

COMPLETION AND BEAM COMMISSIONING OF THE NEW CLEAR BEAM LINE

W. Farabolini*, A. Aksoy¹, R. Corsini, S. Curt, O. Franek, D. Gamba, A. Gilardi, P. Korysko², A. Malyzhenkov³, C. M. Moore, S. Simonsson, G. Tangari⁴, S. Wang², CERN, Geneva, Switzerland
K. Sjobak, University of Oslo, Oslo, Norway

¹Also at Deutsches Elektronen-Synchrotron DESY, Zeuthen, Germany

²Also at University of Oxford, Oxford, United Kingdom

³Also at Swiss International Institute Lausanne (SIIL), Prilly, Switzerland

⁴Also at Sapienza University of Rome, Rome, Italy

Abstract

The CERN Linear Electron Accelerator for Research (CLEAR) is a user facility providing a flexible 200 MeV electron beam for accelerator technology development, radiation studies, and interdisciplinary research. Since its commissioning in 2017, CLEAR has supported a wide range of experiments, often requiring rapid reconfiguration of setups and beam parameters. To address the need for faster turnaround and increased experimental throughput, a new beam line branching from the existing experimental area has been designed, constructed, and commissioned. This addition enables simultaneous preparation or operation of multiple experiments, reducing downtime between user programs. The new line also extends the available range of beam parameters, allowing, for instance, operation with tailored transverse beam sizes at the in-air test stand. This paper presents the design and implementation of the new beam line, reports on its hardware installation and beam commissioning results, and outlines the expected improvements in flexibility, beam quality, and operational efficiency for the CLEAR user community.

INTRODUCTION

The CERN Linear Electron Accelerator for Research is a versatile electron linac facility operated as a user platform since 2017, following the repurposing of the former CLIC Test Facility 3 (CTF3) infrastructure [1,2]. It provides electron beams with energies in the 30–220 MeV range, 10 pC–75 nC per pulse, and flexible bunch structure (from single to multi-bunch operation with picosecond-scale bunch lengths), making it uniquely suited for a wide variety of experimental applications. Designed as a flexible, multi-user facility, CLEAR serves a broad and interdisciplinary scientific community [3–7]. Its program includes accelerator R&D, such as studies of high-gradient acceleration, plasma-based focusing, and THz-driven beam manipulation, as well as the development and testing of advanced beam instrumentation with high temporal and spatial resolution. In addition, the facility is used for radiation effects studies in collaboration with external partners. In recent years, medical applications have become one of the primary research directions at CLEAR, representing a significant fraction of

the available beam time, and the facility has played a key role in the investigation of Very High Energy Electron (VHEE) beams for radiotherapy [8]. A 2024 internal review confirmed the excellence of CLEAR's scientific output and its strategic importance for the laboratory, approving continued operation beyond 2025 at least until 2030 [7]. The facility is the only accelerator at CERN currently providing electron beams to users, a role that takes on heightened strategic significance given the broad consensus around an e^+e^- Higgs factory as CERN's next flagship project [9].

To accommodate growing demand and broaden the parameter space available to users, a second beamline branching from the existing experimental area has been designed, constructed, and commissioned. This new line, based on a dogleg achromat, provides additional in-air and in-vacuum testing space, reduces the need for frequent mounting and dismounting of experiments, and enables the parallel execution of otherwise incompatible experiments within the same day or week [7, 10]. The design also incorporates larger-aperture quadrupole magnets, broadening the achievable transverse beam size and focusing range [10]. This paper describes the final as-built layout of the new beamline, which is optimised from that reported in [10], reports on its first beam commissioning results, and concludes with an outlook on future experiments.

