DEVELOPMENTS IN THE CLARA FEL TEST FACILITY ACCELERATOR DESIGN AND SIMULATIONS

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Abstract

We present recent developments in the accelerator design of CLARA (Compact Linear Accelerator for Research and Applications), the proposed UK FEL test facility at Daresbury Laboratory. These comprise a revised front-end to ensure integration with the existing VELA (Versatile Electron Linear Accelerator) line, simulations of a magnetically compressed ultra-short mode and a post-FEL diagnostics section. We also present first considerations on the inclusion of final acceleration using X-band structures.

THE CLARA ACCELERATOR

CLARA (Compact Linear Accelerator for Research and Applications) is a proposed 250 MeV, 100-400 nm FEL test facility at Daresbury Laboratory [1]. The purpose of CLARA is to test and validate new FEL schemes in areas such as ultra-short pulse generation, temporal coherence and pulse-tailoring. The accelerator will comprise 4 S-Band, normal-conducting linacs with a medium-energy, variable bunch-compression scheme, feeding into a flexible arrangement of FEL modulators and radiators.

For seeding the accelerator includes a pre-FEL dogleg where laser light can be introduced. The accelerator will be driven by a high rep-rate RF photocathode S-Band (2998.5 MHz) gun, operating in single bunch mode at up to 400 Hz, and with bunch charges up to 250 pC. The accelerator is intended to be flexible, with seeded, ultra-short and multi-bunch train modes provided. Compression can be achieved via a variable magnetic bunch compressor between linacs 2 and 3 or velocity bunching in the injector. Linearisation can be provided by a harmonic X-band structure immediately prior to the magnetic compressor.

FRONT END

The VELA user facility, based on the ALPHA-X photocathode gun, has been commissioned and successfully delivered beam to users in 2013 [2]. The proposed FEL test facility, CLARA, is intimately linked to VELA with much common infrastructure. The design of the CLARA Front End (CLARA-FE) has been optimised to meet the requirements of the CLARA injector as well as to transport higher repetition rate, higher energy bunches to the presently operating VELA facility.

The proposed layout shown in Fig. 1 has been designed to use a common RF and drive laser infrastructure to feed two photo-injector RF guns. This will allow the flexibility of sending ~5 MeV high repetition rate bunches to existing VELA user areas, and up to 50 MeV bunches transported through the S-bend placed after the first linac on the CLARA line to the VELA user areas at lower rep-rate. The layout assumes that the present VELA gun moves to CLARA when the front end is ready and installed. The ~55 MeV bunches after linac-1 can either be transported to (1) the CLARA line, (2) around the first dipole in the S-bend, then straight ahead to a diagnostic spectrometer line for characterising high energy bunches and (3) around the second dipole in the S-bend to the VELA user areas (the quadrupole triplet can be energised to eliminate dispersion in the VELA line). When the new High Repetition Rate Gun (HRRG) [3] is ready for commissioning and characterisation, it will be installed in the present VELA gun position. This is attractive as it provides a full set of dedicated diagnostics including the Transverse Deflecting Cavity (TDC). After this characterisation the HRRG will be moved to the CLARA line. Depending on the experimental programme either the original VELA gun or another new gun will be installed on the VELA line. This option will make low energy, short bunches available to proposed electron diffraction experiments on the VELA line [4]. At present, all simulations for the CLARA machine have been performed using a model of the existing VELA low rep-rate gun as it is assumed this will be installed before the HRRG.

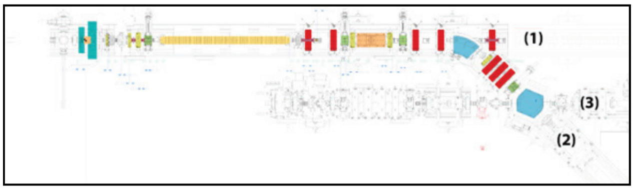

Figure 1: CLARA Front End Layout. The beam can be directed to (1) the rest of CLARA, (2) a diagnostic spectrometer line and (3) the existing VELA line with two user areas. The second "lozenge" dipole also admits beam from the existing VELA gun line allowing to be diverted to (2) or continue to (3).

