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cSTART – A COMPACT ELECTRON STORAGE RING FOR NON-EQUILIBRIUM ACCELERATOR RESEARCH AND TECHNOLOGY

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Abstract

The goals of the compact STorage ring for Accelerator Research and Technology (cSTART) at Karlsruhe Institute of Technology (KIT), are to demonstrate the storage of ultra-short electron bunches and to investigate their non-equilibrium dynamics. Furthermore, it aims to study the application of laser-plasma accelerators (LPAs) as injectors for storage rings.

To achieve these goals, cSTART has a specifically designed flexible magnetic lattice with large momentum acceptance that can be tuned to ultra-low momentum compaction factor operation. cSTART will have two independent injectors: FLUTE (Ferninfrarot Linac und Test Experiment) and an LPA.

In 2024, the collaboration between KIT, RI Research Instruments GmbH, and its subcontractors completed the Technical Design Report (TDR), followed by the Final Design Report (FDR) until mid-2026. Most magnets and power supplies for the injection line (IL), which will connect FLUTE to the storage ring, are already available at KIT. Some of the diagnostics were delivered and are being tested at KIT, the others are in production. Magnets, power supplies, and vacuum chambers for the storage ring are currently in production. This article provides an overview of the current status and outlines the next steps of the cSTART project.

MOTIVATION FOR cSTART

The scientific objectives of the compact STorage ring for Accelerator Research and Technology (cSTART) project [1] are the proof of concept for the injection and circulation of ultra-short electron bunches in a storage ring and the demonstration of laser-plasma accelerators (LPAs) as injectors for storage rings, i.e.:

(i) the injection of ultra-short electron bunches and their circulation,

(ii) studies of injection of electron beams that are generated by novel LPAs, and

(iii) research program to investigate nonlinear non-equilibrium dynamics, ultimately the phase-space manipulation, and control of ultra-short bunches in a storage ring.

The experiments performed at cSTART have the potential to have a paradigm-shifting impact on future accelerator complexes. To achieve this objective, Karlsruhe Institute of Technology (KIT) plans to initially inject ultra-short electron bunches from the linac-based FLUTE accelerator. One technological objective of the cSTART project is to build a very large momentum acceptance compact electron storage ring (VLA-cSR) at KIT. The VLA-cSR has a flexible magnetic lattice and vacuum design that supports different optics: one with a momentum acceptance of up to 4 % suitable for straight injection of LPA-generated beams [2] and one that allows circulation of ultra-short electron bunches with a duration of femtoseconds to a few picoseconds [3].

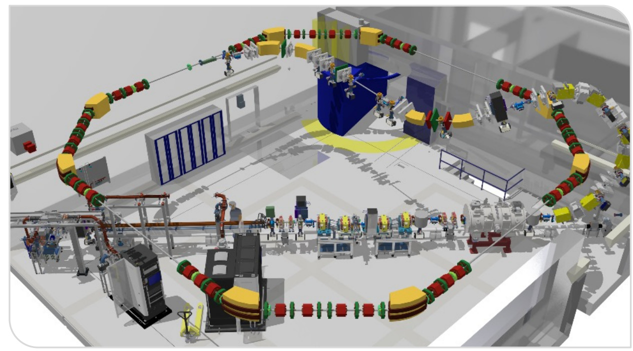

Figure 1: Artistic view of the cSTART project. The VLA-cSR at a height of about 4.5 m is connected to the FLUTE injector (1.2 m above ground floor) by a complex 3D injection line.

With a circumference of less than 45 m and an energy operation range of 40 MeV to 90 MeV, the design of the VLA-cSR is also focused on compact size and energy efficiency as part of KIT's portfolio to develop technologies for compact and energy-efficient accelerators. Figure 1 gives an artistic overview of the accelerator complex.