BEAMLINE DESCRIPTION

The layout of the new beamline is shown in Fig. 1. The beamline branches from the existing CLEAR experimental line at the location of the dipole magnet previously used to direct beam onto the VESPER test stand. A dogleg achromat composed of two dipole magnets bends the beam by 22° in each dipole, creating a second 10 m-long beamline displaced approximately 2 m transversely and parallel to the original beamline, with sufficient clearance for access to both sides of the new line. The quadrupoles used for the new beamline have been recovered from the CTF3 Combiner Ring [11], and all have a 100 mm diameter aperture, maximum gradient of 8.198 T/m, and magnetic length of 293 mm. The dogleg section hosts three such quadrupole magnets (QFG 130, QFG 170 and QDG 155 in Fig. 1) to eliminate the residual dispersion introduced by the dipoles: a defocusing quadrupole is positioned at the centre of the dogleg, flanked

* wilfrid.farabolini@cern.ch

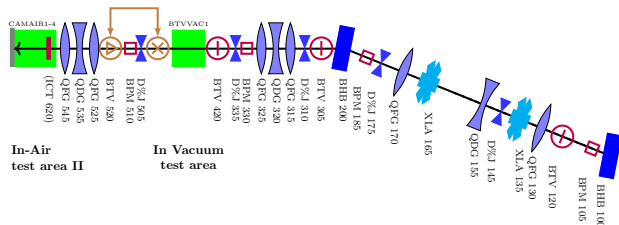


Figure 1: Layout of the second beamline at CLEAR. The beam goes from right to left.

by two focusing quadrupoles placed symmetrically between the midpoint and each dipole. Two sextupole magnets (XLA 135 and XLA 165 in Fig. 1), also from CTF3, capable of giving an integrated field of 6.568 T/m at 100 A [12]) have been incorporated into the achromat at appropriate phase-advance locations to provide chromaticity correction, which is particularly important for high-charge operation where beam loading produces a significant energy spread. The dog-leg achromat has design value of R_{56} of -0.0235 m, which could be used for bunch lengthening/compression if proper energy chirp is set.

A beam profile monitor (BTV screen) is installed between the first dipole and the first quadrupole of the dogleg and can be used as a spectrometer. This station, shown in Fig. 2, also hosts a series of tungsten slit collimators mounted on motorized movers, which can reduce the beam intensity down to a few particles per pulse and reduce the energy spread, potentially enabling a new class of experiments requiring single-electron delivery. Two inductive Beam Position Monitors (BPMs), also recovered from CTF3, are installed at the extremities of the dogleg to monitor the beam trajectory and the beam energy, in a non-destructive way [10].

The straight section hosts two quadrupole triplets. A first triplet controls the beam immediately downstream of the dogleg exit and can be used to match the desired beam optics into a first 2 m-long in-vacuum experimental section (in green in Fig. 1). A second triplet downstream of this section, and installed around a 80 mm diameter beampipe, controls the beam parameters at the final in-air experimental region (also in green in Fig. 1). The larger vacuum chamber aperture compared to the existing beamline (predominantly 40 mm) allows operation with significantly larger beam sizes and stronger final focusing in both transverse planes simultaneously. Orbit correction is provided by a set of dipole corrector magnets (labeled “D%J” in Fig. 1) distributed along the beamline. Two additional BPMs and two scintillating screens are installed along the straight section to monitor and correct the beam trajectory and to measure the transverse beam profile for matching to user requirements. Before the final triplet, a dual-scattering system (in brown in Fig. 1) — consisting of a pre-scatterer and a scatterer, as previously implemented on the existing CLEAR in-air test area [13] — is installed to produce transversely uniform beams, as often required for irradiation experiments.

