ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM027

THE FUTURE OF THE CLEAR FACILITY: CONSOLIDATION, ONGOING UPGRADES AND ITS EVOLUTION TOWARDS FUTURE ELECTRON FACILITIES AT CERN

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Abstract

The CERN Linear Accelerator for Research (CLEAR) is a versatile 200 MeV electron linac followed by an experimental beam-line, operated at CERN as a user facility. Its user community includes research groups working on beam instrumentation R&D, advanced acceleration techniques and irradiation studies, including medical applications. A recent internal review has confirmed the excellence of its scientific output and its strategic interest for the laboratory, extending the facility operation until at least 2030. In this paper we discuss the consolidation actions needed for continued operation together with the ongoing hardware improvements and their impact on the future experimental program. These upgrades include a new front-end for the laser system allowing for a highly flexible time structure, better stability and higher repetition rates, plus the implementation of a second beam line whose optics has been designed to match user requirements and will provide additional testing capability. Finally, we discuss the potential role of CLEAR in the path towards future high-energy electron facilities at CERN.

INTRODUCTION

The CERN Linear Electron Accelerator for Research (CLEAR) [1] has been in operation at CERN as a user facility since September 2017, serving a wide and diverse scientific community and covering many research areas, including development of instruments and components for existing and future accelerators and tests of novel concepts such as plasma and THz acceleration [2, 3]. In recent years, the investigation of medical applications of electron beams with energies above 100 MeV (Very High Energy Electrons - VHEE) has also gained prominence and has become one of its main activities [4].

A CERN internal review held in 2024 assessed the opportunity to extend the operation of the CLEAR facility beyond its planned end in 2025. The outcome was positive with the Review Committee commending the achievements of both excellent operational efficiency and outstanding support for user experiments and concluding that continued operation was scientifically justified. As a result, extended operation beyond 2025 has been approved.

A consolidation plan has been under study, and in part already initiated, in order to ensure stable and reliable operation on a longer time scale. The main activities are discussed and described in the following.

The continued exploitation of the CLEAR facility is well aligned with CERN's long-term goals, especially considering its status as the only user facility at CERN accelerating electrons at the moment, and the present general consensus about an e^+e^- Higgs factory as the next CERN flagship project.

LASER CONSOLIDATION PROGRAM AND NOVEL FRONT-END

The production of electron bunches in the Radio Frequency (RF) gun is based on a Cs_2Te photocathode, which operates efficiently under low-pulse energy Deep-UltraViolet (DUV) illumination. One of the main challenges is obtaining a good photocathode lifetime, which depends upon the vacuum conditions in the RF gun. The gun has therefore been designed to maintain ultra-high vacuum conditions, typically below 10^{-10} mbar. In order to mitigate the impact of a limited cathode lifetime on operation, the CLEAR RF gun is also equipped with in-situ photocathode regeneration using built-in Cesium (Cs) evaporators. This setup allows for rapid, on-demand recovery of the photocathode's quantum efficiency [5]. Normally the photocatode lifetime is long enough to grant standard operation over a whole year, and the regeneration is done at the beginning of each yearly run.

The required DUV pulses are produced by a picosecond Nd:YLF oscillator operating at 1.5 GHz repetition rate, amplified by a pre-amplifier and a power amplifier, and followed by a frequency quadrupling stage [6]. The DUV output is centered at 262 nm, with single pulse energies exceeding 1.5 μJ at the photocathode surface, yielding a single bunch charge of up to 7 nC when a fresh photocathode is used. The adjustable pulse trains contain 1 to 120 pulses and are generated at 10 Hz repetition rate. While this system operates reliably, aging of the main components have been identified as a potential source of failure and downtime.

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ISBN: 978-3-95450-248-6 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2025-TUPM027

To enhance the flexibility and reliability of the laser system, a new Electro-Optic Frequency Comb (EOFC) front-end is currently under development. A key advantage of EOFCs is their ability to adjust laser pulse parameters without requiring modifications to the physical setup. Thanks to the wide operational bandwidth of electro-optic modulators, a Continuous-Wave (CW) laser can be used as a seeder. In contrast to ultrafast oscillators based on mode-locking technology, EOFCs enable precise control of the repetition rate by tuning the driving RF signal, which can easily reach up to tens of GHz. Moreover, by integrating a programmable tunable spectral shaper, it will be possible to adjust the pulse duration on demand over a wide range, from 200 fs to 30 ps. The phase coherence of the laser system also enables its use in phase-sensitive applications, such as feeding Fabry–Pérot enhancement cavities for experiments including inverse Compton scattering [7].

