

COMPRESSION AND LINEARISATION STUDIES ON CLARA

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Abstract

CLARA is a 250 MeV/c electron beam user facility currently undergoing final beam commissioning at Daresbury Laboratory, in the UK. CLARA features a 4-dipole variable bunch compressor, allowing a wide range of R_{56} values up to 60 mm, coupled with an X-band fourth harmonic cavity (4HC) for longitudinal harmonic correction of the S-band main linacs. An S-band transverse deflecting cavity (TDC) situated in a diagnostic straight following the bunch compressor, coupled with a high-resolution spectrometer beamline, enables full transverse and longitudinal reconstruction of the beam phase space. The FEBE arc, which delivers beam to a dedicated user area, can also act as an additional variable longitudinal compressor, with R_{56} variation of ± 50 mm possible with limited dispersion leakage, and with 2 sextupole families for T_{566} correction. A coherent transition radiation (CTR) target is situated at the exit of the arc and can be used for longitudinal tuning. Commissioning of the various longitudinal compression and linearisation systems has recently taken place, to facilitate a first tranche of “friendly” user experiments, several with demanding requirements on the bunch length.

INTRODUCTION

CLARA is an advanced medium-energy accelerator user facility in the north-west of England, UK [1]. Originally envisaged as a free-electron laser test facility, CLARA was designed to explore novel beam dynamics modalities with flexibility in the transverse and longitudinal planes, along with extensive diagnostics capabilities to analyse the resulting beam distributions. As CLARA has transitioned away from FEL science, and towards a user facility for novel acceleration, Very High Electron Energy (VHEE) radiotherapy studies, and advanced diagnostics, it has retained the longitudinal flexibility that is required for these varied application paradigms.

Novel acceleration studies and FELs both benefit from ultra-short electron bunches (< 100 fs rms.), and CLARA was designed to achieve ultra-short bunches through a combination of a 4-dipole variable bunch compressor (VBC) with an X-band fourth-harmonic cavity (11.994 GHz) for linearisation (see Fig. 1). The introduction of the FEBE (Full Energy Beam Exploitation) [2] experimental area and its accompanying 4-dipole s-shaped arc added a positive- R_{56} -like compression structure to the system, increasing flexibility. Longitudinal diagnostics in CLARA are concentrated on the transverse-deflecting cavity placed after the final accelerating structure but, for historical reasons, before the FEBE arc. An additional, relative, bunch length measurement is

possible after the arc using a coherent transition radiation (CTR) target. Longitudinal timing diagnostics include up to three Beam Arrival Monitors (BAMs) placed either side of the VBC, and at the exit of the FEBE arc.

CLARA is currently undergoing a second round of beam commissioning after a recent, successful, friendly user run [3] involving both VHEE and plasma studies, alongside advanced diagnostics experiments. At this time, the 4HC lineariser and the BAM diagnostics have yet to be fully commissioned with beam. A further run of longitudinal compression studies is expected to be performed once these elements are commissioned.

BEAM TRANSPORT AND COMPRESSION

Compressive Elements

CLARA contains a series of elements to manipulate the longitudinal phase space (LPS) as shown in Fig. 1, including the 4HC for linearisation and the VBC for compression.

A positively chirped LPS (with the bunch head at lower energy than tail) without non-linear components increases compression achievable through the VBC. The VBC comprises a dipole chicane mounted upon a moveable translation stage, which moves out with the dipole current (up to 300 mm of transverse displacement), providing a tuneable negative R_{56} (up to 60 mm).

A passive wakefield dechirper is positioned subsequent to the final linear accelerator and prior to the FEBE arc. Within the two dielectric-lined waveguides (each 0.2 m long), electron bunches generate longitudinal wakefields dependent on the bunch current profile and structure gap. These wakefields effectively reduce energy spread for a positive bunch chirp. The dechirper has recently been commissioned on CLARA, details of which can be found in [4].

