	14/11/22	23/08/22	05/12/22

Figure 3: Beam parameters as a function of beam modes.

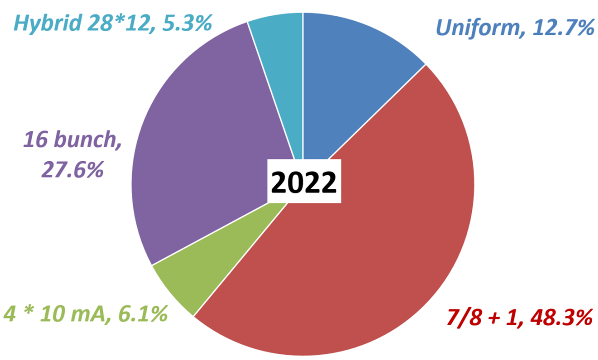

Figure 4: Filling pattern distribution.

High Current per Bunch Regime

Beam parameters are affected by high current per bunch [22, 23, 24]. Lifetime is lower due to Touschek effect, partially compensated by an increased vertical emittance in all modes (1 pm rad after correction, but no request from the beamlines to go below 10 pm rad). The energy spread is increased above the microwave instability threshold (2 mA per bunch). It broadens the undulator spectrum on high harmonics and increases the horizontal source size for bending magnet sources via the dispersion (40% increase in beam size at 10 mA, no dispersion for ID source). Increased horizontal emittance is also due to intra-beam scattering.

Beam instabilities induced by the vacuum chamber impedance forces an increase in the chromaticity, consequently reducing the lifetime. Multibunch feedbacks are available to stabilize beam instabilities but are less efficient. Bunch lengthening with increased current has on the contrary a positive effect on lifetime and the instability threshold. With high current per bunch we are also experimenting a strong decrease in the efficiency.

The risk of failures due to power deposit in the components with high or defective impedance (kickers, stripline connectors, RF fingers, In-vacuum undulators..) requires a careful follow up temperature and vacuum of the machine.

Multibunch Filling Mode Evolution

7/8+1 is the standard mode (introduced in 2007 with 2 mA in the single), delivered for a long time with 4mA and later with 8 mA (also for EBS, see Fig. 5). Uniform was prone to beam-ion instabilities requiring the mutibunch feedback, but EBS is less sensitive.

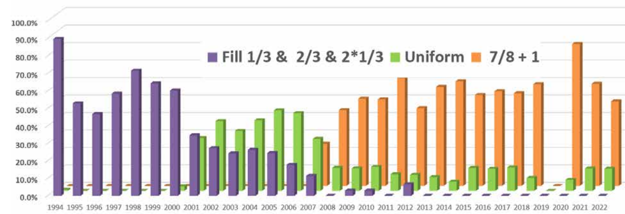

Figure 5: Multibunch filling mode 1994-2022

Hybrid Filling Mode Evolution

Hybrid 24*8 +1 at 200 mA was introduced in 2004 to replace the 1/3+1 (see Fig. 6). It is the most severe mode in terms of beam-induced heating by the vacuum chamber impedances. A 28*12 +1 alternative, less demanding in term of deposit power is being delivered with EBS until new kicker ceramic chambers are installed.

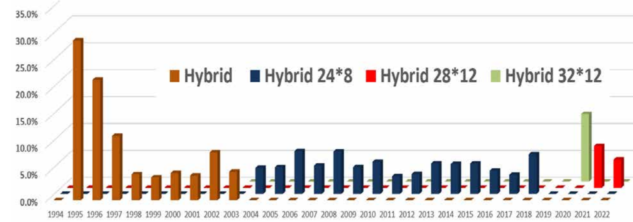

Figure 6: Hybrid filling mode 1994-2022

(Multi) Single Bunch Filling Mode Evolution

16 Bunch mode has always been delivered (see Fig. 7). For EBS the current is presently limited to 75 mA (instead of 90 mA) by the kicker chambers. However, issues with damaged RF fingers experienced with a cryo-in-vacuum undulator in 16 bunch impose further scrutiny. For EBS, 4 Bunch is delivered at nominal current (40 mA). Single bunch mode has not been delivered since 2003, although 20 mA was stored in EBS for test during machine time.

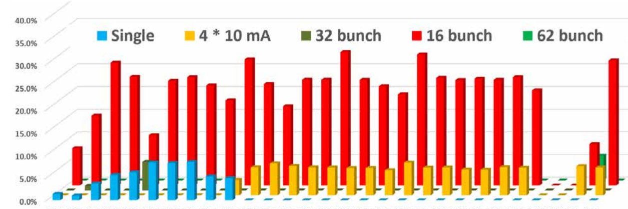

Figure 7: (multi) single filling mode 1994-2022

CONCLUSION

Three years after the commissioning of EBS, despite the impact of the Covid-19 pandemic, the ESRF confirmed a reliable operation with a largely increased brilliance. The operation was stabilized with downtime and machine availability similar to those of the old source. Replacing the kicker ceramic chambers and improving the injection perturbation are the main remaining issues. Several projects are also ongoing to further push the performance.

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