# FEL CONSIDERATIONS FOR CLARA: A UK TEST FACILITY FOR FUTURE LIGHT SOURCES

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## *Abstract*

A new dedicated test accelerator called CLARA (Compact Linear Advanced Research Accelerator) is proposed to test concepts relevant to the development of next generation light sources. The ultimate aim of CLARA is to develop a normal conducting test accelerator able to generate longitudinally and transversely bright electron bunches, and to use these bunches in the experimental production of stable, synchronised, ultra short photon pulses of coherent light from a single pass FEL with techniques directly applicable to the future generation of light source facilities. The parameters of CLARA are now being developed with the aim of establishing a flexible test facility capable of demonstrating ultra short photon pulse generation from a number of alternative schemes that have yet to be experimentally proven.

## INTRODUCTION

The UK Accelerator Science and Technology Centre (ASTeC), together with partners from across the UK, has growing expertise in the field of FEL facilities, gained through major design studies for the 4GLS [1] and NLS [2] projects, and the commissioning of the ALICE energy recovery linac facility (including the successful demonstration of an oscillator FEL operating in the infra-red [3]). The NLS project, currently on hold, identified a number of new technologies and untested FEL schemes that could make a significant positive impact to the cost and performance of such a facility.

Part of ASTeC's future strategy is to develop a next-generation light source test facility to be constructed at Daresbury Laboratory in an existing building previously used for the Synchrotron Radiation Source (SRS). This new test accelerator will be known as CLARA (Compact Linear Advanced Research Accelerator). The CLARA project aims to build on the UK's existing expertise in the field, in preparation for a state-of-the-art FEL user facility in the UK, while contributing to international FEL R&D.

This paper describes considerations for CLARA from an FEL-focused perspective, including the international context, the objectives for the facility, the required machine parameters, and the provisional design.

## INTERNATIONAL CONTEXT

A review of international facilities for FEL test experiments has been carried out within ASTeC [4]. Several facilities have been identified as carrying out FEL test experiments relevant to CLARA, and are given in Table 1. Of the facilities identified, only a few may be considered to be dedicated FEL test facilities.

The FEL concepts that could be studied on CLARA are currently being considered. A number of areas in which FELs could be further developed have been recognised, and include: improving temporal coherence, generating ultra-short pulses, tailored pulse structures, improving stability and synchronisation, and serving multiple users.

Some of the FEL topics under consideration at other facilities are given in Table 1. One of the highest current priorities for FEL test experiments is improving temporal coherence. There are extensive studies underway to achieve this through extending the range of external seeding (HHG, HGHG, EEHG), self-seeding, and short wavelength oscillators. Reducing the size and cost of facilities is another current priority (methods include seeding, short period undulators, high brightness beams, high gradient acceleration etc.).

The relatively small number of FEL test facilities and the large number of possible research topics suggest there is potential for a new FEL test facility to contribute to international FEL R&D, while also developing local expertise necessary for a future FEL user facility. The objectives for CLARA have been established and are given in the next section. This paper is orientated towards techniques involving FEL physics, though it is clear that the further development of FELs is dependent on progress in many areas.

## OBJECTIVES OF CLARA

The ultimate aim is to develop a normal-conducting test accelerator, able to generate longitudinally and transversely bright electron bunches, and to use these bunches in the experimental production of stable, synchronised, ultra-short photon pulses of coherent light from a single pass FEL using techniques directly applicable to the future generation of light source facilities.

In the context of the above, stable means with little variation in transverse position or intensity from shot to shot, synchronised means the photon output pulse should be sufficiently well synchronised to a timing signal to simultaneously control a conventional laser used in a pump-probe experiment, and ultra-short means the photon pulse length should be shorter than, or of the order of, the FEL co-operation length, $l_c = \lambda_r / 4\pi\rho$. [*]

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[*] A test facility such as CLARA might not access the shortest possible pulse lengths in *absolute* terms since it will operate at relatively long radiation wavelength compared to an x-ray FEL facility. The aim is to generate ultra-short pulses relative to the FEL co-operation length, or in terms of optical cycles, using techniques that can be scaled to shorter wavelengths.

