CONSIDERATIONS FOR A LIGHT SOURCE TEST FACILITY AT DARESBURY LABORATORY

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Abstract

This paper presents an overview of a dedicated light source test facility named CLARA (Compact Linear Advanced Research Accelerator), the first phase of which is currently funded and under construction at Daresbury Laboratory in the United Kingdom. The primary aim of the 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 free-electron laser, using techniques applicable to the future generation of light source facilities. The paper discusses the provisional facility outline and the parameters required to enable the proposed FEL research topics.

INTRODUCTION

Part of the future strategy of the Accelerator Science and Technology Centre (ASTeC), based at Daresbury Laboratory in the UK (and a partner in the Cockcroft Institute), is the development of a next-generation light source test facility to be constructed at Daresbury 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 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 cooperation length $l_c = \lambda_r/4\pi\rho$.

Further aims and prerequisites 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. microbunching 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

CLARA will use a 250 MeV normal conducting S-band 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.

The proposed 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 thus comprises two short modulator undulators in which seed lasers can be used to modulate the electron beam. 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 [1]. 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, with an enlarged view of the first 10 m, is shown in Figure 1.

As an initial stage, the Electron Beam Test Facility (EBTF) is under construction. The layout is shown in Figure 2. One of the aims of EBTF is to characterise a photo-

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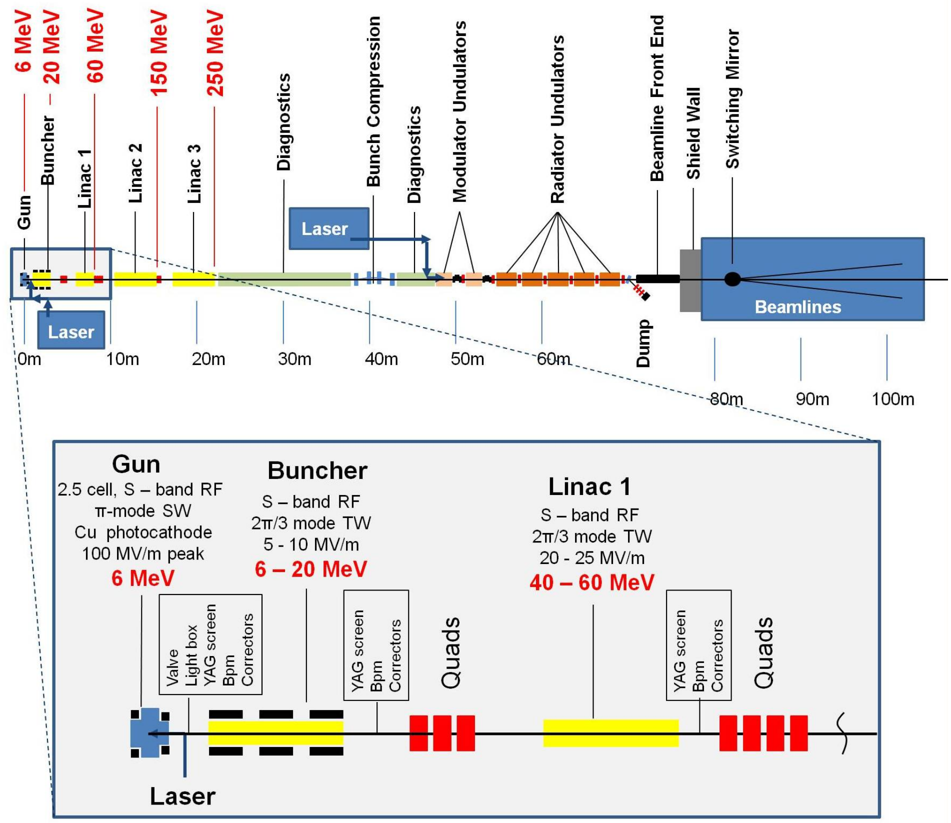

Figure 1: Provisional CLARA Layout (top) and enlarged view of first 10 m (bottom).

