DEVELOPMENTS IN CLARA 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. The layout changes include a dedicated collimator in CLARA front end to provide some control over the dark current, changes to low energy diagnostics section and modifications to FEL modules. The progress in the design simulations mainly focuses on a comparison of using ELEGANT and CSRTrack for the Variable Bunch Compressor and first considerations of requirement of laser heater for CLARA.

THE CLARA ACCELERATOR

CLARA is a proposed 250 MeV FEL test facility at Daresbury Laboratory [1]. The front end of CLARA incorporates an S-bend to transport the beam to presently operational VELA facility [2] and the gun for CLARA will share the same RF and drive laser infrastructure [3]. The changes to CLARA layout presented here since IPAC14 [4] include: a dedicated collimator in CLARA Front End to reduce the dark current from the injector, removal of Transverse Deflecting Cavity (TDC) from the low energy diagnostics section, inclusion of the post-linac diagnostics section with TDC and changes to the FEL modules. Preliminary investigations of requirements on laser heater and updates on simulations in magnetic chicane mode using CSRTrack [5] are presented. The Front End of CLARA will be installed later this year with first beam commissioning starting early 2016.

CHANGES TO ACCELERATOR LAYOUT

There have been a number of changes to the layout of the CLARA accelerator since 2014 (see Fig. 1). The reasons for each change have either been the gaining of operational experience on VELA, unforeseen engineering constraints or the enabling of additional capabilities. The front end has been finalised and components are either delivered or on order. This includes linac-1, a 2 m S-band structure capable of accelerating beam to ~55 MeV and its attendant klystron and modulator; beam transport elements towards linac 2, S-bend to the existing VELA beamline and spectrometer; BPMs and diagnostic stations including screens, slits, collimators and Faraday cups. After linac-2, space for a possible laser heater has been retained, the variable bunch compressor (VBC) layout has been finalised and magnets and other components are currently under engineering specification. To save space the transverse deflecting cavity (TDC) and diagnostics immediately following the VBC have been removed, leaving one TDC section immediately following linac-4, and one immediately following the FEL. The baseline machine simulations have been altered to take account of these changes.

COLLIMATION IN FRONT END

Although CLARA is a relatively low power machine (maximum average beam power of around 10 W [1]), and severe beam loss problems are not anticipated, collimation is included in the front end lattice to mitigate effects of dark current and beam halo. We propose to include a gun collimator similar to that in VELA where a 1mm thick tungsten plate with different hole sizes is used to collimate gun dark current [6]. In CLARA, the collimator will be included in the drive on the first YAG station, immediately upstream of the first linac. The collimator will utilise cylindrical hole diameters of 4, 6 and 9 mm.

In addition, we propose an additional collimator in the matching section between the first two linac modules, where the beam energy is tens of MeV. We envisage a similar arrangement to that used at FERMI where thick copper collimators are used, with tapering to reduce wakefields and a choice of several different apertures [7]. The engineering specifications of this collimator are being finalised.

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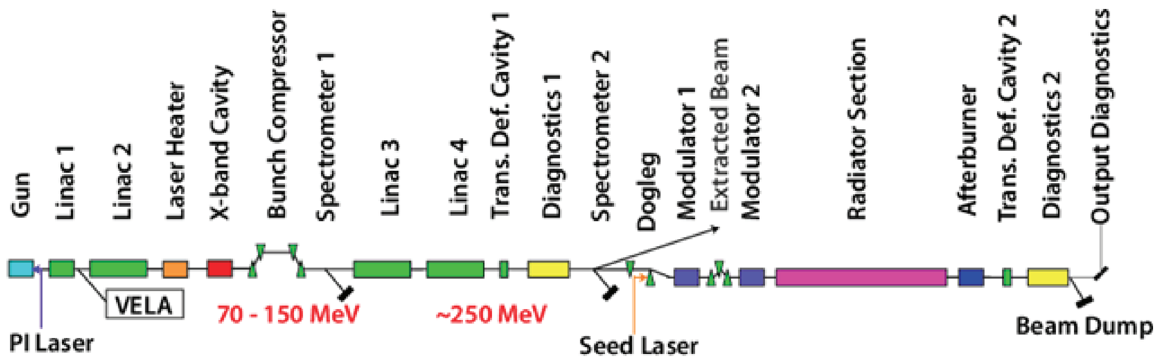

Figure 1: Updated CLARA layout.

VARIABLE BUNCH COMPRESSOR

The seeded FEL schemes which are proposed at CLARA require bunches with a small correlated energy spread at the undulators. This necessitates compression at a rather low energy of ~70 MeV, followed by compensation of the energy chirp required for compression in linacs 3 and 4.

