Measurement Science and Technology

Check for updates

OPEN ACCESS

RECEIVED
14 July 2025

REVISED
19 November 2025

ACCEPTED FOR PUBLICATION
8 December 2025

PUBLISHED
13 January 2026

PAPER

The first electron beam of Turkish Accelerator and Radiation Laboratory (TARLA): the commissioning of TARLA 20 MeV beamline

Ozlem Karsli[1,2,*], Avni Aksoy[3,17], Michael Betz[4], Esra Cansiz[1,5,18], Evrim Colak[1,6,*], Haris Dapo[1], Veliko Dimov[7], Mustafa Dogan[8,19], Can Dokuyucu[9,20], Michael Kuntzsch[10], Refik Kuyrukcu[1], Mustafa Mutlu[1], Hatice Irem Nalcak[1], Zafer Nergiz[11], Suat Ozkorucuklu[12], Arif Ozturk[1], Kutlu Kagan Sahbaz[1], Ahmet Sahin[13,21], Hasan Sansar[11,22], Muhammed Zeki Senturk[1], Can Taner[1], Hamdi Vural[1], Baris Yildirimdemir[1], Hüseyin Yıldız[1], Mustafa Yuksel[1], Pervin Arikan[14] and Omer Yavas[15]

[1] Turkish Accelerator and Radiation Laboratory (TARLA), Bahcelievler Mah., Ankara University Campus, Golbasi, Ankara 06830, Türkiye
[2] Faculty of Veterinary Medicine, Ankara University, Ziraat Mah., Sehit Omer Halisdemir Bulvari, Altindag, 06110 Ankara, Türkiye
[3] Beam Dynamics Group, Beams Department, European Organization for Nuclear Research (CERN) CH-1211 Geneva 23, Switzerland
[4] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States of America
[5] KVG Quartz Technology Gmbh, Waibstadter Str. 2-4, 74924 Neckarbischofsheim, Germany
[6] Electrical and Electronics Engineering Department, Ankara University, Bahcelievler Mah., Ankara 06830, Türkiye
[7] Dimov Consulting, Geneva, Switzerland
[8] Faculty of Electrical and Electronics Engineering Control and Automation Engineering Department, Istanbul Technical University, Maslak, Istanbul 34469, Türkiye
[9] European XFEL GmbH, Holzkoppel 4, 22869 Schenefeld, Germany
[10] Helmholtz Zentrum Dresden-Rossendorf, Institute of Radiation Physics, Bautzner Landstrasse 400, 01328 Dresden, Germany
[11] Department of Physics, Nigde Omer Halisdemir University, Central Campus, Bor Road, Nigde 51240, Türkiye
[12] Department of Physics, Faculty of Science, Istanbul University, Vezneciler Fatih, Istanbul 34134, Türkiye
[13] Hacettepe Teknokent 5. AR-GE binası, Hacettepe Universitesi Beytepe Kampusu, Cankaya, Ankara 06800, Türkiye
[14] Department of Physics, Faculty of Sciences, Gazi University, Emniyet Mahallesi Bandırma Caddesi No: 6/9, Yenimahalle, Ankara 06500, Türkiye
[15] Department of Engineering Physics, Ankara University, Tandogan, Ankara 06100, Türkiye
[16] Institute of Accelerator Technologies, Ankara University, 50. Yil Yerleskesi Bahcelievler Mah.50 Yil Yerleskesi Bahcelievler Mah., Ankara, 06830, Türkiye
[17] Avni Aksoy contributed while at affiliation 16.
[18] Esra Nur Cansiz contributed while at affiliation 1.
[19] Mustafa Dogan contributed while at affiliation 1.
[20] Can Dokuyucu contributed while at affiliation 1.
[21] Ahmet Sahin contributed while at affiliation 1.
[22] Hasan Sansar contributed while at affiliation 1.
[*] Authors to whom any correspondence should be addressed.

E-mail: okarsli@tarla-fel.org and ecolak@ankara.edu.tr

Keywords: TARLA, the first beam, superconducting linear accelerators, free electron laser, bremsstrahlung radiation, continuous wave (CW) mode of operation

Abstract

Turkish Accelerator and Radiation Laboratory (TARLA) is proposed as the first accelerator-based user facility within the framework of the Turkish Accelerator Center project initiative. Following the completion of technical design studies and infrastructure development, the installation of accelerator components commenced. TARLA is designed to produce free-electron laser (FEL) and bremsstrahlung radiation utilizing state-of-the-art superconducting accelerator technology. The facility aims to operate FELs in the wavelength range of 5–350 µm by accelerating electrons to energies between 15 and 40 MeV, and to generate bremsstrahlung radiation with electrons accelerated up to 30 MeV. As a major milestone, the first stable electron beam was successfully generated in April 2024, marking the completion of the facility's first operational phase. This study presents

the commissioning efforts for the electron beam, outlines the current operational status of the facility, and discusses future plans and the research potential of TARLA.

1. Introduction

Turkish Accelerator and Radiation Laboratory (TARLA) [1–3] is the first accelerator-based radiation infrastructure established as a user facility in *Türkiye*. Currently under development, the TARLA facility is strategically positioned as a bridge between *Europe through the Balkans, the Middle East*, and *Asia*. The facility holds strategic importance in providing user access to accelerator-based research infrastructure for research and development activities. The TARLA facility was officially recognized as a National Research Center under Law No. 6550 in the last quarter of 2020.

The primary objective of the facility is to generate an oscillator-mode free-electron laser (FEL) [4–9] and to produce bremsstrahlung radiation [10]. The FEL at TARLA is expected to attract a diverse global user base due to its continuous wave (CW) beam operation, facilitated by advanced superconducting technology, and its broader wavelength range compared to similar facilities [11].

TARLA is primarily conceived as a user-oriented facility designed to provide both coherent and incoherent radiation sources, enabling a wide range of advanced experimental studies. Coherent radiation in the infrared (IR) and terahertz (THz) spectral regions is generated via a FEL [12, 13], while incoherent radiation, extending from x-ray to gamma-ray energies, is produced through bremsstrahlung processes. This dual-capability infrastructure supports cutting-edge research in materials science, condensed matter physics, chemistry, biology, and accelerator physics. Anticipated experimental applications include time-resolved spectroscopy, pump–probe techniques, nonlinear optical studies, advanced imaging methodologies, and the investigation of low-energy excitations in novel and quantum materials, in addition to photonuclear and radiation-based applications facilitated by the bremsstrahlung source.

At TARLA, bremsstrahlung radiation produced by high-energy electron beams interacting with various metal foils as converter targets is envisioned as a highly versatile tool for a wide range of experimental applications. This radiation enables photonuclear research, including studies of nuclear structure, photofission dynamics, and nucleon emission mechanisms in medium to heavy-mass nuclei. While the primary scientific objective of the bremsstrahlung beamline is to support fundamental nuclear physics research, its utility extends to a broad array of applied studies in radiation physics. These include photoactivation analysis, radiation-induced mutagenesis, food irradiation and preservation, pest control, sterilization procedures, microbiological investigations, and the assessment of radiation hardness in materials and electronic components. This multifaceted functionality underscores the strategic role of the bremsstrahlung facility in advancing both basic science and industrial applications across disciplines.

