

## THE ESRF FROM 1988 TO 2018, 30 YEARS OF INNOVATION AND OPERATION

J-L Revol, L Farvacque, L Hardy, P Raimondi (ESRF, Grenoble)

### Abstract

In 1988, eleven European countries joined forces to build the European Synchrotron Facility in Grenoble [France]. The ESRF was the first third-generation light source worldwide. After 30 years of innovation and user operation, the present storage ring was shut down to leave room for a new and brighter source. This paper describes the evolution of the facility from its origin to the Extremely Bright Source (EBS). Firstly, the operational aspects including reliability and beam modes are considered. This is followed by the presentation of the progress of lattice and the implementation of top-up. Finally, the development of the radio frequency and vacuum systems are discussed. To conclude, the lessons learned from 30 years operation are summarized, especially in view of EBS.

### HIGHLIGHTS

The ESRF is a European facility supported and shared by 22 partner nations. This third-generation light source, in routine operation since 1994 [1], delivers 5500 hours of beam per year to 42 beamlines with an availability close to 99 %. The accelerator complex consists of a 200 MeV linac, a 4 Hz full energy Booster synchrotron and a 6 GeV Storage Ring (SR) of 844 m circumference. The 32 cell Double Bend Achromat lattice of the SR provides 4 nm.rad horizontal emittance electron beam. After correction, the vertical emittance is reduced down to 4 pm.rad. A large variety of insertion devices (in-air undulators, wigglers, in-vacuum undulators, cryogenic in-vacuum undulators) are installed in the 28 available straight sections. Bending magnet radiation is used by 12 beamlines. Since 2009, the ESRF has embarked on an ambitious Upgrade Programme of the machine and beamline infrastructures. The second phase (2015-2022), called Extremely Brilliant Source (EBS), will see the implementation of a new storage ring based on a hybrid 7-bend achromat (HMBA), replacing the existing one [2,3]. Reducing the horizontal emittance to less than 140 pm.rad (Table 1) will allow a drastic increase in brilliance and coherence. The long shutdown for installation is ongoing. The old SR is now dismantled and all the new girders have been installed in the tunnel. Infrastructure and instrumentation are in the process of being installed. The beam commissioning will start in December this year. The facility should resume user operation in August 2020.

Table 1: Main Parameters of the Old and New SR

Energy	[GeV]	6.04	6
Circumference	[m]	844	844
Nominal current	[mA]	200	200
Horizontal emittance	[nm.rad]	4	0.130
Vertical emittance	[pm.rad]	4	4

### OPERATION STATISTICS

Until the end, the operation statistics were very good, without major impact induced by the EBS project. 2018 represented not only the last delivery with the present SR but also, an intense period for EBS preparation. Maintaining high machine availability and beam quality, while installing new equipment (like a new timing system) and developing tools in perspective of the new accelerator were challenging. This year of operation was indeed successful with 5430 hours of beam delivered out of the 5527 hours scheduled, giving an availability of 98.47%. The number of failures was significantly low, leading to a very good Mean Time Between Failures of 104 hours (Table 2). In August 2018, the longest interruption occurred which lasted 29 hours. This was caused by a water hose which was crushed between a vacuum vessel and a moving jaw of one permanent magnets insertion device. This resulted in a deformation of the vacuum chamber in the path of the beam. During the last 3 weeks of the year, the beam was delivered at a reduced intensity of 180 mA due to a vacuum leak in one of the RF cavities.

Table 2: Machine Statistics for the Last Years

	2016	2017	2018
Availability (%)	99.06	98.28	<b>98.47</b>
Mean time between failures (hrs)	93.8	64.7	<b>104.3</b>
Mean duration of a failure (hrs)	0.88	1.12	<b>1.6</b>

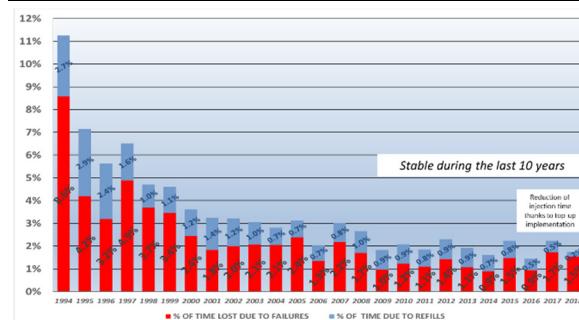


Figure 1: Evolution of the non-availability.

The beam availability for users was less than 88% at the start of ESRF in 1994 (9% for failures, 3% for injection). Thanks to an active program of maintenance, the accelerator reliability steadily increased during the first 10 years of operation with a downtime for failures reaching less than 2% (Fig. 1). With the implementation of the injection front-ends open, the beam remained available to the users during injection since 2003. With the implementation of top-up in 2016, the injection process was further improved, resulting in shorter time lost due to refill. This is illustrated in figure 1 with a constant increase of the user beam availability over the whole lifetime of the machine [4,5].

## FAILURES

Meantime between failures (Fig. 2) is the most important figure characteristic of a light source [6]. Each beam loss not only stops the experiments during the repair time, but drastically affects the stability due to heat load variation. Consequently, efforts have been made to avoid repetitive failures or those that could have been avoided by preventive maintenance. This expertise will benefit to EBS.