**Table 1:** *Some facilities involved in FEL test experiments relevant to CLARA*

| Location | Facility | E [MeV] | FEL topics and test experiments | Operating mode |
|---|---|---|---|---|
| SLAC | LCLS | 3500-15000 | Short wavelength, peak power, temporal coherence (self-seeding), short pulses (single-spike SASE), tailored pulse structures | User facility |
| | NLCTA | 120 | Temporal coherence (EEHG) | Test facility |
| JLab | IR/UV upgrade | 150 | Average power, temporal coherence (range of oscillators) | FEL development + user experiments |
| Brookhaven | SDL | 300 | Temporal coherence, range and tunability of seeding (HGHG), E-SASE | Test facility |
| Soleil | LUNEX5 | 400 | Compact FELs (LWFA, in-vacuum undulators), temporal coherence (HHG, EEHG) | Proposed test facility |
| PSI | SwissFEL Injector TF | 250 | Compact FELs (beam quality) | Injector test facility, possible FEL expts |
| DESY | FLASH | 1250 | Temporal coherence (HHG, EEHG) | User facility |
| MAX-Lab | Test FEL | 380 | Temporal coherence (HGHG, HHG) | Test facility |
| Frascati | SPARC | 250 | Short pulses (energy chirp + tapering), temporal coherence (HHG) | Test facility |
| Trieste | FERMI @elettra | 1500 | Temporal coherence (seeding, HGHG), polarisation control | User facility |
| SINAP | SDUV | 210 | Temporal coherence (HGHG, EEHG) | Test facility |
| RIKEN | SCSS | 300 | Short wavelength, compact FELs (in-vacuum undulators, C-band linac, single-crystal thermionic cathode), temporal coherence (HHG) | Test facility |
| | SACLA | 8000 | | User facility |

Further aims and prerequisites for CLARA are:

- To lead the development of low charge single bunch diagnostics, synchronisation systems, advanced low level RF systems, and novel short period undulators.
- To develop skills and expertise in the technology of NC RF photoinjectors and seed laser systems.
- To develop novel techniques for the generation and control of bright electron bunches including manipulation by externally injected radiation fields and mitigation against unwanted short electron bunch effects (e.g. micro-bunching and CSR).
- To demonstrate high temporal coherence and wavelength stability of the FEL, for example through the use of external seeding or other methods.
- To develop the techniques for the generation of coherent higher harmonics of a seed source.
- To develop new photon pulse diagnostic techniques as required for single shot characterisation and arrival time monitoring.

## FACILITY OUTLINE

The provisional facility outline is described in this section. The justification for the parameter choices is given in following sections.

CLARA will use a 250 MeV normal conducting linac. Electrons will be delivered by an S-band photocathode gun in bunches of charge 20–250 pC at a repetition rate up to 400 Hz. Operating in the so-called ‘blow-out’ regime with a short drive laser pulse will allow bunches of rms length 1 ps and shorter to be produced from the gun. Further bunch compression will be done in two different modes of operation - via a magnetic chicane, or velocity bunching in the first linac module. The position of the magnetic bunch compression chicane is not yet fixed and is currently a priority design topic.

Many of the potential FEL research topics require interaction with seed lasers in one or more modulator undulators, then amplification in radiator undulators. The provisional layout of the CLARA FEL comprises two short modulator undulators in which seed lasers can be used to modulate the electron beam; however it will be important for the undulator configuration to be flexible for testing different concepts. The periods of the modulators will be chosen so that the tuning ranges have an overlap, allowing both modulators to be combined into a single longer modulator for some applications. Chicanes for manipulating the longitudinal phase space and applying phase delays will be positioned after each modulator. The chicanes will have sufficient $R_{56}$ for the FEL to operate in EEHG (Echo-Enabled Harmonic Generation) mode [5]. There will be five or six 2.5 m long radiator undulators. Beam focussing will be with a FODO lattice with the quadrupoles interleaved with the undulator modules. The overall provisional layout of CLARA is shown in Figure 1.

