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STATUS OF CLARA FRONT END COMMISSIONING AND FIRST USER EXPERIMENTS

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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 first exploitation period using CLARA Front End (FE) provided a range of beam parameters to 12 user experiments. Beam line to Beam Area 1 (BA1) was commissioned and optimised for these experiments, some involving TW laser integration. In addition to the user exploitation programme, significant advances were made to progress on machine development. This paper summarises these developments and presents the near future plan for CLARA.

INTRODUCTION

Since completion of installation of the CLARA FE, the progress on commissioning has been reported in conferences in 2018 [1, 2]. From September'18 till March'19, CLARA FE beam was delivered to 12 user experiments covering wide range of disciplines; novel diagnostics and technology, novel acceleration as well as deflection concepts and medical applications. High energy beam from CLARA FE is transported through a compact S-bend beamline (C2V) to VELA beam line which incorporates a separate shielded enclosure for BA1. Five experiments were carried out in the accelerator hall and seven experiments were carried out in BA1, of which four experiments used the TW laser. During the exploitation period, time was shared to make progress on machine development, RF conditioning of high repetition rate gun [3] on the VELA line and to further develop high level software. This paper presents the commissioning of BA1 beamline, progress on machine development and summarises near future plans.

BEAM AREA 1 COMMISSIONING

BA1 has a dedicated beamline for user experiments with a large, 2.3 m long, easily accessible vacuum chamber as well as a set of standard diagnostics (energy spectrometer, YAG screens, and beam position monitors (BPMs)). The vacuum chamber is equipped with further YAG screens on motorised translation stages and a multi-axis in-vacuum motorised support system for user devices at the interaction point (IP). The layout is fully reconfigurable to optimise it for a particular experiment and allows for a flexibility to add additional components, e.g. beam collimators, coherent transition radiation (CTR) targets etc. A number of experiments within the exploitation programme require accurate characterisation of generated CTR or coherent Cherenkov radiation (CCR) in the THz range of frequencies. This is accomplished with a Martin-Puplett interferometer positioned outside the chamber. The radiation from THz sources is collected and collimated with the off-axis parabolic (OAP) mirror and transported out through a z-cut quartz window. The interferometer is removable to provide space for experiments not requiring THz measurements.

Most user experiments in BA1 require smallest transverse beam size at the IP and shortest sub-ps bunch length as a baseline machine setup. Further flexibility is required in terms of bunch charge (from ~100 pC down to a few 10s of pC), bunch length (from sub-ps to a few ps), and even the sign of the energy chirp (positive or negative). A generic baseline machine setup was developed that satisfied the variety of requirements with only minor adjustments in machine settings. Setting transverse beam dynamics was relatively straightforward resulting in no-loss beam transport to BA1 and transverse beam sizes of 70-100 µm (rms) at IP. Special care was taken to ensure minimisation of optical function β_x at the position of the energy spectrometer screen resulting in estimated energy resolution of better than ~50 keV.

Longitudinal compression of the bunch takes place in C2V section. The negative signs of R56 and T566 offered in C2V require the linac to introduce a positive energy chirp (head of the bunch of higher energy). This is followed by a long beam transport of ~ 15 m to reach the IP in BA1. At 35.5 MeV/c beam momentum, simulations demonstrate that although the bunch length is only weakly affected by the beam space charge, the energy spread increases significantly over that distance especially in the case of maximum compression. This is illustrated in Fig.1. The difference between energy spread values increases steadily with further off-crest linac phases until approximately 8° where a sharp increase in ΔE takes place

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indicating minimal bunch length. A drastic drop in ΔE at ~10° can be attributed to the bunch over-compression at this linac phase while the energy chirp becomes negative with a following "dechirping" along the beam transport line to BA1 due to space charge. At linac phases greater than 10°, the bunch chirp remains negative and the energy spread is expected to approach the values in C2V as the bunch length increases. However, this expected trend was not observed at larger off-crest phases above ~15° and will be a subject of further detailed investigation.

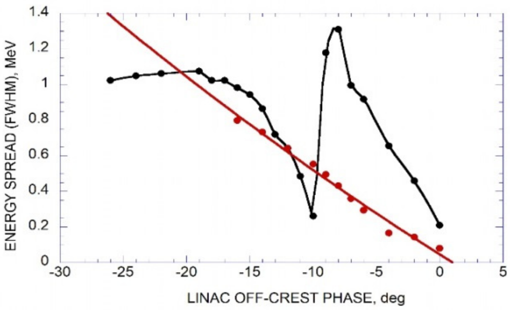

Figure 1: Energy spread vs linac off-crest phase. Red/ Black lines – as measured in the C2V/BA1 spectrometers.