Transport to the FEBE hutch, where user experiments are conducted, is via the FEBE arc. The R_{56} component through the arc is non-zero, positive, and tuneable with a nominal value of +7.7 mm [2]. Given the positive R_{56} contribution, the FEBE arc compresses the bunch in the opposite direction to the VBC. Consequently, maximum effective compression within the FEBE hutch necessitates over-compression with the VBC for the beam exiting the CLARA straight section, upstream of the FEBE arc.

CLARA Longitudinal Diagnostics

Diagnostics are positioned in CLARA for measurements of longitudinal and energy profiles as well as the full LPS. An S-band TDC is positioned after the final linac for longitudinal profile measurements. Dispersive sections are positioned along CLARA (Fig. 1) for measurements of the energy spec-

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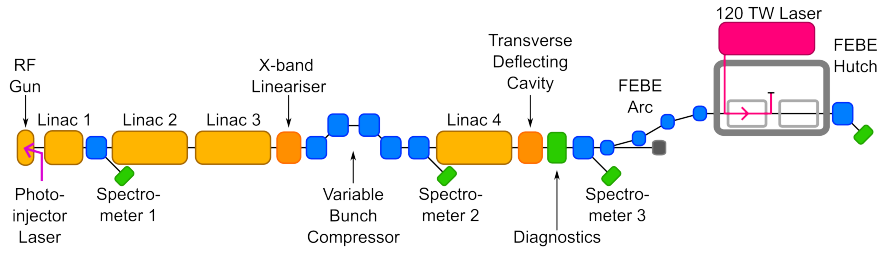


Figure 1: A schematic layout of the CLARA beamline. RF structures are denoted by orange boxes, dipole magnets by blue boxes and diagnostic sections by green boxes [2].

tra; Spectrometer-3 is positioned after the TDC, allowing for measurement of the LPS.

Longitudinal measurements are performed using the TDC following the method described in [5]. The resolution is limited by the minimum beam size achievable without the TDC interacting with the beam. Longitudinal phase space measurement also requires minimization of the beta function at the dispersive plane for optimal performance [5]. To maximise the resolution, it is preferable to conduct three separate measurements: first, assess the longitudinal profile in a non-dispersive section with optimised resolution; secondly, measure energy spectra in a dispersive section (without the TDC) also with enhanced resolution; and thirdly, perform an LPS measurement in the same dispersive section using the TDC to evaluate coupling.

A CTR target is installed at the end of the FEBE arc – specifically between the final FEBE dipole magnet and the hutch entrance in Fig. 1 – where it awaits commissioning with the CLARA beam. Results from this effort are not presented here. As previously discussed, the FEBE arc provides a non-zero, tuneable, R_{56} component; the CTR target is planned to allow for comparison of compression at the CLARA straight section versus that achieved in the FEBE hutch and thus set baseline conditions for experiments conducted there [6].

CONTROLLABLE BUNCH COMPRESSION

Compression in the CLARA Straight

In preparation for external user experiments during CLARA beam commissioning, a series of beam setups with varying bunch charge and compressions were required [3]. The results are presented in Fig. 2.

Longitudinal current profiles corresponding to different bunch charges are displayed in Fig. 3. Minimum bunch lengths of 20 fs, 80 fs and 140 fs (from the fit in Fig. 2) and maximum currents 0.11 kA, 0.8 kA and 1.2 kA were measured at 3.5 pC, 100 pC and 250 pC respectively. The best resolution achieved with the TDC was 15 fs. It is noted that at each charge level, there exists a high current component at the head of the bunch; this part may be resolution-limited by the TDC measurement. Consequently, the maximum currents reported likely represent lower bounds. The compression scans presented in Fig. 2 are comparable to longitudinal emittance measurements. The observed shallower slopes and shorter minimum bunch lengths at lower charges

indicate reduced longitudinal emittance, which aligns with expectations due to shorter bunches exiting the RF gun at lower charges, and therefore smaller RF curvature from the linacs [7].