Additionally, TARLA serves as a testbed for the development of accelerator components and beam diagnostics, thereby contributing to both fundamental and applied research in accelerator technology.

TARLA is intended to serve a broad and interdisciplinary user community comprising researchers from universities, research institutes, and industry, both nationally and internationally. The primary target groups include scientists working in the fields of photonics, nanotechnology, surface science, life sciences, nuclear science and accelerator science. By offering access to advanced radiation sources and beamlines, TARLA aims to foster scientific collaboration and innovation across diverse domains, while also contributing to the development of highly skilled human resources in accelerator-based research.

In the landscape of IR-FEL facilities worldwide such as FELIX (Netherlands), CLIO (France), and ELBE (Germany), TARLA distinguishes itself through its exceptionally broad mid- to far-IR tunability ($\sim$5–350 μm), which extends to significantly longer wavelengths than those routinely provided at the aforementioned facilities. This extended spectral reach will enable experiments in the deep-IR and low-THz regime that are not currently accessible at FELIX, CLIO, or ELBE.

While sources like FELIX ($\sim$1500 μm) achieve longer wavelengths [14], they rely on normal conducting linacs, a technology that inherently yields significantly lower average beam current and energy efficiency compared to TARLA's state-of-the-art superconducting technology. We note that the established superconducting technology at FELBE (Helmholtz Zentrum Dresden Rossendorf (HZDR), Germany) operates up to 250 μm, positioning TARLA as the superconducting facility with the longest wavelength capability in this critical technology class.

The TARLA facility distinguishes itself within the landscape of IR-FEL installations not merely by co-locating an FEL and a bremsstrahlung source, an approach also realized at facilities such as ELBE, but by combining CW superconducting accelerator operation with exceptionally broad mid- to far-IR tunability ($\approx$5–350 μm). This wavelength range extends significantly beyond the limits of leading European

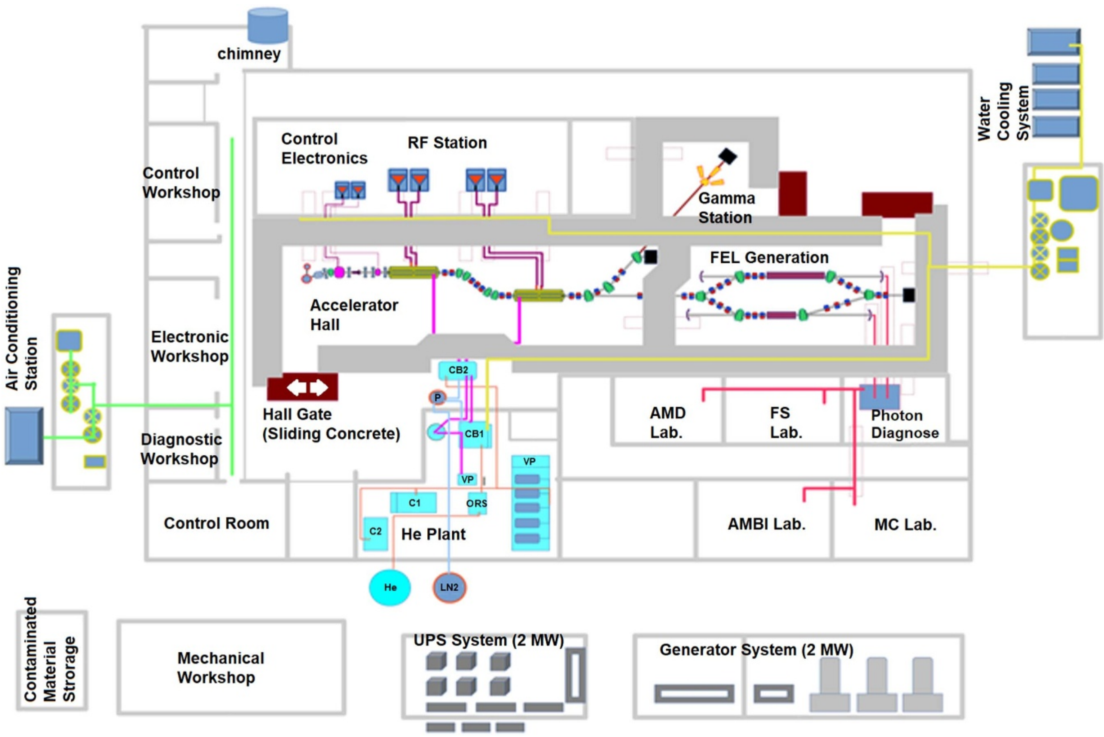

Figure 1. A schematic layout of the TARLA facility [15]. Abbreviations in laboratory (lab.) names: AMD—atomic and molecular dynamics; FS—femtosecond spectroscopy; AMBI—advanced material and biological imaging and MC—material characterization.

IR-FEL centers such as CLIO (≈2–150 µm) [16], and ELBE (≈4–250 µm) [15]. TARLA's extended spectral reach enables experiments in the deep-IR and low-THz regime that are not routinely accessible at these facilities.

In addition to its FEL performance, TARLA integrates a versatile bremsstrahlung γ-ray beamline. Although ELBE also hosts a bremsstrahlung station, TARLA will employ a multi-foil target system consisting of three thin foils (Al, Ta, Nb) and three actively cooled thick foils (C, Cu, W), specifically designed to accommodate both polarized and unpolarized γ-ray generation with enhanced operational flexibility.

The thin foils allow TARLA to reproduce photon fluxes and spectral characteristics comparable to those reported at ELBE and S-DALINAC, thereby enabling direct benchmarking against established CW accelerator-based γ-ray facilities. For on-axis unpolarized operation at 20 MeV, TARLA is expected to deliver integrated photon fluxes of 10^{10}–10^{11} $\frac{\text{photons}}{\text{cm}^2\text{.s}}$ and differential flux values of 0.5×10^6–10^7 $\frac{\text{photons}}{\text{cm}^2\text{.s.keV}}$. These values are consistent with the 2.5×10^{10} $\frac{\text{photons}}{\text{cm}^2\text{.s}}$ observed at ELBE [17] and $\sim 10^6$ $\frac{\text{photons}}{\text{cm}^2\text{.s.keV}}$ at S-DALINAC [18].

Meanwhile, the actively cooled thick foils are approximately an order of magnitude thicker than those typically used at ELBE. This design yields a tenfold (x10) enhancement in photon flux capability, providing substantially higher flux and significantly expanding the accessible γ-ray energy range for high-flux experiments.

Combined with TARLA's status as Türkiye's first IR-FEL user facility and its rare capability of generating polarized bremsstrahlung from a CW accelerator, an operational mode scarcely documented in the literature, TARLA provides a significantly enhanced and flexible γ-ray production platform [19].

In combination with its multi-foil γ-ray beamline, capable of thin-foil benchmarking, thick-foil high-flux operation, and prospective polarized γ-ray generation, TARLA offers a unique combined-modality user environment. As the first comprehensive IR-FEL user facility in Türkiye, TARLA is positioned to provide distinctive opportunities for regional user access, multi-disciplinary studies, and experimental programs requiring sequential or simultaneous use of IR-FEL and γ-ray beams, capabilities not commonly available at FELIX, CLIO, or ELBE.

