

# 10 YEARS OPERATION OF THE SOLARIS STORAGE RING\*

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## Abstract

The SOLARIS storage ring, Poland's first synchrotron light source, has marked a decade of successful operation, contributing significantly to scientific research and technological advancement. Commissioned in 2015 and inspired by the innovative design of Sweden's MAX IV Laboratory, SOLARIS exemplifies the effectiveness of international collaboration in cutting-edge accelerator technologies. Over the past 10 years, the facility has maintained high performance and reliability (97% availability), delivering high-quality photon beams to researchers in diverse fields. Continuous improvements in the accelerator systems, such as enhanced beam stability due to Slow and Fast Orbit Feedback implementation, and optimised maintenance schedules, have enabled SOLARIS to meet the growing demands of the scientific community. A key focus has been the development of new beamlines and experimental stations, broadening the scope of available research capabilities. Looking ahead, SOLARIS aims to further expand its infrastructure (linac upgrade, top-up injection) and enhance beamline performance, ensuring its continued role as a hub for innovation and scientific excellence.

## INTRODUCTION

The SOLARIS National Synchrotron Radiation Centre, located in Kraków, Poland, is the country's first and only synchrotron light source and one of the most advanced research infrastructures in Central and Eastern Europe [1]. Operational since 2015, SOLARIS serves as a multidisciplinary platform for cutting-edge scientific research in fields such as physics, chemistry, biology, materials science, environmental science, and medicine.

The facility is based on a 1.5 GeV electron storage ring designed by MAX IV Laboratory in Sweden [2] and optimized for the generation of synchrotron radiation—a highly intense, tunable beam of light that enables the investigation of matter at the atomic and molecular levels. Currently, SOLARIS operates several beamlines, with more under development, offering researchers access to a wide spectrum of experimental techniques, including photoelectron spectroscopy, X-ray absorption spectroscopy, imaging, and crystallography.

SOLARIS plays a vital role in the national and European research ecosystem, supporting academic institutions, industry partners, and international collaborations. As a user facility, it provides open access to researchers based on sci-

entific merit, while also contributing to the education and training of future generations of scientists and engineers.

With its unique capabilities and growing infrastructure, the SOLARIS Synchrotron is a cornerstone of Polish scientific excellence and a hub for innovation and knowledge transfer in the region.

## OPERATION

The Solaris synchrotron light source operates with the users since October 2018 with the total beamtime divided between the users operation (80%) and machine development and maintenance (20%) (see Fig. 1). Standard operations take place over two shifts, seven days per week. From Tuesday through Sunday, full-scale user operation resumes. During these days, beamlines are made available to external users, and the facility focuses on providing stable, uninterrupted beam delivery to support a wide array of experimental needs. One day (Monday) is reserved exclusively as a machine day, dedicated to maintenance tasks, system upgrades, calibrations, and machine development. On this day, the facility does not provide user beamtime, allowing engineers and operators to carry out essential work without interrupting scientific experiments. Beam injection is carried out twice daily in line with Solaris's decay mode operation. In this mode, the stored beam naturally diminishes over time, and injections are scheduled at fixed intervals to restore beam current. This approach ensures long, stable periods for experiments without frequent disruptions. Solaris employs a uniform filling pattern during injection, meaning the electron bunches are evenly distributed around the storage ring, providing consistent beam properties for all beamlines.



Figure 1: The annual beamtime distribution.

## Operation Statistics

Right from the start of users operation the availability of the beam was high (over 90%, Fig. 2). From 2018 to 2025, the SOLARIS synchrotron demonstrated consistent

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improvements in operational performance, reliability, and beam availability, supporting both scientific research and technical development.

In 2019, the facility delivered 2,530 hours of beamtime (2,008 h for research) with 91.9% availability and a mean time between failures (MTBF) of 22.8 h. By 2020, planned beamtime rose to 4,022 h, though pandemic-related disruptions reduced actual operation to 3,878 h, with improved availability (93%) and MTBF of 76 h. In 2021, total beamtime rose to 4,654 h (3,712 h for research), achieving 99% beam availability and an MTBF of 148.5 h, with mean time to recover (MTTR) below 3 h. Due to facility upgrades in 2022, total beamtime dropped to 3,236 h with 94% availability, mainly due to a vacuum system failure. Despite this, approximately 70% of time was still dedicated to research. In 2023 and 2024, performance stabilized, with beam availability consistently above 97% and MTBF exceeding 100 h. Throughout this period, the average beam current increased from 250 mA to 400 mA, and the beam lifetime remained stable, indicating well-conditioned vacuum systems.