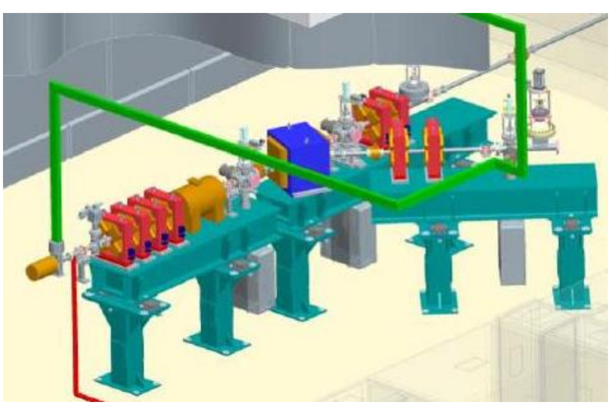

Figure 2: Layout of the first section of the Electron Beam Test Facility (EBTF).

injector, 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 [2] but has never seen operation. Full characterisation of the electron gun six-dimensional phase space is planned and a suitable transverse deflecting cavity is being designed.

PARAMETERISATION STUDIES

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 800nm. This can be used on its own, or to drive an Optical Parametric Amplifier (OPA) covering the range 2–20μm, or a Higher Harmonic Generation (HHG) system giving output from the longest easily available wavelength of $\sim$100nm (12.5eV) to a peak output at $\sim$50nm (25eV).

The resonant wavelength depends on the energy via the resonance condition $\lambda_r = \lambda_w(1+\bar{a}_w^2)/(2\gamma^2)$ where λ_w is the undulator period, γ 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 set-

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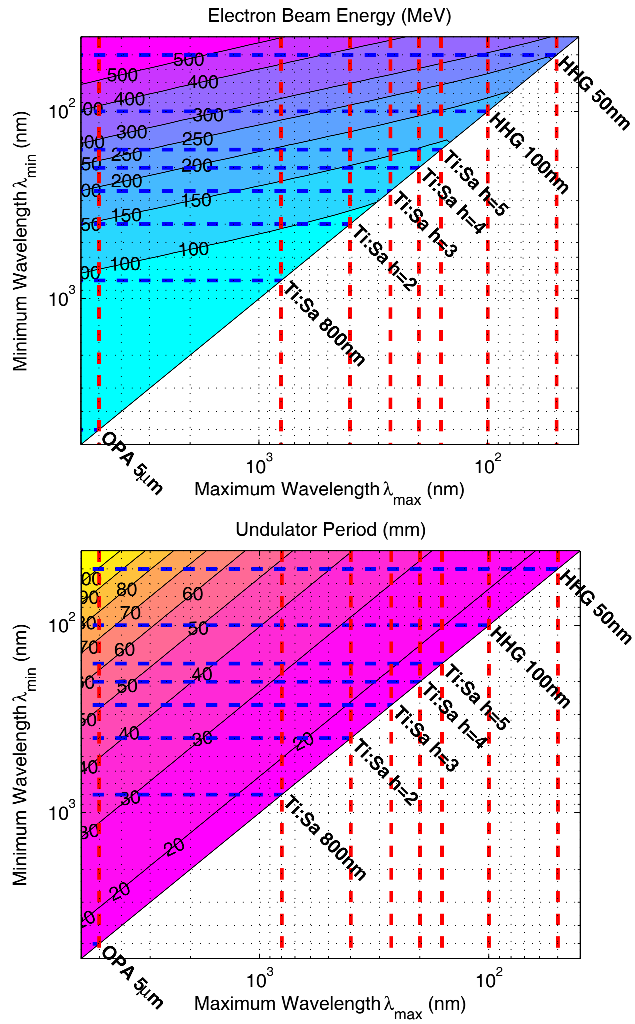

Figure 3: Parameterisation of electron beam energy and undulator period. The contours represent the required electron beam energy in MeV (top) and undulator period in mm (bottom), such that a single undulator can be tuned from λ_{max} at minimum gap of 6 mm to λ_{min} at the gap where $\bar{a}_w$ falls 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 5μm to an HHG source at 50nm.

