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OVERVIEW OF 4-YEAR OPERATION OF THE ESRF-EBS AND THE STRATEGY OF UPGRADES

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Abstract

The user operation of the Extremely Brilliant Source (EBS) marked the beginning of a new era for high-energy, 4th generation synchrotron light sources with its restart on 25 August 2020. Over the subsequent four and a half years, the EBS storage ring has consistently delivered user operations with high availability, reliability, and stability. Continuous performance enhancements have been achieved by reducing injection perturbations, increasing bunch and beam currents across various delivery modes, and reinforcing storage ring operation through the implementation of a hot-swap power supply system. Sustainability has remained a central focus in both the current operation and future upgrades of EBS. Energy-saving measures have been implemented in the RF system and high-quality power supply (HQPS) operation. Looking ahead, projects such as the deployment of solid-state RF amplifiers and a 4th harmonic RF system aim to further improve operational sustainability. Additionally, injector upgrades are under consideration, including the development of a novel linac capable of higher injection energy, which could eventually support full-energy injection into the storage ring as part of the long-term plan for the EBS accelerator complex.

INTRODUCTION

Located in Grenoble, France, the European Synchrotron Radiation Facility (ESRF) has operated since 1994 as the first high-energy, 3rd generation synchrotron radiation light source, delivering X-ray beam time to users for an average of 5,500 scheduled hours per year [1]. The accelerator complex comprises a 200 MeV linear accelerator (linac), a 4 Hz booster synchrotron, and a 6 GeV storage ring (SR) with a circumference of 844 meters.

Following two upgrade phases—particularly the second phase conducted between 2015 and 2020—the ESRF launched the EBS, entering a new era with the start of User Service Mode (USM) on 25 August 2020, after a dark time of one year for dismounting and installation, followed by 6 months of machine and beamline commissioning [2–7].

The EBS storage ring consists of 32 hybrid multi-bend achromat (HMBA) cells, which reduce the horizontal emittance from 4 nm·rad to 133 pm·rad (see Table 1), representing a major leap in brilliance and coherence by replacing the original double-bend achromat (DBA) lattice of the ESRF [8–11].

The storage ring of EBS accommodates more than 60 in-air, in-vacuum and CPMUs to provide photon beams to 40 beamlines along the 28 available straight sections to bring X-rays to 31 independent end-stations. Bending magnet sources, such as short bends and 2-pole or 3-pole wigglers, provide photons for an additional 17 beamlines.

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	*hr*	50	23
Emittance H	*pm·rad*	4000	133
Emittance V	*pm·rad*	4	10*

(*) Vertical emittance adjustable from 1 to 40 pm·rad

USM OPERATION AND MAIN ISSUES

In addition to the 7/8+1 multi-bunch mode, four other filling patterns are employed throughout the year: the uniform mode, 16-bunch and 4-bunch timing modes, and a hybrid mode (28×12+1). These five modes collectively define the annual beam time distribution. To ensure reliable machine performance and facilitate infrastructure upgrades, five scheduled shutdown periods per year are allocated for routine maintenance, insertion device (ID) installation, vacuum interventions, and hardware replacement or installation. Additionally, one Machine Dedicated Time (MDT) day per week during USM operation allows for switching between filling modes, resolving minor faults, tuning the injection system or storage ring, and addressing any unforeseen issues that may arise [12].

Since the start of USM operation, accelerator activities and development programs have prioritized ensuring high reliability, availability, stability, and sustainability of the accelerator complex, along with continuous improvement in beam delivery and machine performance—core objectives of the accelerator team. Beyond these operational goals, user demands for higher brilliance and coherence continue to drive technological innovation, paving the way for enhanced photon sources and laying the foundation for future facility upgrades.

Reaching the Nominal Beam Currents

Throughout USM operation, beam performance has been continuously enhanced during MDTs by optimizing

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beam optics and orbits, lifetime and injection efficiency, etc. Due to the excessive heating issue in the original ceramic chambers of the injection kicker magnets, the 40 mA of the 4-bunch mode were realized after re-coating the inner surface of the 4 kicker chambers and re-installation on the storage ring in late 2022. The final new designed ceramic chamber was installed in the K4 kicker during the 2024 winter shutdown, enabling successful testing of 90 mA in the 16-bunch mode at the beginning of 2025. The peak temperature of the upgraded kicker chamber reached 65°C – well below the anticipated limit. In March 2025, users received beam in the 16-bunch mode at 90 mA for the first time, marking the achievement of nominal beam currents across all operational modes for delivery.

