# CLARA ACCELERATOR DESIGN AND SIMULATIONS

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## *Abstract*

We present the accelerator design for CLARA (Compact Linear Accelerator for Research and Applications) at Daresbury Laboratory. CLARA will be a testbed for novel FEL configurations. The accelerator will consist of an RF photoinjector, S-band acceleration and transport to 250 MeV including X-band linearisation and magnetic bunch compression. We describe the design of the dedicated diagnostic sections and seed laser dogleg. Beam dynamics simulations are then used to define an operating working points suitable for the different FEL schemes.

## INTRODUCTION

The aims of the CLARA project and overview of the proposed layout are presented in an accompanying paper [1]. A high repetition rate gun upgrade is also proposed in an accompanying paper [2]. In this paper we detail the design of the accelerator and present tracking simulations.

Previous work has detailed the RF photocathode gun design, longitudinal phase space linearisation scheme and variable magnetic bunch compressor [3]. Here we discuss the diagnostics sections and dogleg for transferring the beam to the seed laser axis .

## DIAGNOSTIC SECTIONS

Dedicated beam diagnostics sections are situated after the bunch compressor at $70 - 150$ MeV, and again after linac 4 at 250 MeV. The transverse and longitudinal properties of the compressed bunch will be analysed at these points. Specifically we intend to measure the Twiss functions, emittance, energy, energy spread, bunch length, slice emittance and slice energy spread. This is achieved with a five quadrupole system together with TDC and spectrometer line. This arrangement has been used with success at, for instance, FERMI@Elettra [4]. The large relative energy spread required at the bunch compressor, of $\mathcal{O}(2\%)$, dictates that the quadrupole integrated strengths in this section are limited by chromatic aberration to $kl \simeq 0.7\ \mathrm{m}^{-1}$. This in turn implies that these sections are relatively long. Figure 1 shows the optics of these diagnostic sections (starting at 0 m and 19 m respectively). $\beta_x$ is small at the start to minimise the CSR induced emittance growth in the preceding bunch compressor. Large $\beta_y$ at the transverse deflecting cavity and vertical phase advance of $\sim 90^\circ$ is chosen to maximise the vertical size of the streaked beam on a screen situated after the fifth quad, $\sigma_y \equiv \sqrt{\beta_{y1}\beta_{y2}} \sin \Delta\mu_{y,12}$. The following four quadrupole telescope ensures that CLARA can drive the FEL without changing optics from the diagnostic configuration. This ensures minimal intervention from running mode, and allows the possibility of online diagnostics on the upgrade of the spectrometer dipole to a pulsed magnet. We estimate the achievable slice resolution following the method of Craievich [5]. Figure 2 shows that we are able to resolve 5 fs slices in the low energy diagnostics line at 70 MeV with a vertical TDC deflecting voltage of 5 MV. Figure 3 (upper) shows the seeded bunch tracked through the low energy diagnostics section. The bunch is sliced in 0.1 ps time slices at the TDC, and the screen image with TDC on and off is shown. Figure 3 (lower) shows the same information, but with the screen now in the spectrometer line after the fifth quad. The screen is at the same path length from the TDC as the non-dispersive screen with $|\eta_x| = 0.5$ m, allowing energy and energy spread determination. With the TDC on, slice parameters are resolved. A similar analysis in the high energy diagnostics line at 250 MeV produces similar results for a TDC with deflecting voltage of 10 MV.

## DOGLEG

We require an offset of the FEL transversely from the linacs as we must insert the seed laser co-linearly with the undulator axis. A dogleg was chosen instead of a chicane in order to minimise the longitudinal momentum compaction ($R_{56}$), thus preserving bunch length. A spreader with overall angular offset does not fit with existing infrastructure. The longest wavelength seed laser pulse proposed is 50 $\mu$m. This must propagate to the modulator immediately follow-

Table 1: Machine parameters for seeded bunch

| Section | Value | Unit |
|---|---|---|
| Gun Gradient | 100 | MV/m |
| Gun $\phi$ | $-25$ | ° |
| Linac 1 V | 21.0 | MeV/m |
| Linac 1 $\phi$ | $-20$ | ° |
| Linac 2 V | 11.5 | MeV/m |
| Linac 2 $\phi$ | $-31$ | ° |
| Linac X V | 7.3 | MeV/m |
| Linac X $\phi$ | $-168$ | ° |
| BC $\theta$ | 89.0 | mrad |
| Linac 3 V | 20.0 | MeV/m |
| Linac 3 $\phi$ | $+20$ | ° |
| Linac 4 V | 20.0 | MeV/m |
| Linac 4 $\phi$ | $+20$ | ° |