This study presents the results of the first acceleration achieved using the initial superconducting accelerator module at the TARLA facility and provides an overview of the facility's current status in terms of its installation and commissioning. Figure 1 illustrates the layout of the TARLA facility.

Electrons will be accelerated to energies of up to 40 MeV using state-of-the-art superconducting linear accelerator modules [20], enabling the generation of FEL radiation with wavelengths ranging from 5 to 350 μm. Furthermore, bremsstrahlung radiation will be produced using electron beams accelerated to 30 MeV. The electron beam parameters are summarized in table 1 [21].

In this paper, the second section provides an overview of the TARLA accelerator and FEL system. The third section discusses the infrastructure of TARLA and the systems supporting the accelerator. The fourth section covers the installation and commissioning of the electron gun and the injector line. The fifth section addresses the commissioning of the main accelerator, while the sixth section presents the individual and integrated test results of the first electron beam acceleration at TARLA. The conclusions section provides an overview of the planning activities for the completion of the TARLA FEL installation and the commissioning process aimed at achieving full operational capacity.

2. Overview of the accelerator and FEL system

The initial acceleration of electrons is carried out using a thermionic triode DC electron gun. The injector system delivers a 250 keV electron beam with a maximum bunch charge of 77 pC and a repetition rate of 13 MHz, corresponding to an average beam current of 1 mA in CW mode. The repetition frequency is the 100th subharmonic of the main accelerating frequency of 1.3 GHz. Electron beams are generated at the grid-modulated tungsten dispenser cathode with a pulse length of approximately 500 ps (FWHM). Upon exiting the gun, the electron bunches possess an energy of 250 keV and are compressed in the drift space following energy modulation by the subharmonic buncher (SHB) and fundamental buncher (FB), forming an optimal longitudinal (temporal) profile within the first cell of the first superconducting cavity. The longitudinal bunch length at the entrance of the first superconducting cavity is expected to be around $\sigma_t = 10$ ps [21], where σ_t is the RMS bunch length.

The SHB and FB cavities are realized as normal-conducting coaxial resonators operating in the TM_{010} mode. Their nominal operating frequencies are 260 MHz and 1300 MHz, respectively. Both structures exhibit quality factors on the order of approximately 2000. The effective accelerating gap voltages reach 30 kV for the SHB and 15 kV for the FB, supplied by radiofrequency (RF) power amplifiers with maximum output powers of 1.5 kW and 500 W, respectively.

Additionally, the beam can also be modulated in macro-pulse mode using the macro-pulse system mounted on the injector. The macro pulse mode is used to lower the average beam current in order to be able to use destructive diagnostics such as view screens. The RF systems of the accelerator are usually operated in continuous mode of operation.

The main acceleration section consists of two superconducting RF modules (cryomodules), each housing two superconducting Nb structures (TESLA type cavities) [22] operating at a frequency of 1.3 GHz and a temperature of 1.8 K (superfluid helium). The cryostat and tuning system of these modules were originally designed for the ELBE project [23], and the cryomodules as well as the buncher cavities were fabricated by Research Instruments GmbH [24].

Operating in standing wave mode, TARLA cavities achieve an accelerating gradient of up to 12.5 MV m^{-1} in CW mode. The gun is currently operated at a reduced terminal voltage due to unresolved issues in the isolation transformer, which has exhibited signs of insulation degradation. This condition limits the maximum voltage applicable to the gun, as it increases the risk of high-voltage breakdown within the transformer system. Consequently, the beam energy at the injector exit remains around 200 keV. Since the beam is not yet fully relativistic at this stage, it subsequently gains approximately 7 MeV of energy in the first cavity and an additional 11 MeV in the second cavity with a maximum beam current of 1 mA. A comprehensive discussion of this subject is presented in section 6, titled *The First Beam Acceleration through CM1* of the paper. Ongoing efforts are focused on restoring the high-voltage insulation integrity of the transformer to enable stable gun operation at the nominal design voltage of 250 keV.

To mitigate the impact of the capture process from the injector to the first cryomodule, a magnetic bunch compressor (BC) with a dogleg design will be implemented upstream of the second cryomodule. This system will allow the bunch length to be adjusted from 5 ps down to approximately 400 fs (RMS) [25]. TARLA will employ two undulators with period lengths (λ_u) of 35 mm and 110 mm to cover the wavelength range of 5–350 μm.

The electron beam energy will be adjustable between 15 and 40 MeV. The anticipated FEL parameters corresponding to the specified electron beam characteristics (see table 1) are presented in table 2. The short-wavelength FEL line at TARLA is designed to operate within the 5–35 μm range. To support this objective, the first undulator magnet (U35) has been procured from KYMA [26]. The optical resonator

Table 1. Electron beam parameters of TARLA.

Beam energy	15–40	MeV
Max. average current	1	mA
Max. bunch charge	77	pC
Horizontal emittance	<15	mm.mrad
Vertical emittance	<12	mm.mrad
Longitudinal emittance	<85	keV.ps
Bunch length	0.4–6	ps
RMS energy spread	<100	keV
Bunch repetition rate	26–13 000	kHz
Macropulse duration	50	µs → CW
Macropulse repetition rate	1	Hz → CW

Table 2. Expected FEL parameters of TARLA.

Photon energy	4–300	meV
Wavelength	5—350	µm
Pulse length	0.5—10	ps
Polarization	Linear	—
Repetition rate	13	MHz
Max. pulse energy	2	µJ
Max. peak power	2	MW
Max. outcoupled power	100	W

system for this beamline has been meticulously designed, installed, and successfully tested by the TARLA team [27].

The 20 MeV beamline of TARLA was commissioned in 2024, and the first accelerated electron beam was successfully obtained in April of the same year. To achieve this milestone, the following activities were carried out between 2023 and 2024:

- Installation of the injector line,
- High-power RF conditioning of the SHB and FB cavities,
- Integration and commissioning of the low-level radio frequency (LLRF) system with the RF power systems for the normal-conducting bunchers (SHB and FB),
- Beam testing on the injector line,
- High-power RF conditioning of the superconducting cavities,
- Integration of the injector line with the first superconducting module (Cryomodule-1, CM1),
- Integration and commissioning of the LLRF system [28, 29] with the RF power systems for the superconducting cavities,
- Testing of the 20 MeV accelerator line with the electron beam and achieving the first acceleration from CM1.

The successful implementation of the aforementioned commissioning activities depended on the coordinated deployment and stable operation of essential infrastructure and auxiliary systems, the details of which are presented in the following section. At this stage, the commissioning setup downstream of the first cryomodule was restricted to energy diagnostics, as the primary milestone was to demonstrate acceleration to the target energy. A comprehensive beam characterization will follow in the subsequent phase, once the BC is installed. The BC is specifically designed to accommodate the relevant diagnostics required for detailed measurements of bunch charge, energy, energy spread, bunch length, and transverse emittance.

3. Infrastructure and auxiliary systems

By 2023, the necessary infrastructure for the safe operation of the accelerator at the TARLA facility had been successfully established. This infrastructure comprises an uninterruptable power supply (UPS) system to prevent disruptions caused by power outages, a water cooling system to ensure thermal management of the water-cooled equipment within the facility, and a personnel safety system (PSS) designed to protect both personnel and public health during accelerator operations.

