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# STATUS OF THE ADVANCED LIGHT SOURCE*

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### *Abstract*

The LBNL Advanced Light Source, a pioneering third-generation soft x-ray synchrotron radiation source operating at 1.89 GeV with a 2 nm beam emittance, stands as one of the earliest facilities in its class, continually evolving to maintain its status at the forefront of soft x-ray sources. This paper reviews the most significant advancements in the accelerator's hardware and software infrastructures and presents the machine operational statistics over the last 15 years.

## FACILITY OVERVIEW

The Advanced Light Source (ALS) at the Lawrence Berkeley National Laboratory, one of the earliest 3rd generation light sources, celebrated its 30th anniversary in 2023 [1]. Since the completion of the top-off upgrade in 2009 [2] and the brightness upgrade in 2012 [3], the accelerator underwent multiple enhancements preserving and reinforcing its position as a leading facility for scientific research in the soft x-ray region. Some of those enhancements have been in anticipation of the major facility overhaul to be realized by the ALS-U project in the next few years, which will increase the beam brightness in its core area by two orders of magnitude [4].

The present accelerator complex consists of an S-band (3 GHz) 50 MeV linac, a 0.7 Hz cycle full-energy booster ring and a 1.89 GeV storage ring (SR) (see Table 1). The 12 cell triple-bend achromat lattice in the SR provides a 2 nm horizontal emittance electron beam, typically at ~ 2% coupling. More than 40 experimental beamlines, fed from either 14 insertion devices or bend magnets, including three 5T superconducting bend magnets, serve more than 1,500 users per year with photon energies ranging from infrared to hard x-rays. Seven of the insertion devices are elliptically polarizing undulators (EPU) that allow for full polarization control of the photon beam.

Table 1: Advanced Light Source storage-ring parameters

| | |
|---|---|
| Beam energy | 1.89 GeV |
| Circumference | 196.8 m |
| Beam current | 500 mA |
| Top-off beam current variation | ≤ 0.3% |
| Radio frequency | 499.64 MHz |
| Emittance H/V | 2.0 / 0.04 nm·rad |

## MAIN DEVELOPMENTS

### *Accelerator*

**Injector System:** Part of the ALS-U upgrade scope is to completely replace the ALS storage ring and to add a new accumulator ring to supplement the injector chain [4]. The present ALS injector, which includes the linac, the booster ring and the transfer lines in between, are reused and have to reliably operate for another 25-30 years. In response to that, the injector complex underwent and is still undergoing a comprehensive and phased upgrade of its subsystems. Key improvements already implemented include the replacement of the control system and the booster bend power supply (funded by ALS-U and presently being installed) and of some of the transfer line magnets' power supplies (PS). An important part of this initial injector upgrade campaign was the replacement of the thyratron-based linac modulators with state-of-the-art Scandinova solid state devices. The installation of these new modulators was successfully completed during the 2021 winter shutdown and commissioned in 2022.

An additional multi-year, two-phased upgrade plan for the injector is now being executed. It includes the replacement of the low-level RF (LLRF) analog systems and controls for the whole injector chain (125 MHz electron gun, 125 and 500 MHz sub-harmonic bunchers, 3 GHz (S-band) linac and 500 MHz booster RF) with state of the art RF system on chip technology. In addition, it includes the replacement of the sub-harmonic bunchers tube-based RF amplifiers with solid-state amplifiers. Plans are also in place for upgrading the linac timing distribution and for transitioning the booster RF amplifier from an inductive output tube (IOT) to solid-state.

**ALS Storage Ring RF System:** The RF system for the ALS storage ring achieved in 2021 a significant milestone with the completion of a multi-year upgrade, one of the largest in ALS history. A key feature of this upgrade is the incorporation of hardware and controls to enable ALS operation with either one or both of the two 300 kW 500 MHz CW klystrons that generate the RF power. A waveguide switchyard allows each klystron to feed one or both of the two ALS cavities, offering a flexible and robust operational mode that permits to continue regular user operations in case of failure of either klystron. In dual-klystron operation mode, where each klystron feeds one cavity, the extra RF power availability not only increases the reliability of the RF system, but also allows for the addition of future insertion devices. This comprehensive upgrade also included the replacement of the legacy high-power water loads on a klystron circulator and magic tee with high performance ferrite lined loads.

**Insertion Devices:** Two new EPUs have been fabricated at LBNL. Both have a length of 1.9 m and vacuum cham-

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bers of extruded Al with NEG coating. The EPU for the MAESTRO beamline was commissioned in 2016, covers the spectral range $20 - 1000$ eV, and has a period length of 70 mm and a minimum gap of 12 mm. The EPU for the COSMIC beamline was commissioned in 2017, covers the spectral range 0.25 to 2.5 keV, and has a period length of 38 mm and a minimum gap of 10 mm. A new in-vacuum undulator from industry has been installed at the GEMINI beamline and was commissioned in 2019. It has a magnetic length of 2 m and a total length of 2.5 m. The period length is 15 mm and a minimum magnetic gap of 4.3 mm, making it possible to operate at high energies, achieving 12.65 keV photon energy on the 11th harmonic.