An alignment system based on a Structured Laser Beam (SLB) [14] is installed along the new beamline. The SLB is

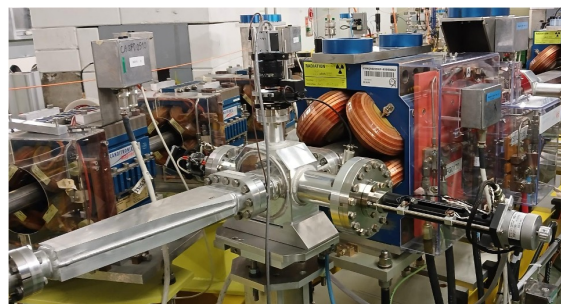


Figure 2: First BTV station downstream of the first dipole. The two movers allow insertion of tungsten slit collimators to select a few particles per pulse.

a pseudo-non-diffractive optical beam with very low central divergence, down to $10\text{ }\mu\text{rad}$, enabling precise long-distance alignment of beamline components.

At the end of the straight section a beam dump and an in-air test area are provided. Both the in-vacuum and in-air experimental areas are equipped with digital cameras (referred to as BTVVAC1 and CAMAIR1–4 in Fig. 1) for beam profile monitoring. Patch panels with BNC and Ethernet connections are available around the test areas to serve experimental needs. The C-Robot 2.0, an upgraded version of the robotic sample-positioning system used on the existing in-air test area, has been designed and built by the CLEAR team and is planned for installation on the new in-air test stand to facilitate automated irradiation campaigns for medical application studies [15]. The majority of hardware for the new beamline has been recovered from the decommissioned CTF3, minimising cost [7].

FIRST COMMISSIONING WITH BEAM

Following the mechanical installation and electrical connection of the new beamline hardware, the first beam commissioning campaign started in autumn 2025 and was completed during the first quarter of 2026. The commissioning proceeded in stages, progressively threading the beam through the dogleg and then through the full straight section to the dump. After initial beam threading, the dispersion was measured at the BTV screens of the new straight section and corrected using the dogleg quadrupoles. To measure the local linear dispersion independently of incoming orbit offsets and quadrupole misalignments, only the strength of the two dogleg dipoles, connected in series, was varied, and the resulting beam position shift was recorded on the downstream BTVs. This method yields the nominal linear dispersion for a given optics configuration in a model-independent way.

The same procedure was used to characterise the effect of the dogleg sextupoles: scanning the dipole current with the sextupoles powered, produced a clear second-order dependence of the beam position on dipole strength, with an extremum when the beam passes through the magnetic centre of the sextupoles. To also capture non-linear contributions from the quadrupoles, a combined scan of both dipoles and quadrupoles of the dogleg was performed, which mimics an actual change of beam energy. After selecting the optimal

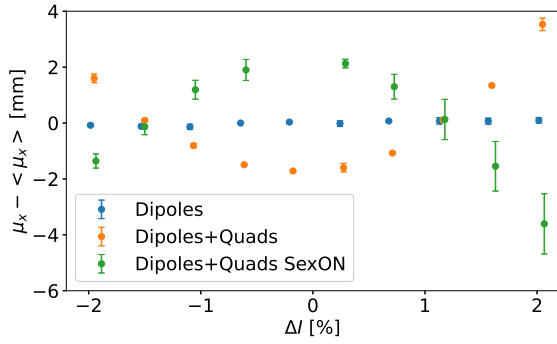


Figure 3: Beam position variation at BTV305 as a function of dogleg magnet currents, varying either the dipoles only (Dipoles) or both dipoles and quadrupoles current simultaneously, without (Dipoles+Quads) and with the sextupoles powered (SexON).

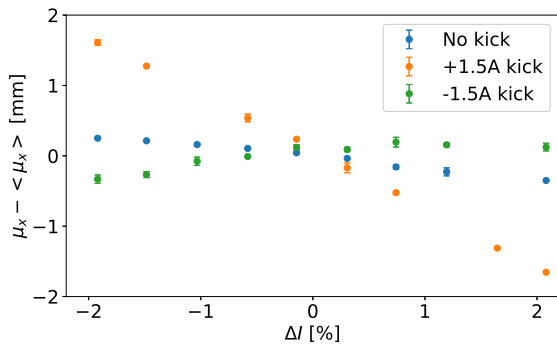


Figure 4: Residual orbit variation at BTV305 while varying both dipoles and quadrupoles simultaneously after correction of both linear and non-linear dispersion, shown for different incoming beam steering conditions induced by powering an upstream orbit corrector.

quadrupole values the linear dispersion is closed and the second order dispersion is highly pronounced (orange curve in Fig. 3). Tuning on sextupoles and repeating the scan, one can inverse the second order dispersion resulting in green curve, as shown in Fig. 3. The sextupole strengths then can be adjusted to close the second order dispersion (not shown).