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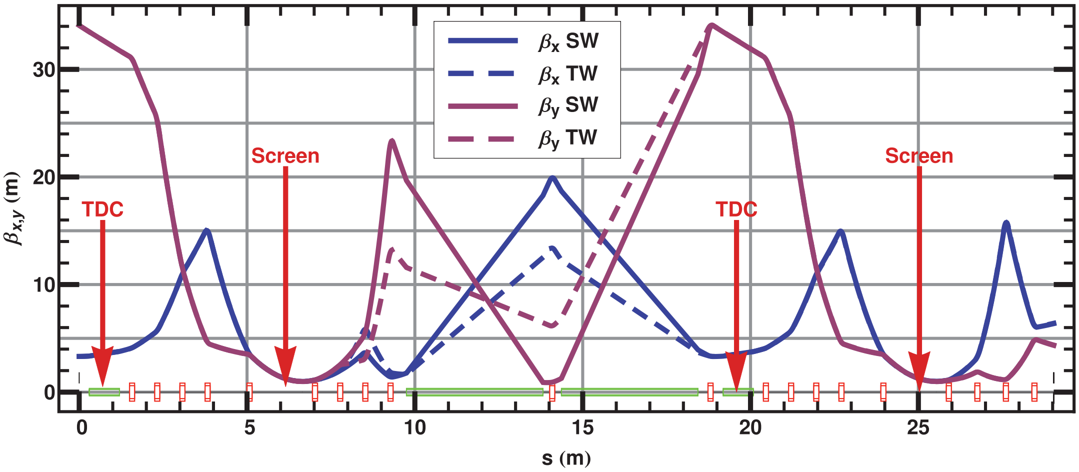

Figure 1: CLARA optics from bunch compressor exit (at 24.5 m from the cathode) to dogleg entrance, comprising low and high energy diagnostics lines with linacs 3 & 4 separating. Matches for both standing wave (SW) and travelling wave (TW) linac focussing are shown. Between each TDC and subsequent screen indicated there is a vertical phase advance of $\pi/2$.

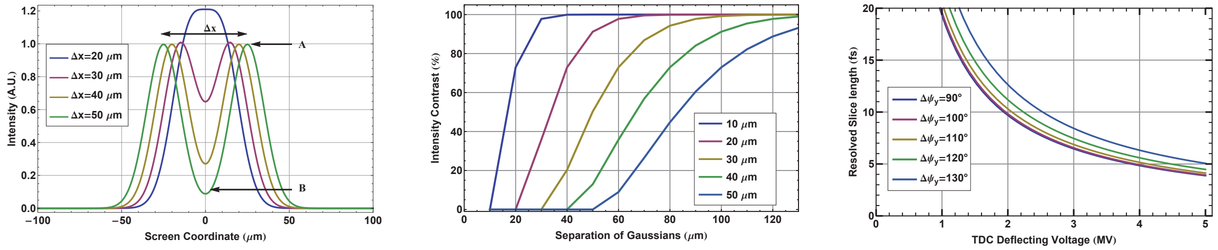

Figure 2: 1.) Two features on a screen modelled as Gaussians separated by $\Delta x$ with $\sigma$ the screen resolution (10 $\mu$m). Intensity contrast (IC) is then defined as $\frac{(A-B)}{A}$. 2.) IC as a function of the separation of the two Gaussian features for 5 screen resolutions from 10 $\mu$m to 50 $\mu$m. 3.) Resolved slice length in low energy diagnostics line as a function of TDC deflecting voltage assuming a screen resolution of 10 $\mu$m and a contrast ratio of 70%.

ing the dogleg in as short a distance as possible, as it is highly divergent. For example at 3.5 m from the laser pulse waist the $3\sigma$ spot radius is 70 mm. In Fig. 4 we show the proposed layout and optics. A five quadrupole achromat with bend angle of 2° has been chosen, providing 100 mm offset in total length of 3.5 m. As this point the relative energy spread in the bunch is small, so chromatic contributions from the quadrupoles are less significant, the maximum $kl$ is 2.85 m$^{-1}$. As expected the $R_{56}$ is small having a value of 67 $\mu$m. One of the high dispersion drifts is suitable for insertion of an energy collimator if required.

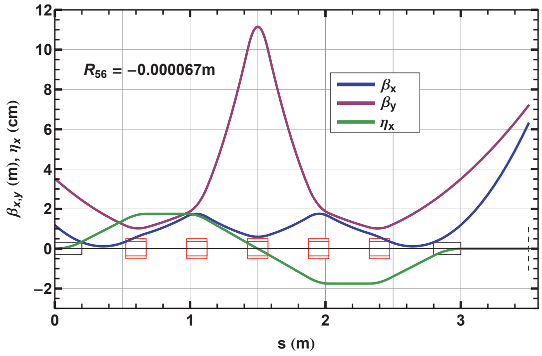

Figure 4: Optics of seed laser dogleg.

## BEAM DYNAMICS

The beam was simulated from the cathode until the exit of linac 1 using ASTRA [6] to include the effects of space-charge, wakefield effects have not yet been included. The rest of the machine was then tracked using ELEGANT [7]. Linac wakefields, longitudinal space-charge and coherent radiation effects were included.