Another key advantage of the EOFC is its capability to generate arbitrary temporal pulse train structures. This feature enables the testing of the FCC-ee injector electron beam scheme, including shot-to-shot charge control required for the top-up scheme [8]. The development is carried out in synergy with ongoing efforts for the Gamma Factory Proof-of-Principle experiment at the SPS and the Compton polarimeter for FCC-ee [9]. Approximately 90% of the components required for this upgrade are already available in-house.

THE NEW DOG-LEG BEAM LINE

Near-term improvements to CLEAR include the construction and commissioning of a second beamline. This addition enables the creation of more areas for in-air and in-vacuum testing, reducing the need for frequent mounting and dismounting of experiments and diagnostics equipment. Consequently, available beam time and operational flexibility is expected to increase, allowing for parallel execution of “non-compatible” experiments within the same week or day, with a faster turnaround.

The new beamline has been designed to also broaden the beam parameter space, for example allowing for larger beam sizes and stronger focusing capabilities. The line is composed by a dogleg achromat and a straight beam-line running parallel to the present one. The initial optics design of the beam line [10] has been further modified and improved, adapting the footprint and making use of available quadrupole magnets, and including chromaticity corrections with two sextupoles properly placed in the achromat, in order to cope with the large beam energy spread caused by beam loading effect for high-charge operation.

The new beam line is currently being implemented, mostly using available hardware from the decommissioned CLIC Test Facility (CTF3). Its installation is expected to be completed in summer 2025, and commissioning is scheduled in autumn. A view of the beam line during the installation phase in winter 2024/25 can be seen in Fig. 1.

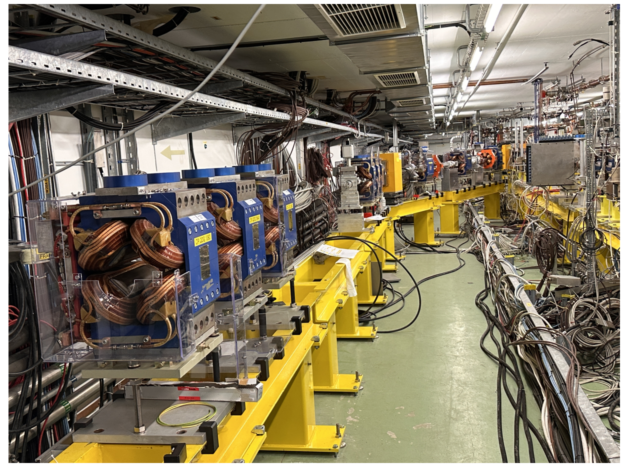

Figure 1: View of the new beam line during installation.

RF SYSTEM AND BEAM INSTRUMENTATION CONSOLIDATION PROGRAM

The facility RF and Beam Instrumentation (BI) systems are largely based on solutions developed more than 20 years ago for CTF3.

The RF modulators were refurbished during CERN Long Shutdown 1 (LS1, 2013-2015), and spare parts are available, but we are now facing scarce availability of the THALES TH2100 klystrons (3 GHz, 35 MW, 5μs) and long delivery delays. The fully analogue LLRF system is outdated and not easily maintainable, mainly due to the use of outdated custom-made solutions for which the know-how is being lost. Nevertheless, it still provides a low-jitter (picosecond-level) timing system with some unique features at CERN. A programme to consolidate RF hardware and strengthen personnel support is currently underway, also benefiting from synergies with ongoing developments for AWAKE and FCC-ee. These efforts include:

- Procurement of new or refurbished klystron tubes;
- Development of a new LLRF system, potentially based on the μTCA technology currently being developed in collaboration with Uppsala University;
- Recruitment of dedicated personnel for the development and deployment of LLRF and timing distribution systems.

This consolidation program is essential not only to maintain the current level of performance, but also to provide an opportunity to enhance the facility’s capabilities — such as improving shot-to-shot and long-term beam stability, enabling faster setup and diagnostics, and potentially increasing the maximum beam repetition rate.