ULTRA-SHORT MODE

One of the required modes of CLARA operation is transport of a medium charge (100 pC) bunch with length less than 25 fs RMS and corresponding high peak current in excess of 1 kA. This should have transverse normalised emittance of < 1 mm mrad and energy spread of <150 keV RMS. This parameter set is specified for research into FEL schemes where the bunch length must be shorter than the typical SASE spike separation of $2\pi l_c$, with l_c the cooperation length. Previously, accelerator simulations have concentrated on a velocity bunching scheme in the injector to achieve these parameters [5]. Here we present a preliminary tuning for the ultra-short mode using purely magnetic compression. The harmonic cavity was turned off and the variable bunch compressor set to maximum deflection, giving an R_{56} of -72 mm. Linacs 3 and 4 were set on crest and linac 2 scanned to find minimum bunch length. The resulting bunch properties are shown in Fig. 2.

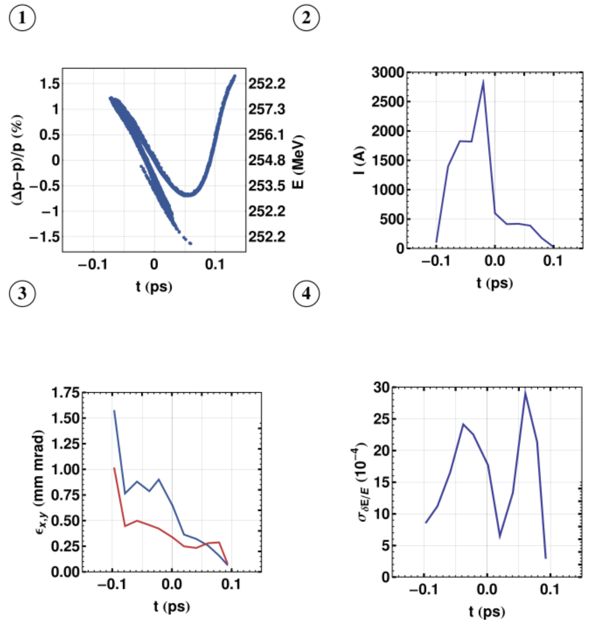

Figure 2: Preliminary beam properties for the magnetically compressed ultra-short mode. (1) Longitudinal phase space. (2) Current profile in 20fs bins. (3) Normalised transverse slice emittances (blue horiz., red vert.) in 20 fs bins. (4) Slice energy spread in 20 fs bins.

It is clear that this setup requires further optimisation as the slice energy spread and chirp exceeds specifications, and the RMS bunch length is 39 fs. However peak current is exceeded and so may be traded off through energising of the harmonic cavity and off-crest running in linacs 3 and 4. It is intended to refine this setup using multi-dimensional optimisation to minimise the energy spread and curvature, and to relax the compression somewhat as we exceed the required peak current by a factor of three. This should also mitigate the emittance degradation seen.

POST-FEL DIAGNOSTICS

Some of the advanced FEL schemes proposed depend on a manipulation of the electron beam properties with characteristic scales of several coherence lengths and shorter than the electron bunch [6,7,8]. To test mode locking and femto-slicing for the production of trains of short pulses [9,10,11] requires a 30 - 50 µm modulation of the beam energy, created via interaction with an IR laser beam in a short undulator.

The performances of these schemes depend on this energy modulation so monitoring the longitudinal phase space is important. A transverse deflecting cavity (TDC) [12] installed in the last part of the FEL line allows the longitudinal beam distribution to be observed on a screen placed after the dipole leading to the beam dump. Figure 3 shows an initial layout of this diagnostic system, with a vertical TDC shown. This deflection maps the electron beam longitudinal coordinate to the vertical coordinate on a screen after the spectrometer dipole whilst the dipole converts energy to the horizontal coordinate.