Initially the operation was largely disturbed by storms and mains disturbances. A High-Quality Power Supply system composed of 10 accumulator/alternator units coupled to diesel motors was installed in 1995. It resulted in a large increase in beam availability. The system, suffering from mechanical problems was replaced in 2008 by 14 units only involving rotating accumulators. Radio frequency has always been the equipment with the largest contribution to the machine down time. Large efforts have been made to reduce the number of frequent failures. For example, the continuous improvement of RF arc detection systems substantially reduced the false detections. The water cooling system required significant efforts in term of curative and preventive maintenance. The water leak to vacuum of a crotch absorber was a major accident in 2005 (2 cells vented, 5 days lost). The thin copper thickness of the cooling channel tube in the copper intercepting the X rays was eroded by a complicated chemical process. All crotches that had been preventively displaced by 2mm, were replaced with a new design (2006-2008). The control of the water chemical properties was also improved. Corrosion and pitting effect on various components were at the origin of numerous failures at that period. Flexible cooling pipes suffered also from radiation damage. Since 1995, a more resistant material has been used for new installation and repair. Nevertheless, between 2007 and 2016, a systematic refurbishment campaign took place. Dust pollution was significantly present in the cooling circuit. After a series of flowmeter blockage a  $1\mu\text{m}$  filtering system, was installed from 2015 to 2017 at the entrance of each cell.

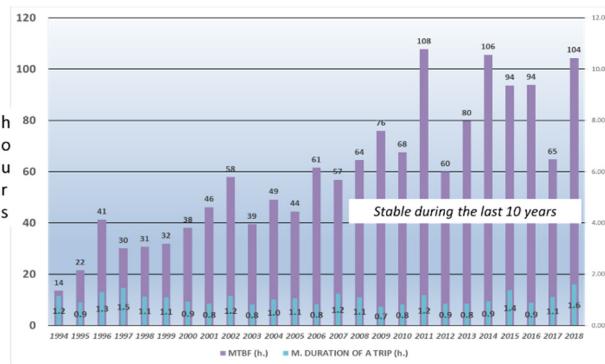


Figure 2: Evolution of the MTBF.

## BEAM MODE DISTRIBUTION

In 1993, 1/3 multibunch, 16-bunch and single bunch modes were available to users. The uniform appeared in 2001 (75 hours lifetime at 200 mA) and was close to 50% of the time until 2007. The 7/8+1 was introduced in 2007 to serve both the users requiring flux and those needing

time structure. The 4\*10 mA replaced the 15 mA single bunch in 2003 and the 24\*8+1 replaced the 1/3+1 hybrid mode in 2003. The 16-bunch filling has always been present. The beam mode distribution stabilized in 2008 and did not change significantly over the years, with a large preference for the 7/8+1 mode (Fig. 3). Today, all modes (except hybrid) are carried out in top-up injection.

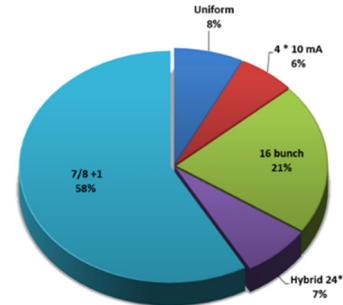


Figure 3: Distribution of the filling modes in 2018.

## LATTICE

The machine started with a modified Chasman-Green lattice giving a 7 nm horizontal emittance. The introduction of dispersion in the straight sections in 1994, allowed it to be reduced to 4 nm. This value remained until the end.

In 1996, a low  $\beta_2$  optics for all cells allowed a reduction of vertical aperture for IDs chambers to 8 mm internal aperture (see vacuum). In 2006 the triplet on both ends of each straight section was reduced to a doublet [7]. With this suppression of 2 quadrupoles, 11 straight sections were lengthened to 6 metres between 2009 and 2012. It mostly consisted of the modification of cabling and piping and the installation of new vacuum chambers. In 2013, one 7 m straight section was installed in cell 23 with new magnets and independent power supplies. It allowed the installation of new RF HOM damped cavities (see RF). 6&7 metres implementation provided essential expertise for EBS.

Until 1999, the vertical emittance remained in the range of 50 pm. With the installation of additional correctors, the vertical emittance could be corrected to 12 pm [8]. Nevertheless, the value was routinely maintained at 20-30 pm for operation. A further improvement of correction methods resulted in an operation at 7 pm, 4 pm being ultimately reached. This value will be maintained for EBS operation.

## INJECTION AND TOP-UP

At the start up in 1993, the ESRF annual report mentioned a typical refilling time of 9 min. The injection process consisted of the manually driven sequence of opening undulator gaps, current injection, bunch cleaning, and gap closure. The duration of the overall procedure was typically 4 min in multibunch, with 2 refills per day. The process did not evolve until the implementation of injection with open front-ends in 2003. This method improved the performance of the source drastically as a result of maintaining the thermal stability on the beamline optics.