BEAM AREA 1 LASER

For the purpose of combined laser-electron beam experiments, BA1 has access to laser light generated by a high energy Ti:Sapphire laser system (Coherent: 800 nm, ~100 mJ, 70 fs), housed in the Lasers, Terahertz and Terawatt Experiments (LATTE) Laboratory. This system consists of a laser oscillator (83.292 MHz; 12th subharmonic of the CLARA clock), regenerative amplifier and multi-pass amplifier, with compression in vacuum. The laser system is synchronized via the laser oscillator to the CLARA timing system with <50 fs residual timing jitter; the arrival time jitter of high energy pulses with respect to the electron beam in BA1 is currently the subject of investigation.

Laser transport to BA1 of compressed pulses is performed in vacuum, at which point they can be introduced to the 'coffin' chamber using a f/19 off-axis parabola (in vacuum), or into air to a breadboard situated parallel to the chamber. The system at installation was capable of delivering 800 mJ pulses at 50 fs (16 TW); efforts over summer 2019 will be made to restore the system output towards these levels, focussing on compressor optimisation, pump laser beam quality and rectification of damage to the Ti:Sapphire multi-pass amplifier.

CATHODE TO BA1 SIMULATIONS

Start-to-end simulations of the CLARA-BA1 lattice have been performed in a variety of lattice codes, including ASTRA [4] and GPT [5]. Optimisation of the beam at the experimental user station in BA1 is complicated by the very strong space-charge forces in the post-compression S-bend C2V section. This section of the lattice has very strong focusing to match to VELA beamline, as well as a long FODO transport section (>15 m) leading to large transverse and longitudinal emittance blow-up at reasonable bunch charges (>25 pC) and momenta (~35.5 MeV/c). Most user experiments require the shortest possible bunch lengths at the highest charges, which exacerbate these effects. Matching of the transverse dynamics between machine and model is complicated by very non-Gaussian laser beam profiles, including laser "hot-spots", which lead to complicated transverse dynamics. Longitudinal comparison is much better and we have seen good agreement between the simulated bunch length and that experimentally measured using CTR and CCR. Recently an online simulation and analysis tool based on ASTRA has been developed that will be available for the next run of CLARA. Combined with improvement in the laser profile, we expect to achieve much better agreement between machine and model in the near future.

OTHER MACHINE DEVELOPMENTS

PI Laser Development

Efforts during 2018 and 2019 on the PI laser have focussed on improving the transverse beam quality of laser pulses (266 nm, 500 µJ prior to transport, 2 ps) reaching the CLARA photocathode. A vacuum spatial filter has been designed to remove high frequency noise in the UV pulses, believed to originate from variation in the output of the laser amplifier (i.e. prior to frequency conversion) due to optical damage. The spatial filter is ~ 2 m long and incorporates a 125 µm fused silica conical aperture. Preliminary tests of the spatial filter have produced positive results; a detailed investigation of the spatial filter and implementation of an additional aspheric lens shaper to produce a flat-top transverse profile are planned for July'19.

Laser transport from the PI laser room to the cathode is performed in vacuum using relay imaging. The efficiency of the vacuum transport up to the CLARA light box has been recently measured as 78%, with some small variation (~10% decrease) observed as a function of decreasing vacuum pressure. The origin of this variation is the subject of ongoing investigation, and in-vacuum photodiodes will be installed along the transport line to help identify critical optics. The light box mirror has recently been replaced with an unprotected aluminium on polished EN aluminium optic (LBP optics) with 93% reflectivity. Significant damage was identified on the previous light box mirror (SiO_2 protected aluminium on diamond-turned copper substrate, LT Ultra), with 50-80% reflectivity observed as a function of position on the optic after ~18 months of beam operation.

Momentum Jitter and Drift

A study to measure and understand the impact of jitter and drift on the RF system on beam momentum is underway. One of the primary goals of this study is to develop an empirical model of the RF system which can quantify the impact on beam momentum due to variation in a RF sub-system (e.g. drive amplifier, modulator voltage). Over 3.5 hours of continuous running the gun Klystron power was found to drift by ±0.09% (rms), while the

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phase drifted by 0.5° which was correlated to 0.15° PTP variation in gun water temperature; this resulted in a beam momentum fluctuation of ±0.15%. The jitter over 250 shots in gun Klystron power and phase was 0.09% and 0.04° respectively. Measurements of Linac-1 RF systems were dominated by power fluctuations of the order of 2.7%; these were identified as originating in the Klystron but were not correlated to the modulator voltage. For more information see [6]. The power fluctuations will be the subject of dedicated study during isolated operation of the linac RF system during summer 2019.

