BEAM DYNAMICS DESIGN OF THE CLARA FEL TEST ACCELERATOR

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Abstract

CLARA (Compact Linear Advanced Research Accelerator) is a proposed FEL test facility at Daresbury Laboratory in the UK. This is proposed to be a 250 MeV normal-conducting linac capable of producing short, high brightness electron bunches which can be synchronised with an external source. CLARA will build upon the EBTF photoinjector under construction at Daresbury, utilising the S-band RF electron gun. Bunch compression will be achieved via two methods: a variable magnetic chicane with fourth harmonic cavity, or velocity bunching in the low energy regime. CLARA will be capable of providing beams for various novel FEL schemes.

INTRODUCTION

CLARA is proposed to be the UK's national FEL test facility. The design approach adopted is to build flexibility in both operation and layout, enabling as wide an exploration of FEL schemes as possible. For a full overview of the aims of the project and details of FEL schemes under consideration see [1]. The accelerator design is aimed at being flexible, allowing for various modes of operation at different energies and ultilising different compression methods.

CLARA will be based on normal conducting S-band RF linac structures, with a maximum energy of 250 MeV. Four linac structures will be used. The first one a short 2 m long section, and the next three either 4 or 5 m in length. A schematic is shown in Fig. 1.

There will be two modes of bunch compression in CLARA: the first uses velocity bunching in the first 2 m linac section, and the second uses a magnetic chicane at around 70 MeV. Two modes are proposed for the velocity bunching scheme, one pushing high peak current for single-spike SASE FEL operation, and the other a more generic bunch with around 300 A peak current.

For the seeded FEL schemes, a bunch with a flat current profile over 300 fs is desirable. The long flat-top will help reduce any effects of jitter between the electron bunch and seed laser. Simulations suggest such a bunch cannot be produced by velocity bunching so compression by a magnetic chicane was also investigated. However, a long, flat-top longitudinal profile cannot be produced if the bunch entering the magnetic chicane has curvature in longitudinal phasespace. As such, various options were investigated for correcting this curvature, including introducing non-linear elements, such as sextupoles, into the chicane. It was found that the best solution was to use a higher harmonic cavity before the chicane.

MODES OF OPERATION

Five different FEL modes have currently been identified: long pulse for the seeded FEL experiments, short pulse for SASE, ultra-short pulse for single spike SASE, multibunch mode for an oscillator FEL and a high repetition rate mode. The high repetition rate mode will be a technology demonstrator to push normal conducting linac technology, with the aim being 400 Hz. It is envisaged that to reach this repetition rate, the gradient in the cavities might need to be reduced, so the final electron beam energy could be lower. Bunch charges of up to 250 pC have been investigated, with 100 pC nominal for the velocity bunched schemes and 200 pC for the magnetic compression. For the oscillator FEL, 20 bunches at a spacing of 200 ns will be required. The RF pulse width will need to be able to accommodate this.

PHOTOINJECTOR

The photoinjector for CLARA will be based around that of the Electron Beam Test Facility (EBTF), currently under construction at Daresbury Laboratory [2]. The electron gun in the first stage will be a 2.5 cell normal conducting S-band RF gun, as shown in Fig. 2. This was originally intended for use on the ALPHA-X laser wakefield project [3]. A solenoid surrounds the gun cavity with a bucking coil to zero the magnetic field on the cathode plane. The design gradient is 100 MV/m.

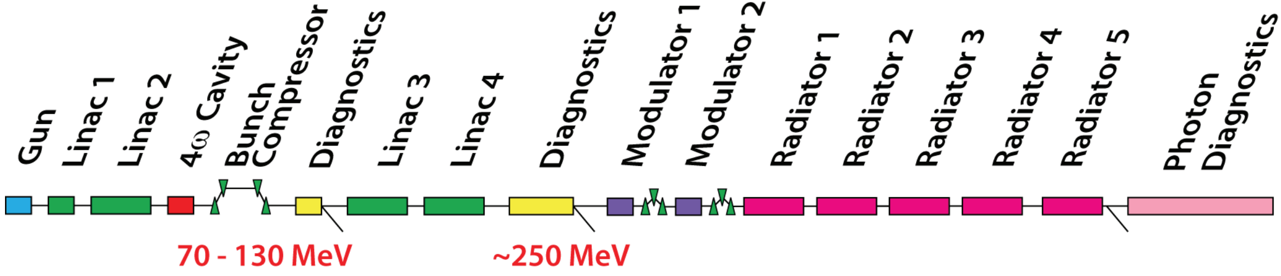

Figure 1: CLARA Schematic.

