CLARA COMMISSIONING AND FIRST FRIENDLY USER EXPERIMENTS

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Abstract

The CLARA facility at Daresbury Laboratory is a medium energy facility for R&D into a wide range of applications such as novel acceleration, cancer-therapy, and advanced diagnostics. CLARA is currently finalizing beam commissioning after an upgrade to 250 MeV followed by technical systems commissioning. During this period CLARA hosted its first set of friendly user experiments in its dedicated full energy beam exploitation (FEBE) beamline. Five different experiments were selected, covering a range of applications including: advanced diagnostics measurements using coherent transition radiation (CTR) and optical transition radiation (OTR) stations; Very High Energy Electron (VHEE) cancer-therapy studies; beam-driven plasma wakefield acceleration studies related to next generation colliders. These experiments exploited the full capabilities of the CLARA facility, including up to 250 MeV bunches with up to 250 pC per bunch at 100 Hz repetition rate, and with variable longitudinal compression. The experiments chosen will help develop and prepare CLARA for user experiments in the future. The installation and commissioning of the 120 TW laser transport system into the FEBE hutch is planned for 2026, which will expand the range of experiments to include those combining electron beams and high-power lasers.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) is a high-brightness electron beam test facility at STFC Daresbury Laboratory. The layout of the accelerator facility is shown in Fig. 1. The CLARA front end, comprising a 2.5-cell S-band 10 Hz gun followed by a 2 m S-band linac, was made available for users in two dedicated experimental runs from 2018 until 2022 [1]. The installation of new components to upgrade the facility from the previously-installed front end at 50 MeV to 250 MeV was completed in 2024, including replacement of the 10 Hz S-band gun with a 1.5-cell S-band 100 Hz gun. This was followed by RF conditioning of the gun, four S-band accelerating structures and one S-band Transverse Deflecting Cavity (TDC). The first full energy CLARA beam was transported to the straight-on beam dump in April 2025, and threaded through the FEBE beam line to the final beam dump in October 2025. Beam commissioning progressed alongside technical systems commissioning, and included the testing and deployment of many high-level software applications for setting and characterising the beam parameters. Table 1 summarises design beam parameters of CLARA at the Interaction Point (IP) in FEBE.

Table 1: Design CLARA Beam Parameters at the FEBE IP Following Initial Commissioning of the Accelerator [2]

Parameter	Low Charge	High Charge
Repetition rate [Hz]	1 – 100	
Bunch charge [pC]	5	250
Bunch length [fs]	50	100
Energy spread [%]	< 1	< 5
RMS spot size [µm]	20	100
Norm. emittance [µm]	2	5

The first friendly user experiments were chosen in November 2025 to cover a wide range of disciplines with the aim to prepare the facility to commission these experiments in collaboration with users. Beam was successfully delivered to multiple experiments from January to April 2026. This paper describes the upgrade of CLARA, highlights from beam commissioning, and a brief description of beam delivery to the five user experiments.

CLARA UPGRADE

The swap of photoinjector gun; installation of three additional 4 m S-band linacs; a chicane-type Variable Bunch Compressor (VBC); an X-band linearizing cavity for harmonic correction; and a dedicated diagnostics section including an S-band TDC and a dielectric dechirper were completed in early 2025. The upgraded beamline is capable of accelerating electron bunches to the facility's design energy of 250 MeV.

A four-dipole arc, located at the end of the full-energy diagnostics section, transports beam to the FEBE user area, a separately-shielded enclosure where the majority of user experiments take place [2]. Installation of the FEBE beamline was completed in parallel with beam commissioning activities in the main accelerator hall. The installation and Site Acceptance Test (SAT) of the 120 TW laser were completed in November 2025 with the laser beam transport planned to be installed and commissioned later in 2026.

Conditioning of the RF structures began in March 2024 using a proprietary automated RF conditioning application, NO-ARC (No Operator Automated RF Conditioner). Details of the RF conditioning strategy, controls framework and procedure automations are described in [3–5].

Technical systems commissioning with beam followed RF commissioning. The first 250 MeV beam was generated using a Cu photocathode and transported to the straight-on beam dump in April 2025; further transport through FEBE to the final beam dump followed in October 2025. The existing