CLARA will utilise the Electron Beam Test Facility (EBTF) as a first stage, as shown in Figure 1. EBTF consists of a 2.5-cell S-band RF gun [6], diagnostics and transport to two experimental areas for industrial applications, and is funded and under construction. One of the aims of EBTF is to characterise the photoinjector, with first beam planned by the end of 2012. EBTF will also provide a low energy (6 MeV) electron beam to user areas dedicated for industrial applications. The gun was originally designed for the ALPHA-X project [7] but has never seen operation. Full characterisation of the

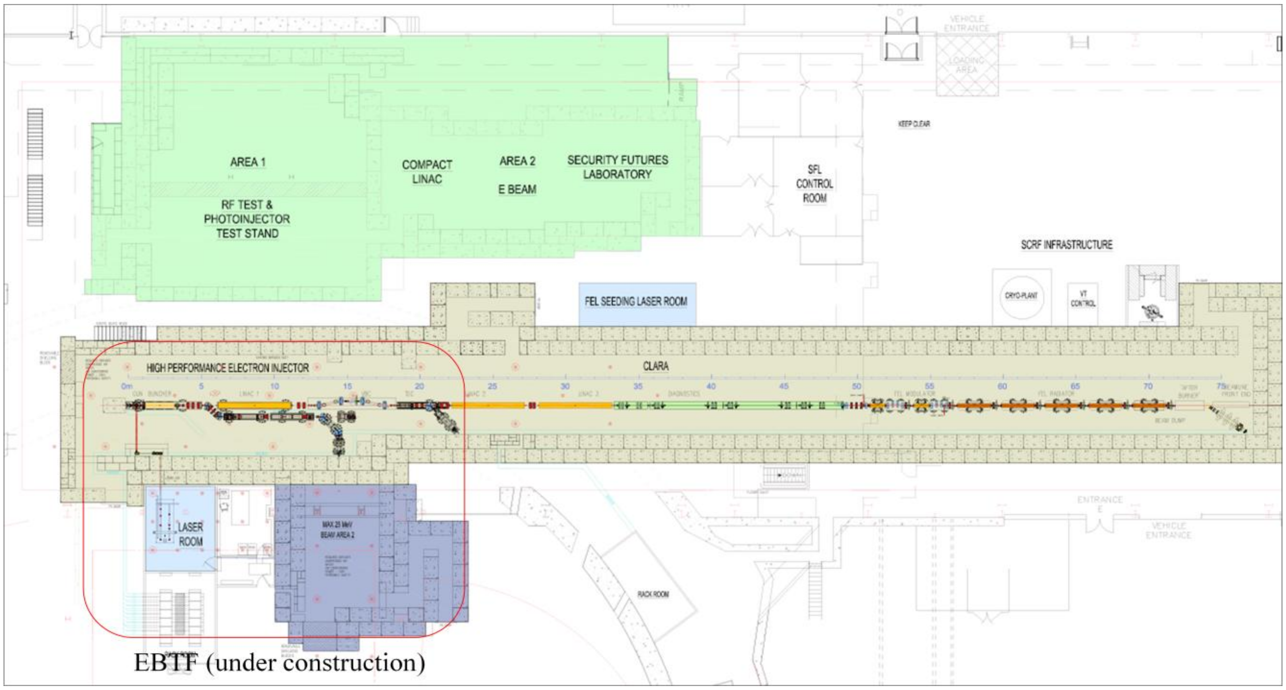


**Figure 1:** *Preliminary layout of the CLARA facility in the existing buildings from the de-commissioned SRS facility at Daresbury Laboratory, including the Electron Beam Test Facility (EBTF) which is currently under construction.*

electron gun six-dimensional phase space is planned and a suitable transverse deflecting cavity is being designed.

## PARAMETERISATION STUDIES

This section describes studies which have been carried out to assess the required parameters of the CLARA facility. Some preliminary FEL modelling has been carried out for this purpose, and is also described here.