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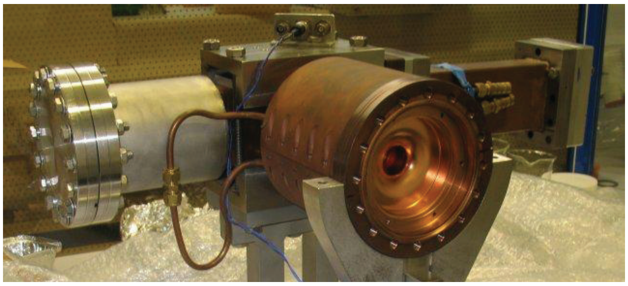

Figure 2: The EBTF/ALPHA-X photoinjector gun.

For all simulations, an intrinsic transverse emittance from the copper photocathode is included as per LCLS measurements of 0.9 mm mrad per mm rms of a flat-top laser spot [4]. The simulated longitudinal laser profile is a Gaussian of around 100 fs rms. This allows the gun to operate in the so-called "blow-out" regime, where the bunch length expands due to space-charge. Figure 3 shows ASTRA [5] simulations of a 200 pC beam from the photoinjector through Linac-1, and shows the bunch length blow-up from 100 fs to 1.2 ps rms.

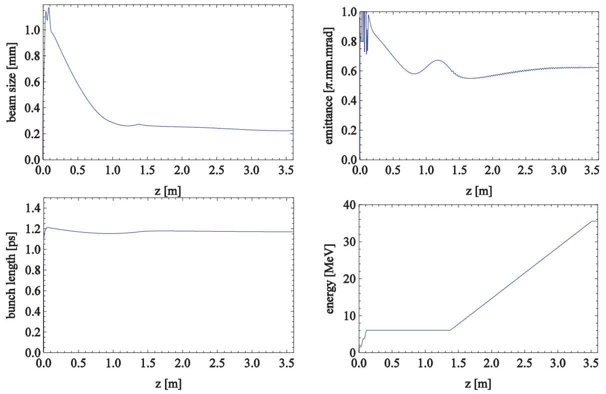

Figure 3: (Top left) rms beamsize, (top right) projected emittance, (bottom left) rms bunch length, (bottom right) energy.

BUNCH COMPRESSOR

To accommodate modes which rely solely on velocity bunching for compression, a variable bunch compression chicane, as shown in Fig.4, has been designed. This way, the bunch compressor can effectively be bypassed without bending the beam. The central two dipoles can be offset transversely up to 300 mm, allowing the R_{56} to continuously vary from 0 to 72 mm. The bunch compressor has been specified to operate at beam energies from 70 - 150 MeV.

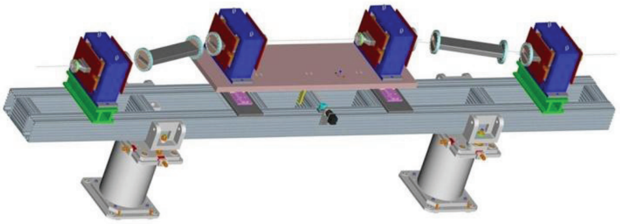

Figure 4: Variable bunch compressor.

