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STATUS OF CLARA AT DARESBURY LABORATORY

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Abstract

CLARA (Compact Linear Accelerator for Research and Applications) is a test facility for Free Electron Laser (FEL) research and other applications at STFC's Daresbury Laboratory. The Front End of CLARA has been used for user exploitation programme from 2018. The second exploitation period in 2021-22 provided a range of beam parameters to 8 user experiments. We report on the status, further machine development, and future plans for CLARA including Full Energy Beam Exploitation (FEBE) beamline which will provide 250 MeV/c high brightness beam for novel experiments.

INTRODUCTION

The first successful period of CLARA exploitation on CLARA Front End (FE) was reported at previous IPACs [1, 2]. The details of beam line and beam delivery of higher momentum (35 MeV/c) to users on CLARA FE and in Versatile Electron Linear Accelerator (VELA) Beam Area 1 (BA1) in 2018-2019 run is summarised in Ref. [3]. A shutdown for preparation for CLARA Phase 2 (acceleration to 250 MeV/c) begun in April'19 and completed in September'19. During this shutdown, a load lock system was installed on the 10 Hz gun and several improvements to other technical systems were undertaken. The shielded wall between the accelerator and user area was removed to prepare for Phase 2 shielding. A temporary wall at the end of BA1 allowed operation of CLARA FE/VELA line whilst Phase 2 preparation continued outside this shield wall.

After completion of the shutdown, beam commissioning programme was resumed. The upgraded 10 Hz gun with load lock system was successfully commissioned with a number of improvements made in the photoinjector laser. The planned start of second exploitation period was suspended due to COVID lockdown and technical issues with the gun waveguide. Additional diagnostics were added: a Bunch Compression Monitor on VELA line; and Electro-Optic in the experimental chamber in BA1 to provide information of longitudinal bunch profile.

Offline build and testing of CLARA Phase 2 accelerator modules have progressed well in past two years. Accelerator modules have been installed in the accelerator hall, beyond the temporary wall, to allow commissioning and operation of CLARA FE for exploitation. The rest of the completed modules will be installed in the accelerator hall during planned shutdown in 2023. FEBE hutch modules are also being procured and assembled offline. Details of FEBE design are presented at this conference [4]. CLARA Phase 2 RF systems are currently being tested at low power and the build of rack rooms is ongoing.

Beam was delivered successfully to users at two locations; straight-on and transporting it through the CLARA-to-VELA S-bend to a dedicated user experimental chamber in BA1 during October'21 – April'22. We summarise here the beam commissioning, beam delivery to users as well as our near future plans.

PHOTOINJECTOR

The 10 Hz repetition rate photoinjector was upgraded for operation with interchangeable photocathode with a final goal to improve beam quality, increase duty factor, reduce the dark current and eventually allow for operation with different types of photocathode materials.

Hybrid photocathodes (Cu tip integrated with a Mo plug) were used during the user run. The Cu surface was cleaned by Ar plasma followed by a 250°C bake. Such activated photocathodes have QE at a level of high 10^{-5} and allow for generation of bunches with a charge of 100 pC and higher with a laser pulse energy on the photocathode of 10's µJ. More detailed description of gun upgrade and operation are presented at this conference [5, 6].

MACHINE STABILITY AND JITTER

Stability of RF system is paramount as it explicitly affects beam stability. Dependence of beam energy (E_b) on RF power (P) and phase (ϕ) can be simply described as,

$$E_b = \sqrt{PZ}\,cos(\phi - \varphi_0), \qquad (1)$$

where, Z and φ_0 are equivalent cavity impedance and crest phase respectively. Impact of RF amplitude and phase jitter

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on the beam can be calculated by measuring beam energy jitter σ_E at various phases around crest phase and fitting to,

$$\sigma_E^2 = \sigma_{E0}^2 + \frac{\sigma_P^2 \; cos^2(\phi-\varphi_0)\; Z}{4P} + \sigma_\phi^2 \; sin^2(\phi-\varphi_0)\; PZ, \qquad (2)$$

where, σ_E, σ_p and σ_ϕ are standard deviation of beam energy, RF power and phase respectively. σ_{E0} is contribution to beam energy jitter from upstream machine components.

Gun RF power and phase had jitter of 0.07% and 0.037° respectively, while Linac-1 had 0.054% and 0.057°. Variation in beam energy and energy variance after Linac-1 at different phases around crest is shown in Fig. 1, with gun on crest. Beam had energy jitter of 0.017% on crest (as extracted from horizontal beam position in CLARA-to-VELA S-bend used as spectrometer), and 0.03% at -6° off-crest, which was normal mode of operation. The phase jitter derived from fitting Eq. (2) to the variance was 0.096° compared to 0.057° from RF measurements, highlighting arrival time error due to upstream jitters. Slow drifts in the RF system were stabilised using PID feedback.