The UPS system at the facility has a full-load capacity of approximately 2.2 MW and can provide uninterrupted power for up to 48 h in the event of a power grid failure. The water cooling system

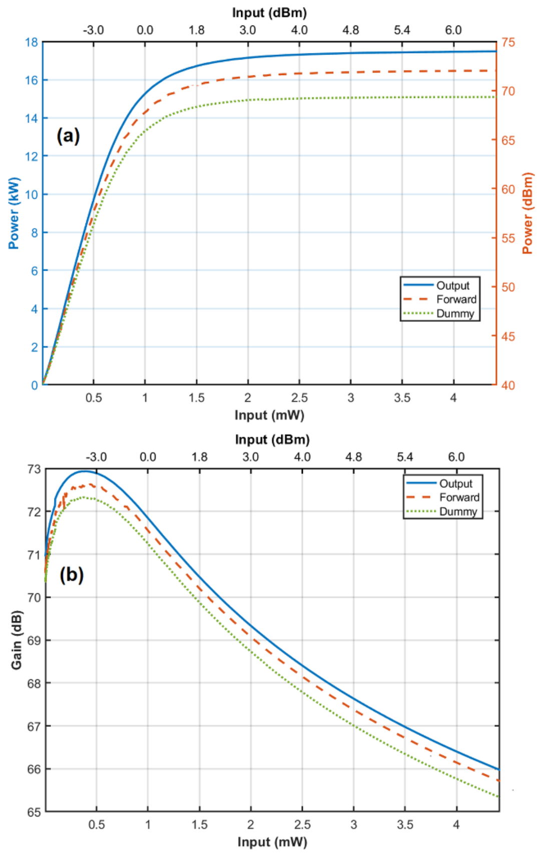

Figure 2. (a) Power transmission and (b) gain characteristics of one of the RF power amplifiers.

is designed to handle a heat load of 1.2 MkCal and can supply cooling water with a conductivity of approximately 200–400 µS cm^{-1} and a pH range of 7.5–7.8.

The PSS, installed by an independent third-party organization [30], is engineered to enforce essential safety protocols before and during accelerator operations. The system features an automated safety interlock mechanism that halts accelerator operations to ensure personnel safety in the event of unauthorized intervention during operation or any accidental incident involving the accelerator.

The TARLA facility is also equipped with a helium cooling system specifically designed [31] to manage a heat load of 210 W at 1.8 K (1.6 $\pm$ 0.2 mbar), ensuring the proper operation of the superconducting cavities within the cryomodules. The commissioning of this system was successfully completed in 2023.

The RF system consists of four solid-state RF amplifiers [32], each with a saturated power of 18 kW. Each cavity is powered by an independent 18 kW RF source based on solid-state transmitters. To accelerate a 1 mA average current, the RF power requirement for each TESLA cavity is more than 10 kW. The power and gain characteristics of one RF amplifier are shown in figure 2. As seen in figures 2(a) and (b), a single CM1 cavity can be driven at 15 kW, achieving an approximately 68 dB gain. However, the cavities and couplers integrated into the cryomodules have been specifically designed to sustain continuous operation at RF power levels of up to 20 kW [33]. Although the design parameters are based on a 1 mA average beam current, infrastructure for an 18 kW saturated RF source has been established to enable operation with a 1.5 mA beam current in the future. An LLRF system has been established for one normal-conducting 260 MHz SHB, one normal-conducting 1.3 GHz FB, and four superconducting 1.3 GHz TESLA cavities. This system is a fully digital system based on µTCA.4, originally developed at DESY [34] for FLASH.

4. Commissioning of the E-gun and injector line

The injector system, consisting of a thermionic triode DC electron gun, two bunching cavities operating at 260 MHz (SHB) and 1.3 GHz (FB), a macro-pulser, five solenoid magnets, a deflector cavity, and two dipole magnets, is entirely based on normal-conducting technology. The beamline of the TARLA injector is illustrated in figure 3.

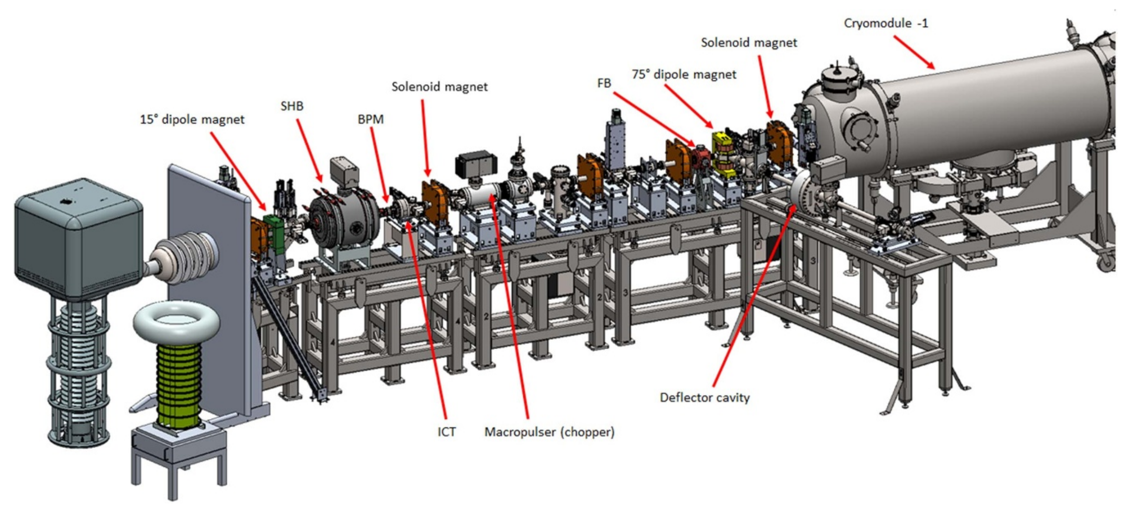

Figure 3. Illustration of the TARLA injector line.

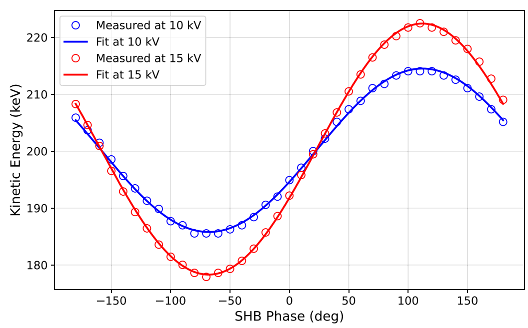

Figure 4. SHB phase scans at two different LLRF amplitudes (blue at 10 kV and red at 15 kV).

The mechanical design of the electron gun was developed in collaboration with the HZDR ELBE Radiation Center [35]. The gun is capable of generating an average current of 1 mA (77 pC bunch charge) at a repetition rate of 13 MHz. Additionally, it can deliver a bunch charge of up to 120 pC to support future upgrades.