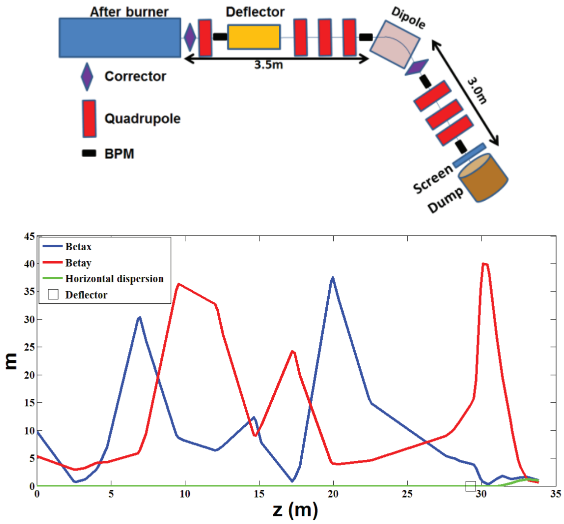

Figure 3: Layout of the phase space diagnostics (top) and potential optics solution (bottom) with transverse deflector and energy spectrometer.

The longitudinal resolution of the screen image can be written as:

$$\sigma_{L,r} = \frac{pc}{eV_0 k|\sin\Delta\Psi|}\sqrt{\frac{\varepsilon_n}{\gamma\beta_{y,D}} + \frac{(\sigma_{screen})^2}{\beta_{y,s}\beta_{y,D}}} \qquad (1)$$

Here $k = 2\pi/\lambda$ and σ_{screen} is the screen resolution. V_0 is the deflecting voltage, $\beta_{y,D}$ an $\beta_{y,S}$ are vertical beta functions at the deflector and screen. $\Delta\Psi$ is the vertical phase advance between the deflector and screen, and λ = 10.01cm for a 2.998 GHz S-band cavity. The energy resolution of the spectrometer can be written as [13]:

$$\sigma_E = \sqrt{\frac{E^2}{\eta^2}\frac{\varepsilon_n\beta_{x,s}}{\gamma} + \frac{E^2}{\eta^2}(\sigma_{screen})^2 + (eV_0k)^2\frac{\beta_{y,s}\varepsilon_n}{\gamma}} \qquad (2)$$

Here η is the horizontal dispersion at the screen. The first two terms represent the resolution of an energy spectrometer while the third term is the energy spread induced by the deflector [14].

The optimum phase advance between deflector and the screen is $\Delta\psi = 90^\circ$. Large values of V_0 and $\beta_{y,D}$ give good longitudinal resolution but decrease the energy resolution via the induced energy spread. A small value of $\beta_{x,S}$ and a large value of η are required for good energy resolution. Figure 3 also shows a possible optical solution form the modulator exit to the screen. The radiators are at maximum gap and the intra-undulator quadrupoles are used along with those shown in Fig. 3 to give the required resolution. The optics shown is for a beam energy of 150 MeV and gives a longitudinal resolution of 6.5 µm and an energy resolution of 50 keV with a deflecting voltage of 5 MV, calculated using Eq. 1 & 2. The vertical RMS beam size on the screen is 1.8 mm. With a beam energy of 250 MeV, similar resolution can be achieved with similar optics but with a deflecting voltage of 7.5 MV. Simulations have been performed with the code elegant to test the analytic results. An example of the simulated phase space imaged on the screen is shown in Fig. 4. - this is from a beam modulated with a few (FWHM 500 fs) cycle 50 µm laser with a peak power of 30 MW. Two million particles were used in this simulation. The screen image clearly shows energy modulations as predicted by the analytical equations above.