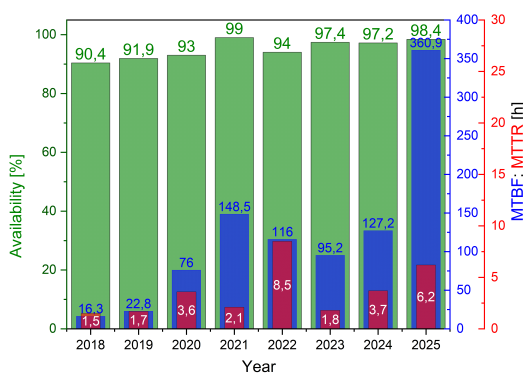


Figure 2: The operation statistics.

### Beam Stability and Reproducibility

Ensuring the stability of the electron beam at the SOLARIS synchrotron has been a key objective throughout its development. Several structural measures, including the installation of a vibro-elastomer mat and concrete block magnet girders, have effectively maintained the stability of the experimental hall within acceptable limits below  $1.6 \mu\text{m}$  rms for low frequency range (below 10 Hz) and below  $0.3 \mu\text{m}$  rms in the frequency range between 10 and 50 Hz. Thermal stability, particularly in the cooling water system, has been progressively enhanced, culminating in a major upgrade in 2022 that achieved a stability level of  $\pm 0.1 \text{ }^\circ\text{C}$ . The orbit correction system has undergone significant improvements, with the Slow Orbit Feedback (SOFB) system being redesigned and accelerated by over an order of magnitude. Additionally, the successful development and implementation of the Fast Orbit Feedback (FOFB) system have further refined beam stability [3]. To optimize performance, an

offloading procedure was introduced, mitigating conflicts between the SOFB and FOFB systems [4]. These advancements have enabled submicron precision in electron beam stability and reproducibility (Fig. 3). While beam position reproducibility remains at a high level, the drifts of several micrometres over 12 h persist in the X-ray Beam Position Monitor (XBPM) readouts (Fig. 4). Continuous efforts are being made to further enhance long-term orbit stability for the most demanding experimental applications.

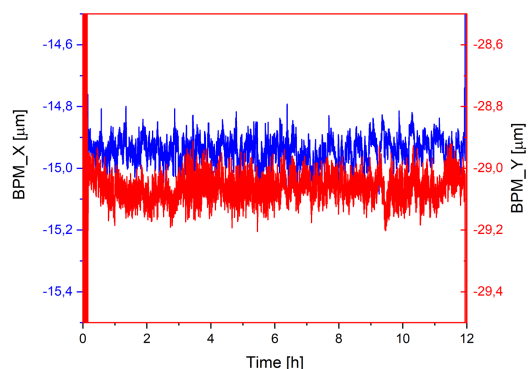


Figure 3: The stability of the electron orbit over 12 h.

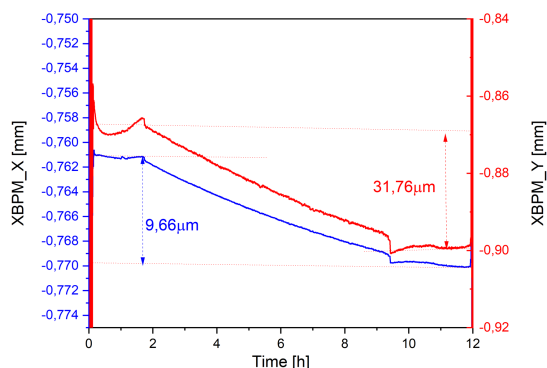


Figure 4: The stability of the photon beam over 12 h.

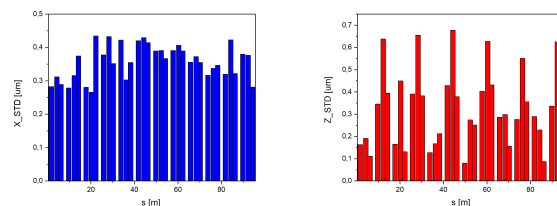


Figure 5: Reproducibility of the electron orbit from injection to injection over months of operation.

Figure 5 shows the standard deviations of the orbit in both planes, calculated from consecutive injections over the

course of a month. It can be seen that the orbit reproducibility is within the range of  $0.7\ \mu\text{m}$ —a significant improvement compared to the past, when this value fluctuated around  $10\ \mu\text{m}$ .