The seeded operating mode is the most challenging as it requires that the bunch slice properties are constant for a large fraction of the bunch length, i.e. 300 fs out of 500 fs FW, and that the peak current is above 300 A for this fraction, without significant energy chirp. This is to ensure that expected jitter between the laser seed and the electron bunch does not result in unacceptable photon output jitter from pulse to pulse. To achieve this an optimisation was

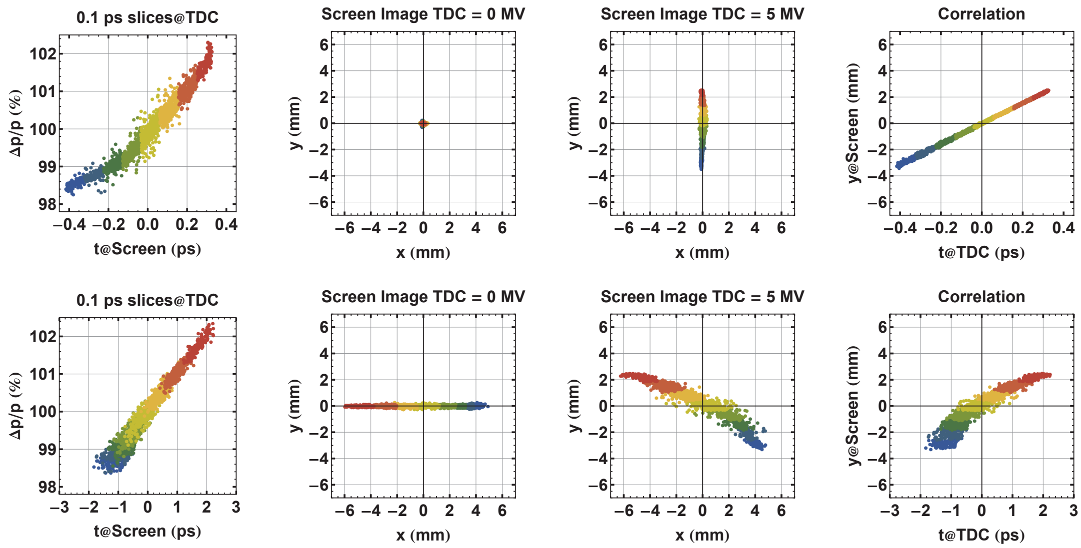

Figure 3: Seeded bunch streaked by TDC in low energy diagnostics section. Upper is in straight-ahead line, lower in spectrometer line. For both: 1.) Long. phase space at screen; 2.) Screen image with TDC = 0 MV; 3.) Screen image with TDC = 5 MV; 4.) Correlation between arrival time at TDC and vertical position on screen.

performed on the longitudinal phase space of the bunch at the FEL. At each step a transverse rematch was necessary to preserve the projected emittance. The optimisation variables are the voltages and phases of the S-band and X-band linacs, and the bunch compressor bend angle. The optimisation constraints are:

- There exists a 300 fs window where the mean current exceeds 300 A
- In that window, the minimum current in a 20 fs slice is greater than 270 A
- In that window, the standard deviation of the charges in a 20 fs slice is less than 20 pC
- In that window, the chirp is no larger than 1% of the energy spread in the central 20 fs slice

In Fig. 5 we show the optimised longitudinal phase space, current profile, slice emittance and slice energy spread at the FEL. This does not yet reach our criteria, however we are confident that further optimisation will satisfy the FEL requirements.

For the unseeded modes, an alternative to magnetic compression is to use velocity bunching in the low energy section of the accelerator. Linac 1 is set to the zero crossing phase to impart a chirp along the bunch. The bunch compresses in the following drift space. Linac 2 then rapidly accelerates the beam and "captures" the short bunch length. Simulations suggest that this mode of compression can produce a similar bunch to that produced by the magnetic compression scheme if the X-band cavity is not used. Thus both compression modes can be used to meet the unseeded mode of CLARA operation. Preliminary simulations [3] suggest that for a 100 pC bunch, a peak current ∼ 1 kA can be achieved with slice energy spread of ∼ 250 keV rms and normalised slice emittance of ∼ 1 mm mrad. With such a short bunch in the injector, wakefields have a significant effect which will be investigated further.

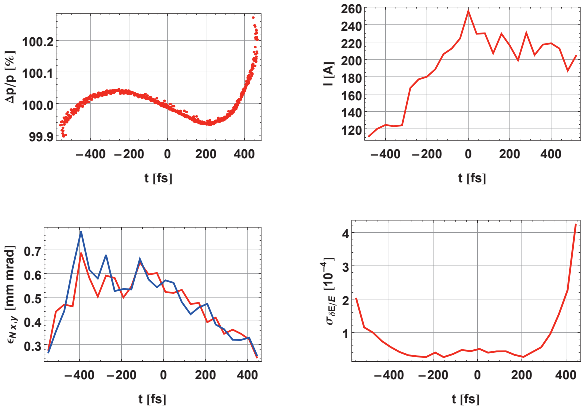

Figure 5: Seeded bunch long. phase space, current profile, normalised slice emittance and slice energy spread.

## REFERENCES

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