Table 1: Bunch Compressor Parameters

Parameter		**Units**
Energy at compressor	70 - 150	MeV
Min. - Max, bend angle	0 - 200	mrad
Bend magnetic length	200	mm
Max. bend field	0.5	T
Min. - Max. transverse offset	0 - 300	mm
Z-distance DIP-01/04 - DIP-02/03	1500	mm
Z-distance DIP-02 - DIP-03	1000	mm
Max. bellows extension	260	mm
Min. - Max. R_{56}	0 -72	mm
Max. σ_x from δ_E ($\pm 3\sigma$)	0 - 10	mm
Max. σ_x from β_x ($\pm 3\sigma$)	1.5	mm

MAGNETIC COMPRESSION

For simulating the magnetic compression scheme, ASTRA was used until the exit of Linac-1, to include space-charge, and then ELEGANT [6] until the exit of Linac-4, to include cavity wakefields and coherant synchrotron radiation, but only longitudinal space-charge. Without linearising the phasespace, only a peaked current profile can be produced, as shown in Fig. 5 for a charge of 200 pC. Simulations were produced with Linac-2 accelerating the beam to both 70 MeV and 130 MeV to look at the effects of compressing and transporting the beam at different energies [7]. It was found that, after the bunch compressor, the beam has a residual chirp which can be removed by operating the post-chicane linac modules off-crest. This is easier to achieve if the compressor is at a lower beam energy, and thus 70 MeV was chosen as the nominal.

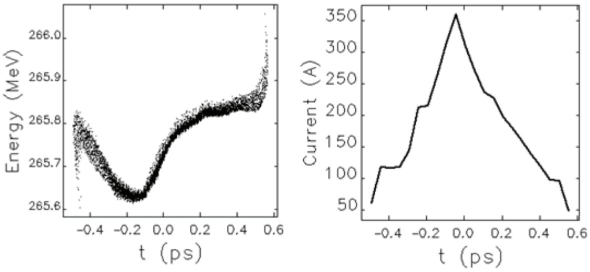

Figure 5: Longitudinal phasespace (left) and current profile (right) of the magnetically compressed bunch without linearisation.

To achieve a long, flat-top current profile as required for the seeded FEL modes, the longitudinal phasespace must be linearised before or during compression. Two options were investigated: magnetic elements in the bunch compressor, or a harmonic RF cavity before the compressor. The sign of the natural T_{566} term in the bunch compressor chicane must be changed. This can be done by adding sextupoles to the chicane. The number, positions and strengths of these were parameters in a Luus-Jaakola optimisation [8]. This scheme could produce the desired beam parameters, however, it was not found to be robust under anticipated RF jitter due to change in energies changing trajectory through the chicane.

The chosen method for phasespace linearisation is by utilising harmonic RF. A fourth harmonic (11.992 GHz) structure 0.7 m long was added immediately prior to the magnetic chicane. A Luus-Jaakola optimisation was then performed with variables being the harmonic voltage and phase, the off crest phase of the preceding linac and the angle of the compressor dipoles. Results for two candidate tunings are shown in Fig. 6, with flat-top current profiles 200 and 300 fs long respectively. The peak voltage on the linearising cavity is ~7 MV/m. It can be seen that the additional complication of a harmonic cavity is justified by the ability to predictably tailor longitudinal phase space.