## RECENT DEVELOPMENTS

Over last 10 years the SOLARIS Synchrotron underwent significant technical and infrastructural advancements, enhancing beam stability, expanding research capabilities, and preparing for next-generation operation. The development efforts were primarily focused on supporting day-to-day operations and improving the stability of the electron and photon beams on the existing beamlines. Beam Position Monitor (XBPM) calibration scripts were implemented on the frontends of the DEMETER, PHELIX, and POLYX beamlines [5]. A key milestone during this period was the modernization of the DEMETER undulator, which involved installing new coil power supplies and relocating the control cabinet from the ring tunnel to the service gallery, thereby improving accessibility. A dedicated diagnostic system was also developed to detect disturbances affecting the undulator's performance, and a thorough investigation into possible sources of instability—such as vibrations and electrical faults—was conducted.

Simultaneously, the Accelerators Department contributed to the design and commissioning of new experimental beamlines. This included the installation of the frontend of the POLYX beamline and support for the vacuum system of the ASTRA beamline [6]. Additionally, a modified VK1 chamber equipped with an M1-FMB mirror and an infrared chamber was ordered for the CIRI beamline. Detailed planning, including the design of installation tools such as a custom installation table, was completed in preparation for beamline commissioning, which took place in 2023. Another significant beamline under development is the hard X-ray beamline, which will utilize a high-field magnet (3 T) as a radiation source. This project requires considerable modification of the vacuum chambers to efficiently extract high-power synchrotron radiation and is scheduled for completion in 2027. Another important innovation was the development of the One Button Machine (OBM) software during the COVID-19 pandemic. Originally intended as a current limiter for remote injection, OBM evolved into an automation system capable of executing nearly the entire injection sequence—from beam dump to beam delivery. With built-in safety interlocks, cavity power modes, and frontend/insertion device configuration, OBM has become an indispensable daily operational tool and a useful training aid for new operators. Advancements in diagnostics and beam monitoring were also notable. In 2021, the final section of the linear accelerator was redesigned to replace the beam dump with an optical monitoring system including a camera, scintillator, mirrors, and shutters. This allows precise measurement of the electron beam's length and transverse dimensions and can support additional experiments. The LUMOS beamline equipped with a streak camera enabling the measurement

of the longitudinal profile of a single bunch also saw the addition of a fast diode connected to an oscilloscope, enabling detailed measurement of the storage ring's electron filling pattern. This capability supports the development of new operating modes, such as single-bunch operation. Parallel to these improvements, significant progress was made in designing a new 1.5 GeV linear accelerator based on C-band RF technology and a photocathode gun [7]. The objective is to produce electron bunches shorter than one picosecond with normalized emittance under  $0.5\ \text{mm}\cdot\text{mrad}$ . Using simulation tools such as ASTRA and Elegant, the optics and beam trajectories were optimized. Work continues on the design of the diagnostic systems, RF distribution, magnets, vacuum systems, and supporting mechanics. In 2022, modernization of the low-level RF (LLRF) systems was initiated to stabilize the phase of RF signals in the linac. A new printed circuit board-based system was developed, integrating necessary components and eliminating redundant elements. It also features ultra-fast ( $<10\ \text{ns}$ ) phase switching. An accompanying application was created to automatically adjust harmonic cavity geometries, optimizing beam parameters such as emittance and voltage ratios between main and harmonic cavities. In support of CERN's Future Circular Collider (FCC) project, SOLARIS developed a Base Band Tune (BBQ) system capable of detecting extremely small ( $\sim 100\ \text{nm}$ ) betatron vibrations [8]. This allows continuous, high-resolution monitoring of the spectral composition of beam vibrations. Additionally, a bunch-by-bunch feedback system (BBFB), developed in cooperation with Dimtel, was implemented [9]. This system improves emittance, beam lifetime, and photon brightness while providing advanced diagnostics, tune, and chromaticity measurement. It can also perform beam cleaning and generate specific filling patterns for time-resolved experiments. The storage ring is equipped with 12 beam loss monitors (BLM) located at critical points, providing continuous information on losses during injection, ramping, and daily operation [9]. Further electronic advancements included the development of an RFCT system to measure beam current as a backup for the conventional DCCT, inspired by solutions from MAX IV. Early tests confirmed consistent measurements.

Through these initiatives, SOLARIS has significantly strengthened its operational stability, expanded its research infrastructure, and laid a solid foundation for future scientific endeavors and accelerator technologies.

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