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CONCEPT AND PRELIMINARY DESIGN OF THE DALI ACCELERATOR LATTICE

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Abstract

The Dresden Advanced Light Infrastructure (DALI) project at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is a visionary initiative to establish a state-of-the-art light source facility, catering to cutting-edge research in materials science, biology, and other interdisciplinary fields. A cornerstone of this ambitious project is the development of an advanced accelerator lattice tailored to meet the unique demands of high-intensity, ultra-bright photon production. This contribution introduces the conceptual framework and preliminary design of the DALI accelerator lattice. Key features include a modular design optimized for stability, flexibility, and scalability, ensuring compatibility with diverse experimental setups. The lattice must integrate advanced beam dynamics solutions to achieve precise control over beam quality, energy spread, and emittance, crucial for generating high-brightness radiation. Early design studies highlight the potential of DALI to set new benchmarks in light source performance. This contribution seeks to engage the accelerator community in refining the lattice design and exploring its applications in cutting-edge research.

DALI CONCEPT

The Dresden Advanced Light Infrastructure (DALI), proposed by Helmholtz-Zentrum Dresden-Rossendorf (HZDR), is a next-generation accelerator-based research infrastructure [1]. Designed as the successor to the ELBE facility [2, 3], DALI aims to explore ultrafast dynamics and strong-field phenomena through high-field terahertz (THz) radiation [4–6] and advanced probe integration—including ultrafast electron diffraction (UED) [7] and high-intensity positron sources (HiPS) [8].

The facility architecture centers around two superconducting continuous-wave (CW) radio-frequency (RF) linear accelerators (linacs), each delivering up to 50 MeV electron beams but tailored for different performance regimes. The first linac (LINAC-1 in Fig. 1) incorporates a superconducting RF (SRF) gun optimized for high-charge, high-repetition-rate operation. It provides up to 1 nC electron bunches at 1 MHz to drive superradiant and optical klystron THz free-electron laser (FEL) beamlines. Additionally, LINAC-1 can operate at 2 MHz with 400 pC bunches for the generation of intense positron beams.

The second linac (LINAC-2) delivers up to 100 pC bunches at repetition rates up to 10 MHz, serving narrowband THz generation as well as high-repetition-rate experiments such as THz/IR near-field microscopy (SNOM) [9,10].

Each accelerator feeds into a set of advanced beamlines optimized for different applications. The superradiant THz and mid-MIR FEL beamlines both provide quasi-narrowband THz pulses with pulse energies reaching up to 1 mJ at repetition rates as high as 1 MHz. These enable strong-field excitation and time-resolved spectroscopy across an extremely broad spectral range. In parallel, the high-intensity positron

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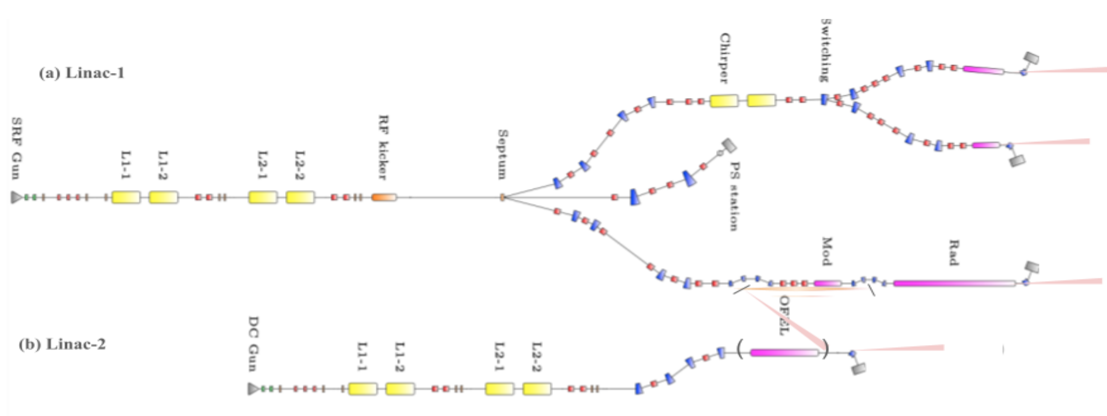

Figure 1: Overview of the DALI accelerator facility layout, consisting of two main accelerator systems: (a) LINAC-1, the primary beamline serving the THz and Positron source; (b) LINAC-2, providing acceleration for advanced high repetition THz applications; and The facility design enables high repetition-rate operation and supports multi-user capabilities with parallel access to distinct scientific instruments.