After this optimisation, scanning both dipoles and quadrupoles simultaneously with the sextupoles powered yields a linear orbit response, as shown in Fig 4. It can be noted, however, that the residual orbit variation still depends on the incoming steering conditions, as illustrated by the different curves obtained by varying an upstream orbit corrector. This sensitivity points to the need for a dedicated dispersion-free steering procedure for the new beamline, analogous to the one already successfully applied on the existing CLEAR straight section [16].

No significant beam losses were observed along the new line once the optics were properly tuned.

After careful verification of the magnet calibration constants, the quadrupole and sextupole strengths required to correct the dispersion were found to be in good agreement

(at a few % level) with MAD-X simulations, providing a first validation of the lattice model of the new beamline. Quadrupole scans are currently being performed at multiple locations along the linac and the new beamline to measure the beam Twiss parameters and emittance, and to verify the accuracy of the lattice model. These measurements will also quantify any beam quality degradation introduced by the dogleg.

Since no RF deflector is presently installed in the new beamline, a direct measurement of the bunch length at the new test areas is not yet possible. Bunch length preservation through the dogleg will therefore need to be assessed in the future using streak camera measurements, pending user requirements. The installation of an RF deflector in the new line is being explored as a longer-term upgrade.

CONCLUSIONS

A second beamline has been successfully designed, installed, and commissioned at the CLEAR user facility at CERN. The beamline, based on a dogleg achromat followed by a 10 m straight experimental section, branches from the existing CLEAR line and runs parallel to it within the same experimental hall. The hardware installation, largely based on equipment recovered from the decommissioned CTF3 complex, was completed in summer 2025. Beam was successfully transported to the end of the new line during the commissioning campaign carried out between autumn 2025 and early 2026. The dispersion introduced by the dogleg was corrected using the quadrupole and sextupole magnets incorporated in the achromat, and the correction was found consistent with MAD-X predictions, validating the lattice model. The next commissioning steps will focus on demonstrating the extended transverse beam size range achievable with the larger-aperture quadrupoles and on the characterisation of single-particle delivery using the tungsten slit collimators installed at the first BTV station. The latter capability has the potential to open new use cases for the facility, in particular for the characterisation of high-energy particle detectors.

The new beamline significantly improves the operational flexibility of CLEAR by providing additional in-vacuum and in-air testing space, reducing the need for disruptive experiment changeovers, and enabling the parallel execution of otherwise incompatible experimental programs. The in-air test area will be equipped with the C-Robot 2.0 robotic system for automated sample positioning in medical application studies. Looking ahead, the new beamline is expected to play a major role in the CLEAR experimental program in 2026 and beyond, including during CERN Long Shutdown 3, when CLEAR could be one of the few CERN accelerators providing beam to users. New experiments profiting from the wider beam parameter space and the improved experimental throughput enabled by the second line are already being planned.