Beam setup and operation at CLEAR still rely predominantly on a limited set of interceptive diagnostics (beam screens) and a few beam intensity monitors [2]. The beam screen/camera systems were recently improved, migrating from analog to digital cameras and introducing advanced concepts like homographic calibration [11]; however, con-

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trol and exploitation software are still under development. While non-interceptive instruments — including beam position monitors (BPMs) and beam loss monitors (BLMs) — are in principle available, they are not yet consistently integrated into routine operation. To address this, a series of dedicated studies and tool developments is currently underway, building on the operational expertise gained over the past years. This effort also leverages novel machine learning techniques to improve diagnostic precision, stability monitoring, and operational efficiency [12, 13].

THE PATH TO FUTURE CERN ELECTRON FACILITIES

The CLEAR programme, although modest in terms of budget and resource requirements, plays—and will continue to play—a central role in the broader CERN accelerator strategy for several key reasons:

- As a testbed for advanced beam instrumentation and methods, it enables the testing and commissioning of prototype systems for both current and future CERN facilities. Numerous examples from past CLEAR runs include contributions to CLIC, AWAKE, and FCC-ee-related developments.
- As a platform for accelerator applications beyond particle physics, it demonstrates the relevance and transferability of CERN's accelerator technologies to societal challenges, including medical and industrial domains.
- As a training ground for the next generation of accelerator and instrumentation experts from CERN Member State institutions, it provides hands-on experience in beam dynamics, diagnostics, and machine operation.

The upcoming Long Shutdown 3 (LS3), scheduled to begin in mid-2026, presents a unique window of opportunity for CLEAR. As one of the few accelerators expected to remain operational during this period, the facility is strategically positioned to absorb increased demand for beam time from both internal CERN users and external collaborations. Although some operational challenges are foreseen—such as disruptions to infrastructure and reduced access to central services—experience from LS1 and LS2 confirms the viability of autonomous operation. Plans are in place to strengthen local access control, improve automation tools, and implement advanced control systems. Importantly, LS3 is also an ideal timeframe for long-awaited control infrastructure modernisation, including the deployment of CERN-wide tools for beam control and performance/fault tracking.

The new beamline under construction and the integration of the novel EO frequency comb laser front-end discussed earlier will open the door to new classes of experiments, such as FLASH radiotherapy, Compton-scattering-based X-ray sources, and beam structure emulation for FCC-ee. With its robust uptime and flexible setup, CLEAR is increasingly seen as a suitable platform for prototyping and integration of FCC-ee injector components. Its similarity to the FCC-ee frontend design further supports this role.

While the FCC-ee studies have not yet matured to the point of requiring a dedicated test facility, this need may arise in the near future as ideas are quickly taking shape. CLEAR already provides a solid foundation for this purpose and is actively supporting FCC-ee-relevant campaigns, particularly in the field of beam instrumentation. Near-term experimental needs could include testing the electron source front-end and studying positron target damage via irradiation—both identified as high-priority items during recent reviews. Today, CLEAR also offers opportunities for coherent radiation studies, supporting longitudinal diagnostics for FCC-ee.

CLEAR could also become a key player in providing test beams for detector R&D in the period 2026-2030, during which other test beams will be scarce, due to the CERN long shutdown LS3 and coincidental shutdown periods in other laboratories.

Beyond its technical contributions, the facility offers a unique environment for the training of students and researchers. Its operational independence from the LHC injector chain allows for a flexible and evolutionary approach to accelerator operation, making it ideal for the development and validation of novel techniques—such as artificial intelligence for accelerator control systems—prior to their broader deployment at CERN. In this context, the continued exploitation and development of CLEAR aligns well with CERN's long-term goals, offering capabilities and training platforms vital for the success of next-generation lepton colliders, and for shaping the accelerator workforce of the future.

Note Added

It is with great sadness that we note the passing of our co-author, Stefano Mazzoni, which occurred during the review process of this manuscript.

ACKNOWLEDGEMENTS

We would like to acknowledge the strong contribution of all CERN technical support groups involved in the consolidation work for the CLEAR facility, and in particular the new beam line construction and installation.

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