The operational beam currents, lifetimes, and the corresponding vertical emittances for the all filling modes delivered during USM operation are summarized in Table 2.

Table 2: Operational Beam Currents and Relevant Specifications of EBS Storage Ring

	Uniform	7/8+1	28x12+1	16-bunch	4-bunch
I (mA)	200	192+8	192+8	90	40
Lifetime (hrs)	~29	~25	~19	~6	~5.5
Ver. emit.(pm)	10	10	20	40	40

Injection Perturbation Reduction

Since the EBS project primarily upgraded the ESRF storage ring while retaining the conventional 4-kicker injection scheme from the previous machine, the perturbations caused by the injection kickers during beam top-up have become a significant issue. This is especially critical given that the horizontal emittance has been reduced by about a factor of 40 compared to the previous ESRF storage ring. The emittance increase caused by these perturbations can be as much as 2 to 3 times the nominal value, corresponding to a 40–70% increase in beam size in both directions, which seriously impacts some user experiments. To address this, continuous efforts have been made, including the adoption of kicker power supplies with lower rise times, reducing the injection kicker bump amplitude, and repositioning the septum magnet S3 along with its adjacent section on the TL2 transport line in the injection region by 5 mm closer to the storage ring. Together, these measures have achieved a 20–50% reduction in the horizontal beam size at the injection point. Figure 1 shows the measured emittance during top-up in different filling modes, both before and after the S3 magnet was moved. The results clearly demonstrate a reduction in beam emittance during beam current top-up. However, in the 16-bunch mode, injection perturbations remain significant despite this improvement. Further improvement is expected by implementing nonlinear kickers, which now are in prototyping.

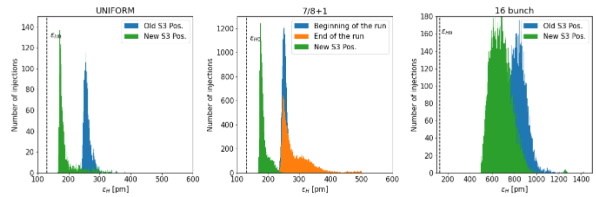

Figure 1: Horizontal emittance reduction in 3 filling modes before and after S3 movement. The nominal horizontal emittance of all the modes keeps 130 pm.

Hotswap System Secures Power Supply Operation

The implementation of the hotswap system for the main power supplies in the EBS storage ring was previously detailed in [13]. After several years of design, deployment, and installation, by June 2024 the hotswap system had been fully deployed to caver all DQs, quadrupoles, sextupoles and octupoles around the ring. In 2024 alone, the system successfully preserved the electron beam 23 times without any beam loss caused by the hotswap itself or any unintentional switching events. This successful deployment significantly enhanced the availability and reliability of the power supplies, contributing to the EBS operation.

Main Hardware Issues in the Past Years

RF cavity breakdowns and failures of transmitters and couplers have accounted for most of the RF-related issues in recent years. In the first year of USM (2021), coupler leakage – particularly in cavity #7 – resulted in significant downtime, requiring extensive efforts to replace the coupler, restore functionality, and recondition the cavity. In the following years, RF-related downtime steadily decreased, thanks to careful maintenance and the implementation of the Electricity Consumption Optimization (ECO) mode, allowing two RF cavities to remain on standby.

In Nov. 2023, a major water leak occurred during USM operation due to the rupture of a copper water-cooling tube in the S3 septum. The incident required 78 hours for replacement, reinstallation, and vacuum conditioning, leading to a direct reduction in annual availability by ~1.4%. To mitigate the impact on users, additional beam time was arranged by reorganizing MDTs before the end of the year, resulting the availability for 2023 restored to 99.28%.

In the spring of 2024, the ageing 35-year-old ESRF linac experienced serious failures, including issues with the thyratron, conductors, control panels within the modulators of the RF units, and the water-cooling system. These failures triggered a refurbishment initiative targeting the linac's obsolete components. Additionally, in early Sept. 2024, a severe storm caused a 17-minute power outage by disabling one of the external substations. This event also revealed vulnerabilities in the High-Quality Power Supply (HQPS) system, particularly with the diesel generator. Systems that were shut down during the blackout were gradually restored within 13 hrs after grid power returned. These two major incidents significantly reduced beam availability for 2024. Table 3 summarizes the operational statistics for EBS over the 4 years since the start of USM.

