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PRESENT STATUS AND FUTURE PROJECT OF SYNCHROTRON LIGHT SOURCES AT KEK

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Abstract

The Photon Factory (PF) is a synchrotron radiation facility in the High Energy Accelerator Research Organization, KEK. The PF operates two electron storage rings: the 2.5-GeV PF Ring and the 6.5-GeV PF Advanced Ring (PF-AR). Both rings have been in stable operation for nearly 40 years. This paper first describes the current operational status and recent developments at PF, then describes a future project based on a new concept of hybrid light source (PF-HLS), which combines the advantages of a superconducting linac and a low-emittance storage ring.

INTRODUCTION

The Photon Factory (PF) [1] has been operating since its commencement in 1982. It has contributed to advancing fundamental sciences, particularly materials science and life sciences with a primarily role as an inter-university research institute. Currently, the facility operates two synchrotron radiation (SR) sources, the 2.5-GeV PF Ring and the 6.5-GeV PF Advanced Ring (PF-AR), providing the SR wavelength ranged from ultraviolet to X-rays for over 3,000 users annually. Figure 1 shows a photograph of the accelerator complex that makes up the PF Ring and PF-AR. The linear accelerator, serving as the injector for two SR rings, also achieves simultaneous top-up injection into the SuperKEKB high energy ring (HER) and low energy ring (LER) [2]. Figure 2 shows a typical day's beam operation history and beamline status at the PF Ring. The PF Ring comprises 23 beamlines with 39 experimental stations, which utilizes the SR from bending magnet or insertion devices (IDs). A total of 12 IDs have been installed in the PF Ring. The top-up injection maintains the flatness of the beam current, typically within the range of 0.05% to 0.1%. This technique ensures a consistent and stable beam quality, which is crucial for conducting precise and reliable experiments. For detailed parameters of the accelerators, please refer to the status reports from previous IPAC conferences [3,4].

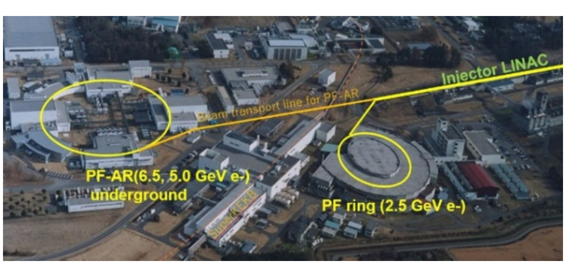

Figure 1: Photo of PF accelerator complex.

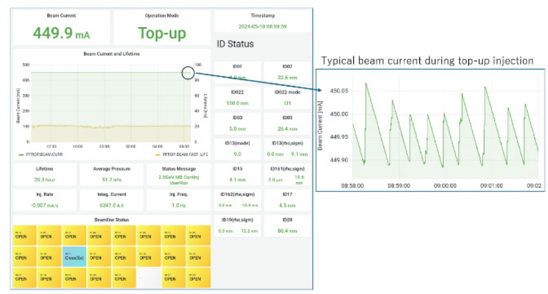

Figure 2: A typical 24-hour cycle of user top-up operation at the PF Ring is depicted. The left panel shows a Grafana-based web interface displaying the overall operational status, while the right panel provides an enlarged view of the beam current history over a four-minute interval.

OPERATIONAL HISTORY OF THE PF

Figure 3 illustrates the history of machine operating hours from the commencement of SR user's operations in 1982 through 2023. During this period, the PF Ring has continuously enhanced its performance through several upgrades, including major emittance improvements in 1987 and 1997, and straight section upgrade in 2005. From 2009, the introduction of top-up operations and, from 2012, the establishment of hybrid operations allowing the coexistence of multi-bunch and single-bunch modes improved the convenience for user experiments. Operating hours have declined since 2010 due to stringent financial conditions. However, there has been a recovery trend in the fiscal years 2021 and 2022. There was a slight decrease in FY2023 due to replacing and conditioning work of aged accelerating tubes in the injector linac, but 4,400 hours for machine operation are expected in FY2024.

Originally built as an injector for the TRISTAN collider, the PF-AR started its SR user's operation in 1987. Following this, in 1990, it achieved the world's first extraction of high-brightness X-rays from in-vacuum type undulator. In 2002, a significant upgrade was made to become a high intensity pulsed light source, now operating as a dedicated

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synchrotron light source. For the fiscal year 2024, the PF-AR plans to provide 3,000 hours of machine operation.

