THE CONCEPTUAL DESIGN OF CLARA, A NOVEL FEL TEST FACILITY FOR ULTRA-SHORT PULSE GENERATION

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Abstract

CLARA will be a novel FEL test facility focussed on the generation of ultra-short photon pulses with extreme levels of stability and synchronisation. The principal aim is to experimentally demonstrate that sub-cooperation length pulse generation with FELs is viable, and to compare the various schemes being championed. The results will translate directly to existing and future X-ray FELs, enabling them to generate attosecond pulses, thereby extending their science capabilities. This paper gives an overview of the motivation for CLARA, describes the facility design (reported in detail in the recently published Conceptual Design Report [1]) and proposed operating modes and summarises the proposed areas of FEL research.

INTRODUCTION

Free-electron lasers (FELs) have made huge advances in the past few years with the first successful demonstration of an X-ray FEL at LCLS in the USA in 2009 [2], followed by similar success at SACLA in Japan in 2011 [3]. Whilst the new X-ray FELs are remarkable in their performance the potential for improvements is still great. There are many proposals for improving the FEL photon output in terms of temporal coherence, wavelength stability, increased power, intensity stability and ultra-short pulse generation. However given the low number of operating FELs and the need to dedicate the majority of beam-time for user exploitation many of these ideas remain untested experimentally. This paper describes the design of CLARA (Compact Linear Accelerator for Research and Applications), a dedicated flexible FEL Test Facility, which will be able to assess several of the most promising new schemes. The successful proof of principle demonstration with CLARA will be a vital stepping stone to the implementation of any new scheme on an existing or planned FEL facility. CLARA is effectively a major upgrade to the existing VELA RF photoinjector facility at Daresbury Laboratory [4], targeted at industrial applications and technology developments.

Our vision for CLARA is that it should be dedicated to the production of ultra-short photon pulses of coherent light. Existing FELs are already capable of generating pulses of light that are only tens of femtoseconds in duration, but proposals have been made for generating pulses that are two or three orders of magnitude shorter than this (hundreds or tens of attoseconds) and a recent paper has proposed sub-attosecond pulse generation [5]. Many exciting applications of attosecond pulses have already been demonstrated [6, 7, 8], including coherent X-ray imaging, femtosecond holography, real-time observations of molecular motion and capturing the movement of electrons in atoms and molecules. Attosecond X-ray science could revolutionise how we understand and control electron dynamics in matter.

In order to achieve this vision for ultra-short pulse generation, CLARA must be able to implement advanced techniques, such as laser seeding, laser-electron bunch manipulation, and femtosecond synchronisation. These can only be achieved by developing a state-of-the-art accelerator with the capability to drive current FEL designs. CLARA is therefore of direct relevance to the wider international FEL community and will also ensure that the UK has all the skills required should it choose to develop its own future FEL facility.

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Table 1: CLARA Operating Modes

Mode	Seeding	SASE	Ultra-Short Pulse	Multibunch
Energy (MeV)	250			
Macropulse Rep Rate (Hz)	1-100			
Bunches/Macropulse	1	1	1	16
Bunch Charge (pC)	250	250	20–100	25
Peak Current (A)	125-400	400	~1000	25
Bunch Length (fs)	850–250 (flat top)	250 (rms)	< 25 (rms)	300 (rms)
Energy Spread, rms (keV)	25	100	150	100
Norm. Emittance (mm-mrad)	≤ 1			
Radiator Period (mm)	27			
Radiator Type	Hybrid, Planar			

GOALS AND BENEFITS

The goals and benefits of CLARA will be:

