FRONT END SIMULATIONS AND DESIGN FOR THE CLARA FEL TEST FACILITY

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Abstract

We present the design and simulations of the Front End for CLARA (Compact Linear Accelerator for Research and Applications), the proposed UK FEL test facility at Daresbury Laboratory. This is based around an S-band RF photocathode gun. Initially this will be the 2.5 cell gun, currently used on VELA facility at Daresbury, which is limited to 10 Hz repetition rate. Later, this will be upgraded to a 1.5 cell gun, currently under development, which will allow repetition rates of up to 400 Hz to be reached. The beam will be accelerated up to 50 MeV with a booster linac which will be operated in both bunching and boosting modes for different operating regimes of CLARA. Simulations are presented for a currently achieved performance of the RF system and drive laser with optimisation of the laser pulse lengths for various operational modes of CLARA.

INTRODUCTION

CLARA (Compact Linear Accelerator for Research and Applications) is a proposed 250 MeV FEL test facility at Daresbury Laboratory [1]. It will comprise a photoinjector, a four section S-band linac and FEL test area. The first 2 m long linac section serves as a booster or a buncher. CLARA is designed to test out various novel FEL schemes which require different beam pulses varying from ultra short very high current bunches for single-spike SASE to relatively long for seeded FEL. To cover all the range of the bunch lengths, longitudinal compression is going to be provided through both magnetic compression and velocity bunching. For many of these schemes, the required beam parameters can be met by either compression scheme. However, seeded FEL operation can only be met with the magnetic compression as a constant current profile is desired along the bunch, while single-spike SASE can only be met with velocity bunching to a very short bunch with high peak current. A comparison of the compression schemes can be found in [2].

A staged approach is taken to construction and commissioning, with stage one comprising of a photoinjector and booster linac to be installed in 2016. This links in to the existing VELA facility at Daresbury [3] and shares its RF and laser infrastructure.

The electron source for CLARA will initially be the 2.5 cell S-band RF gun currently used at VELA. This is limited to 10 Hz repetition rate, at bunch charges of up to 250 pC. The gun is fed from a 10 MW klystron with 8.5 MW of power available at the gun. The maximum beam momentum measured around 5.0 MeV/c. To reach repetition rates of up to 400 Hz, a 1.5 cell High Repetition Rate S-band Gun (HRRG) has been designed and is currently under construction [4].

The VELA photoinjector laser will also be used to drive CLARA, with a beam split in the transport line. The laser pulse has a length of 76 fs rms that allows short low charge electron bunches to be produced. In this paper we analyse the beam parameters which can be obtained with the currently achieved performance of the RF system and laser and investigate the use of a longer pulse laser for the different modes of CLARA.

OPERATION OF THE BASELINE INJECTOR WITH REDUCED GUN FIELD

The original design of the 2.5-cell gun assumed operation at a peak field of 100 MV/m. However, the measured beam momentum in VELA is lower than was expected based on simulations and measured quality factors [5]. To match the measured beam momentum of 5 MeV/c, simulations show the peak electric field to be 70 MV/m.

In this work, beam dynamics simulations were carried out with the ASTRA code. The photoinjector laser spot size was simulated as a 1 mm diameter flat-top with a 76 fs rms Gaussian temporal profile. An intrinsic emittance of the beam from the copper photocathodes assumed to be of 0.9 mm·mrad per mm rms as per LCLS measurements [6].

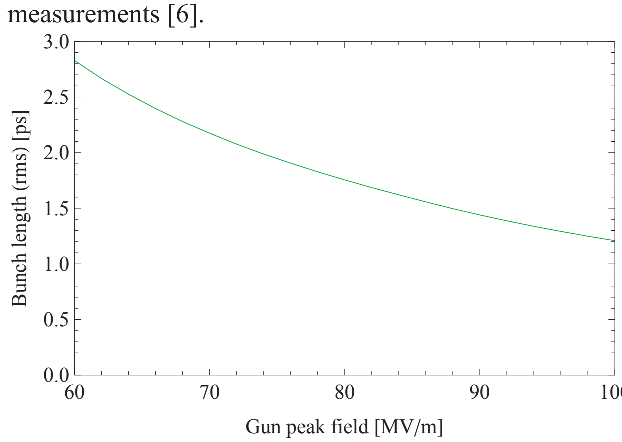

Figure 1: Simulated dependence of the length of a 250 pC bunch at the exit of the 2.5 cell gun.