REFERENCES

- [1] D. Gamba *et al.*, “The CLEAR user facility at CERN,” *Nucl. Instrum. Methods Phys. Res. A*, vol. 909, pp. 480–483, 2018.
[doi:10.1016/j.nima.2017.11.080](https://doi.org/10.1016/j.nima.2017.11.080)
- [2] CLEAR – CERN Linear Electron Accelerator for Research.
<https://clear.cern>
- [3] K. N. Sjobak *et al.*, “Status of the CLEAR electron beam user facility at CERN,” in *Proc. IPAC'19*, Melbourne, Australia, May 2019, paper MOPTS054, pp. 983–986.
[doi:10.18429/JACoW-IPAC2019-MOPTS054](https://doi.org/10.18429/JACoW-IPAC2019-MOPTS054)
- [4] L. A. Dyks *et al.*, “Consolidation and future upgrades to the CLEAR user facility at CERN,” in *Proc. IPAC'21*, Campinas, Brazil, May 2021, paper WEPAB043, pp. 2700–2703.
[doi:10.18429/JACoW-IPAC2021-WEPAB043](https://doi.org/10.18429/JACoW-IPAC2021-WEPAB043)
- [5] P. Korysko *et al.*, “Updates, status and experiments of CLEAR, the CERN linear electron accelerator for research,” in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, paper THPOMS030, pp. 3022–3025.
[doi:10.18429/JACoW-IPAC2022-THPOMS030](https://doi.org/10.18429/JACoW-IPAC2022-THPOMS030)
- [6] P. Korysko *et al.*, “The CLEAR user facility: a review of the experimental methods and future plans,” in *Proc. IPAC'23*, Venice, Italy, May 2023, paper MOPL141, pp. 876–879.
[doi:10.18429/JACoW-IPAC2023-MOPL141](https://doi.org/10.18429/JACoW-IPAC2023-MOPL141)
- [7] R. Corsini *et al.*, “The future of the CLEAR facility: consolidation, ongoing upgrades and its evolution towards future electron facilities at CERN,” in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, paper TUPM027, pp. 1220–1223.
[doi:10.18429/JACoW-IPAC2025-TUPM027](https://doi.org/10.18429/JACoW-IPAC2025-TUPM027)
- [8] R. Corsini *et al.*, “Studies on the impact of the beam time structure on VHEE/FLASH irradiation biological effects,” presented at IPAC'26, Deauville, France, May 2026, this conference.
- [9] CERN Courier, “European Strategy Group recommends FCC-ee,” 2026. <https://cerncourier.com/european-strategy-group-recommends-fcc-ee/>
- [10] L. A. Dyks *et al.*, “The design of a second beamline for the CLEAR user facility at CERN,” in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, paper THPOST018, pp. 2479–2482.
[doi:10.18429/JACoW-IPAC2022-THPOST018](https://doi.org/10.18429/JACoW-IPAC2022-THPOST018)
- [11] G. Geschonke and A. Ghigo, Eds., “CTF3 design report,” CERN, Geneva, Switzerland, Rep. CERN/PS 2002-008 (RF), 2002.
- [12] CERN, “Sextupole magnet specification,” CERN EDMS no. 754421, AT-MTM-IN-2006-032, 2006.
- [13] C. Robertson *et al.*, “Dual-scattering foil installation at CLEAR,” in *Proc. IPAC'23*, Venice, Italy, May 2023, paper THPM073, pp. 5059–5062.
[doi:10.18429/JACoW-IPAC2023-THPM073](https://doi.org/10.18429/JACoW-IPAC2023-THPM073)
- [14] J.-C. Gayde and M. Šulc, “Introduction to structured laser beam for alignment and status of the R&D,” CERN, Geneva, Switzerland, Rep. CERN-CDS-2849065, 2023.
- [15] P. Korysko *et al.*, “Operational improvements and upgrades of the CLEAR user facility,” in *Proc. LINAC'24*, Chicago, IL, USA, Aug. 2024, paper THPB017, pp. 670–673.
[doi:10.18429/JACoW-LINAC2024-THPB017](https://doi.org/10.18429/JACoW-LINAC2024-THPB017)
- [16] A. Aksoy *et al.*, “Application of beam-based alignment to the CLEAR facility,” in *Proc. IPAC'23*, Venice, Italy, May 2023, paper WEPL025, pp. 3166–3169.
[doi:10.18429/JACoW-IPAC2023-WEPL025](https://doi.org/10.18429/JACoW-IPAC2023-WEPL025)