### *Electron Beam Energy and Undulator Period*

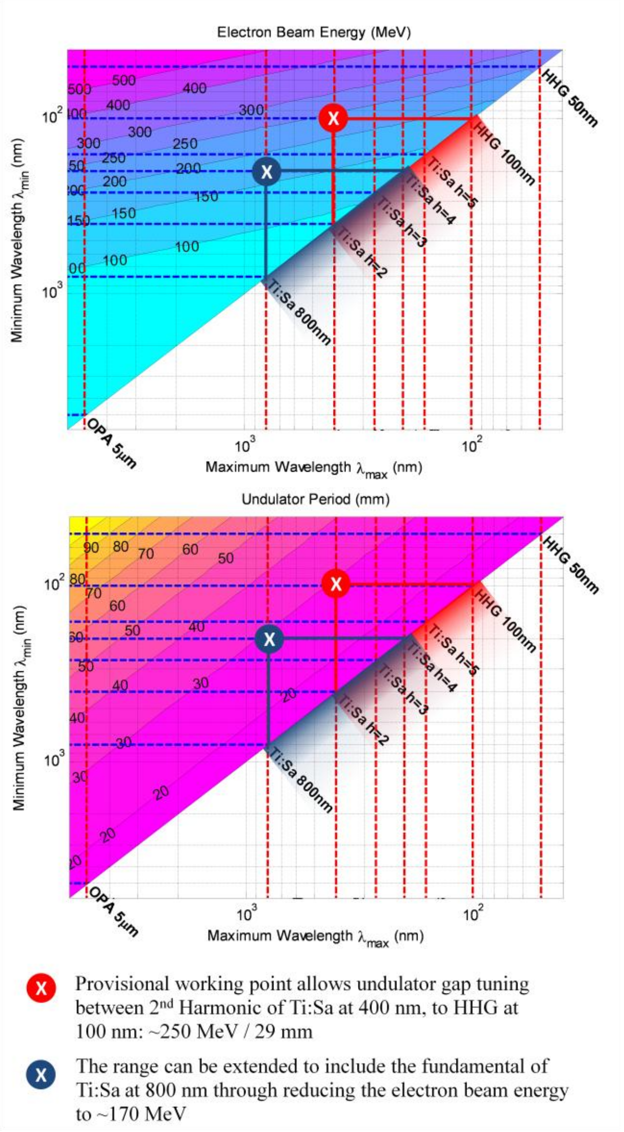
The beam energy and undulator period determine the cost and scale of the facility and the tunability of the radiation sources. Many of the experiments require interactions with seed fields (and then possibly conversion to higher harmonics) so the electron beam energy should be chosen to give the appropriate tuning. The primary external radiation source will be a Ti:Sa laser operating at 800 nm. This can be used on its own, or to drive an Optical Parametric Amplifier (OPA) covering the range 2–20 μm, or a Higher Harmonic Generation (HHG) system giving output from the longest easily available wavelength of ~100 nm (12.5 eV) to a peak output at ~50 nm (25 eV).

The resonant wavelength depends on the energy via the resonance condition, $\lambda_r = \lambda_w(1+\bar{a}_w^2)/(2\gamma^2)$ where $\lambda_w$ is the undulator period, $\gamma$ is the electron energy and $\bar{a}_w$ is the RMS undulator parameter, defined for a planar undulator by $\bar{a}_w = e\lambda_w\bar{B}_w/(2\pi m_e c)$. Here $\bar{B}_w$ is the RMS magnetic field and other symbols have their usual meanings. For a permanent magnet undulator $\bar{B}_w$ depends on the undulator gap. As the gap is extended the field falls away until $\bar{a}_w$ falls below a useable level for FEL applications. This defines the minimum wavelength end of the tuning range. As the gap is reduced the field increases until the minimum gap imposed by the vacuum vessel is reached, hence setting the maximum wavelength. Thus, setting the minimum $\bar{a}_w$ and the minimum undulator gap means that the electron beam energy and undulator period are uniquely determined for any given wavelength tuning range.

The initial assumption made for CLARA, subject to revision after an ongoing wakefield assessment, is that the minimum gap will be g = 6 mm and the minimum $\bar{a}_w = 0.7$. The conclusions which result from these assumptions are illustrated in Figure 2. In each plot the horizontal axis is the maximum required wavelength, $\lambda_{max}$ and the vertical axis is the minimum required wavelength, $\lambda_{min}$. The bold dashed lines are the wavelengths of the seed sources discussed above (and their harmonics), from an OPA at 5 μm to an HHG source at 50 nm. The contours represent the required electron beam energy in MeV (top) and undulator period in mm (bottom), such that a single undulator can be tuned from $\lambda_{max}$ at minimum gap to $\lambda_{min}$ at the gap where $\bar{a}_w$ falls below the threshold value. So for example: to tune from an OPA at $\lambda_{max}$ = 5 μm to a Ti:Sa at $\lambda_{min}$ = 800 nm the required beam energy/undulator period is 92 MeV/34 mm; to tune between the 3rd and 5th harmonic of the Ti:Sa the energy/period should be 156 MeV/21 mm; to interact with an HHG source at 100 nm, with no tunability, the energy/period would need to be 175 MeV/16 mm.