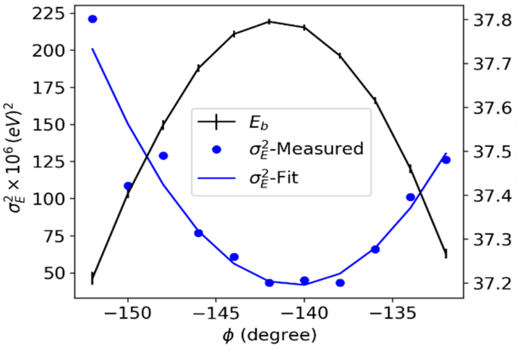

Figure 1: Beam energy and energy variance at different phases around crest, fitted to the above error propagation equation.

DIAGNOSTICS

Several new diagnostic devices were installed and commissioned during the last CLARA run. These include developments on bunch charge monitors, Bunch Compression Monitor (BCM) and Electro-Optic bunch diagnostics.

Charge Monitors

A new electronics front-end for charge measuring devices has been developed and used to provide more precise measurement of bunch charge using Faraday Cups (FCUPs) and Wall Current Monitors (WCMs) to users. The new front-end has a range of features, such as a charge-injection module for calibration across a wide range, a device-agnostic signal chain which is compatible with WCMs, FCUPs and Integrating Current Transformers. The measured FCUP uncertainty is of the order of 1% above 2 pC, and will be further quantified in the near future. The new front-end was used with in-air charge diagnostics for multiple experiments, measuring charges below 200 fC with 5% uncertainty.

Bunch Compression Monitor

Bunch compression for experiments in BA1 was achieved through variation of Linac-1 off crest phase and transport through the CLARA-to-VELA S-bend. A BCM was implemented to reliably find maximum compression settings and define reasonable compression working points. The BCM is made from a polished aluminium disc set at 45° to beam propagation to generate coherent transition radiation (CTR), which was coupled to air through a fused silica window, and collected with TPX lenses onto a bespoke pyroelectric detector. This pyroelectric detector had active noise cancellation and variable amplifier gain. Example data from the BCM is shown in Fig. 2.

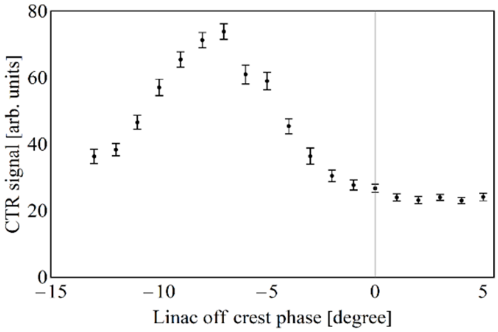

Figure 2: Measurement of CTR intensity detected on the BCM for a charge of 100 pC. In the region –2° to 5° there is insufficient signal to be detected above the detector noise floor.

Electro Optic Bunch Diagnostics

We designed and built an Electro-Optic Spectral Interferometry (EOSI) system for CLARA with the aim of overcoming EO spectral decoding's resolution limitations. To accomplish this we implemented inline spectral interferometry in a system that is as simple and robust as a spectral decoding set up. Its resolution is now limited by probe laser spectrum and EO material only. Pulse profiles were retrieved live at 10 Hz in the control room, at charges ranging from 2 pC to 150 pC, and durations measured to be in agreement with models and other characterisation experiments. Note the Coulomb field is transposed into a laser pulse, with the envelope encoding the charge profile. See Fig.3 for an example measurement. The jump in carrier phase represents a sign change in the Coulomb field.

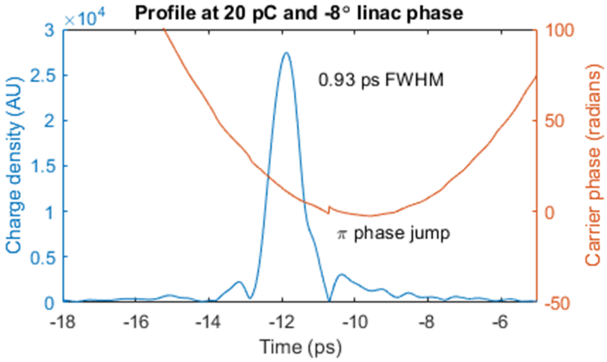

Figure 3: Example longitudinal profile measurement.