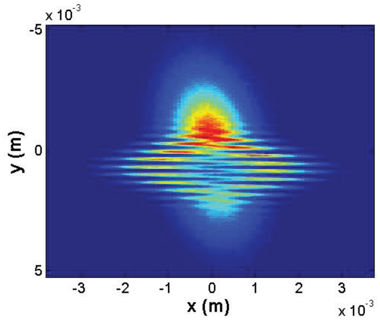

Figure 4: Beam imaged on the spectrometer screen.

X-BAND FINAL ACCELERATION

Recently interest has developed in using X-band (11994 MHz) CLIC structures as accelerating elements in a FEL [15]. To address this, we propose the replacement of the S-band linac 4 in CLARA with an equivalent length of such structures operating at 65 MV/m. We term this CLARA-X and will enable the beam energy to reach 426 MeV in the seeded mode. Figure 5 shows the optics for CLARA-X with the 4th S-band cavity replaced with an X-band equivalent. Almost no additional optimisation has been performed with the X-band cavity in-place.

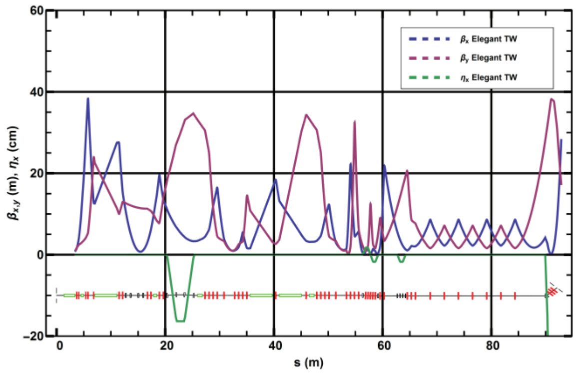

Figure 5: Optics for CLARA with X-band structures in the final linac. The energy reached is 426 MeV.

Figure 6 shows initial simulations of this mode at the same upstream configuration as in the S-band case with the X-band structures on crest. As the bunch is relatively long in this mode, additional curvature arising from the stronger wakefields has only a small effect. This will be mitigated with a small reduction in the gradient of the harmonic linearising cavity prior to the bunch compressor.

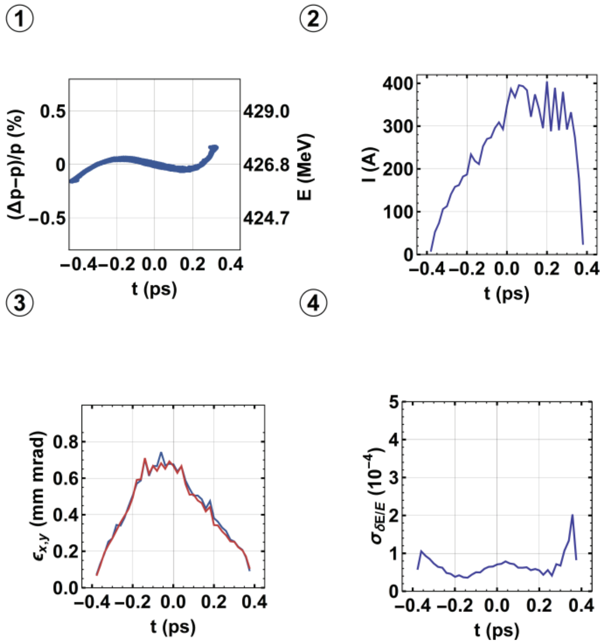

Figure 6: Beam properties, as described in Fig. 2, at the FEL for CLARA-X at 426 MeV in the seeded mode.