Based on this parameterisation the energy has been chosen provisionally as 250 MeV. A radiator undulator of period 29 mm can then tune from the 2nd harmonic of the Ti:Sa at 400 nm to the longest operating wavelength of the HHG seed at 100 nm, as seen in Figure 2. Reaching

50 nm will be possible, but space will allow only a short, dedicated afterburner undulator, giving the opportunity to test different undulator technologies including super-conducting prototypes and variably polarising devices.



Provisional working point allows undulator gap tuning between 2nd Harmonic of Ti:Sa at 400 nm, to HHG at 100 nm: ~250 MeV / 29 mm

The range can be extended to include the fundamental of Ti:Sa at 800 nm through reducing the electron beam energy to ~170 MeV

**Figure 2:** *Parameterisation of electron beam energy and undulator period. The contours represent the required electron beam energy in MeV (top) and undulator period in mm (bottom), such that a single undulator can be tuned from $\lambda_{max}$ at minimum gap of 6 mm to $\lambda_{min}$ at the gap where $\bar{a}_w$ falls below the threshold value of $\bar{a}_w$ = 0.7. The bold dashed lines are the wavelengths of the seed sources (and their harmonics), from an OPA at 5 µm to an HHG source at 50 nm.*

## Beam Emittance

The usual criterion on the electron beam emittance is $\varepsilon_n < \lambda_r \gamma / 4\pi$. This is plotted in Figure 3. For 100 nm operation at 250 MeV, a relatively modest normalised emittance of < 4 mm-mrad will be required. Reducing the emittance below this will help to reduce the FEL saturation length, which will be important for some schemes where the saturation length might be increased compared to the normal SASE regime, but otherwise is not necessary for successful lasing on CLARA. Developing beams with the lowest possible emittance will nevertheless be important in preparation for a future FEL user facility.

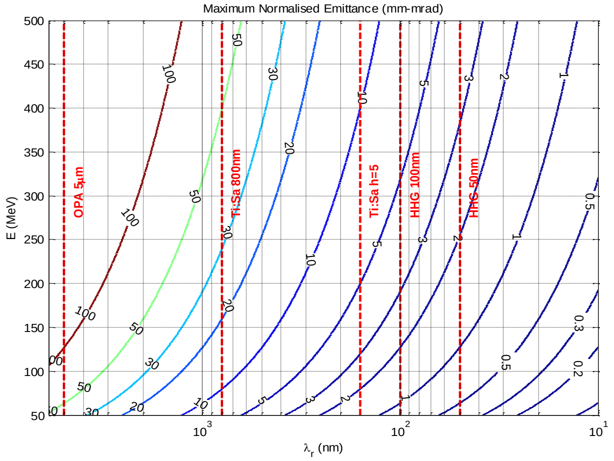


**Figure 3:** *Normalised emittance to satisfy $\varepsilon_n < \lambda_r \gamma / 4\pi$. For 100 nm operation at 250 MeV requires a normalised emittance of <4 mm-mrad.*

## Bunch Charge

The range of required bunch charge to cover the proposed FEL topic areas has been determined as 20–250 pC. A key driver is the available space for radiator undulators, which is approximately 15–20 m, so the FEL must saturate, if required, in this distance with allowance made for space between each undulator module for quadrupole, BPM, screen, phase-matching unit and vacuum components. The peak current is thus calculated to allow saturation in the available distance, and the bunch charge follows from considering the bunch length required for each application. Gun simulations indicate a nominal emittance of $\varepsilon_n$= 0.2–2.0 mm-mrad over bunch charge 10–200 pC and rms energy spread of 40–60 keV - these values are assumed in the subsequent analysis.

### SASE at 100 nm

From initial simulations in Genesis 1.3 [8] the peak current requirement is $I_{pk}$ = 400 A. From the Ming Xie formulation [9], with $\varepsilon_n$= 1 mm-mrad, it is found that at 100 nm resonant wavelength $\rho = 3\times10^{-3}$. For conventional ‘long bunch’ SASE [10] the bunch length $L_b \gg 2\pi l_c$. Initially choosing $L_b = 6\times2\pi l_c$ (to be assessed further in simulations using ideal bunches and those obtained from start-to-end simulations) gives $T_b \geq 330$ fs and Q ≥ 130 pC. For single-spike SASE operation, otherwise known as ‘weak superradiance’, the electron bunch length must satisfy $L_b \leq 2\pi l_c$ [10]. The intention is to generate low-charge bunches with low transverse and longitudinal emittance for this application and the *estimated* bunch charge is 20 pC. Preliminary results of start-to-end simulations of CLARA operating in SASE and single-spike SASE (where velocity bunching is used [11]) modes are shown in Figure 4.