TARLA is equipped with a thermionic triode electron gun. It consists of a heated filament (cathode), and an aperture (anode). Electrons emitted by the heated cathode pass through a pulsed grid before being accelerated through the anode at a high voltage of 250 kV. A conventional cathode and a pulse generator are used to generate the electron bunches. The pulser delivers up to 150 V with a pulse width of approximately 500 ps (FWHM) at a frequency of 26 MHz. Although a repetition rate of 13 MHz is sufficient for FEL operation, the pulser frequency was set to 26 MHz in consideration of potential future user demands within the scope of TARLA's upgrade program and the anticipated need for higher frequencies for additional secondary particle production (e.g., positron annihilation studies).

The initial beam tests were conducted with a 200 keV beam due to a high voltage issue with the electron gun. In order to minimize the number of free parameters during the initial tuning phase, the beam transmission through the injector was first optimized using steering magnets and solenoids, while the buncher cavities were kept deactivated. To achieve optimal injector performance, the bunchers are required to operate at the zero-crossing phase. Therefore, they were activated sequentially and a phase scan was conducted to identify the precise phase setting relative to the beam. For each cavity, the cavity phase was scanned over the full range of -180° to 180° at two different amplitude levels to identify accelerating, decelerating, bunching and debunching phases.

The energy measurements were conducted using a 75° spectrometer arm positioned at the end of the injector line. The corresponding measurement graphs obtained during the phase and voltage scans of the SHB are presented in figures 4 and 5. For the sake of conciseness, only the results corresponding to the SHB are presented here.

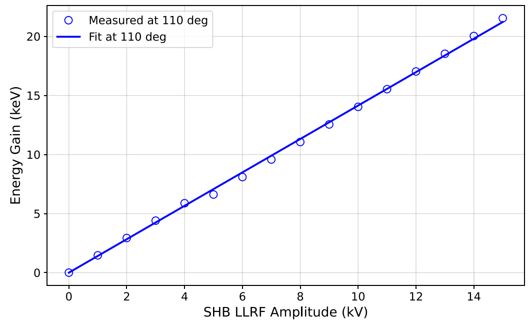

Figure 5. SHB amplitude scan at the accelerating phase (LLRF phase: 110°).

As shown in figure 4, the two zero crossings of the energy gain were determined to be −160° and 20°, while the accelerating and decelerating phases were identified as 110°and −70°, respectively. The longitudinal bunching (LLRF at 20°) and debunching (LLRF at −160°) phases were identified by measuring the transverse RF focusing or defocusing effect of the cavity at the two zero crossings of the energy gain curve. Figure 5 presents the energy gain curve obtained during voltage scans of the SHB at an LLRF phase of 110°. Following the calibration of the SHB, its phase was set to the bunching condition with an effective voltage of 26 kV as defined by beam dynamics simulations.

The same measurement procedure was subsequently applied to the FB to perform its beam-based phase and amplitude calibration. The FB was then operated at the bunching phase with an effective voltage of 15 kV. For both cavities, the LLRF parameters were updated according to the calibration factors derived from the beam measurements.

5. RF commissioning of the cryomodule-1 (CM1)

Upon successful completion of injector tests and establishment of effective bunching, the main accelerator system, CM1, was integrated with the injector line. During this process, meticulous precautions were taken to prevent contamination of the superconducting TESLA cavities within CM1, which were maintained under an ultra-high vacuum of approximately 10^{-10} mbar. Additionally, since CM1 was cooled by superfluid helium, the cavities also functioned as cryo-pumps.

The injector line was maintained under ultra-high vacuum conditions, comparable to those of the superconducting cavities, at approximately 10^{-10} mbar. Prior to the integration, the fifth solenoid magnet, which is the final solenoid in the injector line, underwent an extensive bake-out process. Subsequently, it was connected to the injector line, and equivalent vacuum conditions were ensured. The connection to CM1 was performed with the vacuum valve at the module's entrance kept in the closed position. The vacuum levels of both systems were carefully monitored, and once equilibrium was achieved, the valve was gradually opened. This controlled approach ensured the successful and contamination-free integration of the two systems.

Simultaneously with the connection process, power and gain tests of the high-power RF amplifiers were completed (see figure 2).

Additionally, the integration of the CM1 control units with the machine protection system was finalized, enabling the initial conditioning of both CM1 cavities using high-power RF. During this initial conditioning phase, it was verified that each cavity achieved the expected acceleration gradient of 12.5 MV m^{-1}. The target accelerating gradient of 10 MV m^{-1} was chosen as a design parameter to ensure reliable and stable operation of the TESLA-type superconducting cavities used at TARLA. Although the TESLA cavities can reach technological limits of up to 25 MV m^{-1} or slightly higher depending on the applied fabrication procedures [33], taking into account the available cryogenic power of the facility and the CW operation mode of the accelerator, a gradient of 12.5 MV m^{-1} provides a sufficient and reliable safety margin against quench and field emission. The measurement results for the first conditioning of Cavity 1 (the upstream cavity) in CM1 are presented in figure 6.

The green line represents the drive power from the high-power RF amplifier, operating at a 3% duty cycle (pulse width of 15 ms, period of 500 ms) with a power of 3.6 kW. The yellow line indicates the loaded power in Cavity 1 of CM1, corresponding to an electric field of 12 MV m^{-1} in the cavity.

In parallel with the aforementioned activities, the integration of the LLRF system with CM1 was actively pursued. This process encompassed the main frequency generator of the accelerator (master

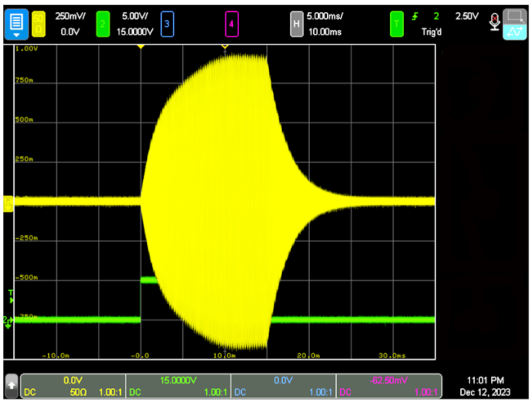

Figure 6. Measurement results recorded at maximum power during the initial conditioning of the first cavity of the CM1.

oscillator), power measurement sensors along the high-power RF transmission lines, cavity probes, motor driver connections, and high-power RF amplifier interfaces. The accuracy of the connection points and signal levels was meticulously verified. The entire system was successfully integrated with the machine protection system, tested, and validated. Subsequently, calibration and fine-tuning procedures were performed within the software to finalize the integration of the cavities in CM1 with the LLRF system.

6. The first beam acceleration through CM1

With the completion of the connection work and system integration, the first beam acceleration process commenced. The initial step involved optimizing the LLRF system to achieve the desired acceleration gradient in the cavities using high-power RF.

Beam physics simulations were performed using OPAL [36], an open-source, parallel computational tool designed for charged particle optics in linear accelerators and storage rings. For energy measurements, a simplified spectrometer, consisting of two steering magnets aligned horizontally and vertically along with a scintillating screen, was utilized downstream of CM1 (see figure 7). Energy measurements were performed by scanning the magnet current and measuring the beam deflection on the scintillating screen. During energy measurements, a comparative analysis was performed based on simulation results.