In order to confirm that the insertion of X-band structures does not compromise the nominal seeded operation mode of CLARA at 230 MeV tracking has also been performed in CLARA-X at reduced gradient. This is shown in Fig. 7. Again we see that the additional curvature from the stronger wakefields is a relatively

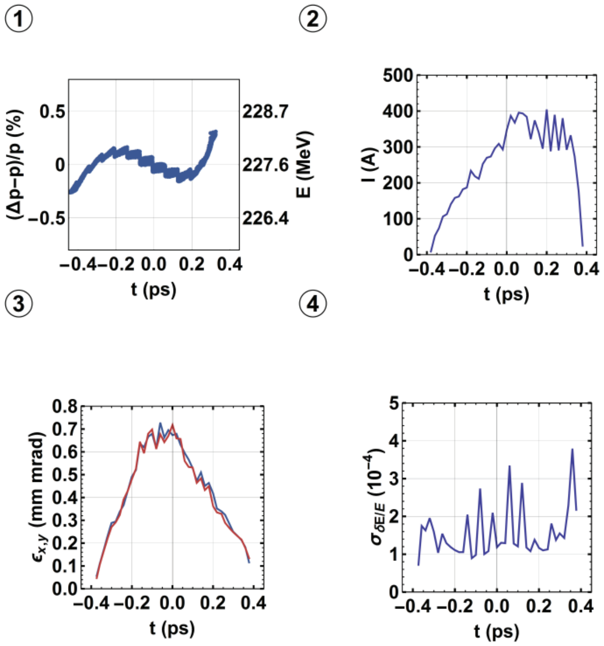

Figure 7: Beam properties, as described in Fig. 2, at the FEL for CLARA-X at 230 MeV in the seeded mode.

small effect and will be compensated for by a reduction in the gradient of the linearising cavity prior to the compressor. All other beam specifications for this mode are met adequately.

For completeness we reproduce the magnetically compressed ultra-short mode setup in the CLARA-X case. Results are shown in Fig. 8. We see that as in the S-band case a re-optimisation is required to compensate for the chirp and a relaxation in compression will mitigate the emittance growth seen.

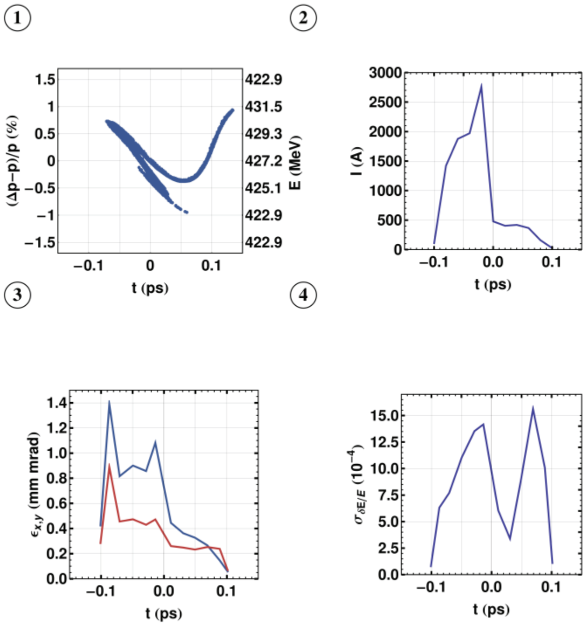

Figure 8: Beam properties, as described in Fig. 2, at the FEL for CLARA-X at 426 MeV in the magnetically compressed ultra-short mode.

CONCLUSION

Design work on the CLARA FEL test facility has been progressing throughout the year. The front end is now in procurement phase, correspondingly we have presented an updated layout taking into account engineering constraints. We have defined a preliminary tuning for the required ultra-short bunch mode using purely magnetic compression. We have presented results on the viability of post-FEL diagnostics on CLARA, and their expected performance. Finally, we have presented first considerations of performance upon replacing linac 4 with an equivalent length of X-band CLIC structures. With minimal optimisation of the machine design, we reproduce similar beam parameters to previous CLARA designs with either lower gradients and a similar energy, or higher gradients and a near-doubling of the CLARA beam energy. Initial studies also show we can maintain the newly-proposed magnetically compressed ultra-short bunch mode at this increased energy. Further optimisation of the machine design should lead to improvements of the beam parameters presented here.

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