FLUTE [4], [5] will be used as one of the injectors for the VLA-cSR. FLUTE was upgraded to produce a wide range of electron pulses with a charge of 1 pC to 1 nC, bunch length of a few fs to 300 fs, and energy between 40 and 90 MeV. Using the FLUTE bunch compressor (BC) and the injection line (IL) the operators will tune the electron beam to ultra-short bunches just before the septum. The ultra-short duration of the electron bunches that circulate in the storage ring causes the emission of coherent synchrotron radiation with frequencies of up to tens of THz, leading to substantial energy loss and results in rapid, very rich and highly nonlinear dynamics [6]. As mentioned previously, part of the scientific program of the VLA-cSR is to study this non-equilibrium

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phase-space dynamics. In the future, LPAs will be investigated as injectors for the VLA-cSR [7]; [8]; [9]. LPAs are compact accelerators that generate electron bunches from nearly 1,000 times shorter acceleration distances than current RF-based machines. The simulation of a first LPA injector design for cSTART shows the generation of approximately 20 fs bunches with a charge of nearly 100 pC and an energy of 90 MeV from an acceleration distance of only 1 mm, albeit with a comparably large energy spread of nearly 2%. The LPA will be driven by a terawatt laser system, which was built through the Helmholtz ATHENA project at KIT.

STATUS OF THE cSTART PROJECT

Vacuum Chamber

The ultra-high vacuum system of the injection line as well as the VLA-cSR ring was designed to operate with a pressure of 10^{-8} mbar or lower [10]. A requirement is the usage of oil- and polymer-free components and vibration-free pumps during operation throughout the system. Full-metal gate valves equipped with RF-shields are used to separate the four arc and four straight sections of the VLA-cSR with a magnetic permeability of far less than 1.05 in the vicinity of the electron beam. The beam pipe has DN63 flanges and transitions to rectangular-shaped chambers in the arc dipole magnets (inner size: approximately $36 \times 64\,\mathrm{mm}^2$) via appropriate tapers. Due to the very compact design of the VLA-cSR, some components, such as the BPMs or bellows (also equipped with RF shields), have been welded into the vacuum chamber assembly. The dipole vacuum chamber has been designed to out-couple a maximum horizontal and vertical angle of synchrotron radiation, mostly in the THz range. In the beginning, these light ports will be equipped with view-ports made of high resistivity float zone silicon with an undoped resistivity of $\geq 10\,000\,\Omega\,\mathrm{cm}$.

Magnets and Power Supplies

The dipole (Danfysik A/S), quadrupole and sextupole magnets (both Scanditronix Magnet AB) for the first two sections of the FLUTE injection line (IL) and their power supplies are delivered to KIT after successfully passing the factory (FAT) and site (SAT) acceptance tests. KIT will deliver the magnets mid-2026 to RI so that they can be mounted on the IL girders. The dipoles and sextupoles for IL section 3 are in production to be ready for delivery from Scanditronix to RI mid 2026, followed by the Scanditronix magnets for the VLA-cSR. The 8 dipoles and 40 quadrupoles of the VLA-cSR are in production, and 28 of the quadrupoles have successfully passed the FAT. The FDRs for the 48 sextupoles, the 8 octupoles and the three types of correctors for the VLA-cSR are approved [11]; the yoke material is in stock.

The cSTART power supplies, provided by CAEN ELS, are high-stability units ordered and in production, with delivery expected in Q4/2026, and will be installed in two cabinets: one housing two water-cooled dipole power supplies (two families) and six air-cooled sextupole power supplies, and the other five water-cooled quadrupole power supplies (five families). The corrector power supplies, provided by iTest, have already been delivered to KIT.

Injection Straight

cSTART will have a quasi one-turn on-axis injection. The septum and kicker magnets, as well as the septum pulser electronics are in production. The kicker and its pulser electronics are designed and manufactured by RI and are currently undergoing optimization to suppress the magnetic field as effectively as possible after one revolution. RI is also manufacturing a motorized screen that will allow operators to diagnose the stored electron beam and part of the following injected bunch in parallel.