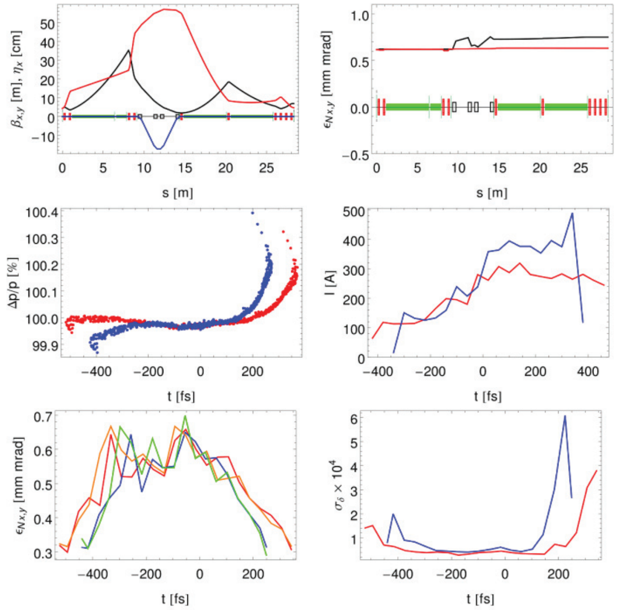

Figure 6: (Top left) $\beta_{x,y}$ (black, red) and η_x, (top right) emittance (x,y), (middle left) Longitudinal phase space (blue - optimised for 200 fs flat top, red - optimised for 300 fs flat top). (middle right) Current profile (40 fs slices, optimised for 200 fs flat top, red - optimised for 300 fs flat top). (bottom left) Normalised slice emittances (40 fs slices): horizontal / vertical (blue / red - optimised for 200 fs flat top, green / orange - optimised for 300 fs flat top) (bottom right) Slice energy spread (20 fs slices) optimised for 200 fs flat top, red - optimised for 300 fs flat top.

VELOCITY BUNCHING

An alternative to magnetic compression is to use velocity bunching in the low energy section of the accelerator. The first 2 m linac section is set to the zero crossing to impart a time-velocity chirp along the bunch. The bunch then compresses in the following drift space. The second linac section is positioned at the waist of the bunch length evolution, after 3 m of drift space to rapidly accelerate the beam and "capture" the short bunch length. Solenoids are required around the bunching section to control the transverse beam size and prevent emittance degradation.

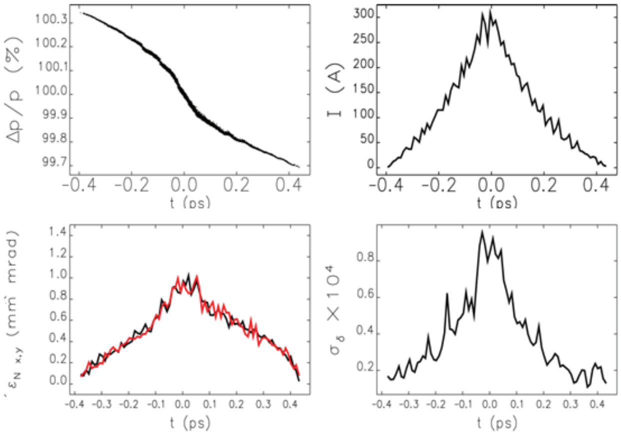

Figure 7: Short pulse velocity bunched beam (Top left) Longitudinal phase space (top right) Current profile (bottom left) Normalised slice emittances (40 fs slices) (Bottom right) slice energy spread.

Optimisation of these schemes were performed using a multi-objective genetic/evolutionary algorithm based on the non-dominated sorting approach, similar to NSGA-II [9]. The optimisation was performed using ASTRA only up to the exit of Linac-2, optimising on both transverse emittance and bunch length simultaneously. Two tunings are shown for a bunch charge of 100 pC. The first, shown in Fig. 7, has a peak current of 300 A, which possesses a similar current profile to the non-linearised magnetically-compressed bunch but with a less desirable emittance profile, although slice emittance does remain less than 1 mm mrad at the peak. The current distribution is too peaky and thus cannot be used for the seeded FEL scheme, however can be used for the long-pulse SASE mode.

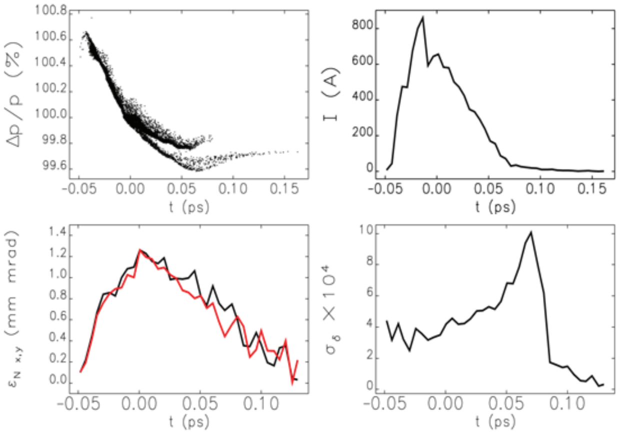

Figure 8: Ultra-short pulse velocity bunched beam (Top left) Longitudinal phase space (top right) Current profile (bottom left) Normalised slice emittances (40 fs slices) (Bottom right) slice energy spread.