Phase scans were conducted for Cavity 1 and Cavity 2 within CM1 to determine their operational phase and amplitude settings. Maintaining the stability of the helium cooling system pressure at 1.6 ± 0.2 mbar is crucial for the proper cooling of the superconducting cavities, and even minor phase adjustments could disturb the pressure stability.

To mitigate this issue, the phase scan range was restricted to the interval necessary for accurately determining the acceleration phase. Phase scans of CM1 Cavity 1 were carried out with the LLRF amplitude set to 11 kV. By comparing the measured data and the simulations, the operational phase of CM1 Cavity 1 was determined to be 70°. The results of the phase scan of Cavity 1 can be found in figure 8. Under these conditions, the energy was measured to be 7.77 MeV, since the electron beam has not yet been relativistic when they first enter the first cavity. Subsequently, CM1 Cavity 2 was activated. Phase scans of CM1 Cavity 2 were performed at a moderate LLRF amplitude (7 kV) to prevent beam loss. By comparing the measured data and simulations, the operational phase of CM1 Cavity 2 was determined to be -12 degrees. Under these conditions, the energy after the first accelerating module was measured to be approximately 14.3 MeV. Once the phase scan is completed and the optimal accelerating phase is established, subsequent increases in cavity voltage do not necessitate additional phase adjustments, since the synchronous phase of the beam with respect to the RF field remains unchanged.

The TESLA cavities are designed to accelerate relativistic particles, with their longitudinal dimensions determined by the requirement that the electric field must invert during the time a relativistic particle takes to travel from one cell to the next. Consequently, the cell-to-cell separation is given by $c/2f$ [33]. At TARLA, electrons reaching Cavity 1 from the injector line with an energy of 200 keV are not yet fully relativistic and therefore traverse the first two cells too slowly to remain in phase with the accelerating field. As a result, even when a relatively high RF power (corresponding to an amplitude of 11 kV) is

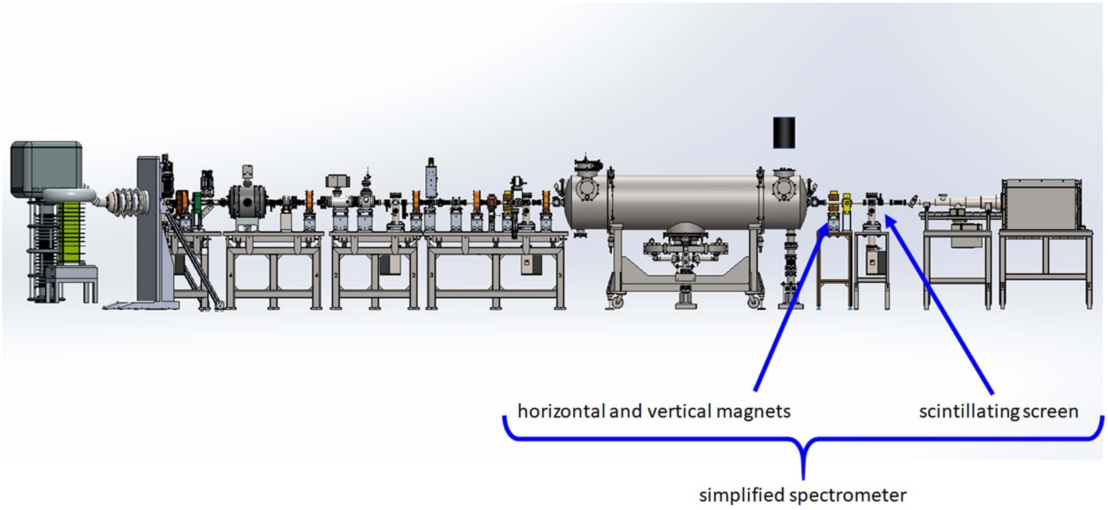

Figure 7. The 20 MeV test bench layout at TARLA.

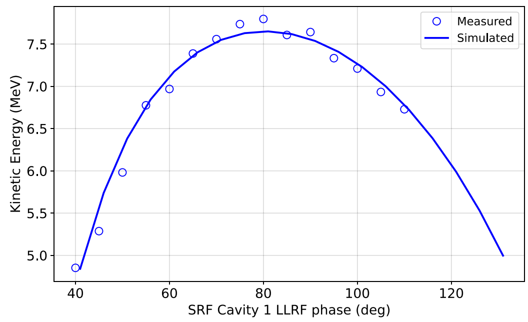

Figure 8. Comparison of SRF Cavity 1 phase scans between simulation and measurement. The simulations were performed at a 97.9% field level.

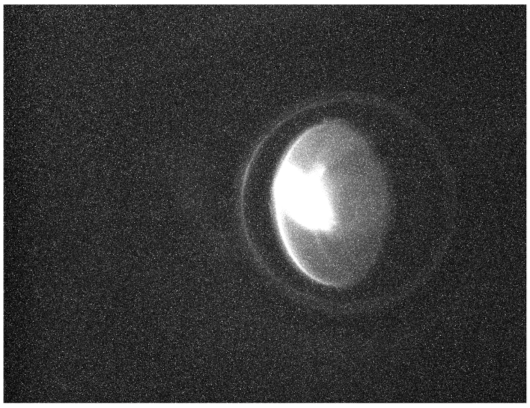

Figure 9. Observation of the first accelerated electron beam at TARLA on a scintillating screen.

applied to Cavity 1, the first two cells are effectively used to accelerate the beam to reach relativistic velocities and to synchronize it to the proper accelerating phase.

Figure 9 shows a snapshot of the first electron beam achieved from the first cryomodule of TARLA. The screen displays the main beam alongside electrons emitted from the surface of CM1 Cavity 2. To prevent any interference with the energy measurements of the main beam, these electrons were deflected using the first horizontal steering magnet of the test bench prior to the energy measurement. The phase scan results for Cavity 2, with Cavity 1 active, are presented in figure 10. After the scans, the LLRF phase

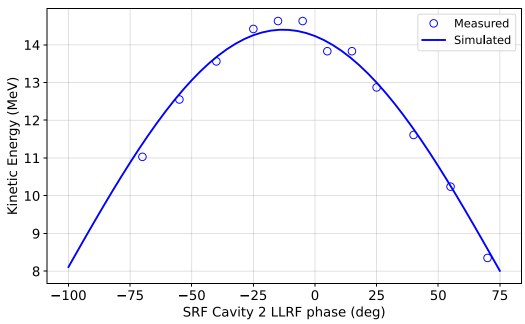

Figure 10. Comparison of SRF Cavity 2 phase scans between simulation and measurement with Cavity 1 active. The simulations were performed for an input energy of 7.77 MeV and at a 66.3% field level.

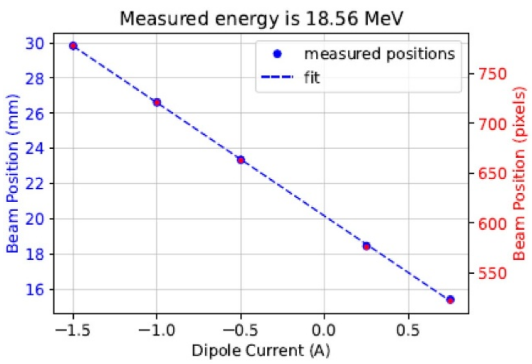

Figure 11. Beam energy measurement showing the final accelerated beam at 18.56 MeV in the optimized TARLA beamline.

of CM1 Cavity 2 was set to −12 degrees, and the amplitude was raised to 12 kV to increase the beam energy. The beam energy at these operating conditions was measured as 18.56 MeV. The measurement results obtained after the optimization process are presented in figure 11.