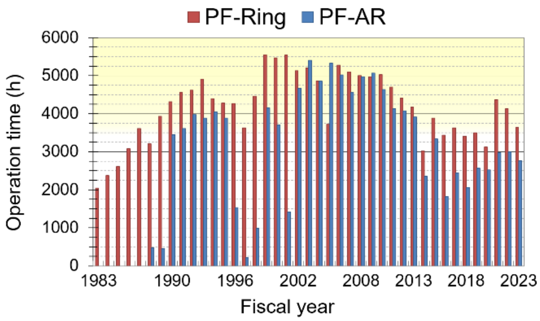

Figure 3: Machine operation time for PF-Ring and PF-AR in each fiscal year since the commencement of user operations.

Table 1 and Table 2 presents the operational statistics of each ring for recent three years. The PF Ring maintained excellent performance metrics, with downtime further reduced from the previous year to approximately 15.2 hours, a failure rate of about 0.5%, and a mean time between failures (MTBF) of around 172.0 hours. A breakdown of the failures shows that approximately 35.9% were related to the injection system, and 33.2% were related to the control monitoring system, indicating that these two areas accounted for most issues. The leading cause of these failures was the aging of the kicker power supply. The failure rate due to RF-related issues was low enough at 4.2%, almost the same level as the previous year, indicating that the RF system operated stably with minimal trouble.

Table 1: Operation Statistics of the PF-Ring

Fiscal Year	**2021**	**2022**	**2023**
Total Operation Time [h]	4368	4128	3648
Schduled user time [h]	3744	3616	3096
Number of failures	17	25	18
Total down time [h]	23.2	25.8	15.2
Failure rate	0.6	0.7	0.5
MTBF [h]	220.2	144.6	172.0
Mean down time [h]	1.4	1.0	0.8

Table 2: Operation Statistics of the PF-AR

Fiscal Year	**2021**	**2022**	**2023**
Total Operation Time [h]	2796	3000	2760
Schduled user time [h]	2416	2440	2184
Number of failures	10	17	16
Total down time [h]	11.3	21.7	30.3
Failure rate	0.5	0.9	1.4
MTBF [h]	241.6	143.5	136.5
Mean down time [h]	1.1	1.3	1.9

For the PF-AR, downtime was about 30.3 hours with a failure rate of 1.4%, which shows a slight deterioration compared to the previous year. This was primarily due to issues with the septum magnet's cooling water, beamline-related troubles, and problems with the bunch purification system. About 62.5% of the failures were related to beam injection.

R&D IN EXISTING FACILITIES

PF Ring

Orbit Stabilization System To improve the stability of the beam orbit, we have been upgrading the Beam Position Monitoring (BPM) system and the small magnet power supplies since fiscal year 2021. The existing small power supplies, manufactured around 1997 to accommodate the PF's low-emittance upgrade, have become significantly aged and frequently fail. Their control interface was also limited to analog voltage control from external VME boards. Therefore, we began procurement and completed the update of approximately half of the total units by 2023. Currently, we are preparing to connect the new BPM system [5] with the small power supply system to establish a high-speed orbit stabilization system.

Renewal of LLRF System In FY2023, we completed the renewal of the Low-Level RF (LLRF) system. Previously, the system consisted of numerous analog modules, but it is now being updated to the latest digital control system with the MTCA.4 standard. Details will be reported at this conference [6]. Since autumn 2023, user operations have been conducted with the new system, which runs without significant issues. The new system has improved phase stability and enables advanced control and data analysis that were impossible with the previous system.

PF-AR

Ring Energy-Independent Top-Up Injection When operating the PF-AR at 6.5 GeV, the injector linac achieved simultaneous top-up injections at a 50 Hz repetition to four rings (PF Ring, PF-AR, SKEKB HER, LER) [2]. However, when operating the PF-AR at 5.0 GeV, settings of the DC magnet installed at the downstream of the linac had to be changed, making injection switching per pulse impossible.

In response to the recent rise in electricity prices, the percentage of operating time at 5.0 GeV has been increased to achieve operating cost reductions in PF-AR. In addition, we aimed to improve the convenience of each ring's independent operation. The switchyard section's optical function was redesigned, and the corresponding magnets and vacuum equipment were updated [7].

This modification has made it possible to conduct simultaneous top-up injections to four rings regardless of the PF-AR's operating energy.

Construction of Test Beamline In order to carry out the R&D for particle detectors, constructing a test beamline supplying GeV-class electrons at KEK has been a longstanding desire within the high-energy physics experiment community. With funding allocated for establishing the test beam line in the PF-AR south experimental hall

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(AR-TBL), construction began in fiscal year 2020 and was completed in September 2021. After fine-tuning the internal target, we verified the GeV-scale electrons at the beamline. Subsequent machine tuning continued to accommodate both synchrotron radiation and internal target insertion, leading to the successful start of AR-TBL user operation in the spring of 2023 [8].