For the seeded FEL operating mode of CLARA, a bunch length of 250fs (RMS) is required, with a peak current of around 400A, and a normalised emittance of ≤ 1mm-mrad. Simulations of the CLARA bunch compressor were performed initially using ELEGANT [8], however this code neglects important parameters when projecting the bunch charge density into 1-d. CSRTrack has the capability of including space charge and CSR effects in both transverse and longitudinal planes. In addition, the reliability of projecting the bunch density onto a line is questionable when dealing with short bunches. This model depends on the Derbenev criterion being satisfied [9]:

$$\frac{\sigma_x}{\sigma_z} 2^{1/3} \left[3 \frac{R^2}{\sigma_z^2}\right]^{1/9} \ll 1$$

where $\sigma_{x,z}$ are the transverse and longitudinal (RMS) bunch sizes and R is the bend radius of the magnet. This is not met at the exit of the CLARA bunch compressor.

CSRTrack uses Gaussian sub-bunches to represent the 3-d distribution of the whole bunch, and the size of these sub-bunches can have an effect on the numerical noise in the simulation. A balance must be found between smoothing out space charge and CSR effects, which occurs when the sub-bunch size, σ_{SB} is of the order of the actual bunch size, and introducing a high level of numerical noise, which is created when the sub-bunch size is much smaller than the inter-particle spacing:

$$< \sigma_{SB} > \ll n^{-1/3}$$

where $n = N/(\sigma_x \sigma_y \sigma_z)$, and N is the number of macroparticles used in the simulation. Simulations were run in CSRTrack for 10^4 macroparticles. It was determined that a sub-bunch size of ~10% of σ_z gave the best results in terms of accurately simulating the effects of CSR, as it was observed that the simulation failed to converge with much smaller sub-bunch sizes, and the effects of CSR were underestimated with much larger sub-bunches.

The results of these CSRTrack simulations have been benchmarked with ELEGANT. We found the projected (normalised) horizontal emittance at the exit of the VBC increased from 2.0 mm-mrad to 2.50 mm-mrad, and the RMS energy spread increased slightly, from 2.04% to 2.09%.

LASER HEATER CONSIDERATIONS

The CLARA facility can potentially be affected by the longitudinal microbunching instability (MBI) [10, 11], as are other accelerators that drive high gain FEL facilities [12, 13]. A first estimate of the MBI in CLARA can be provided by the linear 1-d model [14]. Following the same approach used in [15] we can calculate the gain in density modulation after the bunch compressor as a function of the initial modulation wavelength. The result depends on beam focusing, initial current, compression factor and on the accelerator layout. A typical result is shown in Fig. 2.

The spectrum of energy modulation and the slice energy spread accumulated at the end of the accelerator depend on the initial modulations present in the beam. Considering only the shot noise contribution to the initial longitudinal charge distribution we derive an energy modulation spectrum peaked around 60 µm and with a maximum value of 35 keV. These values of energy modulation are well tolerated by the CLARA FEL. The amplitude of the longitudinal energy modulation on the photocathode laser should be lower than 0.06% in the range 20-150 µm to tolerably maintain microbunching in the FEL. The effective solution to prevent MBI, used in several FEL facilities, is the laser heater (LH) [12, 13]. A laser heater consists of a short, planar undulator located in a magnetic chicane where an external infrared laser pulse is superimposed temporally and spatially over the electron beam. The electron-laser interaction within the undulator produces an energy modulation on a longitudinal scale length corresponding to the laser wavelength.

The second half of the chicane smears the energy modulation in time, leaving the beam with an almost pure incoherent energy spread. This controllable incoherent energy spread suppresses further MBI growth via energy Landau damping in the bunch compressor. A layout of a laser heater is shown in Fig. 3.

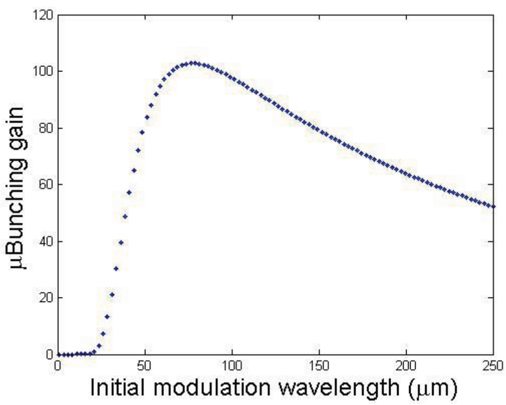

Figure 2: Microbunching gain as a function of the initial modulation wavelength.

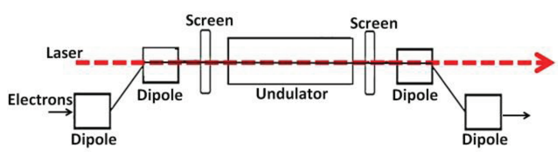

Figure 3: Laser heater layout.