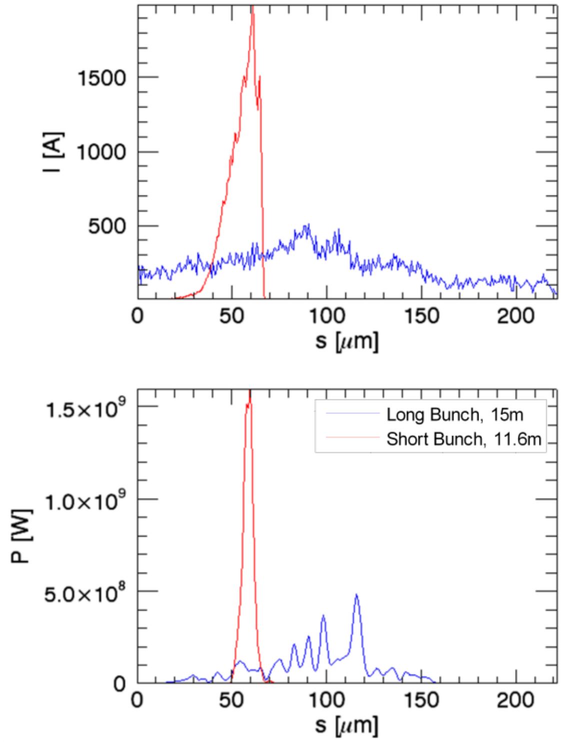


**Figure 4:** *The results of preliminary start-to-end simulations of CLARA operating in SASE mode (blue lines) where magnetic compression is used, and in single-spike SASE mode (red lines) where velocity bunching is used [11]. The upper plot shows the current profile of the electron bunch at the FEL, while the lower plot shows the FEL output at saturation. The results indicate that both modes will be accessible with the provisional CLARA parameters.*

### Short-Pulse Slicing Schemes at 100 nm

The Ti:Sa can be used to energy modulate a short section of the beam, and through various mechanisms it can be arranged that this 'sliced' section of the beam lases preferentially [12]. Some simple arguments are applied to define the parameters here, though more detailed studies are currently underway. For $\rho = 3\times10^{-3}$ (as in SASE) the co-operation length is $l_c = 2.6$ µm, comfortably greater than the single cycle laser pulse length - this is important to ensure that if using a single cycle laser pulse in a single period undulator the sliced section of the bunch effectively evolves to be temporally coherent. The length of the emitted photon pulse is expected to be $\sim\pi l_c$ so the whole bunch must be considerably longer than this to distinguish the output properties of sliced and unsliced bunches and hence demonstrate the effect of the slicing. For bunch length five times longer than $\pi l_c$ the required bunch duration is $T_b \geq 140$ fs, hence $Q \geq 56$ pC.

Preliminary studies of one particular slicing scheme [13], indicate that using a Ti:Sa seed at 800 nm may not be optimal for implementing such a scheme on CLARA since the sliced section is significantly shorter than the co-operation length, resulting in increased saturation length. A longer wavelength seed such as an OPA operating at ~10 µm might therefore be preferable.

### Seeding and Harmonic Generation

The FEL can be seeded with the Ti:Sa at 800 nm in a modulator undulator (or undulators) and lase in the radiator at 2nd–8th harmonic, using various configurations of harmonic conversions including EEHG. Alternatively, direct seeding with the 100 nm HHG source can be done. To mitigate the effect of relative temporal jitter between electron bunch and laser, a flat-top current profile over some region of the bunch longer than the relative jitter is required. For a 40 fs seed laser pulse (either the Ti:Sa at 800 nm or the HHG pulse produced by the same Ti:Sa), and assuming a worst-case ±100 fs temporal jitter, the length of the flat-top region of the bunch should be up to 240 fs. The charge in this region, with peak current 400 A, is 100 pC. Assuming the same charge again split between the head and tail of the bunch the total required charge is 200 pC. To allow contingency for all applications the photoinjector laser system has been specified to deliver sufficient power to generate a 250 pC electron bunch from the Cu photocathode, allowing for a minimum quantum efficiency of $2 \times 10^{-6}$. The operational bunch charge will thus vary from 20–250 pC.