Due to the short laser pulse length, the gun operates in the "blow-out" regime, where the space-charge expands emitted bunch. Thus, the electron bunch length in this case is determined by the bunch charge and the rate of acceleration. Fig. 1 shows how the rms length of a 250 pC bunch after the gun depends on the peak field (for the same operational phase). It can be seen then that reducing the gun peak field from 100 MV/m to 70 MV/m, causes

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an increase of almost a factor of two in the electron bunch length.

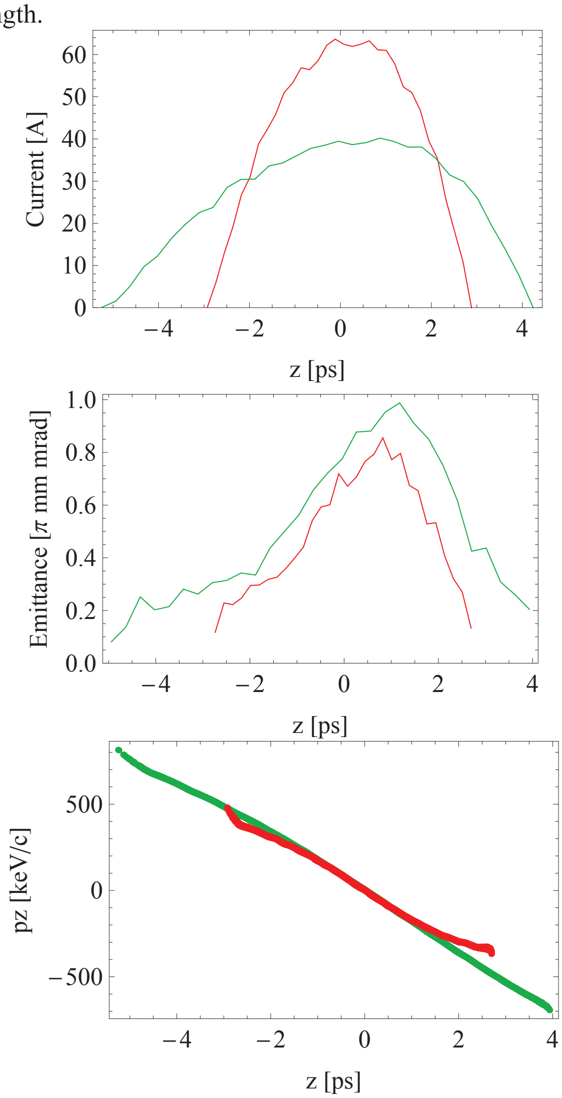

Figure 2: Distribution of the current (top), slice emittance (middle) and the momentum deviation (bottom) in 250 pC electron bunch for 100 MV/m (red) and 70 MV/m (green).

Figure 2 shows the results of comparison of the original, published in the CDR [1], CLARA bunch simulation at the FEL entrance at 100 MV/m and 250 pC, and that at reduced gun peak field of 70 MV/m. A few further modifications are included in the simulation. The main one being that the distance from photocathode to the entrance of the linac has been reduced slightly due to engineering considerations. The reduction in gun peak field also causes a rise in transverse emittance. The solenoids, surrounding first linac section, have been switched off to allow for a flat transverse beam profile at the exit of the second linac section and the linac phase set to give the same chirp in longitudinal phase space for compression downstream in the magnetic chicane.

Simulations with linac wakefields have shown no effect on the transverse beam dynamics and only have a small effect on the longitudinal beam dynamics (increasing the energy spread) as the bunch length is relatively long.

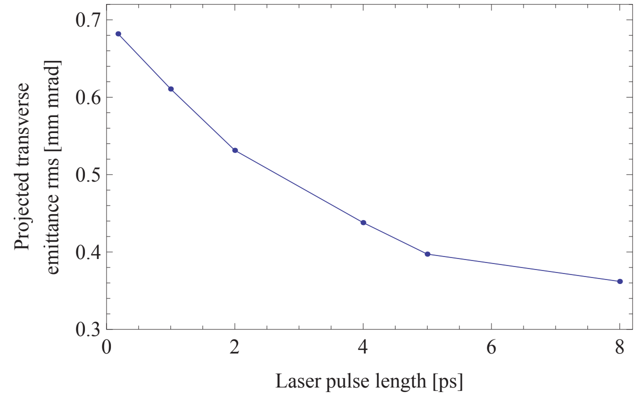

Figure 3: Dependence of the projected rms emittance of 250 pC bunch on drive laser pulse length.

