OPERATION AND DEVELOPMENTS AT THE ESRF-EBS LIGHT SOURCE

J. L. Revol, K. Andre, C. Benabderrahmane, O. Benezech, P. Borowiec, L. Bortot, N. Carmignani, L. Carver, A. D'Elia, M.Dubrulle, F. Ewald, P Falaise, L. Hardy, G. Le Bec, B. Joly, I Leconte, S. M. Liuzzo, M. Morati, M. Penot, T. Perron, Q. Qin, Z. Qiu, B. Roche, A. Sauret, K. B. Scheidt, V. Serrière, R. Versteegen, J Wade, S. White,
European Synchrotron Radiation Facility, Grenoble, France

Abstract

The European Synchrotron Radiation Facility – Extremely Brilliant Source (ESRF-EBS) represents a major upgrade that enables the scientific community to benefit from the first high-energy fourth-generation storage-ring light source. In December 2018, following three decades of operation, user activities were suspended for a 12-month shutdown to allow the installation of a completely new storage ring. On 25 August 2020, the user program resumed with beam parameters close to nominal values. Since then, the facility has returned to full operational performance, demonstrating excellent reliability.

This paper presents the operational performance of the source over the past year, with particular emphasis on ongoing and planned developments. Current projects aimed at upgrading the injector are also described, including the proposal of a full-energy linear accelerator.

INTRODUCTION

The European Synchrotron Radiation Facility (ESRF), located in Grenoble, France, is a research infrastructure supported by a consortium of 19 partner countries. Since the start of user operation in 1994 [1-3], the facility has provided approximately 5,500 hours of beam time annually from up to 49 beamlines. The accelerator complex comprises a 200 MeV linear accelerator (linac), a 4 Hz full-energy booster synchrotron, and a 6 GeV storage ring (SR) with a circumference of 844 m. The ESRF upgrade programme (2015–2022) involved the design and installation of a new storage ring based on a hybrid multi-bend achromat (HMBA) lattice, replacing the former double-bend achromat configuration [4-9]. This upgrade reduced the horizontal emittance from 4 nm.rad to 133 pm.rad (see Table 1), resulting in a dramatic increase in beam brilliance and transverse coherence.

A wide range of insertion devices —including in-air, in-vacuum, and cryogenic in-vacuum undulators, and wigglers [10] —are installed along the 28 available straight sections (33 beamlines). In addition, radiation from bending magnets, now generated by short bending-magnets and wigglers, serves 16 beamlines.

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 [11-13]. The renewal of the infrastructure and the construction of the new storage ring provided the opportunity to significantly reduce the energy consumption [14].

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

The reliability of the new accelerator complex is comparable to that of the previous machine in 2018 (see Table 2). In 2025, a total of 5431 hours of beam were delivered to users out of 5489 hours initially scheduled, corresponding to an availability of 98.95% (Fig. 1). Notably, the operational period included eleven one-week intervals without any recorded failures.

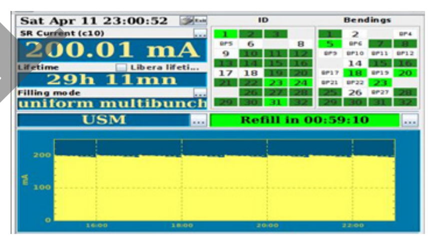

Figure 1: Delivery in April 2026.

Two significant events occurred in 2025. In February, one of the two dipole power supplies of the ramped injector power supply of the booster magnets was damaged and subsequently replaced with a spare unit. During the intervention, the impact on users remained minimal, as the beam current decayed smoothly over a period of 30 hours without any failures. The repair of the H-bridge cabinet took five months before full operational status was restored. On 3 September, a power outage led to an abrupt shutdown of most of the machine's equipment, with full restoration achieved after 12 hours. The root cause was identified as an animal coming into contact with the high-voltage capacitor bank of the high quality power supply system. This rare event has occurred twice in 33 years.

In addition to these events, six beam interruptions were attributed to blocked water flowmeters. These failures were caused by a sudden drop in the pH of the deionised water, leading to the formation of copper oxides that obstructed several needle valves. Following improvements in pH monitoring and regulation, no further incidents of this type were observed. During the last winter shutdown, the Sextupole and Octupole hot-swap modules were installed, completing the quadrupoles and dipole-quadrupole units already in service. The hot-swap system is now fully operational, improving both reliability and maintenance. Moreover, reliability enhancements resulted in zero time loss attributable to the linac system.