A possible design of the chicane has bending angles of 1.72 degrees, a separation between the first and the second dipole as between the third and fourth dipole of 75 cm, a dipole length of 10 cm and a total chicane length of 2.60-3.1 m. The middle drift of the chicane is occupied by a variable gap planar undulator (9 periods of 3.8 cm) and two CROMOX screen. A reliable solution for the laser could be a dedicated Yb:CaF2 laser (1040 nm) capable of delivering pulses with a maximum energy of 500 μJ and a duration of 3-10 ps.

The presence of the laser heater could be exploited to study some less explored aspects of MBI such as the microbunching induced by the laser heater chicane and the effects that the VBC could have on the microbunching gain [16]. The laser heater chicane could also be used to implement the diagnostics presented in [17]. These are possible experiments of relevance to future FEL facilities.

REOPTIMISED FEL SECTION

The layout of the FEL section has been revised since the publication of the CDR [1]. The previous layout included a single modulator undulator to provide an interaction between seed/modulating lasers and the electron beam. It was found in simulations however that for the 30-120 μm seed wavelength range the amplitude of the modulation obtained was smaller than that required for optimum performance in some modes. This was due to the modest seed power available and the fact that the slippage limited the interaction length to only a few undulator periods. The revised layout comprises two modulators with dispersive chicane in between, i.e. an optical klystron configuration. The small modulation induced in the first modulator can be bunched in the chicane giving strong coherent emission in the second modulator which then slips over the whole bunch driving the energy modulation more strongly. The amplitude of the energy modulation is expected to be enhanced by nearly an order of magnitude, compared to the original design comprising a single modulator.

The layout of the radiator section has also been revised. The length of the individual undulator modules has been reduced from 1.5m to 0.75m and the gaps between modules have also been halved in length from 1.1m to 0.5m. There are several motivations for this change. First, two of the schemes to be investigated on CLARA, Mode-Locking [18] and HB-SASE [19], have been seen in simulations to perform more effectively for a lattice comprising a greater number of shorter undulators, in agreement with other research [20]. Second, reducing the FODO period reduces the FEL gain length which benefits all CLARA FEL schemes. Third, the natural focussing of the FEL undulators becomes less significant allowing easier matching into the FODO channel. In order to reduce the length of the intermodule gaps the diagnostic screens and vacuum components will now be incorporated within the length of the undulator modules, rather than in the gaps. Design of the vacuum solution and diagnostic screens is ongoing.

CONCLUSION

We have presented updates to the design and simulation of the CLARA accelerator. The layout of the front end has been changed, and the FEL section has been reoptimised to improve the performance of the machine. A collimation system is presented to mitigate the effects of dark current and beam halo. The bunch compressor has been simulated in detail, and we have also considered the inclusion of a laser heater in order to study the microbunching instability. Future work will involve start-to-end simulations of the machine in 3-d, and detailed simulations of the various FEL schemes planned for CLARA.

REFERENCES

[1] J. A. Clarke et al., JINST 9 T05001 (2014).
[2] D. J. Scott et al., "VELA Machine Development and Beam Characterisation", Proc. IPAC2015, http://www.jacow.org/
[3] P. H. Williams et al., THPRO029, Proc. IPAC2014, http://www.jacow.org/
[4] P. H. Williams et al., THPRO030, Proc. IPAC2014, http://www.jacow.org/
[5] M. Dohlus and T. Limberg, "CSRtrack", http://www.desy.de/xfel-beam/csrtrack/
[6] B. L. Militsyn et al., Proc. IPAC2014, http://www.jacow.org/

[7] S. Di Mitri et al., PRST-AB 15, 061001 (2012).
[8] M. Borland, APS LS-287, (2000).
[9] Y. S. Derbenev et al., TESLA-FEL-1995-05 (1995)
[10] E. L. Saldin, E. A. Schneidmiller and M. V. Yurkov, Nucl. Instrum. Methods Phys. Res. A 490, 1(2002).
[11] T. Shaftan and Z. Huang, Phys. Rev. ST Accel. Beams 7, 080702 (2004).
[12] Z. Huang et al., Phys. Rev. ST Accel. Beams 13, 020703 (2010).
[13] S. Spampinati et al., Phys. Rev. ST Accel. Beams 17, 120705 (2014).
[14] Z. Huang et al., Phys. Rev. ST Accel. Beams 7,074401 (2004).
[15] S. Seletskiy et al. Phys. Rev. ST Accel. Beams 14, 110701 (2011).
[16] D Ratner at al Phys. Rev. ST Accel. Beams 18, 030704 (2015).
[17] R. Fiorito et al., Phys. Rev. ST Accel. Beams 17, 122803 (2014).
[18] N. R. Thompson and B. W. J. McNeil, Phys. Rev. Lett. 100, 203901, (2008).
[19] B. W. J. McNeil et al, Phys. Rev. Lett. 110, 134802, (2013).
[20] N. R. Thompson et al, Phys. Procedia 52, 52-61, (2014).