Beam Diagnostic Digitisation

Parameters from Faraday Cups, ICTs, the Optical Beam Loss Monitor (oBLM), the Wall Current Monitor and other beam diagnostic signals previously determined from oscilloscope traces are now acquired into the EPICS control system using dedicated data acquisition hardware. This allows us to acquire diagnostic waveforms and parameters at the full machine repetition rate utilised during this running period of up to 100 Hz.

Two different data acquisition systems are used, one based on VME hardware from IOxOS which gives us integration with the CLARA electronic timing system, and another based on the DRS4 evaluation board from PSI which provides the high sample rate of 5Gsps needed to acquire waveforms for the oBLM [7]. Both systems are fully integrated into the EPICS control system and they transmit their data over the Channel Access network. This allows us to monitor parameters and archive them using the EPICS Archiver Appliance [8]. Data acquired using this system can be correlated easily and has been used in studies of beam stability across many diagnostics, RF breakdown, laser diagnostics, charge scans and long term monitoring of machine performance. Data is currently timestamped using the local clocks synchronised with NTP (Network Timing Protocol).

To support operation during this exploitation period a number of changes were required to the electronic timing system. This included commissioning a new repetition rate of 100 Hz for gun conditioning, supporting multiple repetition rates for laser/e-beam interaction and also providing a timing signal well in advance of laser operation to allow pre-injection of gas jets.

Beam Position Monitor Characterisation

The stripline BPM systems on CLARA require calibration in order to minimise noise at the individual pickups, and to ensure that the cable lengths from the BPM to the digitisers are similar, such that the beam signal sampled at the BPM is optimal for all four pickups. In addition to this, there is a limited range over which the analogue-to-digital converters have a linear response. Beyond these limits (+/-1V), the position measurements from the BPMs may give spurious readings.

Experiments performed with beam, and comparing the BPM readings with camera images, have confirmed the linear response range of the BPMs. Using the mid-level control system [9] users can now discard BPM readings which are known to be unreliable. The mid-level control system can also be used to measure the bunch charge at each of the BPMs, showing good agreement with the charge diagnostic devices. Provided that the BPM is calibrated correctly for a given bunch charge, the charge reading at the BPM can be calculated simply as the sum of the voltages on the four pickups, multiplied by a calibration factor. The error on the charge measurements from the BPMs is larger than that from the dedicated charge diagnostics as the bunch charge increases, but due to the low number of non-invasive charge diagnostics between the CLARA gun and BA1, the bunch charge readings from BPMs proved very useful in optimising beam transport through C2V to BA1.

RF Pulse Shaping of the PI

Due to previous issues with breakdowns causing damage to the CLARA waveguide, precautions were required to limit the peak reflected power from the RF photoinjector cavity. A square RF pulse was used until recently. This was replaced by a pulse with a linear ramp at the start of the pulse. This has the effect of spreading out the reflected power in time as the cavity fills, leading to a lower peak reflected power in the waveguide and any standing wave having a lower amplitude.

High Level Software Developments

An integrated framework of tools, combining operations and simulations has been developed, called CLARA-NET. Within this framework are a series of tools and methods that form an abstract interface to the Control System. These tools provide a human readable interface in Python designed to open up Control Room Application Development to experts and non-experts alike. Applications were developed for myriad of purposes: online image analysis, setting the RF phase, magnetic steering, scanning parameters such as charge on the cathode, measures of the momentum, momentum spread and emittance, set-up of the laser beam on the cathode, loading and applying settings, performing unmanned RF conditioning [10] etc. Using shared solutions greatly increases CLARA's capabilities. For more information see [9].

NEAR TERM PLANS

After the first successful period of CLARA exploitation, a shutdown period for preparation for CLARA Phase 2 (acceleration to full energy) has begun in April'19. During this shutdown, a load lock system similar to 400 Hz gun will be installed on the 10 Hz gun. Planned improvements on the PI laser and the load lock system will help us achieve the design parameters. CLARA Phase 2 accelerator modules are being assembled and tested offline with installation in the accelerator hall currently planned in 2021. Changes to shielding required for Phase 2 require removal of the shielding wall between the accelerator hall and the BA1. This will affect the flexibility for future experiments in BA1. CLARA FE will be operated from September'19 till March'21. The next external exploitation is pencilled in for early 2020.

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