OPTIMISATION OF THE LASER PULSE LENGTH

Since the electron bunch length increases to such a large extent in the "blow-out" regime, longer laser pulse lengths were investigated where the length of the electron bunch thus depends on the length of the drive laser pulse directly. To see any effect, the drive laser pulse length should be longer than the "natural" electron bunch length which is formed due to the space-charge induced blow-up. To investigate this, the drive laser pulse length was scanned in simulation.

For the simulations, a flat-top laser pulse was varied in 1 ps steps, with 0.2 ps rise and fall times. For each case, the gun phase and solenoid were optimised to produce minimum projected transverse emittance after the first linac section. The linac solenoids were then adjusted to further reduce the transverse emittance without overfocussing which had been seen to result in halo development in previous simulations. The scan was repeated for the 2.5-cell gun at a peak field of 70 MV/m, and for the 1.5 cell HRRG at a peak field of 100 MV/m and 120 MV/m.

2.5 Cell Gun at a Field of 70 MV/m

Figure 3 shows the biggest effect from increasing the laser pulse length is the reduction in transverse emittance. As is seen in the slice emittance profiles, shown in Fig. 4, this arises due to the reduction in the sharp peak in slice emittance that presents with the short laser pulse. Increasing the laser pulse length and flattening of its temporal profile, decreases this hump in slice emittance until there is a flat profile. It can be seen from these profiles, and also the current profiles that the overall bunch length does not change until the laser pulse length is longer than the natural space-charge blow-out bunch length. At this point, the bump in slice emittance is flattened out. Therefore there is an optimum laser pulse length for reducing slice emittance whilst keeping the electron bunch length as short as possible, in this case around 5 ps.

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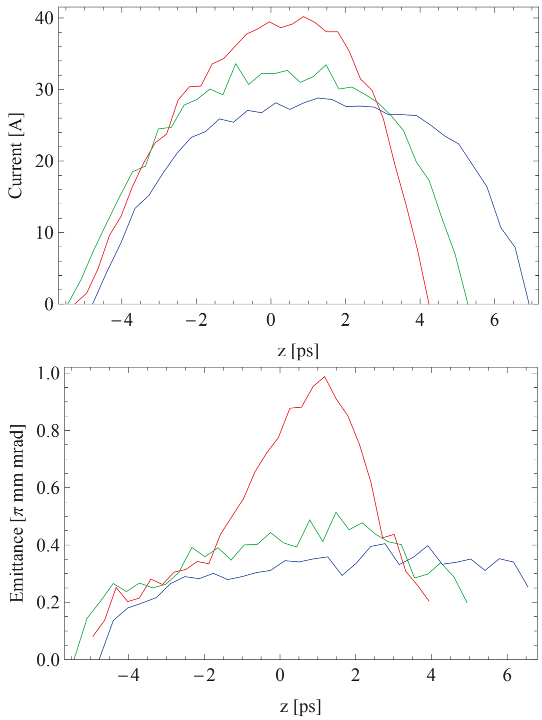

Figure 4: Current (top) and emittance (bottom) profiles for laser pulse lengths of 5ps (green), 8 ps (blue), compared to the previous 76 fs rms laser pulse (red).

1.5 Cell HRRG at 100 MV/m and 120 MV/m

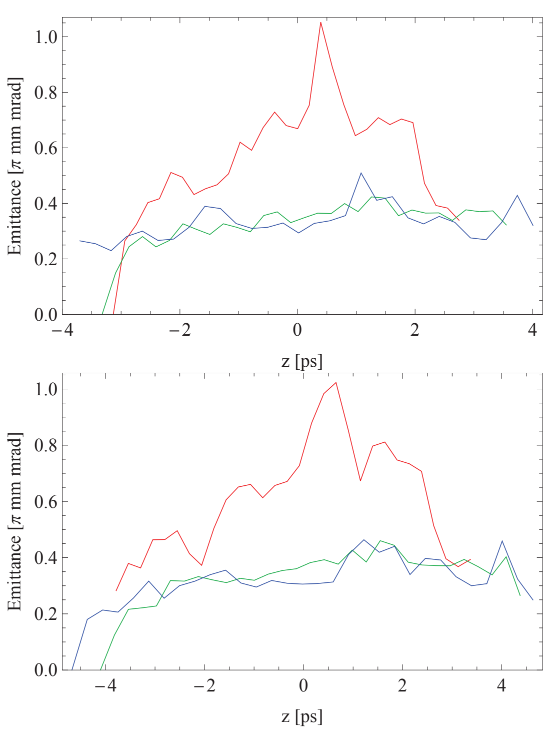

Figure 5: Current profiles at 120MV/m (top) and 100 MV/m (bottom) for laser pulse lengths of 3ps (green), 5 ps (blue), compared to the previous 76 fs rms laser pulse (red).