SOFTWARE TOOLS & SIMULATIONS

An integrated framework of tools, combining operations and simulations (CLARA-Net) has been under continued development [7]. Within CLARA-Net there are a series of high-level APIs (CATAP, SimFrame, Virtual Accelerator) and procedures that form an abstract interface to the Control System. These tools provide a human readable interface in Python, designed to open Control Room Application Development to experts and non-experts alike. The high-level APIs also provide a way to rapidly create bespoke Viewing, DAQ, and online-analysis applications for users during their beamtime. A vital part of managing this framework is the use of continuous integration, nightly builds, and testing that have enabled daily changes to be accessible to all developers. The simulation framework is being constructed such that switching between simulation and machine control and measurement is as transparent as possible enabling an "online model" mirror of beam measurements within simulation.

For instance, these software tools were used to implement new procedures for emittance measurements on CLARA [8]. Prior to beam time, simulations within the online model were used to validate the measurement procedure, and to optimise the magnet strengths at each step of a quadrupole scan. The same procedure was then deployed to the real machine via a single Python script, using CATAP as a high-level interface to perform hardware operations such as degaussing magnets and inserting screens.

The ability of CLARA-Net to compare the real accelerator against an equivalent online model is a vital tool for characterising machine performance. The data collected for emittance measurements was later repurposed for a beam-based alignment study, where the online model was used to build a response matrix relating various misalignments to the observed beam position.

Additionally, a selection of tasks are aided by software incorporating element of machine learning. To date these are automated RF conditioning [9] and longitudinal pulse shaping in the PI laser [10].

USER PROGRAMME

A call for applications for a further round of user experiments was issued in July 2019. 22 applications were received of which 10 were approved by the allocation panel, including three trans-national access proposals (ARIES Horizon 2020 scheme). The beginning of the run was delayed from late 2019 to late 2021 as a result of the global pandemic and technical issues with the accelerator (RF waveguide). Before the run commenced two of the experiments were withdrawn.

Ultimately, all the allocated beam time was delivered (62 days) with the vast majority of experiments being very successful. An extremely diverse programme of research was carried out covering areas such as alternative acceleration techniques (laser induced plasma wakefield, dielectric wakefield and THz based), diagnostics and detector development, medical physics and radiation biology. A feedback survey issued after the user programme indicated high levels of satisfaction from all the experimental teams.

BEAM SET-UPS FOR USER EXPERIMENTS

The user experiments were carried out at two locations in CLARA: at the straight-on line after Linac-1; and in the dedicated Beam Area 1 (BA1) on the VELA line. The experiments carried out at the straight-on location were in-air experiments, with transmission through a Beryllium window. One experiment was carried out at beam momentum of 4 MeV/c without following acceleration in Linac-1, whilst the second experiment operated at various beam momenta up to 35 MeV/c. In both experiments the gun cathode field was reduced to minimise dark current (DC), in addition to using apertures/collimators in the beamline, reducing the measured DC by at least an order-of-magnitude.

The experiments in BA1 were performed with a variety of specific beam setups, each setup meeting the experimental requirements. All experiments were performed at a momentum of 35.5 MeV/c, with charges ranging from 5 pC – 100 pC. Each charge setup required tuning of the photoinjector, with the compression achieved through variation of Linac-1 off-crest phase coupled with a fixed R_{56} dogleg chicane. High peak current setups were made at 100 pC, with the beam compressed to ~300 fs RMS length and with a minimum spot size of 100 µm at the interaction point (IP). Setups with low transverse emittance were achieved by reducing the bunch charge to 20 pC, through reduction of the laser pulse energy, and projected RMS energy spread of ~10 keV. The 20 pC setups achieved IP spot sizes of 20 µm and an estimated RMS bunch length of 1.5 ps. Minimum bunch length ($<$ 200fs RMS) setups were achieved at 5 pC bunch charge with measured IP spot sizes of $<$ 20 µm, limited by the Ce:YAG imaging system. A flexible approach of continuous improvement of each beam setup as the experiments were performed, and data analysed, proved beneficial for all experiments in comparison to providing a rigid menu of standardised setups.

FUTURE PLANS

Currently preparations are under way to start RF conditioning of the 400 Hz gun currently installed on the VELA line, this will be followed by beam commissioning and preliminary characterisation of the beam. This will allow swapping this gun to CLARA line to meet CLARA specification of 100 Hz rep rate.

Phase 2 build, installation and commissioning plans are progressing. FEBE hutch beamline procurement is under way and services in the hutch are being finalised. Phase 2 shut down is planned to start in the first quarter of 2023 to complete installation of CLARA including the gun swap. It is planned that the technical commissioning followed by beam commissioning will start in Autumn 2023. It is anticipated that FEBE beam line including high power laser will be commissioned to achieve nominal beam parameters by end of 2024.

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