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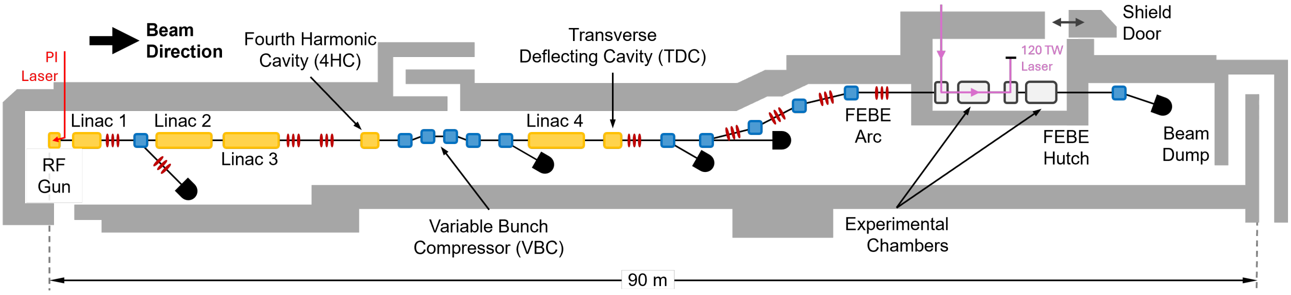

Figure 1: Schematic of the CLARA linear accelerator test facility, including the FEBE beam line, and shielded FEBE hutch. The 120 TW laser system is situated above the FEBE Hutch.

Cu cathode was replaced with a Cs_2Te cathode in September 2025, following a dedicated in-house R&D programme. This new cathode delivers the design bunch charge of 250 pC at a repetition rate of 100 Hz with significantly reduced laser power requirements. The details of CLARA diagnostics are described in [6].

BEAM COMMISSIONING HIGHLIGHTS

Photocathode and Dark Current

In 2025, the CLARA photocathode was upgraded from Cu to Cs_2Te. The Cs_2Te photocathodes developed for CLARA were manufactured using INFN-style photocathode plugs in the APPF deposition system [7], and now deliver ~18 % (at 266 nm) as the deposition process has been refined [8]. Two photocathodes were transferred to the gun load-lock system, and after RF conditioning up to 1.25 µs pulse length and gradients of ~95 MV/m, both cathodes demonstrated effective QEs of ~10 % – 12 %. The first cathode was removed due to significant visible ‘spotting’ on the surface [9], though later studies showed similar spotting on the current cathode. However, significant QE degradation has not been observed, with effective QE values still above 10 %.

Dark current (DC) from the Cs_2Te cathode is low. Compared to the previous Cu cathode at equivalent pulse lengths and solenoid currents, we see a 30 % reduction in DC per pulse, from ~150 pC on Cu to ~100 pC with Cs_2Te [10].

Emittance Measurements

Emittance measurements were performed regularly with automated quadrupole scans, which were carried out at points along the CLARA beamline and inside the FEBE user area. The generative phase space reconstruction (GPSR) technique is used for high-resolution measurements of the beam’s transverse phase space [11]. A normalised emittance of <1 µm is typically measured for the 35 MeV beam produced by the CLARA front end. The emittance of the full-energy (250 MeV) CLARA beam can vary significantly depending on the beam parameters required by users. For an uncompressed beam with minimal energy spread, an emittance of ~2 µm is typically measured at the maximum bunch charge of 250 pC [12]. Further improvement of the beam quality [2] is expected after future machine development (MD) periods.

Bunch Compression

For some user experiments, the CLARA beam must be compressed from ~4 ps RMS to <100 fs RMS using the VBC (see Fig. 1) with an R_{56} range of 0 mm to −60 mm. An X-band (11.994 GHz) fourth-harmonic cavity (4HC) is situated before the VBC to linearise the longitudinal phase space; however the 4HC is currently undergoing RF conditioning after waveguide vacuum issues, and was unavailable for first experiments. The FEBE arc is non-isochronous, with a nominal R_{56} of +7.7 mm; for maximum compression in FEBE, the VBC must therefore operate in an overcompression regime. Bunch length diagnostics include a TDC [13], and a 4-plate dielectric wakefield structure that can act as a diagnostic deflecting cavity as well as a passive longitudinal beam dechirper [14].

Measurements of the bunch length at the TDC with 250 pC bunch charge give a value of ≈150 fs [13] – higher than the design value of 100 fs but not unreasonable given the present lack of longitudinal linearisation.

The most notable result, however, is a strong non-linearity in the longitudinal phase space near maximum compression that appears as a variation in energy density in the bunch, and can be tuned by varying the compression ratio. The origin of this effect is poorly understood and will be a focus of the upcoming machine development period on CLARA.

Software Development

A cornerstone of the High-Level Software (HLS) development on CLARA has been the CATAP [15] controls abstraction package, which has simplified the writing of Python-based applications for accelerator control. CATAP standardises interactions with the existing EPICS-based accelerator control system. CATAP derives its controls information from an ontological description of the lattice using LAURA, a Pythonic package serving as the accelerator *ground truth*. Together, they give HLS applications a standardised and documented method of interacting with accelerator components. PUMBA extends this further by automating multi-step procedures, data collection and alert handling. Applications built on these components range from the everyday (opening valves, cresting RF cavities) to advanced user experiments (robust dose delivery, and performing multi-dimensional parameter scans with multi-diagnostic acquisition).