A series of frequent top-up tests with an automatized sequence started in 2014 with users, during machine time. The determination of the optimal injection periodicity and

the estimation of the induced stability perturbations were the main objectives. In April 2016, the 16-bunch mode was delivered in user mode with a refill every 20 min. This drastically improved the brightness of the source by maintaining the current at 90 mA (5 mA variation instead of 40 mA) while keeping the vertical emittance below 10 pm.rad (Fig. 4) [5]. Previously, the emittance was blown up to 50 pm to increase the lifetime. From 2015 to 2017 a series of improvements of the injection kicker system and the addition of several active cancellation systems were implemented to minimize the perturbations to users [9]. Since June 2018 the 7/8+1 was delivered in top-up with a refill every 20 min, maintaining the current in a range of 2 mA.

In 2018, top-up represents more than 11,000 refills, highlighting the high level of reliability of the injector system as well as the stability of the new booster power supply. The bunch cleaning was initially applied in the storage ring, now this is performed in the Booster. This process, which is carried out for all modes, avoids beam stability disturbances in the storage ring.

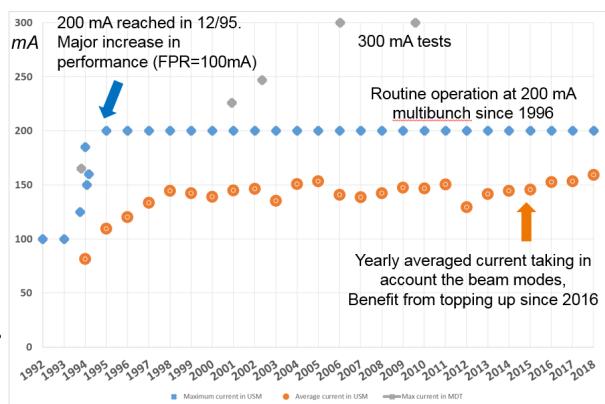


Figure 4: Evolution of the beam current.

## RADIOFREQUENCY

The initial configuration of the radiofrequency system was one klystron feeding two five-cell cavities for the booster and two klystrons feeding four five-cell cavities for the storage ring. In 1997, two additional cavities powered by a new klystron transmitter were installed for a reliable operation at 200 mA [10]. The improvement of the temperature control of the cavity complement it for HOM damping for any fill pattern. In 2006, 300 mA (Fig. 4) were stored after HOM tuning and thanks to the longitudinal feedback system. Nevertheless, for various reasons it was decided to limit the current to 200 mA. From 1998 to 2001, the control and the low-level RF were upgraded.

For the operation in top-up, the klystron of the booster was replaced in 2012 by four 150 kW Solid State Amplifiers. In addition, two five cell cavities were installed in 2015 to improve the reliability.

An R&D program for the development of normal conducting HOM damped cavity for the ESRF started in 2005. In 2013, three HOM-damped cavity prototypes fed by three solid state amplifiers were installed on SR. This additional RF system remained operational until the shutdown. EBS will be equipped with 13 identical cavities.

## VACUUM

Since the beginning, vacuum interventions took place during each shut-down for maintenance, repairs or upgrades [11]. In 1993, and then during the period 1997-2006 vessels contaminated by corroding chemical products had to be changed. Glidcop absorbers for 200 mA operation replaced all the initial copper absorbers. The RF fingers (Beryllium bronze springs) were replaced with stainless steel (SS) springs design at the beginning of operation. Nevertheless, due to systemic problems, an intensive campaign (1996-99) was performed to characterize it, to improve the quality control of installation, and systematically change the defective ones.

Initially, all the 5 metre insertion device chambers were made in SS with 19 mm vertical dimension (16 mm inner aperture) using distributed NEG strips for pumping. The evidence of magnetic dust in the chambers coming from NEG imposed to suppress it. During the period 1995-1999, 15 mm SS chambers, 10 mm SS chambers and expensive 10 mm copper-plated SS chambers were progressively installed. In order to further reduce the bremsstrahlung radiation, the NEG-coated aluminium chamber technique was developed. The installation of the first 10 mm Aluminium NEG-coated chamber (5 m long, 8 mm inside), coated in house, took place in 2001. All ID chambers were then installed or upgraded using this technique, including the 6 metre long one. The first in-vacuum undulator was installed in 1999 while the first cryogenic unit was operated at 180 K in 2008. Table 3 gives the present status.

Table 3: Status of ID Straight Section in 2018

5 metres AL NEG coated	7
6 metres AL NEG coated	6
2 metres AL Neg coated	8
In vacuum undulators	10
Cryogenic in-vacuum undulators	3

## CONCLUSION: LESSONS LEARNED

The operation 1993-2018 was characterized by a large increase in beam availability (less failures, injection fronts open, top-up) associated to a large increase in performance (current, emittances, stability...). A lot of hardware developments and upgrades took place from the beginning and during the operation period. The EBS project is a continuation of those efforts at a larger scale.

### Lessons learned:

- Preventive maintenance and development are essential for availability and performance
- After construction, the EBS SR will require development and maintenance to stabilize the operation
- Expertise and availability of the teams are essential for operation and development projects

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