Diagnostics Hardware and Electronics

cSTART will be operated using the following diagnostics: screens, beam loss monitors (BLM), beam position monitors (b-BMP, c-BPM) and current monitors (ICT, TurboICT). All essential beam diagnostics for the cSTART operation have been designed, ordered, and a large part of the instrumentation has arrived at KIT. Both the injection line (IL) and the VLA-cSR will have pneumatically driven screen stations, except for one which will be motorized in the injection straight. All stations are based on YAG screens and CCD cameras, which will be used for beam orbit alignment during commissioning, as well as for beam emittance measurements. Beam position monitors (BPM) are based on button-BPMs following the ESRF design. In the VLA-cSR, 29 b-BPMs will be installed between magnets in the arc sections and will be read-out by Libera SPARK ERXR from I-Tech Instrumentation Technologies d.o.o. In the IL, in addition to seven b-BPMs that will be read by Libera SPARK EL; four cavity BPMs (Beam Position Monitors, [12]) with their DBPM3 readout box will be installed [13]. For charge measurements in the IL, two Turbo-ICTs (Integrating Charge Transformers) will be used with their BCM-RF-E electronics from Bergoz . In the VLA-cSR, a standard Bergoz ICT will be connected to a Libera Digit 500 digitizer to provide turn-by-turn charge measurements. The beam loss system is based on plastic scintillators and photo multipliers serving as beam loss detectors (BLDs), which will be read out by the Libera BLM readout box. More than 40 BLDs will be installed outside the vacuum chamber at potential loss positions. For tune measurements, a stripline kicker is designed to kick the beam in both planes in the VLA-cSR, and the tunes will be measured using a bunch-by-bunch feedback system from Dimtel Inc.

Support Structure and Girders

The VLA-cSR and the injection line for the transfer of electrons from the source to the VLA-cSR, will be installed in the existing FLUTE experimental hall on the KIT North Campus. This reduces the costs of building and infrastructure, provides radiation protection, and gives the advantage of a negligible concrete shrinking rate. To realize a compact overall footprint that includes the VLA-cSR, the injection

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line, and the injector, the VLA-cSR will be installed at a height of approximately 4.5 m, while FLUTE will remain at a level of 1.2 m diagonally in the hall. To mitigate concrete shrinkage, which amounts to between 0.2 and 0.5 mm/m within the planned minimum service life of 20 years, the VLA-cSR is mounted on a 3.3 m high steel platform. The injection line girders that bridge the different levels of FLUTE and VLA-cSR are also made of steel to ensure the same expansion coefficient. The injection line is specifically designed to deliver ultra-short electron bunches from FLUTE to the VLA-cSR while bridging the height difference [14]. In parallel to the cSTART project, which combines the VLA-cSR with FLUTE as electron source, an LPA will be added as an injector at the level of the VLA-cSR.

Installation and Adjustment

Most of the heat loads are located in the dipole, quadrupole, and sextupole magnets and are dissipated via cooling water. In addition, recirculating air coolers will be installed in the basement, on the ground floor, and on the storage ring level to maintain room temperature at a constant level with a precision better than 0.5 K. The cooling water pipes are fixed to the hall wall, whilst the manifolds are mounted either on the hall wall or on their own supports. Plastic hoses run from the manifolds to and from the magnets. This is intended to minimize the transmission of vibrations from the cooling water system to the magnets. The cables supplying power to the magnets and the cables to and from the diagnostic components are routed separately from the racks, which are mainly located in the basement, via different cable trays beneath the stage to the girders and their base and from there to the respective components to reduce electromagnetic noise. Next to the feet of the girders are girder alignment units, and above the girders are magnet positioning units to align the components on the girder level and the girders to each other once the storage ring and injection line have been installed. Components such as magnetic yokes and cavity-BPMs are fitted with fiducial so that precise alignment with laser trackers of down to about 120 μm can be carried out before the final alignment is performed using the electron beam.

Control System

We will use the already-established EPICS-based control infrastructure that previously supported FLUTE, while taking advantage of the FLUTE downtime to modernize the entire software stack and workflow [15]. Specifically, we will upgrade all controls-related subsystems, including a new graphical user interface (GUI) and related middle-layer services [16]. We are currently in the process of preparing the on-site integration of all control-system-related components.

Timing System

cSTART will be installed with its own timing distribution system following the main FLUTE timing system. This ensures that all diagnostic units of FLUTE, the IL and the VLA-cSR are synchronized with the FLUTE laser beam at the cathode in the electron source, as well as with the septum and kicker in the injection line of the VLA-cSR. The main is the EVR event-receiver in the low-level radio-frequency (LLRF) cabinet, and the other type of EVR is distributed throughout the accelerator. The EVR is placed in the so-called VME crate providing the electrical power for the EVR card.