- Proof-of-principle demonstrations of ultra-short photon pulse generation (of order of the cooperation length or less) using schemes which are applicable to X-ray FELs (such as laser slicing, mode-locking, or single spike SASE) and with extreme levels of synchronisation.
- The ability to test novel schemes for increasing the intrinsic FEL output intensity stability, wavelength stability, or longitudinal coherence using external seeding, self seeding or through the introduction of additional delays within the radiator section.
- The ability to generate higher harmonics of a seed source using Echo Enabled Harmonic Generation (EEHG) [9], High Gain Harmonic Generation (HGHG) [10], or other novel schemes.
- The generation and characterisation of very bright (in 6D) electron bunches and the subsequent manipulation of their properties with externally injected radiation fields, and the testing of mitigation techniques against unwanted short electron bunch effects.
- The development and demonstration of advanced accelerator technologies such as a high repetition rate normal conducting RF photoinjector, novel undulators, RF accelerating structures and sources, single bunch low charge diagnostics, novel photocathode materials and preparation techniques. The potential to test the new generation of plasma-based accelerators as drivers of FELs is also a significant consideration.
- The enhancement of VELA (Versatile Electron Linear Accelerator), in terms of energy, beam power, and repetition rate, enabling new industrial applications of electron beams.
- The provision of a flexible, high quality, electron test accelerator for the UK accelerator community on a proposal-driven basis, enabling wide ranging, high impact accelerator R&D.
- The development and retention of vital skills within the UK accelerator community, including providing excellent opportunities for attracting the best PhD students and early stage researchers to work on a world class accelerator test facility.
- The possibility to use the high quality bright electron beam for other applications such as ultra-fast electron diffraction, plasma wakefield accelerators (as a witness bunch or a drive bunch), as the drive beam for a Compton scattering source of X-rays or gamma photons, and for other novel acceleration schemes such as dielectric wakefield accelerators and exotic storage rings.

PARAMETER SELECTION

The wavelength range chosen for the CLARA FEL is 400–100 nm, appropriate for the demonstration of advanced FEL concepts on a relatively low energy accelerator. Key drivers for this choice are the availability of suitable seed sources for interacting with the electron beam and the availability of single shot diagnostic techniques for the characterisation of the output. The proposal is to study short pulse generation over the range 400–250 nm, where suitable nonlinear materials for single shot pulse profile characterisation are available. For schemes in this regime it is often necessary to produce a periodic modulation in the properties of the electrons along the bunch such that it can be arranged that only some sections of the beam can lase. Often the scale length of each independent FEL interaction is given by the cooperation length l_c, so the modulation of the electron bunch should have a period significantly longer than this to enable an independent temporally-separated interaction for each period of the modulation. For the lasing wavelength range 400–250 nm this leads to the requirement that to cover most of the short-pulse research topics the modulating laser should have wavelength ~20 – 50 µm with the possibility of extending to 120 µm in the future.

For schemes requiring only spectral characterisation (for example producing coherent higher harmonics of seed sources, or improving the spectral brightness of SASE) the operating wavelength range will be 266 – 100 nm, with the possibility of output down to 80 nm at a later stage. For these schemes the most appropriate seed source (if required) is an 800 nm Ti:sapphire laser from which can be generated coherent harmonics up to the 8th

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harmonic, or 10th harmonic later on. To operate at shorter wavelengths than 80 nm would currently offer little advantage, but many complications. Finding a suitable material to perform the non-linear mixing required for a FROG or SPIDER type analysis of the pulse temporal profile becomes very difficult at wavelengths shorter than c. 100 nm. Temporal diagnostics at short wavelengths become dependent on transfer of the spectral phase information onto a photo-electron wave packet, generally accomplished by photo-ionising a gas in the presence of a strong laser field. The FEL wavelength has to be not only short enough to photo-ionise the gas, but to do so in the presence of the ponderomotive potential of the laser field and this requires a move to much shorter wavelengths. Furthermore, such diagnostic techniques are very challenging and have not been successfully demonstrated on the single-shot basis necessary for the CLARA research program.

The required electron beam energy and undulator parameters depend on the required tuning range. For CLARA the minimum useful undulator parameter is set to be K~1 and the minimum undulator gap set to 6 mm. For a hybrid planar undulator, and a tuning range of 400-100 nm, this defines the required electron beam energy to be 228 MeV and the undulator period to be 27 mm. However, CLARA has been designed to provide a maximum beam energy of 250 MeV. This allows sensible contingency in three areas. First, it allows the full wavelength tuning range to be achieved at a slightly reduced linac gradient. Second, it allows the linac cavities to be operated further off-crest for added flexibility. Third it allows the FEL wavelength to be pushed to around 80 nm with only a slight reduction in undulator parameter enabling the generation of even higher harmonics of the seed sources.

OPERATING MODES

The approach we have adopted is to design a flexible, diagnostic rich facility for testing a variety of advanced FEL concepts. We recognise the dynamic nature of FEL research and aim not just to demonstrate and study the novel concepts of today but also be well positioned to prove the novel concepts of tomorrow. For these reasons we have planned a number of different CLARA operating modes, each of which is designed to be appropriate for a different class of FEL experiments. The parameters for the different operating modes are given in Table 1.