**Vacuum System:** All the legacy ion pump controllers in the ALS storage ring were replaced in 2020-21 with new state-of-the-art units. Besides the increase in terms of reliability, these new compact units replaced their bulky legacy counterparts allowing for electronic racks consolidation, and contributing to providing additional real estate necessary for the installation of new components required by ALS-U. The new units were selected and procured in coordination with the ALS-U project with the goal of being compatible and re-usable in the new ALS-U accumulator ring.

## *Controls*

**Control System:** The ALS has recently undertaken substantial upgrades to its control system, a process crucial for standardizing and modernizing a system that has evolved over a span of 30 years. This extensive overhaul encompasses several key areas. Firstly, the transition to a complete EPICS (Experimental Physics and Industrial Control System) based control system represents a major step forward in control system technology for the ALS and marked the end of the original ALS control system utilizing CMM/DMM/ILCs.

Moreover, there has been a significant focus on modernizing both the user-facing control room applications and the back-end services, such as the archiver. This modernization is aimed at enhancing the user experience and improving the efficiency and reliability of data management. Secondly, the migration to Linux operation consoles and virtual machines marks a substantial technological shift, enabling more robust and flexible operations while concurrently retiring the older crate-based systems. Another major aspect of the upgrade is the transition of relay-based interlock systems to more advanced and reliable Allen Bradley PLC solutions. Additionally, there have been comprehensive network upgrades, a vital step in bolstering the overall cybersecurity of the control and development networks at ALS.

**Timing System:** A comprehensive upgrade of the timing system was finalized in September 2017. It included the deployment of primarily commercial hardware and installation of a large fiber network and fan-out infrastructure, designed to distribute all timing events to each timing client via a high speed serial data stream. This infrastructure directly integrates with a wide array of diagnostics and operational systems, including BPMs, bunch current monitor, user timing interfaces, and provides the necessary triggers and clocks for bunch-by-bunch FB, CCD cameras, oscilloscopes, and injection elements. To meet the additional challenges of ALS-U, new timing hardware is being developed in-house [5]. The fiber infrastructure will also be expanded significantly, primarily to support additional BPMs and integration with new PS controllers. The in-house production of high-speed digitizers [6] leverages the timing system infrastructure to provide a state-of-the-art RFSoC data acquisition solution with RF-synchronous sampling and flexible triggering.

**High-Level Applications:** Recent high-level application developments include four feedback (FB) systems: the slow phase FB, which maintains constant beam phase crucial for micro-bunch stability and synchronization in experiments; the booster-to-storage ring (BTS) trajectory FB, ensuring accurate beam injection into the SR despite long-term drifts; the septum FB, supplementing the BTS trajectory FB by adjusting the pulsed septum for optimal capture efficiency; and a FB for the SR RF klystron high voltage PS, designed to mitigate line voltage fluctuation impacts on LLRF loop stability which previously could cause beam dumps.

Another significant advancement involves transitioning our operational software to utilize tune measurements directly from the transverse bunch-by-bunch FB system [7] instead of relying on Fourier analyses of BPM signals during injection transients. This ensures continuous access to up-to-date tune readings without necessitating injection shots or firing kickers. This enhancement has notably improved tune FB performance and stability during operations, and has significantly increased flexibility during physics shifts.

Utilizing Machine Learning (ML) methods, recent initiatives have effectively tackled the issue of transverse beam size fluctuations. Proof-of-principle experiments [8–10] initially demonstrated the potential of ML culminating in the 2021 Klaus Halbach Award for Innovative Instrumentation [11]. Further development led to systematic implementation of an advanced ML algorithm within the ALS controls frameworks [12,13]. Notably, this revised algorithm features the ability for continuous online fine tuning, affording it the flexibility to adjust to variations in operational conditions dynamically and in real time. This system has been in routine user operation since late 2023.

## *Diagnostics*

**BPMs:** A total of 175 BPM electronics, covering both storage ring and injector BPMs, were replaced to enhance the precision and reliability of beam position measurements. These new BPMs have been smoothly integrated into the fast and slow orbit feedback systems with data rates up to 10 kHz. Additionally, advancements in pilot tone calibration processing have significantly improved measurement accuracy, achieving 60 nm rms error across 0.01 Hz to 1 kHz and 20 nm below 100 Hz [14]. The next generation of BPM electronics, being developed in-house for ALS-U, uses RFSoC technology to oversample the signal, enhancing performance across the relevant frequency bands [14].

