

STATUS OF THE DELTA SYNCHROTRON LIGHT SOURCE

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Abstract

DELTA, a 1.5-GeV electron storage ring facility operated by TU Dortmund University in Germany, celebrated its 30th anniversary in fall 2024. During its time in operation, the facility has been continuously developed to provide synchrotron radiation (SR) users with the most reliable and attractive radiation source possible. This includes continuous improvements of electron beam stability and lifetime, the installation of a new 7-T superconducting wiggler magnet with a specially adapted SR outlet chamber, as well as the integration of a second solid-state amplifier-driven radiofrequency system. In recent years, there have also been many exciting developments in the field of accelerator physics. These include the construction of a facility for generating ultrashort and coherent SR pulses, studies involving laser-induced terahertz radiation, and experiments conducted in single-electron mode that complemented ongoing research activities. Furthermore, projects focusing on intelligent system control using machine learning methods were successfully implemented. This report summarizes the most significant developments over the past years.

INTRODUCTION

The DELTA synchrotron light source, which is operated by the TU Dortmund University in Germany, consists of a linear pre-accelerator (70 MeV), a full energy booster synchrotron (70 MeV to 1.5 GeV) and a storage ring with 115.2 m circumference [1] (see Fig. 1). The maximum stored beam current amounts to 140 mA (nominal multibunch operation) with a lifetime of about 60 hours (at 100 mA) (see Fig. 2). The facility is operated 24 hours a day, 5 days a week, where 2000 hours/year were used for synchrotron radiation (SR) studies and 1000 hours/year for maintenance work and accelerator physics research [2]. To save electricity costs, accelerator operation has been cut by 50% since 2023. During the last decade, the yearly averaged availability time remained above the 90% mark [3] (see Fig. 2). Two undulators (electromagnetic undulator U250 and permanent-magnet undulator U55) and a newly installed 7-T superconducting wiggler magnet cover generation of highly intense SR in the range from ultraviolet to hard X-rays. Moreover, a short-pulse source based on the so-called coherent harmonic generation (CHG) principle was completed in 2011 [4, 5]. The laser-electron interaction also generates THz radiation, which is used for CHG diagnostics, as well as other applications [6]. In fall 2022, short-pulse emission via echo-enabled harmonic generation (EEHG), an advanced seeding

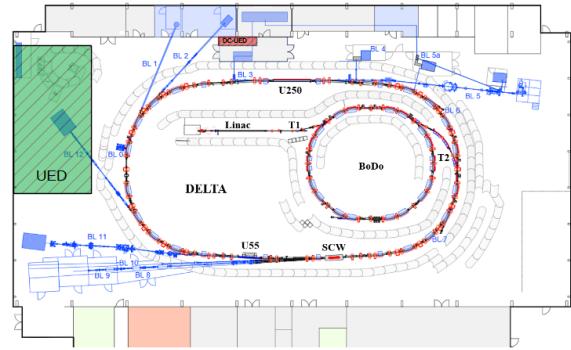


Figure 1: DELTA floorplan. The green area indicates the location of the upcoming UED project. The red area depicts the currently installed 100-keV UED demo project. The SR beamline infrastructure is shown in blue [1, 3].

scheme proposed for free-electron lasers (FELs) [7], was implemented for the first time at a storage ring [8–11]. At present, a new facility for ultrafast electron diffraction (UED) in the MeV range, which allows for direct visualization of structural dynamics on femtosecond timescale, is in the design phase. It will provide two 5 MeV electron sources based on photocathode guns. Commissioning is scheduled for late 2026. In April 2024, a prototype setup of a UED system with a 100-keV DC electron gun was transferred from the University of Duisburg/Essen to DELTA and is currently being tested and upgraded [12].

STORAGE RING OPERATION

Energy Consumption and Radiofrequency Systems

In addition to the cut in beam time, DELTA implemented measures to minimize power usage during both operation and shutdown periods. Electrical, thermal, and cooling energy consumption data have been recorded since July 2021, categorized into user operation, accelerator physics studies, and shutdown weeks [13]. In early 2023, RF power was reduced by operating only one 500-MHz HOM-damped EU-type cavity which is fed by a high-efficiency solid-state amplifier while the second klystron-powered DORIS-type resonator was switched off. This adjustment reduced power consumption during beam time by approximately 100 kW, saving over 12% of power input during operation [14]. Furthermore, a "sleeping mode" configuration was introduced to reduce RF power and magnet current during predictable operational breaks while avoiding larger thermal changes. Identifying components that could be safely turned off and increasing energy-saving awareness lowered power consump-