Table 2: Machine Statistics

	2018	*2023*	**2024**	**2025**
Availability (%)	98.5	97.9	97.9	99.0
Mean time between failures (h)	104.3	105.6	76.2	133.9
Mean duration of a failure (h)	1.6	2.3	1.6	1.4
Skipped refills (%)		1.2	2.1	2.4

As in previous years, five different modes were delivered in 2025: 7/8 + 1, uniform, 16-bunch, 4-bunch, and hybrid 28x12+1 modes in top-up (every 1 hour). Following the installation and validation of the new ceramic kicker chambers beginning of 2025, the 16-bunch mode was delivered this year at nominal current (90 mA), with a lifetime maintained at 4.5 hours at 20 pm.rad vertical emittance.

STORAGE RING DEVELOPMENT

Besides the efforts to increase the reliability, developments of the source are ongoing to improve the beam quality and performance.

Solid-State Amplifiers (SSA)

At present, 10 RF cavities are powered by a single klystron transmitter [15], with a spare unit available for redundancy, while three additional cavities are each driven by individual solid-state amplifiers (SSAs). Due to the obsolescence of klystron technology, and in order to improve system redundancy and maintenance flexibility, the klystron transmitters will be replaced by ten SSAs. The amplifiers are currently under procurement and, despite some delays, are expected to be delivered and progressively commissioned in the coming years.

4th Harmonic Cavities

An active fourth-harmonic RF system operating at 1.41 GHz (4HC) is being developed to lengthen the bunches by a factor of 2 to 3 [16]. This bunch lengthening mitigates intra-beam scattering and Touschek-induced beam losses, which are particularly critical in low-emittance, high bunch-current timing modes. The implementation of the 4HC system is expected to increase the beam lifetime in 16-bunch mode from approximately 4.5 hours, at a beam current of 90 mA with the present 20 pm.rad vertical emittance delivery, in accordance with to the bunch lengthening. It will contribute to an increase in brilliance, enabling operation at the nominal 10 pm.rad, with a reduced blow-up. Furthermore, the higher microwave instability threshold, together with the reduction of heat load and mechanical stress on critical vacuum components [17], will provide a more favourable experimental environment for time-resolved and photon-sensitive beamlines. The design and procurement of the damped copper cavity and the SSAs are currently in progress, with testing and commissioning planned for 2028.

Photon source

The ESRF is pursuing the development of advanced X-ray source technologies to extend the spectral range, improve brilliance, and provide enhanced control of polarization [10]. Preliminary tests of lower gap in-vacuum IDs (4 mm) showed promising results for beamlines. NEG-coated ID chambers with a reduced inner aperture (6 mm) were also tested. High temperature superconducting undulators are under study, a winding machine being in construction[18]. Control system modernization, including synchronization and integration with beamline mono-chromators, is also ongoing and will provide a major improvement.

INJECTOR UPGRADE

During the first phase of the upgrade, the injector was enhanced to ensure reliable and efficient operation in top-up mode, which has been in use since 2016. The RF klystron transmitter was replaced with SSAs, and two additional five-cell cavities were installed to provide redundancy. The 10 Hz resonant magnet power supplies were upgraded to a 4 Hz ramped system. For the linac, a new thermionic gun was installed, a spare modulator was implemented, and an additional buncher was procured. New beam position monitor electronics were also installed in the booster. For the ESRF-EBS upgrade, the existing booster injector was retained for reasons of cost, planning constraints, and risk mitigation, with only a realignment performed to match the new RF frequency, with off-energy operation. In particular, the four-kicker bump injection scheme into the storage ring was preserved. Due to the significant reduction in beam size of the upgraded machine, residual injection perturbations have become much more noticeable than previously. As a mitigation, the top-up injection frequency was reduced from 20 minutes to 1 hour, allowing the most sensitive beamlines to acquire data with minimal disturbance. An injection efficiency of up to 80% can be achieved under optimal conditions; however, in user service mode the value is typically around 65%. The limitation is mainly due to the booster lattice, which produces a beam with relatively large emittance and long bunch length. During the last few years, the injector system has experienced reliability issues, including septum failures, several magnet water leaks and extended failures of both the linac and the ramped booster power supplies. Upgrades of the injector are currently underway to improve performance and reliability, as well as to prepare for future developments of the storage ring.

Injection Upgrade

Despite improvements in the kicker power supply systems, the use of compensation techniques and the displacement of the septum closer to the stored beam to reduce the injection bump amplitude, the current four-kicker bump injection continues to disturb the stored beam during top-up [19, 20]. Design studies have shown that the non-linear kicker (NLK) injection scheme would provide full transparency while maintaining injection efficiency [21]. The storage ring injection cell and transfer line optics and layout will be modified to integrate such NLK. A prototype non-linear kicker and ceramic chamber was manufactured and delivered for experimental validation in the storage ring in the summer of 2026 [22]. Under study, the deployment of fast stripline kickers could further improve the transparency [23]. Both projects are paving the way for continuous top-up with negligible disturbance. This evolution will be essential for exploiting the ultra-low emittance of ESRF-EBS and its successors. This project will also enable the low-gap IDs to be installed in the storage ring for higher brilliance.