Seeding Mode

This mode is designed for any FEL scheme where a seed source interacts with the electron beam. For operation at 100 nm the electron bunch has a ~250 fs flat-top current profile to mitigate up to 100 fs jitter between the electron bunch and seeding laser. The required peak current to reach saturation at 100 nm in a sufficiently compact undulator section, taking into account the expected emittance and energy spread, is 400 A giving bunch charge 250 pC. For schemes where the beam is modulated with the long wavelength seed the bunch length must be longer because of the increased slippage so the flat top region is extended to ~850 fs. To maintain the same saturation length as for 100 nm operation the peak current is only 125 A which also can be achieved with the 250 pC bunch charge. In this mode it is important to make the magnitude of the energy modulation induced by the laser large compared with beam energy spread to enable strong bunching to be generated at high harmonics. This requires a small energy spread in the beam.

SASE Mode

This is the 'base' FEL operation required for validating the performance of the accelerator, the properties of the electron bunch and the alignment within the undulator sections. In addition, many of the schemes proposed for CLARA aim to improve the temporal coherence and/or stability of SASE so it is important to be able to use SASE as a control. There is no requirement for a flat-top profile. The SASE FEL performance is quite insensitive to energy spread at the 25 – 100 keV level so in this mode we allow the energy spread to be higher than in the seeding mode.

Ultra-Short Pulse Mode

This mode is for research into ultra-short bunch generation and transport, and the use of such bunches for single spike SASE FEL operation, where the bunch length must be shorter than the typical SASE spike separation of $2\pi l_c$. To generate and transport very short bunches is only possible if the charge is quite modest due to space charge limitations. A study of the parameter space has led to the conclusion that a bunch charge of 20 – 100 pC is appropriate for 100 nm wavelength operation with a peak current requirement of up to 1000 A.

Multibunch Mode

This mode is designed to allow research into short-wavelength oscillator FELs. To operate the FEL in oscillator mode would require some rearrangement of components to install an appropriate optical cavity. The proposed scheme is to demonstrate a Regenerative Amplifier FEL (RAFEL) for the generation of transform limited pulses at wavelengths as short as 100 nm. Such a system requires only a very low feedback optical cavity. Initial studies show that the undulator length needs only be one third of the SASE saturation length, therefore even using only five of the seven radiator undulators the peak current can be reduced to a modest 25 A while maintaining the appropriate gain length. The electron bunch must be longer than the slippage length giving required length of ~300 fs rms and hence minimum bunch charge of 15 pC. The bunch repetition rate must be matched to the ~17.5 m optical cavity round trip time giving f = 8.5 MHz and bunch spacing 120 ns. Typically 8 cavity round trips are required to reach saturation so the minimum macropulse duration is 1 µs. The macropulse duration is therefore 2 µs to allow time to diagnose the

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FEL output (and its stability) at saturation. The total charge in the macropulse is thus 250 pC which is consistent with other operating modes. The average power demands on the accelerator systems are therefore no greater than in any other operating mode.

DESIGN AND LAYOUT

An overview of the proposed layout of CLARA is shown in Figure 1 and a detailed explanation is given in [11]. The S-band RF photocathode gun is followed by a short (~2 m long) S-band linac, chosen such that it may be used in acceleration or bunching configurations. A spectrometer line which also serves as injection to VELA branches at this location. A second S-band linac (~4 m long) is then followed by a linearising X-band cavity and a magnetic bunch compressor. Two further S-band linacs (each ~4 m long) then allow acceleration to 250 MeV. Following a dogleg, to enable laser seed injection, is the FEL modulator undulator and chicane for longitudinal phase space manipulations. The FEL radiator consists of seven linear polarizing undulators, each 1.5 m long. Space has been reserved after the radiators for an afterburner system which could test exotic short pulse schemes, generate shorter wavelengths than the FEL resonance, or investigate novel methods for polarisation control. The ability to test short period, narrow gap, advanced undulator designs will also be possible at this location.

Initially the existing VELA RF photoinjector will serve as the electron source for CLARA [12]. However, as this is limited to 10 Hz operation a bright, high repetition rate, 400 Hz, RF gun is being designed and will be installed in the future [13].