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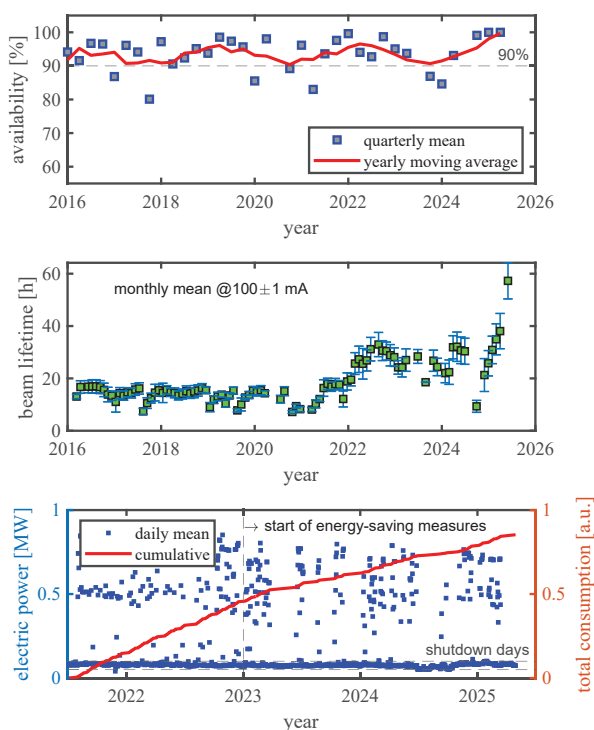


Figure 2: Evolution of averaged availability (top), beam lifetime (middle) and electricity consumption (bottom).

tion during shutdowns by about 10%. While in total these measures dropped electricity consumption by almost 50% compared to previous years (see Fig. 2), they also significantly limited the research time available and made the machine more prone to malfunction due to its infrequent operation. The interventions reflect DELTA's ongoing efforts to balance operational efficiency with energy savings while addressing infrastructure upgrades for long-term sustainability.

Beam Lifetime, Survey and Magnet Alignment

Over the last decade, the vacuum pressure has been continuously reduced due to improved bake-out procedures at the storage ring and beamline vacuum chambers, as well as installing and (re)activating additional vacuum pumps (non-evaporable and ion getter pumps). Combined with progress on the survey and alignment of the storage ring magnets, this has resulted in a significant increase in beam lifetime, reaching up to 60 hours in the second quarter of 2025 (see Fig. 2) [15, 16]. Realignment also improved orbit stability, reproducibility of magnet settings, injection efficiency and reduced the radiation level in the DELTA hall. Furthermore, the resurvey significantly decreased the required average and peak currents for the orbit corrector magnets, making it feasible to integrate weaker spare power supplies provided by DESY. Mixed operation with already installed devices and DESY spare parts was implemented successfully without issues, allowing for gradual replacement. The new devices provides higher regulation accuracy and reliability and the additional spare components will help to reduce maintenance challenges.

Superconducting-Wiggler Operation

In the summer shutdown 2020, the old 5.5-T superconducting asymmetric wiggler (SAW) with 5 periods was replaced by a new superconducting wiggler (SCW) with ten 7-T symmetric periods in order to provide higher photon energy and intensity [17]. Vertical tune shifts and orbit kicks induced by the strong SCW field were measured and compensated via an adapted optics through readjusted quadrupole and corrector magnets settings [18, 19].

The new SCW delivers four times the radiation power of the old SAW. As the old outlet chamber was not designed for this increased load during nominal operation, the SCW's magnetic field was limited to 5 T (at 130 mA) until summer 2024 when a newly designed outlet chamber was installed (see Fig. 3). The redesigned chamber features exchangeable copper absorbers for handling high radiation power and includes interlock controls for waterflow, pressure and temperature [20]. An additional lead shielding hutch was installed around components exposed to SCW hard X-rays to reduce background radiation outside the concrete shielding wall [21].

The SCW operates successfully at fields up to 5.5 T without significant increases in cooling water temperature or alignment issues. User experiments profit from higher intensity and improved signal-to-noise ratio of the measurements.

Beamline BL 9 resulted in a flux increase of about 30% at photon energies of 27 keV. Beamline BL 10 profits from an increase of 75% at 14 keV and beamline BL 8 extended its operational range from 22 keV to 27 keV [20]. Further improvements are currently being planned for beamline and monochromator cooling systems to enable higher SCW magnetic field settings during regular user operation.