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In addition to the beam failures, 2024 also marked a new milestone for the EBS, with a record-setting continuous beam delivery of 22.9 days in USM operation – without any beam losses, apart from scheduled MDT interruptions.

Table 3: Statistics of the USM Operation of EBS

	2021	2022	2023	2024
Availability (%)	96.4	99.1	99.3	97.9
MTBF (hrs)	66.4	88.5	107.1	76.2
MDF (hrs)	2.42	0.83	0.77	1.59
No. of failures	74	64	56	76

Sustainability in USM Operation

Since Oct 2022, the ECO mode has been implemented to reduce power consumption through two key measures: lowering the RF voltage from 6 MV to 5.5 MV by switching 2 of the 13 RF cavities in the storage ring to standby, and reducing the number of active HQPS units from 14 to 12 to conserve energy and maintain a reserve of spare units. These measures result in an estimated energy saving of around 1.6 GWh/year, while preserving beam lifetime – an outcome consistent with simulation predictions. Figure 2 shows a typical schematic of the RF system in ECO mode during USM operation. Additional strategies for further power reduction are currently under investigation.

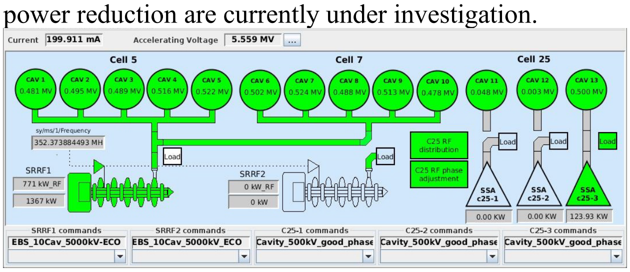

Figure 2: RF system in the operation of the ECO mode.

STRATEGY OF FUTURE UPGRADE

In parallel with the consolidation of machine operation, future upgrade efforts are focused on several key areas: achieving transparent injection with no perturbation to beamlines, increase beam lifetime through adapting a 4th harmonic RF system, developing new sources to deliver higher brilliance and coherence, and upgrading the injector to ensure compatibility of future upgrade of storage ring.

Machine Performance Improvement

Transparent injection, aiming for 100% injection efficiency and zero perturbation, requires a reduction in the booster emittance and the implementation of non-linear kickers as the injection scheme. Design studies and prototyping of the non-linear kicker are currently underway, with the project targeted for completion by the end of 2028.

The active 4th harmonic RF system, previously delayed by one year due to the economic crisis, has now been relaunched in collaboration with SOLEIL, where a similar project is underway. This RF system aims to increase the beam lifetime by a factor of 2 to 3 across all EBS beam delivery modes. As a result, the top-up injection frequency for multi-bunch modes can be significantly reduced, and the vertical emittance in timing modes is expected to decrease to 10 pm – matching that of the multi-bunch modes.

The injector upgrade program comprising the refurbishment of the existing linac, a light upgrade of the booster, and the development of a new linac test facility (COLD: C-band Operational Linac Demo) – has been launched to enhance future machine performance and support the potential adoption of a new storage ring as part of ESRF's long-term plan. The linac refurbishment will reinforce current operations, enabling to have the potential for further improvement with C-band accelerating structures. The booster light upgrade is expected to reduce beam emittance by approximately 30% [14], thereby improving injection efficiency into the storage ring and releasing 18 quadrupoles from the booster for use as spare components.

New Linac and New Source in the Future

Based on investigations and beam dynamics studies, the COLD project will adopt the so-called C³ technology, developed at SLAC for prospective future e^+e^- colliders, as the core accelerating structure. Further details are presented in a dedicated contribution to this conference [15].

New sources are under development, including a permanent magnet 3-pole wiggler designed for the specific requirements of beamline BM18, and undulators based on High Temperature Superconducting (HTS) materials.

CONCLUSION

All specifications of EBS have been met after four years of USM operation. Various measures have been implemented to enhance beam performance and consolidate operations, including improvements to the injection, the introduction of a hot-swap system for power supplies in storage ring, as well as beam optics optimization and stability studies. These efforts have collectively improved the machine performance, aiming for high availability, reliability, stability, and sustainability. As part of the ESRF long-term plan, a future upgrade of EBS is currently under study. The most promising option is the addition of a full-energy linac, which would be compatible with a subsequent upgrade to a lower-emittance storage ring, ensuring that EBS remains advanced and competitive for the next 10 to 20 years.

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