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COMMISSIONING OF THE CLARA FACILITY: STATUS UPDATE AND DIAGNOSTICS PERFORMANCE

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Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) is STFC Daresbury Laboratory's flagship accelerator facility. We present the latest data from the commissioning of the CLARA facility at Daresbury Laboratory. This will include initial beam measurements and diagnostic performance for the 250 MeV high brightness, highly compressed electron bunches. An overview of the diagnostic requirements and anticipated challenges for these high impact user experiments will be provided. The future direction of diagnostics at CLARA, including potential system upgrades and plans for virtual diagnostics, is also discussed.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) is a high-brightness electron beam facility at Daresbury Laboratory [1]. Following an upgrade and commissioning period, the accelerator reached the final design energy of 250 MeV in April 2025. Bunches at CLARA are generated at 100 Hz from a 1.5 cell S-Band photoinjector gun and then accelerated with 4 S-band linacs (one 2 m long and three 4 m long). The Full Energy Beam Exploitation (FEBE) beamline, which includes a shielded user experiment hutch, has been installed [2]. A 120 TW laser system has been installed (2.8 J, 23 fs at 5 Hz), which can be brought to a focus within the FEBE experimental chambers for interaction with the CLARA electron beam. A schematic of the CLARA facility is shown in Fig. 1, the total length is ≈ 80 m. The target beam parameters to be delivered to the FEBE hutch for first experiments are shown in Table 1, alongside future research and development targets following a periods of machine development.

BEAM DIAGNOSTICS AT CLARA

The CLARA lattice is highly instrumented with 94 diagnostic systems; utilising both commercial off-the-shelf and in-house developed bespoke systems. A breakdown of these systems is given in Table 2. Further experimental systems are utilised to verify the parameters in Table 1 [3]. A S-Band transverse deflecting cavity is installed at CLARA, providing bunch profile and longitudinal phase space measurements before the FEBE arc (see Fig. 1).

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Table 1: Specification for CLARA Beam parameters delivered to FEBE hutch. All beam parameters are specified for 250 MeV, with Q: bunch charge, σ_i: RMS value, $\epsilon_{N,i}$: normalised projected RMS emittance.

	Target		R&D	
Parameter	**High Q**	**Low Q**	**High Q**	**Low Q**
Q (pC)	250	5	250	5
σ_t (fs)	100	50	≤ 50	≪ 50
$\sigma_{x,y}$ (µm)	100	20	50	~ 1
σ_E (%)	< 5	< 1	1	0.1
$\epsilon_{N,x}$ (µm-rad)	5	2	< 5	< 1
$\epsilon_{N,y}$ (µm-rad)	5	2	< 1	< 1

Table 2: System Breakdown of the 94 Electron Beam Diagnostic Systems Installed in the CLARA Beamline

System	No. of devices
Charge Measurement	10
Scintillator Screens	35
Beam Position Monitors	44
Beam Arrival Monitors	3

Charge Measurement

The ten charge measurement devices on CLARA break down as follows: 1 wall-current monitor (WCM), 5 Faraday cups and 4 integrating current transformers (ICT).

The WCM is a non-interceptive diagnostic located between the photoinjector gun and first linac. The WCM signal is processed using a variable sensitivity front-end. This allows for absolute measurement of the dark-current from the gun and simultaneous relative measurement of the primary bunch charge. The WCM bunch charge is cross-calibrated against the readings from a Faraday cup.

The Faraday cups are interceptive diagnostics integrated into the 3 energy spectrometers and 2 final beam dumps. Each dump consists of a 300 mm diameter stainless steel core, with a length of 300 mm to dissipate the electron beam. A 20 mm aluminum insert is used to reduce backscattering. Each core is suspended in HDPE and encased in a concrete and lead clamshell to manage radiation from activation. They are instrumented using the same variable sensitivity front-ends as the WCM, which have a dynamic range from