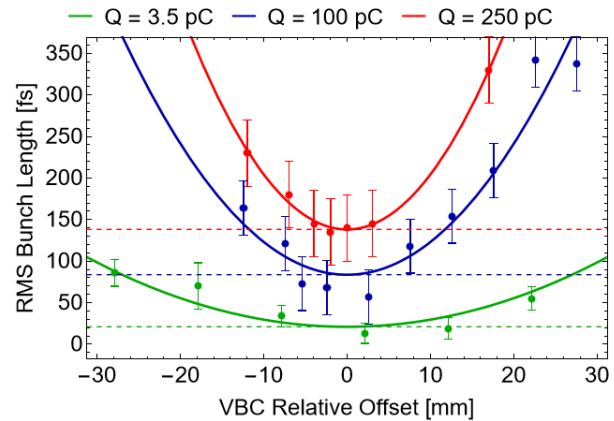


Figure 2: Bunch length as a function of relative offset in the VBC, given as difference from the offset at maximum compression. Lines represent fits to the bunch length measurement points.

During commissioning, a series of machine setups were tested to characterise different levels of compression. Variable off-crest phases were used in the second and third linacs ($+12^\circ$ to $+30^\circ$, equal in both) across different days, and bunch lengths measured. The bunch lengths for a series of these measurements at 250 pC are shown in Fig. 4. There are observable differences between days, however the maximum compression for all datasets sits on the overall ≈ 150 fs average within the resolution of each measurement. This sug-

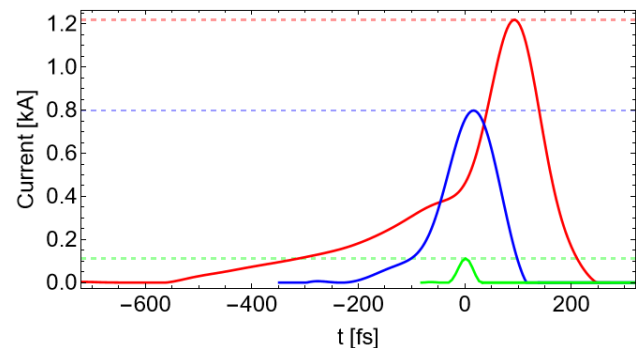


Figure 3: Current profiles measured at maximum compression for 3.5 pC (green), 100 pC (blue), and 250 pC (red).

gests that, despite variation in the longitudinal emittance shown by the varying slopes on each day, the achievable compression / bunch-length is limited by non-linear components to the longitudinal phase space.

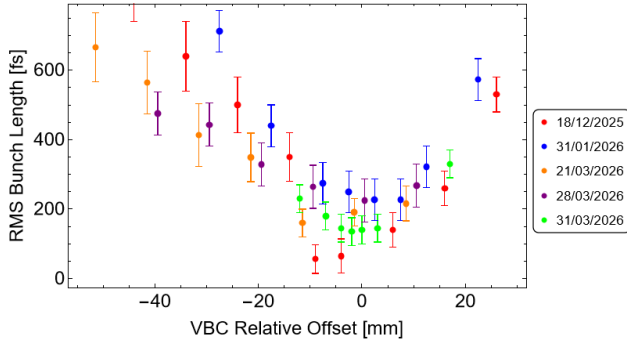


Figure 4: Measured bunch length, with 250 pC on different days, as a function of VBC offset relative to the offset for maximum compression.

Non-linear and higher-order components can also be seen in the longitudinal phase space. The LPS measured with the TDC is shown in Fig. 5 at approximately equal RMS bunch lengths (≈ 170 fs) for under, maximally, and over-compressed bunches.

Non-linearity grows with increasing compression, and features observed in the LPS also move with compression, allowing for the energy spectra to be used as a qualitative measurement of the non-linearity. It is expected that with the use of the 4HC these components can be minimised and any further non-linear or higher-order LPS components can be investigated as part of future machine development.