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Table 1: Representative Beam Parameters for DALI Linacs

Parameter	LINAC-1 (SRF Gun)	LINAC-2 (Thermionic Gun)
Beam Energy [MeV]	up to 50	up to 50
Bunch Charge [pC]	400–1000	100
Repetition Rate [MHz]	1–2	10
Normalized Emittance [mm·mrad]	<3	<5
Energy Spread [%]	<0.1	<0.2
Timing Jitter [fs RMS]	<50	<50

source (HiPS) generates pulsed beams with energies from 0.5 to 30 keV and fluxes up to 10^9 positrons per second, allowing defect studies in materials with high spatial and temporal precision. Table 1 summarises the Representative Beam Parameters for DALI Linacs.

DALI is uniquely positioned to enable frontier research in multiple domains. In condensed matter physics, its THz sources support the study of nonlinear dynamics in quantum materials, including light-induced superconductivity and spin-lattice coupling. In chemistry and catalysis, few-cycle THz pulses allow selective excitation of vibrational modes and surface reactions. For biophysics, DALI enables time-resolved studies of collective water and biomolecule dynamics, in collaboration with initiatives such as the Cluster of Excellence Physics of Life. Moreover, the integrated positron capabilities provide new tools for defect spectroscopy in semiconductors, quantum materials, and battery research.

In alignment with the long-term research strategy of HZDR and the Helmholtz roadmap [11] for photon science, DALI builds upon the ELBE facility and extends its capabilities toward high intensity, high-repetition-rate FEL pulses and ultrafast investigations. Its combination of high-field THz sources and synchronized probes offers new opportunities for precision measurements of electronic, structural, and defect-driven phenomena. As a central infrastructure within the DRESDEN-concept research alliance, DALI will support interdisciplinary collaboration and strengthen the region's role in next-generation light source research.

DALI ACCELERATOR LATTICE AND BEAM OPTICS

The DALI accelerator lattice is designed to deliver high-brightness, low-emittance electron beams with excellent energy and timing stability, supporting a variety of user applications ranging from THz FEL to ultrafast electron diffraction. The lattice includes two independent linac sections based on superconducting CW technology, each optimized for different operational regimes. The linacs incorporate a modular lattice structure with symmetric quadrupole doublets and triplets, supporting flexible optics for high-charge beam delivery. Dispersion-free straight sections and diagnostic insertions ensure precise control over beam properties. Start-to-end first-order optics simulations have been performed by Ocelot [12] and Elegant [13] to assess beam quality and phase space preservation across key beamlines.

The schematic of the proposed accelerator is depicted in Fig. 1. The layout is divided into four sections: injector section, superconducting Linac section including switching yard, Positron source, and FEL sections.

SRF and Thermionic Guns, and Linac Section

The DALI facility employs dual-injector and dual-linac configuration that enables flexible beam delivery. The first accelerator, LINAC-1, is driven by a superconducting radio-frequency (SRF) photoelectron gun [14, 15], capable of continuous-wave (CW) operation. This SRF gun generates high-bunch-charge beams (up to 1 nC) at repetition rates up to 1 MHz, enabling superradiant THz radiation generation and positron production. The SRF gun cavity is based on 3 modified TESLA-type cells and a half cell for velocity matching, featuring a $\beta = 1$, 1.3 GHz structure, optimized for high-current, low-emittance operation with Cs_2Te photocathodes.

The second accelerator, LINAC-2, uses a DC thermionic gun to produce high-average-current electron beams. It delivers 100 pC electron bunches at a repetition rate of up to 10 MHz. This beam is tailored for narrowband THz generation using FEL oscillators and for driving high-repetition-rate ultrafast experiments.

The accelerator cavities of both Linacs are based on 1.3 GHz elliptical designs, adapted from TESLA superconducting technology [16–19] for continuous-wave (CW) operation. Each linac section utilizes high-Q_0 cavities to minimize dynamic losses and enable efficient CW performance at gradients of 10–15 MV/m, ensuring efficient energy consumption during CW operation. The SRF cavities are operated at 2 K in a saturated superfluid helium bath to achieve the required surface resistance and stability. Dedicated CW cryomodules house two 9-cell cavities with individual thermal shields, mechanical tuners, and magnetic shielding to suppress external disturbances. The cryogenic system is supported by a centralized helium refrigeration plant, designed to deliver a stable 2 K supply with minimal pressure fluctuations.

Active microphonics compensation and slow frequency tuners are implemented to stabilize the cavity fields during CW operation, ensuring high beam quality and phase stability. These cryogenic and RF stabilization measures are crucial for maintaining synchronized multi-beam delivery across DALI's experimental stations [20].