The above scans were repeated for the 1.5 cell HRRG at the design peak field of 120 MV/m, and a reduced field of 100 MV/m, as contingency for not achieving the design field. The behaviour is the same as for the 2.5 cell gun at 70 MV/m, but with a different optimum for the laser pulse length of 3 ps, as shown in Fig. 5.

Rise/Fall Times

A further investigation was made to look at the effect of the rise and fall times for the laser pulse. The 4 ps laser pulse was used, and simulations carried out at a higher number of macroparticles (100,000) to see the effect, with varying the rise and fall times in 0.1 ps steps. There was no effect on the current profile, however longer rise and fall times give rise to spikes in the slice emittance at the start and end of the bunch, as shown in Fig. 6. To reduce these spikes, the rise and fall times should be kept 0.2 ps or shorter. However, it is under question whether these slice emittance spikes where the current is low have any consequence to overall machine performance of the FEL.

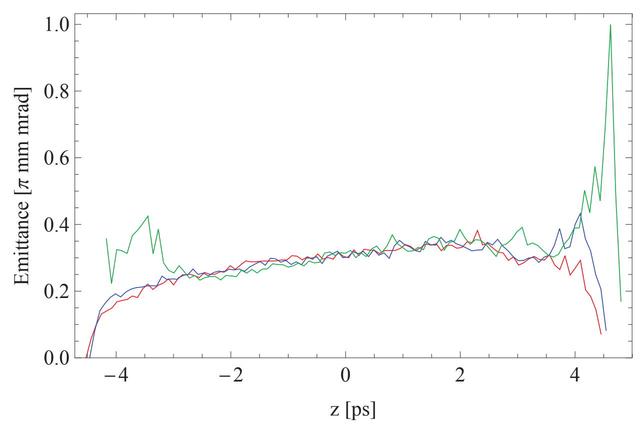

Figure 6: Slice emittance rise/fall times of 0.2 (red), 0.3 (blue), and 1 ps (green) for a 4 ps long laser.

VELOCITY BUNCHING MODE

The alternative to the magnetic bunch compression mode of CLARA is velocity bunching in the low energy section of the machine. Gentle compression with velocity bunching can provide similar bunch lengths as magnetic compression, however, it can also be used to produce very short bunches with high peak current, which are necessary for single-spike SASE FEL operation.

The optimal parameters of a 100 pC CLARA bunches using velocity bunching scheme were achieved with a 50 fs Gaussian laser pulse of diameter 1.8 mm on the photocathode. These laser parameters were found as result of a larger optimisation to provide the shortest bunches via velocity bunching in CLARA operated with the 2.5 cell gun [7]. The optimal velocity bunching compression was already obtained at the lower gun field of 70 MV/m, as at lower beam momentum for the same energy chirp velocity difference of the particles within the bunch is greater.

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The effect of changing the laser specifications in the velocity bunching mode to the currently available drive laser parameters – a diameter of 1 mm and a length of 76 fs rms Gaussian, is shown in Fig. 7. The beam has similar rms length, but a less sharp current profile, with a drop of peak current by almost a factor of two. There is also a large increase in slice emittance. Further simulations have shown that the slice emittance can be reduced, but at the expense of further decreasing the peak current.

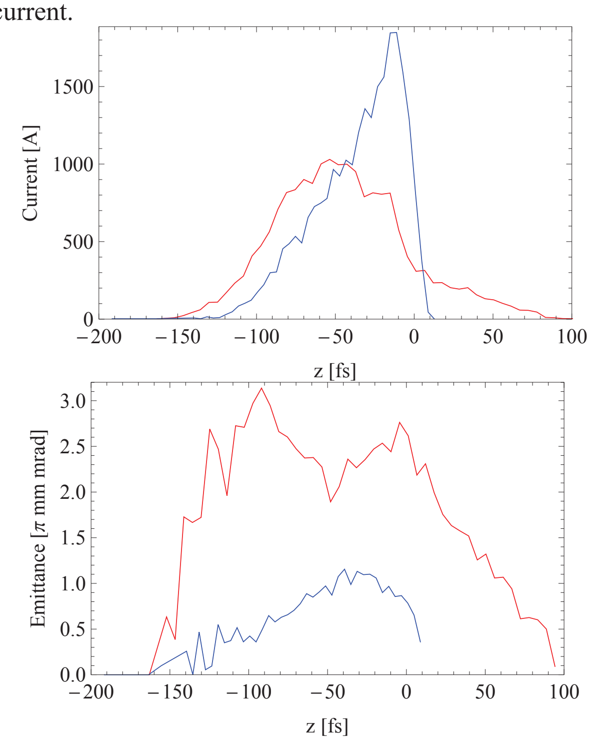

Figure 7: Optimised laser pulse (blue) and VELA laser pulse (red)