Combining CATAP, LAURA, and PUMBA with a start-to-end simulations framework [16] (SIMBA) and a soft-IOC generator (SARABI) results in an integrated *digital shadow* [17,18], a step towards a full digital twin that reflects the physical machine, allowing advanced optimisation and HLS development without impacting machine operations.

CLARA has begun the integration of machine learning applications into machine development. Development of customisable longitudinal photoinjector laser shaping using an acousto-optic modulator is ongoing and expected to enter day-to-day operations soon.

FIRST FRIENDLY USER EXPERIMENTS

The design of FEBE involved extensive engagement from CLARA FE users as well as feedback from other similar facilities. Further engagement with users was actively pursued throughout the CLARA upgrade period. The experiments were picked on the criteria of: stakeholder engagement; the need to develop expertise in setting up varied and complex experiments. Five different experiments (two of these including additional sub-experiments) were chosen covering advanced diagnostics, medical applications and novel acceleration. All seven experiments were highly successful meeting, or exceeding, the goals set by users.

Optical Transition Radiation (OTR)

University of Liverpool/The Cockcroft Institute

An experiment to investigate emittance measurement using a single-shot optical pepper-pot (micro-lens array) with OTR. The experiment was installed after the FEBE hutch in the dump line. The 10 quadrupoles and 4 screens upstream allowed for measurement and delivery of a wide variety of input Twiss parameters to the OTR diagnostic. Emittance measurements were benchmarked against quadrupole scans using CLARA YAG screens. The captured images of spatially coherent OTR demonstrated a minimum beam size of less than 30 µm at 250 MeV and 250 pC.

Coherent Transition Radiation (CTR)

DESY

An experiment to optimise the compression of low charge beams on CLARA and to demonstrate <10 fs RMS bunch lengths using CTR. An array of 4 photodiodes and a CMOS camera were installed on a translation stage at the CTR station just after the FEBE arc. The CTR was generated from a polished gold target, transported through a fused silica window and focused with parabolic mirrors. The compression after the FEBE arc was optimised by changing the upstream R_{56} from the VBC. Coherent optical transition radiation was observed on the camera, and the photodiodes resolved sections of the CTR spectrum; the results suggest bunch structure at < 5 fs.

VHEE - Scattering

CERN/University of Oxford/John Adams Institute

Dual scattering foils were designed and installed in the second FEBE experimental chamber (in-air) to generate large (~1 cm RMS), uniform beam profiles. Similar, flattened beam profiles were also generated using the FEBE beamline quadrupole magnets and a single conical scatterer. The experiment was carried out at two energies: 200 MeV and 250 MeV. The intensity profiles of the scattered beams were confirmed using an in-air YAG screen, and their dose distributions were measured using radiochromic films placed in a water phantom.

VHEE - Cell Irradiation

University of Manchester/The Cockcroft Institute *with contributions from* **The Christie Hospital**

Firstly, dose measurements using Gafchromic films were taken at several depths within a water phantom and compared with Monte Carlo simulations based on the measured ICT bunch charge and transverse beam profile measured on a YAG. Secondly, lung cancer cells were irradiated in Eppendorf tubes. Conventional dose was delivered using 125 pC bunches at 10 Hz, whilst FLASH dose was delivered using 250 pC bunches at 100 Hz. Transverse RMS beam sizes of 1 mm to 2 mm were obtained using a combination of quadrupoles and solid water plate scatterers.

Plasma Wakefield and Lensing

University of Oxford/John Adams Institute *with participation from* **the Universities of Manchester and Oslo** *and* **DESY**

A high voltage discharge capillary plasma module was installed in the first experimental chamber in FEBE for beam-driven plasma acceleration studies. Firstly, generation of plasma (using 16 kV HV with argon, cell pressure ≈10 mbar, continuous gas flow) was successfully demonstrated. A highly compressed 250 MeV drive beam was used to generate and sample decelerating gradients up to 1 GV/m. Secondly, studies into non-linear plasma lensing (Ar and He) with this setup were also performed, which will be crucial for the staging of plasma modules for applications in future high energy colliders.

SUMMARY

Following the upgrade of CLARA, the facility has been commissioned to deliver an electron beam with its design energy, bunch charge and repetition rate. Five friendly user experiments have been successfully completed, demonstrating the flexibility of the facility to carry out a wide range of complex experiments.

ACKNOWLEDGMENTS

The work presented here was carried out by the CLARA team at Daresbury Laboratory and we thank them all for their work on the design, installation, beam commissioning and software development for CLARA.We would like to thank our friendly users for their collaborative work to setup and commission their experiments with CLARA beam.

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