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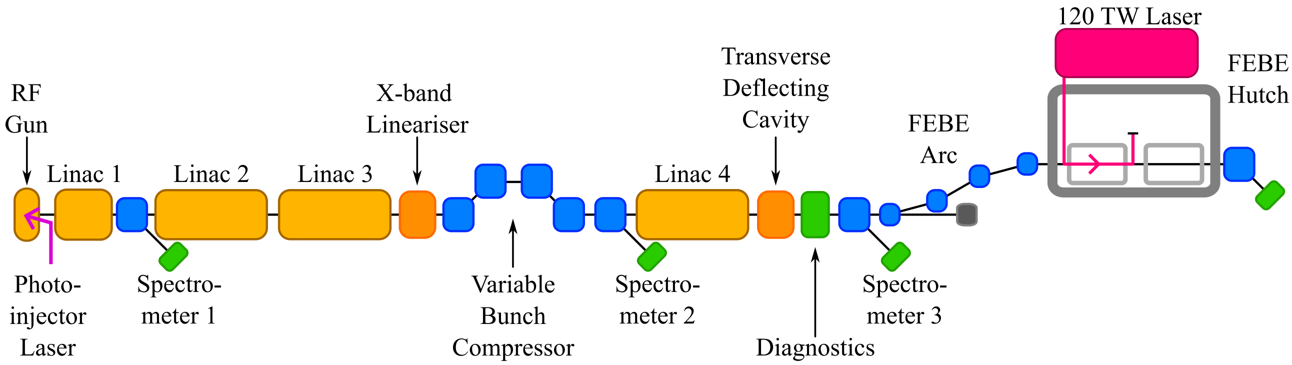

Figure 1: Schematic of the CLARA facility.

5.0 ± 0.1 pC to 250 ± 3 pC. Each front-end contains a charge injection circuit for automatic remote calibration [4].

The ICTs are non-interceptive in-flange Turbo-ICTs from Bergoz [5], two are located in the CLARA beamline and two in the FEBE beamline. The manufacturer's BCM-RF-E front-end is operated in Sample and Hold mode, to measure bunch charge, and each unit includes an integrated calibration circuit for absolute charge calibration. The integrated front-end amplifier supports measurement between 0.5 pC to 300 pC, with 1 % precision.

All charge signals are routed to diagnostic racks outside the accelerator bunker via coaxial cables, where they are digitized. CLARA uses IOxOS ADC 3110/3111 eight channel, 16-bit, 125 Msps digitizers, hosted in a VME-standard dual FMC carrier [6]. Each FMC carrier hosts an EPICS IOC, which exposes both raw and processed signals to the control system.

Scintillator Screens

The 35 beam imaging screens are distributed throughout the CLARA lattice and provide measurement of: beam position, transverse optics, energy and energy spread, and bunch length (when use in tandem with transverse deflector). The scintillators crystals are 200 µm thick cerium doped YAG (YAG:Ce) with an 20 nm optically transparent and electrically conductive ITO coating. The majority of the YAG:Ce screens are 30 mm diameter with exception of larger diameter crystals used in higher dispersion regions; up to a maximum of 100 mm. The beam is incident normal to the face of the screen and a silver mirror (silicon substrate) is behind the screen at 45° to the beam propagation. Two cameras systems were chosen for the imaging the scintillators, pco.Edge 5.5 and Allied Vision (AV) Manta G-235B, their specifications are provided in Table 3. The pco.edge 5.5 system provides 16-bit full frame 100 Hz rate only when a 'global-reset' shutter mode is used; where the sensor rows are read from outside to in. This shutter mode is appropriate for use with short light pulses as given by the YAG:Ce scintillator. The AV Manta G-235B provides 12-bit 100 Hz frame rate with a global shutter when the vertical frame size is reduced to 275 pixels.

Table 3: Specifications of the Scintillator Imaging Cameras at CLARA

Parameter	pco.edge 5.5	AV Manta G235B
Resolution	2560x2160	1936x1216
Pixel size (µm)	6.5	5.86
Bit-depth	16	12
Data connection	CLHS	GigE
Frame rate (Hz)	100	20
No. installed	17	18

The cameras are placed on an optical periscope to drop them > 1 m below the beam pipe to reduce radiation damage to the sensor. The imaging system is formed from two aberration corrected achromatic doublet lenses with 2″ diameter (ThorLabs AC-508 range). The first doublet has a focal length of 1 m (providing the periscope drop), for the pco.edge the second lens has focal length 0.5 m and for the AV Manta system it has a focal length of 0.25 m. This provides a ≈ 28 mm field of view for both systems, and bench-top tests found the optical PSF to be 12.7 µm for the high resolution pco.edge system. The resulting spatial calibration is 13 µm/pixel for the pco.edge 5.5 and 26 µm/pixel for the AV Manta G235B. An aperture of 27 mm diameter is used in front of the first doublet lens to ensure adequate depth of field through the imaged YAG:Ce crystal. Finally an optical bandpass filter at 550 ± 50 nm (formed from Thorlabs FESH0600 and FELH0500) is used to isolate the YAG:Ce emission spectrum. Calibration graticules are installed on the same insertable carriage as the YAG:Ce crystals, an example is shown in Fig. 2a). An example image of a 250 MeV 17 pC beam is shown in Fig. 2b).