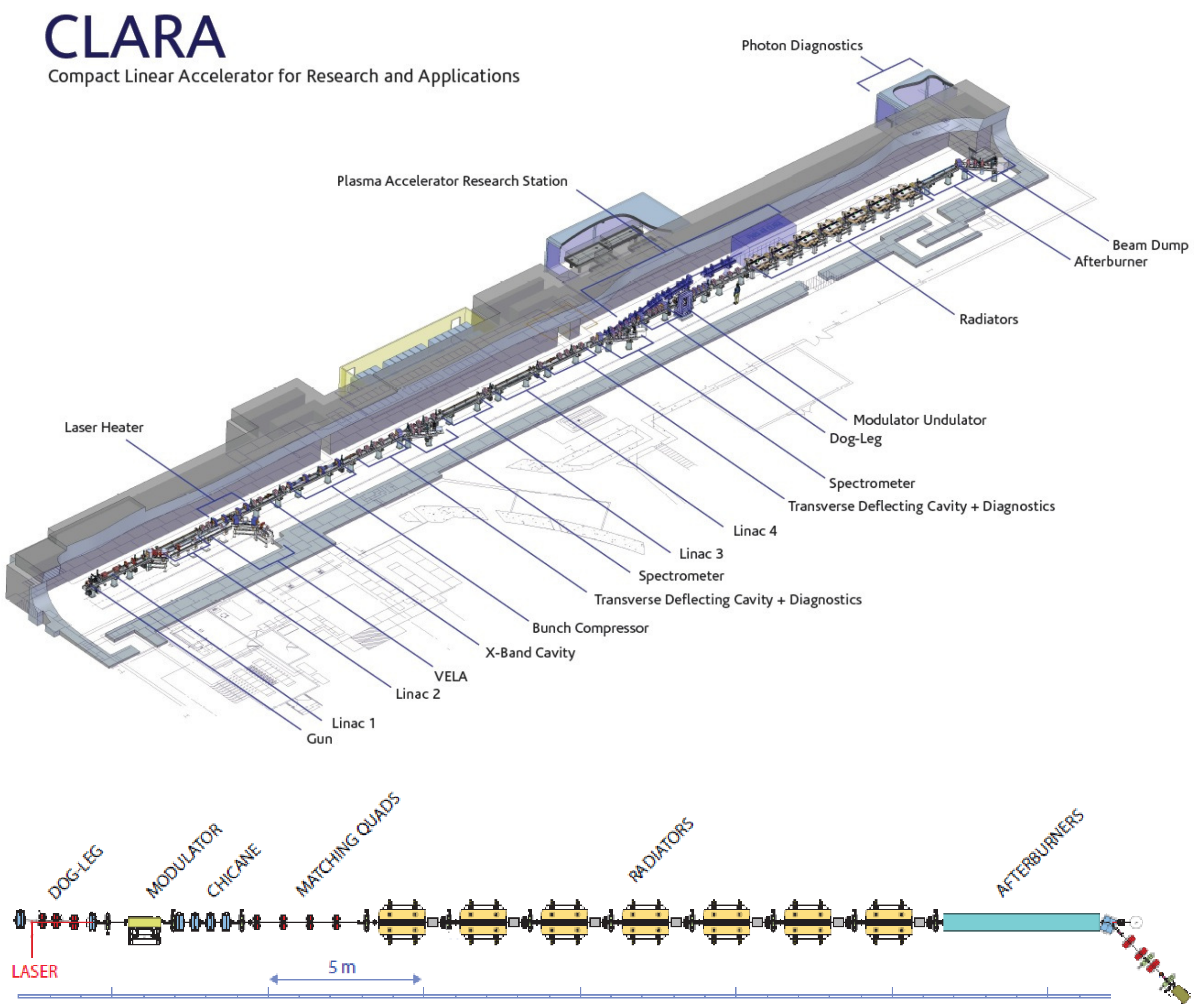

Figure 1: 3D Engineering representation of the CLARA facility (top) and enlarged 2D representation of the FEL systems (bottom).