7. Conclusion

This paper presents the details of the first acceleration operation conducted with the initial superconducting module at the TARLA facility, which is currently in commissioning, and provides an update on the current status of the facility. The results of post-acceleration optimization studies demonstrate that the operationally achieved energy levels are in excellent agreement with the design parameters.

The installation and commissioning processes at TARLA are currently underway. According to the planned schedule, the completion and commissioning of the 40 MeV acceleration line, including the beam compression system, will be prioritized, followed by the commissioning of the bremsstrahlung radiation line, making both available for user experiments. In parallel, the installation of the short-wavelength FEL line is underway, with the aim of enabling first lasing and user operation. Subsequently, the long-wavelength FEL line will be integrated. Provided that key technical milestones, including stable operation of the 40 MeV accelerator, precise beam compression, synchronization of the optical cavity, and electron beam quality within FEL tolerances, are achieved on schedule, **first lasing at TARLA for short-wavelength FEL line is anticipated to take place around 2030**. Compared to similar oscillator-mode FEL facilities employing state-of-the-art superconducting accelerator technology, the TARLA facility will offer a broad wavelength coverage from 5 μm to 350 μm, complementing existing infrastructures worldwide.

In addition, TARLA will integrate a versatile **bremsstrahlung γ-ray beamline** with a multi-foil target system featuring thin foils for benchmarking and actively cooled thick foils for high-flux operation, including the potential for polarized photon generation. Upon reaching full operational capacity, TARLA is expected to serve as a major user facility in the Middle East and Balkans region, complementing global research infrastructures through its unique operational wavelength range and specialized bremsstrahlung capabilities.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work is supported by the Presidency Strategy and Budget Directorate of Türkiye, together with the Scientific and Technological Research Council of Türkiye (TUBITAK). The authors would like to thank Andreas Wagner (HZDR ELBE, Helmholtz-Zentrum Dresden-Rossendorf, Saxony, Germany), Cagil Gumus (Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany), Christian Schmidt (Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany) and the TARLA Facility Team for their valuable contributions during the installation and commissioning phases of the beamline. Special thanks are also extended to Peter Michel (HZDR ELBE) for his significant support throughout the installation and commissioning of the TARLA facility.

Ethical statement

This study does not involve any experiments on humans or animals. All experimental activities were conducted using the TARLA accelerator facility under strict adherence to institutional and national safety regulations. Although secondary x-ray radiation is produced during operation, the facility is fully shielded, and continuous monitoring with high-energy radiation detectors ensures compliance with international radiological safety standards.

Author contributions

Ozlem Karsli 0000-0002-1466-4989
Conceptualization (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Resources (lead), Supervision (lead), Validation (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Avni Aksoy 0000-0001-6926-1522
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Software (lead), Supervision (lead), Validation (lead), Visualization (lead)

Michael Betz 0000-0002-1708-1543
Formal analysis (lead), Methodology (lead), Supervision (lead), Validation (lead), Visualization (lead)

Esra Cansiz 0009-0006-4019-987X
Conceptualization (equal), Formal analysis (equal), Investigation (equal), Methodology (equal), Validation (equal), Visualization (equal)

Evrim Colak 0000-0002-4961-5060
Data curation (equal), Formal analysis (equal), Investigation (lead), Methodology (lead), Software (equal), Supervision (lead), Visualization (equal), Writing – review & editing (lead)

Haris Dapo 0000-0001-9767-1625
Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Software (lead), Supervision (lead), Validation (lead), Visualization (lead)

Veliko Dimov 0000-0002-9910-3186
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Resources (lead), Software (lead), Supervision (lead), Validation (lead), Visualization (lead), Writing – original draft (supporting), Writing – review & editing (supporting)

Mustafa Dogan 0000-0001-5215-8887
Investigation (supporting), Methodology (supporting), Supervision (equal), Validation (supporting), Visualization (supporting)

Can Dokuyucu 0009-0003-2472-1988
Data curation (supporting), Formal analysis (supporting), Investigation (supporting), Methodology (lead), Validation (lead), Visualization (lead)

Michael Kuntzsch 0000-0002-8145-5837
Formal analysis (lead), Methodology (lead), Supervision (lead), Validation (lead), Visualization (lead)

Refik Kuyrukcu
Conceptualization (lead), Investigation (supporting), Methodology (supporting)

Mustafa Mutlu 0009-0008-8971-4718
Conceptualization (lead), Investigation (lead), Methodology (lead), Project administration (lead), Supervision (lead), Validation (lead), Visualization (lead)

Hatice Irem Nalcak 0009-0002-4578-8092
Conceptualization (lead), Investigation (lead), Methodology (lead), Visualization (lead)

Zafer Nergiz 0000-0002-3442-160X
Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (lead), Project administration (lead), Supervision (lead), Validation (lead), Visualization (lead)

Suat Ozkorucuklu 0000-0001-5153-9266
Project administration (lead), Supervision (lead)

Arif Ozturk 0009-0001-6640-6201
Formal analysis (equal), Methodology (equal), Validation (equal), Visualization (equal)

Kutlu Kagan Sahbaz 0000-0001-5491-2265
Data curation (supporting), Formal analysis (supporting), Validation (supporting), Visualization (supporting)

Ahmet Sahin
Investigation (supporting), Methodology (supporting), Validation (supporting), Visualization (supporting)

Hasan Sansar 0000-0001-6763-6191
Conceptualization (supporting), Formal analysis (supporting), Investigation (supporting), Methodology (supporting), Software (supporting), Validation (supporting), Visualization (supporting)

Muhammed Zeki Senturk 0009-0008-2480-9249
Data curation (supporting), Formal analysis (supporting), Investigation (supporting), Visualization (supporting)

Can Taner 0000-0002-6760-6926
Formal analysis (equal), Investigation (equal), Methodology (equal), Validation (equal), Visualization (equal)

Hamdi Vural 0009-0000-5402-425X
Formal analysis (equal), Investigation (equal), Methodology (equal), Validation (equal), Visualization (equal)

Baris Yildirimdemir 0009-0009-3342-5551
Conceptualization (lead), Investigation (lead), Methodology (lead), Project administration (lead), Supervision (lead), Validation (lead), Visualization (lead)

Hüseyin Yıldız 0000-0003-4752-3231
Formal analysis (lead), Methodology (lead), Supervision (lead), Validation (lead), Visualization (lead)

Mustafa Yuksel 0000-0003-4319-3327
Formal analysis (supporting), Visualization (supporting)

Pervin Arikan 0000-0002-5462-3292
Conceptualization (equal), Investigation (equal), Project administration (equal), Resources (equal), Supervision (equal)

Omer Yavas 0000-0002-5724-4968
Funding acquisition (lead), Project administration (lead), Resources (equal), Supervision (supporting), Writing – original draft (supporting), Writing – review & editing (supporting)