ting 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 3—in each plot the horizontal axis is the maximum required wavelength λ_{max} and the vertical axis is the minimum required wavelength λ_{min}. The bold dashed lines are the wavelengths of the seed sources discussed above (and their harmonics), from an OPA at 5μm to an HHG source at 50nm. 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 λ_{max} at minimum gap to λ_{min} at the gap where $\bar{a}_w$ falls below the threshold value. So for example: to tune from an OPA at $\lambda_{max} = 5\mu$m to a Ti:Sa at $\lambda_{min} = 800$nm the required beam energy/undulator period is 92MeV/34mm; to tune between the 3rd and 5th harmonic of the Ti:Sa the energy/period should be 156MeV/21mm; to interact with an HHG source at 100nm, with no tunability, the energy/period would need to be 175MeV/16mm.

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 100nm, as seen in Figure 3. 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.

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 ε_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 [3] the peak current requirement is $I_{pk} = 400$ A. From the Ming Xie formulation [4], with $\varepsilon_n = 1$ mm-mrad, it is found that at 100 nm resonant wavelength $\rho = 3 \times 10^{-3}$. For conventional ‘long bunch’ SASE [5] the bunch length $L_b \gg 2\pi l_c$. Initially choosing $L_b = 6 \times 2\pi l_c$ (to be assessed further in simulations using ideal bunches and those obtained from start-to-end simulations) gives $T_b \geq 330$ fs and $Q \geq 130$ pC. For single-spike SASE operation, otherwise known as ‘weak superradiance’, the electron bunch length must satisfy $L_b \leq 2\pi l_c$ [5]. 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. Full parameter optimisation is underway with the aim to generate high-intensity, single-spike FEL output with sufficient shot-to-shot stability using the available space.

Short-Pulse Slicing Schemes at 100 nm The Ti:Sa can be used to energy modulate a short section of the beam,

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and through various mechanisms it can be arranged that this 'sliced' section of the beam lases preferentially [6]. Simulations for this case have not yet been done, so to 1st order some simple arguments are applied to define the parameters. For $\rho = 3 \times 10^{-3}$ (as in SASE) the cooperation length is $l_c = 2.6\mu$m, 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 πl_c the required bunch duration is $T_b \geq 140$ fs, hence $Q \geq 56$ pC.

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 photo-injector 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 2×10^{-6}. The operational bunch charge will thus vary from 20–250 pC.

Beam Emittance

The usual criterion on the electron beam emittance is $\varepsilon_n < \lambda_r \gamma / 4\pi$. This is plotted in Figure 4. Of the example cases considered above, the one requiring the smallest emittance is lasing at 50nm with a 250MeV electron beam—in this case the required emittance is a relatively modest 2 mm-mrad. Reducing the emittance below this will help to reduce the FEL saturation length, which will be important for example in the single-spike SASE regime where the saturation length can be somewhat longer than in the long pulse SASE regime, but otherwise is not necessary for successful lasing.

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.

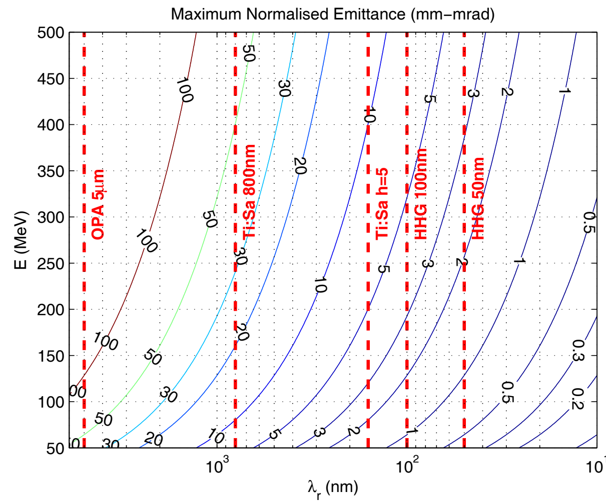

Figure 4: Normalised emittance to satisfy $\varepsilon_n < \lambda_r \gamma / 4\pi$

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