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FEL RESEARCH TOPICS

Ultra-Short Pulses

The generation of short pulses is one of the important research themes for CLARA. The aim is to generate pulses with as few optical cycles as possible with durations of the order of, or shorter than, the FEL cooperation length l_c. The SASE process generates spikes of duration $\sim\pi l_c$ with each SASE spike developing independently from the shot noise in the electron beam [14]. Many of the short pulse schemes aim to slice out, or isolate, a single SASE spike and the duration of the output pulse is therefore typically no shorter than $\sim l_c$. The plan is to research two types of schemes with this level of potential: schemes based on slicing a section of the electron bunch with a laser and single-spike SASE.

To generate shorter pulses than l_c requires fundamentally altering the FEL process. One scheme, Mode-Locking [15], can be implemented with a 30 - 50 μm beam modulation and the standard undulator lattice (Phase I) and then extended to the production of even shorter pulses with the inclusion of extra intra-undulator delays (Phase II) or isolated pulses with a ~120 μm beam modulation. A further scheme, the Mode-Locked Afterburner [5], can be implemented with the standard undulator lattice and the inclusion of a bespoke afterburner section comprising a series of few-period undulator sections interspaced with small integrated delays. These schemes have all been studied for implementation on CLARA with further details provided in the CDR. Table 2 indicates the predicted pulse durations in fs and number of cooperation lengths. It is seen that the Phase II Mode-Locking and Mode-Locked Afterburner schemes are predicted to produce sub-cooperation length pulses. Scaling these results to hard X-ray wavelengths indicates pulse durations at 0.15 nm of ~10 as for Mode-Locking and 2.5 as for the Mode-Locked Afterburner.

Of course other schemes will be proposed in the future and the flexibility of CLARA will enable practical investigation of these schemes on relatively short timescales.

Improved Longitudinal Coherence

Currently the full potential of X-ray FELs is not realised because they operate in SASE mode for which the temporal coherence is relatively poor. For this reason, their spectral brightness is typically two orders of magnitude lower than that that of a transform limited source. Improvement of SASE FEL temporal coherence would greatly enhance scientific reach and allow access to new experimental regimes. There are a number of methods for improving SASE coherence, many of which have been tested or are already in routine use. Existing methods fall into two classes. In the first class, an externally injected seed source of good temporal coherence 'seeds' the FEL interaction so that noise effects are reduced. This seed field may be either at the resonant radiation wavelength, where available, or at a subharmonic which is then up-converted within the FEL. Such methods include HGHG and EEHG. In the second class, the coherence is created by optical manipulation of the FEL radiation itself, for example by spectrally filtering the SASE emission at an early stage for subsequent re-amplification to saturation in a self-seeding method [16-19], or via the use of an optical cavity [20-27]. A third, more recently proposed class of methods, rely on artificially increasing the slippage between FEL radiation and electron bunch to 'slow down' the electrons which extends the coherence length [28-30] or even completely 'delocalises' the FEL interaction allowing the radiation coherence length to grow exponentially [31]. Schemes in all three classes have been studied for feasibility of execution on CLARA and can be optimised, validated or even demonstrated for the first time on the facility. The schemes investigated so far are a Seeded Harmonic Cascade, EEHG, a RAFEL, and High Brightness SASE/iSASE. Further details are available in the CDR and in [32].

Table 2: Predicted pulse durations from CLARA short pulse schemes measured in femtoseconds and number of cooperation lengths.

		FWHM Pulse Duration	
Scheme	**λ**	**fs**	**# lc**
Slice/Taper	266 nm	50	2.2
EEHG	100 nm	25	2.6
Single-Spike SASE	100 nm	23	2.3
Mode-Locking Phase I	266 nm	43	1.9
	100 nm	18	1.8
Mode-Locking Phase II	266 nm	17	0.7
	100 nm	14	1.4
Mode-Locked Afterburner	100 nm	1.6	0.16

SUMMARY

The conceptual design for CLARA, a novel FEL test facility for ultra-short pulse generation, has now been established and this has been published in July 2013. The design is flexible and able to operate in a number of different modes to ensure that it is able to adapt to new schemes as they are proposed in the future. The project has now entered the detailed technical design phase which includes specifying the first accelerating section which is expected to be ready to be installed towards the end of 2014. Since CLARA is intimately linked to the existing VELA facility, much of the essential infrastructure for the project already exists. This will significantly reduce the time required to implement CLARA in full. We believe that within 3 years of funding we could procure and install all of the equipment and commence beam commissioning.

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