The second tuning pushes the velocity bunching to a high level, achieving a peak current over 2 kA after Linac 2. Tracking the bunch through to 250 MeV in ELEGANT with wakefields on, shows degradation down to 800 A.

Table 2: Beam Parameters for the Various Operating Modes

Parameter	Long pulse	Short pulse	Short pulse	Ultra-short pulse	**Units**
Compression mode	Magnetic	Magnetic	Velocity	Velocity	
Bunch charge	200	200	100	100	pC
Projected emittance	0.7	0.7	0.8	1.7	mm mrad
Slice emittance @ Peak I	0.6	0.6	1.0	1.2	mm mrad
Bunch length	400	350	350	100	fs (FWHM)
Peak current	400	350	300	800	A
Projected energy spread	160	100	400	630	keV (rms)
Slice energy spread @ Peak I	10	10	25	250	keV (rms)

The bunch profiles are shown in Fig. 8. This mode will be used for single-spike SASE FEL operation. It is expected that arrival time jitter will be greater for the velocity bunched modes than for the magnetically compressed modes. This has yet to be verified in simulation, and is less important for SASE rather than seeded operation, as the beam does not need to be synchronised to an external source. Further details can be found in [10].

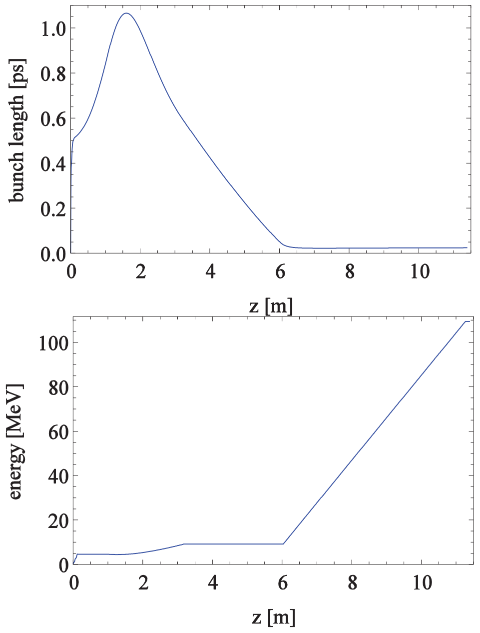

Figure 9: Bunch length (rms) (top) and energy (bottom) evolution for the first two linac modules during velocity bunching.

Figure 9 shows the evolution of beam parameters in the first two linac sections for the ultra-short pulse mode. It can be seen that even operating the first linac at the "zero-crossing", due to phase slippage of the low energy beam, there is a substantial amount of energy gain.

SUMMARY

CLARA is proposed to be the UK's national FEL test facility, based on normal conducting S-band RF linac structures, with a maximum energy of 250 MeV. Beam dynamics simulations have been presented with meet a variety of operational modes suitable to FEL operation.

Short pulse SASE can be met using short pulse modes from either velocity bunched or magnetically compressed bunches. Single-spike SASE operation may be reached by a different velocity bunched optimisation. Seeded FEL operation may be met with a long pulse mode. This mode uses linearisation of the longitudinal phasespace before the magnetic compressor to achieve a 300 fs long flat-top current profile.

Two further modes of CLARA involve technological challenges outside the beam dynamics area. The first involves development of RF technology to enable normal-conducting linac cavities to operate at repetition rates up to 400 Hz. The second involves operating in a macro-pulse mode with 20 bunches at a spacing of 200 ns to profile an oscillator or regenerative amplifier type FEL.

Further investigations will be carried out as to whether to use solenoids around both linac modules instead of quadrupoles before the magnetic compressor, to retain transverse symmetry. Tolerance and jitter studies of all operational modes will be carried out to estimate FEL stability.

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