Booster Upgrade

The project consists of replacing 18 quadrupole magnets—namely, the first and last three quadrupoles in each of the six booster arcs—with newly designed magnets providing different gradients at identical current [24, 25]. This modification introduces three additional quadrupole families, increasing the total number from two to five and significantly enhancing the flexibility of optics tuning. All magnets will remain powered by the existing ramped power supplies. The revised lattice is expected to reduce the equilibrium horizontal emittance from 85 nm.rad to 59 nm.rad and the bunch length from 22.6 mm to 19.9 mm. These improvements in phase-space characteristics, increasing beam brightness at injection, should enhance the storage ring injection efficiency by approximately 10%. The replacement of the 18 quadrupoles will substantially increase the stock of spares (currently two), thereby reducing the risk of down-time due to the aging magnets. Mass production of the new magnets is scheduled for completion by mid-2027, followed by installation and commissioning in 2028. Particular attention is given to the vacuum system, as existing chambers are fragile, scarce, and associated with long procurement times. To secure the intervention, additional spares will be ensured by replacing, in 2026, the dipole-chambers in the transfer line from booster to SR with standard stainless steel chambers. Overall, the booster light upgrade constitutes a cost-effective and low-risk approach to improving beam quality and reinforcing injector reliability.

Linac Refurbishment

Failures encountered during user operation in 2024 with the S-band linac have highlighted the urgent need to improve the reliability and maintainability of aging components based on obsolete technologies. To address these issues, an additional accelerating structure and a klystron RF modulator unit have been procured. After tests and conditioning, the new accelerating structure will serve as a spare for the existing operational units, thereby ensuring operational continuity in the event of failure. The new modulator has been installed as a hot spare to further enhance system availability. The refurbishment program also includes the modernization of auxiliary systems, notably the water-cooling infrastructure, focusing power supplies, grounding network, and the consolidation of diagnostics and control systems. In addition, a fallback operational scenario has been prepared, allowing injection into the booster at 100 MeV instead of 200 MeV in case of unavailability of the second section.

COLD Project

The ESRF long-term strategy includes the potential upgrade of the injector complex to a full-energy 6 GeV linac. Such a linac must be accommodated within the ESRF site, imposing a maximum footprint of approximately 145 m [26]. High-gradient accelerating structure technology, developed at SLAC, has been selected as the key enabling solution to achieve this level of compactness [27]. The use of a photoinjector is expected to provide a beam with a reduced six-dimensional phase space at extraction, while the implementation of an RF pulse compression scheme will contribute to a significant reduction in overall cost. In this context, the Cool Copper Operation Linac Demonstrator (COLD) project has been initiated at the ESRF [28]. Its objective is to develop a pre-injector linac and to validate all critical technologies required for a future high-gradient, cost-effective 6 GeV linac. COLD will be installed within the available space in the existing linac tunnel and modulator hall, originally foreseen for a positron injection option. The infrastructure is currently being adapted, including liquid nitrogen (LN_2) distribution and water-cooling systems. The beam safety authorization process is ongoing and is expected to be completed in due time. Budget is presently secured and additional human resources dedicated to the project are being hired. Importantly, the COLD project is fully compatible with ongoing ESRF user operation.

As a technology demonstrator, COLD represents a key step toward ensuring the medium- and long-term reliability and performance of the facility.

CONCLUSION

Five years after the commissioning of the Extremely Brilliant Source, the European Synchrotron Radiation Facility has demonstrated reliable operation with a significantly increased brilliance. Operational stability has been achieved, with downtime and machine availability comparable to those of the previous source. Several projects, fully integrated into the ESRF Long-Term Scientific Plan (LTSP), are currently underway to further enhance performance of the facility, paving the way for the future.

ACKNOWLEDGEMENTS

These achievements have been made possible by the sustained commitment of the Accelerator and Source Division staff, together with the support of the other ESRF divisions.

REFERENCES

[1] "ESRF Documentation", `https://www.esrf.fr/about/information-material`

[2] J.L. Revol *et al.*, "The ESRF from 1988 to 2018, 30 years of innovation and operation", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1400-1403. doi:10.18429/JACoW-IPAC2019-TUPGW009

[3] J.-L. Revol *et al.*, "ESRF Operation Status", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4088-4091. doi:10.18429/JACoW-IPAC2018-THPMF021

[4] "ESRF upgrade programme phase II", ESRF, `https://www.esrf.fr/about/upgrade`

[5] P. Raimondi *et al.*, The extremely brilliant source storage ring of the European Synchrotron Radiation Facility, Commun. Phys. 6, p. 82, 2023. doi:10.1038/s42005-023-01195-z

[6] L. Farvacque *et al.*, "A Low-Emittance Lattice for the ESRF", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOPEA008, pp. 79-81