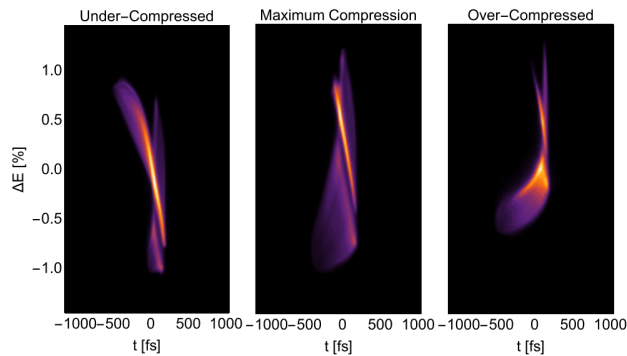


Figure 5: Longitudinal phase space, measured with 100 pC bunch charge, with the VBC at maximum compression ($R_{56} = -57.6$ mm) and relative offset +10 mm (over-compressed, $R_{56} = -62.8$ mm) and -20 mm (under-compressed, $R_{56} = -47.8$ mm). All bunches have an RMS length of ≈ 170 fs.

Transport and Compression to FEBE

The observed LPS plots at varying compression (Fig. 5) suggest that the energy spectra can be used as a quasi-compression proxy measurement. Without the use of a dedicated longitudinal diagnostic in FEBE, the energy spectra

on the final spectrometer screen can therefore serve this purpose. The FEBE arc is designed to provide an additional +7.7 mm R_{56} contribution [2]. Therefore, to achieve maximum compression in FEBE, it is necessary to over-compress through the VBC and re-compress through the FEBE arc.

This methodology was tested by finding the VBC position which corresponds to maximum compression as measured on Spectrometer-3, at the end of the CLARA straight-on section, using the TDC. The beam was then transported through to the FEBE spectrometer and the optics set to measure the energy spectrum on this screen. The VBC was adjusted to find the position where the energy spectra in FEBE was qualitatively comparable to the energy spectra previously measured in CLARA Spectrometer-3 at its maximum compression point.

At 100 pC it was found that the VBC setting with $R_{56} = -49$ mm corresponded to maximum compression in CLARA Spectrometer-3. In FEBE, maximum compression was then estimated, using the measured energy spectrum, with the VBC set to $R_{56} = -57.6$ mm. The energy spectra at both screens are shown in Fig. 6, with a good match between the two. This qualitative observation estimates the contribution of the FEBE arc to be +8.6 mm. Further studies with a dedicated longitudinal diagnostic are required to confirm the arc R_{56} contribution, compare with simulations, and confirm the tunability of this contribution.

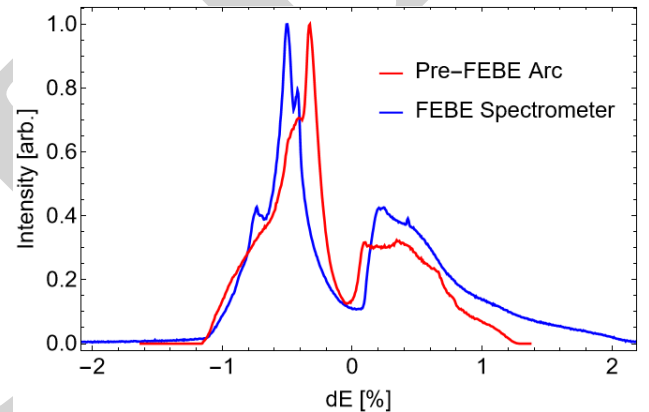


Figure 6: Energy spectra of maximally compressed bunches at CLARA Spectrometer-3 (pre-FEBE) and in the FEBE spectrometer.

CONCLUSIONS

We have demonstrated controllable bunch compression across a range of bunch parameters, with kA-scale peak currents delivered and longitudinal phase space characterised at the end of the CLARA straight. Over-compressed bunches have been transported through the FEBE arc and, with the energy spectra on the FEBE spectrometer screen, demonstrated the reproducibility of maximum compression. Further machine development, with the introduction of the X-band lineariser and dedicated longitudinal diagnostics in FEBE, will further enhance the tunability and characterisation of the longitudinal phase space of bunches on CLARA and in FEBE.

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