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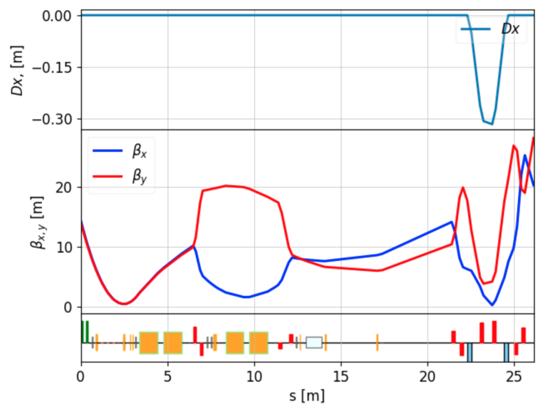

Figure 2: The magnetic lattice and the beam beta functions and dispersion from the SRF gun to the positron source.

To distribute the beam efficiently among these beamlines, DALI employs an RF transverse deflecting cavity (RF kicker) in LINAC-1 [21]. This system enables pulse-to-pulse beam steering at the sub-microsecond scale (273MHz), allowing dynamic delivery of bunches to the THz FEL, broadband THz beamline, and positron converter. The beam switching operates at MHz frequencies with high temporal precision and minimal beam loss.

The Optics of Linac and Positron Source Sections

Figure 2 presents the beam optics and the magnetic lattice from the SRF gun to the positron source. The first accelerating cavity (L1-1) is located 4 meters downstream of the SRF gun, and the RF kicker is positioned approximately 14 meters after the gun. About 1.5 meters downstream of the kicker, a septum magnet separates the beam paths: 1 nC bunches are directed left toward the superradiant THz FEL, right toward the MIR FEL, while 400 pC bunches continue straight toward the positron source (see Fig. 1). To guide the electron beam to the positron converter, a Double Bend Achromat (DBA) cell is employed. This configuration allows for precise suppresses dispersion and beam focusing, ensuring that the 400 pC bunches are transported with minimal emittance growth and energy spread.

The Optics of Mid Infrared FEL Section

The Mid Infrared FEL at DALI utilizes an optical klystron configuration [22] to generate highly coherent and stable radiation for users. The beamline consists of segmented undulator sections and a dispersive section (chicane), optimized for coherent emission in the far-infrared to THz range. In this configuration, the 1 nC electron beam is energy-modulated by radiation extracted from the FEL oscillator (FELO) driven by the LINAC-2 system (see Fig. 1). Achieving high peak current and low slice energy spread is critical for maximizing gain in this setup. The upstream beam optics are carefully designed to minimize the β-functions and suppress chromatic aberrations. A variable R56 section upstream of the undulator allows fine control of bunch compression, enabling high gain seeded operation modes. Figure 3 illustrates the

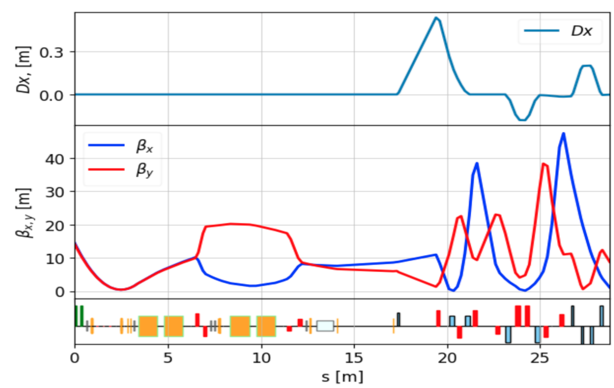

Figure 3: The magnetic lattice and the beam beta functions and dispersion from the SRF gun to the modulator section of the optical klystron.

beam beta functions and dispersion from the SRF gun to the modulator section of the optical klystron. Comprehensive start-to-end simulations, including space-charge and collective effects, are being conducted to evaluate the sensitivity of FEL performance to input beam parameters and compression settings. The results of these studies will be presented in a separate publication.

CONCLUSION AND OUTLOOK

The Dresden Advanced Light Infrastructure (DALI) represents a next-generation light source facility that combines high-repetition-rate, high-brightness electron beams with advanced synchronization and beam delivery systems. The dual-linac architecture, RF kicker-based beam switching, and integrated ultrafast probes will enable new experimental regimes in condensed matter physics, chemistry, biophysics, and materials science.

Initial lattice design and beam dynamics studies demonstrate the feasibility of delivering tailored beam parameters across multiple beamlines, supporting coherent THz generation, ultrafast electron diffraction, and high-intensity positron beams. The modular layout and flexible timing infrastructure are designed to support pump–probe experiments with femtosecond resolution at MHz repetition rates.

DALI is a key component of HZDR's long-term strategy and aligns with the Helmholtz roadmap for photon science. Construction is planned for 2027–2033, with early commissioning phases enabling scientific operation of first beamlines by the early 2030s. The facility will provide a unique experimental platform within the DRESDEN-concept research alliance and offer new opportunities for collaborative research at the frontiers of ultrafast science.

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