**Fast Orbit Feedback System:** The upgrade to the fast orbit FB (FOFB) system marks a significant boost to ALS' performance and serves as a prototype for ALS-U. Central to this upgrade has been the implementation of BPMs and cell controller hardware capable of a low latency 10 kHz throughput, a development arising from collaboration between LBNL and BNL. These systems have been successfully operated at the ALS for several years, contributing to improved beam stability and precision. During the 2020 summer shutdown, 44 new 5 kHz Caen PSs were installed, significantly enhancing the FOFB's PS capabilities. Complementing these electronics upgrades, 22 aluminum vacuum chamber spools were replaced with higher bandwidth stainless steel chambers, thereby improving the overall response and efficiency of the FOFB system. The rms orbit improvement factor is about a factor of 10 at low frequency with a closed loop cutoff frequency at about 200 Hz [15].

**Bunch-by-Bunch Feedback System:** The bunch-by-bunch FB system [7] has seen major upgrades in both transverse and longitudinal components. A crucial upgrade was replacing the transverse FB amplifier, which now offers better phase linearity and bucket isolation, enhancing instability damping and tune perturbation resistance. This effectively mitigates instabilities previously observed during certain ID gap adjustments. Additionally, the improved system supports resonant excitation at higher amplitudes, facilitating new machine studies and deeper insights into beam dynamics. The longitudinal FB iGp 8 has been replaced with Dimtel's newer iGp 12 model [16]. This upgrade significantly boosts the system's longitudinal diagnostics, enabling higher resolution spectra, real-time modal analysis, and more precise resonant excitation and transfer function determination.

**Diagnostic Beamlines:** The diagnostic beamlines 3.1 [17] and 7.2 [18], which measure beam shape and size using synchrotron radiation, have undergone significant upgrades to enhance operational efficiency. For 3.1, the replacement of the obsolete BGO scintillator with an advanced LYSO scintillator marks a notable improvement, offering superior light yield, increased resolution, and enhanced radiation hardness. This upgrade is complemented by the transition from an analog camera and acquisition system to digital systems which have been seamlessly integrated into the control system. The expansion of the endstation with a fast-gated camera now enables the measurement of the beam on a turn-by-turn basis, providing detailed insights into beam dynamics. Similarly, 7.2 has seen the transition to digital systems for its camera and acquisition system. Upgrades also included an enhanced acquisition system to the streak camera, introducing remote control capabilities.

## OPERATIONAL PERFORMANCE

The operational performance of the Advanced Light Source over the last 15 years is shown in Fig. 1.

The beam availability goal was set at 95% until 2017 when we decided to increase it to the more challenging value of 97%. The figure shows an overall satisfactory performance with a dip in performance in 2021 due to COVID pandemic effects and to a delay in a major upgrade of the linac modulators. The Mean Time To Recovery (MTTR) and the Mean Time Between Failures (MTBF) over the years are also shown, with the first satisfying in most years the internal goal of less than 90 min, and the second only approaching the goal of greater than 50 hours.

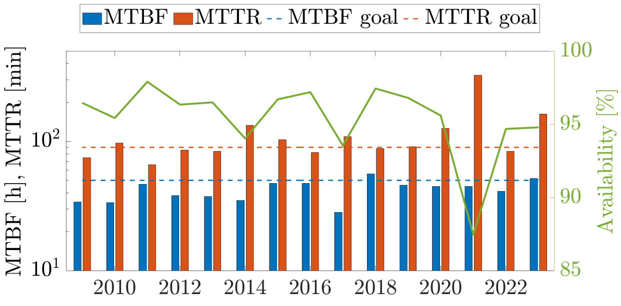

Figure 1: Beam availability (green) and mean time between failures (MTBF, blue, goal > 50 h) and mean time to recovery (MTTR, red, goal < 90 min) over the past decade.

The breakdown of beam time loss by subsystem failures is illustrated in Fig. 2, with losses spread across multiple subsystems, notably recurring in the power supplies and, more recently, cooling water areas. The significant SR RF losses in 2017 and the linac/injector losses in 2021 correspond to the commissioning/debugging of two major ALS upgrades: the reconfiguration of the storage ring RF source and the replacement of linac modulators. Despite these challenges, the ALS maintains robust operational performance and a commitment to continuous improvement amidst evolving demands and technological advances.

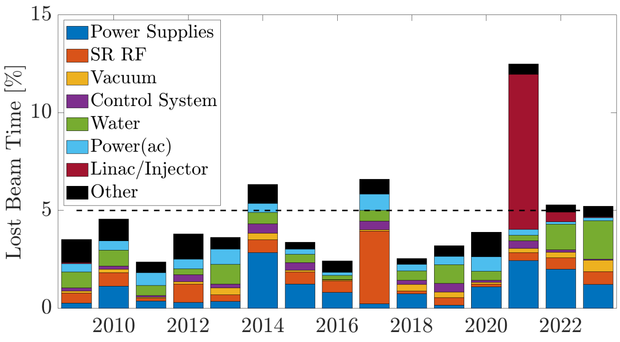

Figure 2: Distribution of beam time loss percentages at the Advanced Light Source from 2009 to 2022, categorized by the cause of failure. The 7 categories that contribute most are explicitly listed with the dashed line marking the target.

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