[7] J.-L. Revol *et al.*, "Status of the ESRF-Extremely Brilliant Source Project", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2882-2885. doi:10.18429/JACoW-IPAC2018-THXGBD3

[8] P. Raimondi *et al.*, "Commissioning of the hybrid multibend achromat lattice at the European Synchrotron Radiation Facili-ty", Phys. Rev. Accel. Beams, vol. 24, p. 110701, 2021, `https://doi.org/10.1103/PhysRevAccelBeams.24.110701`

[9] S. M. White *et al.*, "Commissioning and Restart of ESRF-EBS", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1-6. doi:10.18429/JACoW-IPAC2021-MOXA01

[10] G. Le Bec *et al.*, "In-vacuum and cryogenic permanent-magnet undulators at the ESRF", presented at the IPAC'26, Deauville, France, May 2026, paper THP2151, this conference

[11] J.-L. Revol *et al.*, "ESRF-EBS: Implementation, Performance and Restart of User Operation", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3929-3932. doi:10.18429/JACoW-IPAC2021-THPAB074

[12] J.-L. Revol *et al.*, "First Year of Operation of the ESRF-EBS Light Source", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1413-1416. doi:10.18429/JACoW-IPAC2022-TUPOMS009

[13] L. Hardy *et al.*, "Operation and developments at the ESRF-EBS light source", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1270-1273. doi:10.18429/JACoW-IPAC2024-TUPG25

[14] J.L. Revol *et al*, "Sustainability in storage ring based light sources", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3936-3939. doi:10.18429/JACoW-IPAC2023-THODB3

[15] J. Jacob, P. B. Borowiec, A. D'Elia, G. Gautier, and V. Serrière, "ESRF-EBS 352.37 MHz Radio Frequency System", in Proc. IPAC'21, Campinas, Brazil, May 2021, pp. 395-398. doi:10.18429/JACoW-IPAC2021-MOPAB108

[16] L Carver *et al.*, "Harmonic Cavity Simulations for the ESRF", presented at the IPAC'26, Deauville, France, May 2026, paper THP2026, this conference

[17] L. R. Carver *et al.*, "Beam based characterization of the European Synchrotron Radiation Facility Extremely Brilliant Source short range wakefield model", *Physical Review Accelerators and Beams*, vol. 26, no. 4, 2023. doi:10.1103/physrevaccelbeams.26.044402

[18] L. Bortot *et al.*, "Prototype Development and Testing of a Compact HTS Wiggler for Synchrotron Light Sources", presented at the IPAC'26, Deauville, France, May 2026, paper MOP7071, this conference

[19] S. White *et al.*, "Damping of injection perturbations at the European Synchrotron Radiation Facility," Physical Review Accelerators and Beams, vol. 22, no. 3, 2019. doi:10.1103/physrevaccelbeams.22.032803

[20] S. M. White *et al.*, "Commissioning of New Kicker Power Supplies to Improve Injection Perturbations at the ESRF", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2683-2685. doi:10.18429/JACoW-IPAC2022-THPOPT041

[21] A. Sauret *et al.*, "Design of a non-linear kicker injection scheme for the European Synchrotron Radiation Facility Extremely Brilliant Source", presented at the IPAC'26, Deauville, France, May 2026, paper THP2024, this conference

[22] A. Sauret *et al.*, "Development of a Non-Linear Kicker injection scheme for the ESRF-EBS storage ring", presented at the IPAC'26, Deauville, France, May 2026, paper THP2025, this conference

[23] T. Perron *et al.*, "Strip-Line based Kicker Design for The ESRF Storage Ring", presented at the IPAC'26, Deauville, France, May 2026, paper THP2145, this conference

[24] N. Carmignani *et al.*, "Light upgrade of the ESRF booster," in Proc. *IPAC'25*, Taipei, Tai-wan, May. 2025, pp. 730–732, isbn: 978-3-95450-248-6. doi:10.18429/JACoW-IPAC2025-MOPS051

[25] C Benabderrahmane *et al.*, "Magnets development for the ESRF-EBS injection upgrade", presented at the IPAC'26, Deauville, France, May 2026, paper MOP7058, this conference

[26] S. M. Liuzzo *et al.*, " Preliminary studies for a high gradient 6GeV injector linac for EBS," *in Proc. IPAC'25*, Taipei, Taiwan, May. 2025, pp. 1399–1402, isbn: 978-3-95-450248-6. doi: 10.18429/JACoW-IPAC2025-TUPM107

[27] E. A. Nanni et al., "Status and future plans for C3 R&D," Journal of Instrumentation, vol. 18, no. 09, P09040, Sep. 2023. doi: 10.1088/1748-0221/18/09/P09040.

[28] S. M. Liuzzo *et al.*, "The cool copper operation linac demonstrator project", presented at the IPAC'26, Deauville, France, May 2026, paper THP2023, this conference