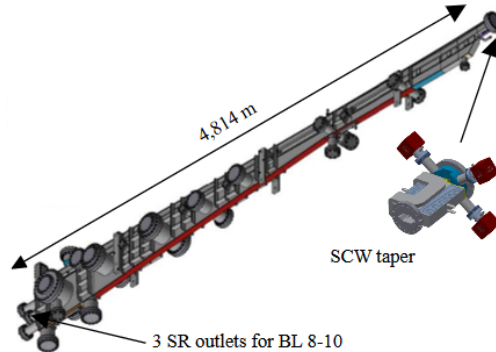


Figure 3: 3D CAD model of the SCW outlet vacuum chamber. The chamber profile adapter ("SCW taper") attached downstream to the SCW includes a cooling block, a steerer coil, four pump ports and a beam position monitor.

ACCELERATOR PHYSICS RESEARCH

Generation of Coherent THz Pulses

The interaction of laser pulses with a short slice within an electron bunch creates a gap in the electron density distribution, whereby THz radiation is emitted coherently in a following dipole magnet [22, 23]. Without laser-electron interaction, the coherent synchrotron radiation (CSR) impedance

causes a longitudinal modulation in electron density, leading to substructures in the bunch and coherent emission in the (sub-)THz range. At the nominal beam energy (1.5 GeV), the extrapolated threshold is 17 mA, which is near practical limits for single-bunch currents. However, THz bursts were observed at reduced beam energies (1.0 to 1.2 GeV) with different bursting modes: quasi-continuous emission and repetitive bursts separated by several thousand turns. The bursting threshold scales linearly with beam energy, as predicted by theoretical models [24]. This kind of THz pulses may be of interest for experiments requiring far-infrared radiation at high repetition rate.

Worldwide First EEHG Signal at a Storage Ring

The EEHG seeding scheme is based on the manipulation of relativistic electrons with two femtosecond laser pulses, enabling the generation of ultrashort radiation pulses at high harmonics of the laser wavelength. The EEHG method was proposed in 2009 [7] and demonstrated in 2012 at linear accelerators [25], but its application to storage rings has not yet been verified so far. The SPEED project (Short-Pulse Emission via Echo at DELTA) was initiated to demonstrate the EEHG principle at the DELTA storage ring for the first time worldwide [8–10]. In order to meet the hardware requirements, the U250 was substantially rewired during summer shutdown 2022 to create two modulators, two chicanes and one radiator [26]. The reconfiguration allows to implement EEHG in a single compact straight section within a length of 4.75 m [9].

Initial coherent emission at 267 nm was observed in September 2022, confirming the basic functionality of EEHG as this wavelength could not be explained by CHG alone [9]. First signals at shorter wavelengths (160 nm and 114 nm) were detected in June 2024 [10, 11]. While the current setup is not optimal due to its short undulators and limited modulation capabilities, it offers valuable insights into the potential of EEHG for storage rings.

Single-Electron Operation

Since February 2023, the DELTA storage ring has been repeatedly operated with a single (0.42 pA) or a small number of electrons at an energy of 1.5 GeV [27]. To achieve single-electron operation, a low initial current is injected into the ring, followed by scraping that progressively removes electrons until only one remains. At beamline BL 4, single photons from the undulator U250 are counted using a photomultiplier tube connected to a digital oscilloscope sampling the signal every 10 ns over a period of 1 s. Photon counting rates show discrete steps corresponding to each electron loss. This experimental setup opens new possibilities for studying SR quantum effects and enhances diagnostics capabilities for accelerator physics research.

Machine Learning Applications

Due to its high availability of beam time for accelerator physics studies, the DELTA facility offers an excellent test environment for the development of novel innovative machine

learning-based (ML) control and optimization methods. Potential use cases cover a wide range of applications [28]. Until now, a neural-network (NN)-based orbit correction (an alternative for the SVD-based method) [29], as well as NN-based feedback systems to control the betatron tune and chromaticity values of the storage ring [30, 31], have been successfully implemented. Moreover, the electron transfer rate from the booster synchrotron to the storage ring (injection efficiency) can be optimized automatically through the support of ML-based algorithms [32]. Furthermore, convolutional multilayer neural networks were applied in the analysis of CHG-based radiation spectra [33].

Prototype Design of Time-of-Flight Spectrometers

As part of the BMBF-funded SpeAR-XFEL project, a prototype electron time-of-flight detector was developed for angular streaking applications [34] which enables a non-invasive measurement of X-ray pulse shapes with sub-fs resolution. The detector design includes electrostatic lenses and drift tubes optimized for broad energy windows. Initial tests at DELTA's beamline BL 5 successfully measured arrival times of electrons emitted by Argon atoms during Auger-Meitner transitions. The experimental results matched theoretical expectations but were influenced by Earth's magnetic field. Future improvements include shielding against magnetic fields using mu-metal layers and enhancing mechanical stability [35].

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