R&D FOR FUTURE LIGHT SOURCE

The PF Ring and PF-AR are facilities that have been utilized by many SR users and remain highly competitive, even after approximately 40 years of operation. However, it is indisputable that constructing new SR sources is essential for further performance improvements.

The new facility needs to be highly versatile and flexible, aiming not only to meet the demands of existing facilities but also to accommodate exploratory experiments, innovative experiments, and long-duration studies. This design approach ensures that the facility can support the scientific community's evolving needs, fostering groundbreaking research and the development of new experimental methodologies.

Thus, we propose the "Hybrid Light Source (PF-HLS)" as a new concept that combines versatility and cutting-edge accelerator technology. This facility would utilize both high-quality beams from a superconducting linac and beams from a low-emittance storage ring. Figure 4 shows a conceptual diagram of PF-HLS, typical beam patterns, and examples of beam orbits. The foundational ideas are introduced in a submitted article [9], and a Conceptual Design Report (CDR) summarizing the studies to date was published in January 2024 [10].

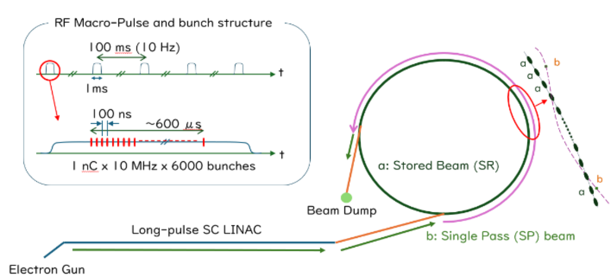

Figure 4: Conceptual diagram of hybrid (Linac/Ring) light source and typical beam patterns.

In the following part of this report, we will introduce some of the basic concepts of the PF-HLS based on tentative design parameters. By switching the storage ring energy at 2.5 GeV and 5.0 GeV, we aim to provide SR that accommodates a broad wavelength range while keeping construction and operational costs under the existing facilities. The circumference of the ring is approximately 750 m, with an emittance of 1 nm-rad at 5.0 GeV operation and 0.25 nm-rad at 2.5 GeV.

Two insertion devices (IDs) for low and high energies are arranged in tandem in a long straight section to enable high-brightness beams across a wide wavelength range. Figure 5 shows that when switching the beam energy between 2.5 GeV and 5.0 GeV, 1) SR from ID can cover photon energies continuously at each energy, and 2) can be utilized from the low energy (starting from 10 eV) to the high energy range (up to 100 keV).

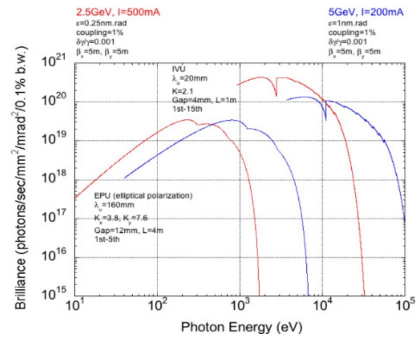

Figure 5: Example energy spectra with a 1-m long in-vacuum undulator and a 4-m long EPU. Note that the brilliance values are provided as indicative values to illustrate the coverage.

In typical designs of synchrotron radiation sources, it is popular to determine a target electron energy and optimize the lattice and various components (such as magnets, power supplies, RF systems, IDs, and vacuum systems) accordingly. While some degree of energy variation is usually permissible, it is uncommon for designs to accommodate significant energy changes. However, to realize the concept previously described, we propose the energy switch from the design phase. This approach allows for greater flexibility in meeting diverse experimental needs and extending the facility's utility and lifespan.

When designing for variable energy, it is particularly important to study beam instabilities at lower energies. The various accelerator apparatus may require different performance characteristics compared to designs optimized for a single energy. Furthermore, it is essential to consider the construction, operational, and maintenance costs in subsequent years. While there are many factors to consider, we will continue to advance optimization studies to ensure the facility can effectively accommodate these broader operational and financial considerations.

The parameters for the superconducting linear accelerator are primarily based on the accelerating cavities used for the International Linear Collider (ILC), and these specifications are sufficient to fulfil the target of PF-HLS.

SUMMARY

The report covers the operational status and recent statistics of the Photon Factory, as well as the research and development activities in the two rings. The development of a new synchrotron radiation (SR) facility is urgent, and efforts to advance this will be vigorously pursued.

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