As with the magnetic compression case, longer laser pulses were also investigated (whilst keeping the laser spot diameter at 1 mm). For each case, the beamline settings were optimised at the exit of the second linac section. As can be seen in Fig. 8, increasing the laser pulse length causes a reduction in the peak current, but in all cases slice emittance can be kept reasonably low, unlike in the case of the existing laser pulse.

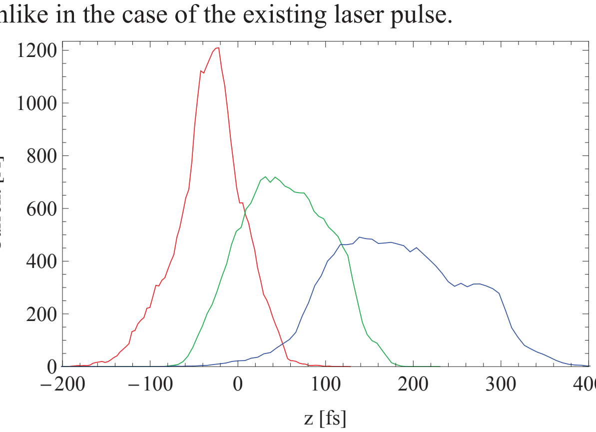

Figure 8: Current profiles for laser pulse lengths of 1 ps (red), 2 ps (green), 4 ps (blue).

It is seen then, that to produce the very high peak currents that make velocity bunching scheme ideal for single-spike SASE FEL operation, that a different photoinjector laser tuning has to be used compared to the magnetic compression mode.

A further consideration has to be made for wakefields as the bunch length is so short. Wakefields were then included for the booster and linac sections in the ASTRA simulations. For the case of the original optimised laser pulse, the simulated wakefields significantly decrease high peak current spike, although the overall bunch length remains similar, as shown in Fig. 9. Further investigation is required to analyse these wakefield effects.

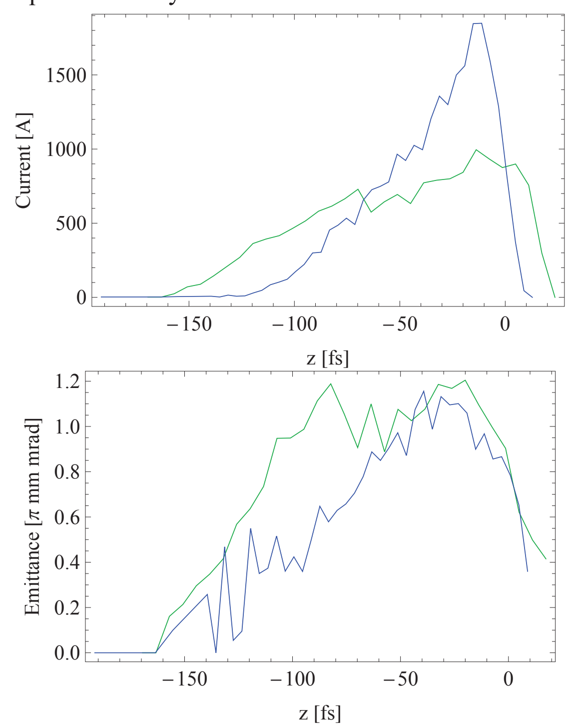

Figure 9: Current (top) and emittance (bottom) profiles with (green) and without (blue) linac wakefields.

CONCLUSION

Detailed analysis of the possibility of CLARA front end to deliver beams required for operation of the FEL in SASE, single spike SASE and seeded modes can be achieved with the current operational performance of the laser and RF system. However, the optimised beam parameters are met for a different photoinjector laser tuning for each case that may require an upgrade of the drive laser. Preliminary estimation of the impact of wakefields in booster and linac on the beam parameters at FEL shows that these leads to significantly decrease of the peak current for the single-spike case.

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