CONCLUSION AND OUTLOOK

Based on KIT specification, KIT hired RI as the main contractor and its sub-contractors with the preparation of the Technical and Final Design Reports (TDR and FDR). After a well-defined work split, the FDR has been finalized by RI and KIT. In parallel, components such as vacuum chambers, magnets, power supplies, diagnostics, and girders are in production, and the first components are being tested on an FAT level or have already been delivered. RI plans to begin assembling the first girder in the second half of 2026 and to install the cSTART hardware for the VLA-cSR and the IL at KIT in 2027. KIT plans to rebuild FLUTE and begin commissioning in 2028.

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REFERENCES

[1] M. Schwarz, A. Bernhard, E. Bründermann, D. El Khechen, B. Härer, A. Malygin, *et al.*, "Recent Developments of the cSTART Project", in *Proc. 67th ICFA Adv. Beam Dyn. Workshop Future Light Sources (FLS'23)*, Luzern, Switzerland, Aug.-Sep. 2023, pp. 155–158. doi:10.18429/JACoW-FLS2023-TU4P34

[2] A.I. Papash, E. Bründermann, A.-S. Müller, R. Ruprecht, and M. Schuh, "Design of a Very Large Acceptance Compact Storage Ring", in *Proc. IPAC'18*, Vancouver, BC, Canada, Apr. 2018,, pp. 4239–4241, doi:10.18429/JACoW-IPAC2018-THPMF071

[3] A. Papash *et al.*, "Quasi-isochronous conditions and high order terms of momentum compaction factor at the compact storage ring", in *Proc. IPAC'24*, Nashville, TN, May 2024, pp. 3039–3042. doi:10.18429/JACoW-IPAC2024-THPC27

[4] M.J.Nasse *et al.*, "First THz Light Generated in High Engery Section of FLUTE", in *Proc. IPAC'25*, Taipei, Taiwan, May 2025, pp. 1186–1188. doi:10.18429/JACoW-IPAC2025-TUPM010

[5] https://www.ibpt.kit.edu/flute.php

[6] M. Schwarz *et al.*, "Impact of the cSTART impedance on beam dynamics", in *Proc. IPAC'25*, Taipei, Taiwan, Jun.

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2025, pp. 2160–2163.
doi:10.18429/JACoW-IPAC2025-WEPM080

[7] N. Ray *et al.*, "Laser-plasma injector for an electron storage ring", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 557–560. doi:10.18429/JACoW-IPAC2024-MOPR44

[8] A. Y. Saw *et al.*, "Laser-plasma electron injector development for the cSTART storage ring" in *Proc. IPAC'26*, Deauville, France, May 2026, paper TUP3046, this conference

[9] D. Squires *et al.*, "Gaussian Process Regression and Bayesian Optimization for a 40 - 90 MeV Laser-Plasma Injector for the cSTART Storage Ring" in *Proc. IPAC'26*, Deauville, France, May 2026, paper TUP3044, this conference

[10] B. Krasch *et al.*, "Conceptual design of the vacuum system of cSTART", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 2499–2502.
doi:10.18429/JACoW-IPAC2025-THPB001

[11] A. Bernhard *et al.*, "Magnetic design of the cSTART magnets", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 1788–1791.
doi:10.18429/JACoW-IPAC2025-WEPB026

[12] B. Keil *et al.*, "Design of the SwissFEL BPM System", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, pp. 427–430.

[13] B. Keil, R. Ditter, M. Gloor, G. Marinkovic, and J. Purtschert, "First Application of a Multiprocessing System-on-Chip BPM Electronics Platform at SwissFEL", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 245–248.
doi:10.18429/JACoW-IBIC2022-TUP12

[14] J. Schaefer *et al.*, "Simulation-based optimization of the injection of ultra-short non-Gaussian electron beams into a storage ring", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 2028–2031.
doi:10.18429/JACoW-IPAC2025-WEPM031

[15] E. Blomley *et al.*, "Management of EPICS IOCs in a Distributed Network Environment Using Salt", in *Proc. ICALEPCS'23*, Cape Town, South Africa, Oct. 2023, pp. 1340–1345.
doi:10.18429/JACoW-ICALEPCS2023-THPDP020

[16] E. Blomley *et al.*, "CSS to Phoebus transition at Karlsruhe Institute of Technology", in *Proc. ICALEPCS2025*, Chicago, IL, USA, Sep. 2025, pp. 1789–1794.
doi:10.18429/JACoW-ICALEPCS2025-THPD087