## PROVISIONAL PARAMETERS

The provisional parameters of the CLARA facility are given in Table 2. The results of further FEL modelling will be used to feed back onto the machine requirements.

**Table 2:** *Provisional CLARA parameters*

| Parameter | Value |
|---|---|
| Electron Beam Energy | 250 MeV |
| Minimum Undulator Gap | 6 mm |
| Radiator Period | 29 mm |
| Radiator Tuning | 100-400 nm ((2nd to 8th harmonic of Ti:Sa + HHG) |
| Bunch Charge | 20-250 pC |
| Emittance (predicted from injector simulations) | 0.2-2.0 mm-mrad |
| Seed Sources | 800 nm Ti:Sa + 100 nm HHG |
| Afterburners | To reach 50 nm, novel undulator technology |
| Modulators | Strong $R_{56}$ to enable EEHG |

## FUTURE WORK

The next stage of FEL studies will include selecting potential concepts and carrying out detailed modelling. Work is underway on modelling a laser slicing scheme [13], and the mode-locked FEL scheme [14], and others are under consideration. The EBTF project, which will serve as the first stage of CLARA, is under construction with the aim of first beam by the end of 2012. The aim is to secure funding and build up the remainder of the CLARA facility over the next few years.

## CONCLUSION

The aim of the CLARA project is to develop a normal-conducting test accelerator, able to generate longitudinally and transversely bright electron bunches, and to use these bunches in the experimental production of *stable*, *synchronised*, *ultra-short* photon pulses of coherent light from a single pass FEL. The project which will eventually comprise the first phase, a photo-injector test stand for gun characterisation and industrial applications, is currently funded and under construction. Initial assessment shows that, by assuming a minimum undulator gap of 6 mm, an electron beam energy of 250 MeV would provide FEL radiator tunability over the range 400–100 nm. Two short modulator undulators and short magnetic chicanes will allow interaction with a Ti:Sa seed laser at 800 nm and an HHG source at 100 nm. This design will allow a flexible research programme investigating techniques applicable to the future generation of light sources.

## REFERENCES

[1] 4GLS Conceptual Design Report, CCLRC, (2006).

[2] J. Marangos, et al. NLS Project: Conceptual Design Report, STFC, (2010).

[3] N. Thompson et al. ‘First Lasing of the ALICE Infra-Red Free-Electron Laser’, NIM A, (2012).

[4] D. Dunning, ‘A Review of Worldwide Test Facilities for Free Electron Lasers’, ASTeC internal report (2012).

[5] G. Stupakov, ‘Using the beam-echo effect for generation of short-wavelength radiation’, Phys. Rev. Lett. 102, 074801 (2009).

[6] B. Militsyn, ‘Ultra High Brightness Photoinjector for EBTF/CLARA Facility at Daresbury’, these proceedings (2012).

[7] J. Rodier et al., Construction of the ALPHA-X photo-injector cavity, Proceedings of EPAC (2006).

[8] S. Reiche, Nucl. Inst. Meth. Phys. Res. A 429, 243–248 (1999).

[9] M. Xie, ‘Design Optimisation for an X-Ray Free-Electron Laser Driven by SLAC Linac’, Proceedings of PAC, p183 (1995).

[10] R. Bonifacio, L. de Salvo, P. Pierini, N. Piovella & C. Pellegrini, ‘Spectrum, Temporal Structure and Fluctuations in a High-Gain Free-Electron Laser Starting From Noise’, Phys. Rev. Lett. 73, 7073 (1994).

[11] J. McKenzie and B. Militsyn, ‘A velocity bunching scheme for creating sub-picosecond electron bunches from an RF photocathode gun’, IPAC 2011

[12] A. Zholents, Methods of Attosecond X-Ray Pulse Generation, Proceedings of PAC (2005) p39.

[13] E.L. Saldin et al., Phys. Rev. STAB, 9, 050702, (2006).

[14] N. Thompson and B. McNeil, ‘Mode-Locking in a Free Electron Laser Amplifier’, Phys. Rev. Lett., 100, 203901, (2008).