Beam Position Monitors

The 44 beam position monitors (BPMs) are distributed throughout the CLARA beamline. All are stripline type BPMs, the majority of which have an internal diameter of 35 mm. Larger diameter bore BPMs are used in sections with large dispersion. The first 29 BPMs are connected to a bespoke signal processing system. Signals from opposing pick-ups are passed to an analogue front end module which lengthens and multiplexes the signals. These multiplexed

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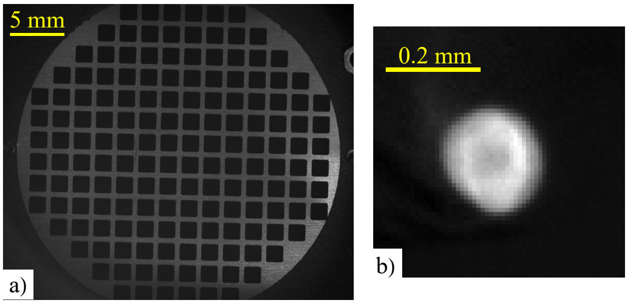

Figure 2: Images taken from a pco.edge 5.5 camera at a CLARA scintillator station after linac 4. a) Calibration graticule shown at full frame, b) cropped image of a 250 MeV 17 pC beam. Scale bars shown in yellow.

signals are then routed to a analogue processing card in a VME crate. The signals are then digitised into EPICS using an IOxOS Technologies ADC (model ADC3112) at 1 Gsps with 12-bit resolution. The system has been proven to work down to 5 pC during commissioning.

The final 15 BPMs (on the FEBE beamline) are connected to a proprietary front-end and digitisation system; 'Libera Single Pass E' from Instrumentation Technologies [7].

Beam Arrival Monitors

The beam arrival monitors (BAMs) on CLARA were provided by DESY and use a cone-shaped pick-up [8]. Two BAMs are positioned either side of the variable angle magnetic chicane compressor and the final BAM is placed after the transfer arc to the FEBE hutch. The BAMs have a bandwidth of 40 GHz and the system can provide on-shot time of arrival measurement of 3 fs at 250 pC, reducing to 6 fs at 100 pC. Arrival time is measured with respect to the clock provided by an Optical Master Oscillator (Origami-15, NKT Photonics), distributed by stabilised single-mode optical fibre links.

FUTURE R&D SYSTEMS

The R&D parameters in Table 1 are challenging from the perspective of both machine performance and validation with diagnostics. In order to experimentally validate these parameters the following systems are being developed.

For transverse measurements we have considered knife edge/wire scanners - utilising our high precision and high dynamic range charge diagnostics [4]) - and OTR imaging and GAGG+ scintillators for high charge density measurements, as shown in [9].

The FEBE beamline does not have a transverse deflecting cavity; novel, compact and cost effective longitudinal diagnostics are required to support user experiments.To this end, we are developing a coherent transition radiation (CTR) THz spectrometer system [10] which will allow for optimisation of the bunch compression and support tuning of the FEBE arc sextupoles. For direct bunch profile measurement we have developed dielectric wakefield streaker [11]. There are two ICTs in the FEBE beamline which will provide on-shot charge measurements which is vital for accurate reconstruction of bunch profiles from a wakefield streaker.

We will also leverage the large volume of data from our highly instrumented beamline with machine learning techniques to support the use of 'virtual diagnostics' for predicting on-shot properties during experiments [12]. Our high resolution beam imaging system, in combination with large number of imaging stations, allows for transverse phase space tomography techniques to be used at numerous locations in the beamline for detailed emittance measurements [13].

DISCUSSION

The CLARA facility has reached final beam energy of 250 MeV. The highly instrumented beamline is undergoing commissioning, with completion of commissioning expected in early 2026. We have developed a number of high performance bespoke diagnostic systems, alongside deploying commercial solutions where applicable. An instrumentation R&D programme has been developed to support the future requirements of both measuring high brightness beams and support the exploitation of the CLARA beam for experiments.

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