References

[1] TARLA. Turkish accelerator and radiation laboratory web (available at: http://tarla-fel.org/) (Accessed 25 May 2025)
[2] Aksoy A, Karsli O and Yavas O 2008 The Turkish accelerator complex IR FEL project *Infrared Phys. Technol.* **51** 378–81
[3] Aksoy A, Karsli O, Aydin A, Kaya C, Ketenoglu B, Ketenoglu D and Yavas O 2018 Current status of Turkish accelerator and radiation laboratory in Ankara: the TARLA facility *Can. J. Phys.* **96** 837–42
[4] Colson W B 1976 Theory of a free electron laser *Phys. Lett. A* **59** 187–90
[5] Deacon D A G, Elias L R, Madey J M J, Ramian G J, Schwettman H A and Smith T I 1977 First operation of a free-electron laser *Phys. Rev. Lett.* **38** 892–4
[6] Piovella N, Chaix P, Shvets G and Jaroszynski D A 1995 Analytical theory of short-pulse free electron laser oscillators *Phys. Rev. E* **52** 5470–86
[7] Saldin E L, Schneidmiller E A and Yurkov M V 1995 The physics of free electron lasers an introduction *Phys. Rep.* **260** 187–327
[8] Piovella N, Chaix P, Shvets G and Jaroszynski D 1996 Theory of short pulse FEL oscillators *Nucl. Instrum. Methods Phys. Res. A* **375** 156–9
[9] Kumar V and Krishnagopal S 1998 A simple theory of gain and saturation in FEL oscillators *Nucl. Instrum. Methods Phys. Res. A* **470** 130–5
[10] Koch H W and Motz J W 1959 Bremsstrahlung cross-section formulas and related data *Rev. Mod. Phys.* **31** 920
[11] Michel P 2008 The radiation source ELBE at the Forschungszentrum Dresden-Rossendorf *IEEE Nucl. Sci. Symp. Conf. Rec.* pp 3078–80
[12] Patterson B D and van Daalen M(eds) 2016 Whitebook on Science with Free Electron Lasers, Fels of Europe Collaboration, PSI Bericht 16-01 (available at: www.fels-of-europe.eu/sites/site_fels-of-europe/content/e212752/e214604/e278214/e286060/Whitebook120517.pdf) (Accessed 25 August 2025)
[13] FELs of Europe Consortium, FELs of Europe webpage n.d. (available at: www.fels-of-europe.eu) (Accessed 25 August 2025)
[14] Claessen V, Barel M, van Buuren R, van der Meer A, Pijpers P and Redlich B 2022 Report on the FELIX wavelength range extension *Proc. FEL2022, 40th Int. Free Electron Laser Conf.* (*Trieste*) PaperMOP33
[15] Helm M *et al* 2023 The ELBE infrared and THz facility at Helmholtz-Zentrum Dresden-Rossendorf *Eur. Phys. J. Plus* **138** 158
[16] Blau J, Cohn K, Colson W B and Vigil R 2013 Free *ELECTRON LASERS IN 2013, Proc. FEL2013* (*New York, NY, USA*) (available at: https://proceedings.jacow.org/FEL2013/papers/wepso01.pdf) pp 486–90
[17] Schwengner R *et al* 2005 The photon-scattering facility at the superconducting electron accelerator ELBE *Nucl. Instrum. Methods Phys. Res. A* **555** 211–9
[18] Sonnabend K *et al* 2011 The Darmstadt high-intensity photon setup (DHIPS) at the S-DALINAC *Nucl. Instrum. Methods Phys. Res. A* **640** 6–12
[19] Zilges A, Balabanski D L, Isaak J and Pietralla N 2022 Photonuclear reactions—from basic research to applications *Prog. Part. Nucl. Phys.* **122** 103903
[20] Kaya C, Aksoy A, Karsli O, Koc B and Elcim O F 2019 *Proc. 9th Int. Conf. on RF Superconductivity (SRF2019)* (*Dresden, Germany*) THP048pp 900–4
[21] Aksoy A, Karsli O, Kaya C, Kazanci E, Aydin A, Koc B, Basaran A, Karakilic V, Korkmaz G and Dursun B 2015 *TARLA Design Report Technical Report* (TARLA)
[22] Aune B *et al* 2000 Superconducting TESLA cavities *Phys. Rev. ST Accel. Beams* **3** 1–25
[23] Büchner A, Gabriel F, Grosse E, Michel P, Seidel W and Voigtländer J (Elbe-crew) *Proc. EPAC 2000* (*Vienna, Austria*) pp 732–4
[24] Research Instruments GmbH, Research Instruments GmbH webpage n.d. (available at: https://research-instruments.de/en/) (Accessed 26 August 2025)
[25] Aksoy A and Lehnert U 2014 Beam transport and bunch compression at TARLA *Nucl Instrum. Methods Phys. Res. A* **762** 54–63
[26] KYMA undulators, KYMA undulators webpage n.d. (available at: https://kyma-undulators.com/?lang=en) (Accessed 25 May 2025)
[27] Yildirimdemir B *et al* 2025 Design, manufacturing, and testing of a high-power optical resonator at the Turkish Accelerator and Radiation Laboratory *Nucl. Instrum. Methods Phys. Res. A* **1081** 170895
[28] Rutkowski I, Rybaniec R, Czuba K, Butkowski L, Hoffmann M and Ludwig F, Schmidt C and Schlarb H 2015 MTCA.4-based digital LLRF control system for CW SRF linacs *IEEE Trans. Nucl. Sci.* **62** 3186–92
[29] Zenker K, Gümüş C, Hierholzer M, Michel P, Pfeiffer S, Schlarb H, Schmidt C, Schurig R, Steinbrück R and Kuntzsch M 2021 MicroTCA.4-Based low-level RF for continuous wave mode operation at the ELBE accelerator *IEEE Trans. Nucl. Sci.* **68** 2326–33
[30] Systemanalyse & Automatisierungsservice GmbH (SAAS), SAAS webpage n.d. (available at: https://saas-online.de/en/home/) (Accessed 25 May 2025)
[31] Air liquide Advanced Technologies (A.L.A.T.), A.L.A.T. webpage n.d. (available at: https://advancedtech.airliquide.com/) (Accessed 25 May 2025)
[32] SigmaPhi Accelerator Technologies, SigmaPhi webpage n.d. (available at: www.sigmaphi.fr/en/) (Accessed 25 May 2025)
[33] Karsli O, Aksoy A, Kaya C, Koc B, Dogan M, Elcim O F and Bozdogan M 2019 High power RF operations studies at TARLA facility *Can. J. Phys.* **97** 1171–6
[34] Forschungszentrum Deutsches Elektronen-Synchrotron (DESY), DESY webpage n.d. (available at: www.desy.de/) (Accessed 25 May 2025)
[35] Gabriel F, Gippner P, Grosse E, Janssen D, Michel P, Prade H, Schamlott A, Seidel W, Wolf A and Wünsch R ELBE-crew 2000 The Rossendorf radiation source ELBE and its FEL projects *Nucl. Instrum. Methods Phys. Res. B* **161-163** 1143–7
[36] Adelmann A *et al* OPAL (available at: https://gitlab.psi.ch/OPAL) (Accessed 25 May 2025)