THE CONCEPTUAL DESIGN OF CLARA, A NOVEL FEL TEST FACILITY FOR ULTRASHORT PULSE GENERATION

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Abstract

The conceptual design of CLARA, a novel FEL test facility focussed on the generation of ultra-short photon pulses with extreme levels of stability and synchronisation is described. The ultimate aim of CLARA is to experimentally demonstrate that sub-coherence 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 the science capabilities of these intense light sources. This paper will describe the design of CLARA, pointing out the flexible features that will be incorporated to allow multiple novel FEL schemes to be proven.

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, followed by similar success at SACLA in Japan in 2011. Whilst the new X-ray FELs are remarkable in their performance their potential for improvement has largely been untapped so far. There are many suggestions which have been proposed for how the FEL photon output can be improved in terms of temporal coherence, wavelength stability, increased power, intensity stability, and ultra-short pulse generation. Unfortunately, very few of these ideas have been tested 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, targeted at industrial applications and technology developments [1].

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 FEL experts have proposed several schemes which have the potential to generate pulses that are three orders of magnitude shorter than this (tens of attoseconds) and a recent paper has even proposed a novel idea for sub-attosecond pulse generation from a FEL [2]. In order to achieve this vision CLARA will necessarily have to implement state of the art techniques, such as laser seeding, laser-electron bunch manipulation, and femtosecond synchronisation and this will also be of considerable relevance to the accelerator community.

The wavelength range chosen for the CLARA FEL is 400 to 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, as required by many of the FEL topics we propose to study, and the availability of single shot diagnostic techniques for the characterisation of the FEL output. In detail the goals, opportunities and benefits of CLARA will be:

- The proof of principle demonstrations of ultra-short photon pulse generation (of order coherence length or less) using schemes which are applicable to X-ray FELs (such as laser slicing, mode locking, or single

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spike SASE) and with extreme levels of synchronisation.

- The ability to test other novel schemes for increasing the intrinsic FEL output intensity stability, wavelength stability, or the longitudinal coherence using external seeding, self-seeding or through the introduction of additional phase delays within the radiator section.
- The ability to generate higher harmonic radiation of a seed source using EEHG, HGHG, or other novel scheme.
- The generation and characterisation of very bright (in 6D) electron bunches and the subsequent manipulation of the bunch properties with externally injected radiation fields and also the testing of mitigation techniques against unwanted short bunch effects.
- The development and demonstration of advanced accelerator technologies, with many wide ranging applications well beyond just FELs, such as a high repetition rate normal conducting RF photoinjector and high gradient accelerating structures, single bunch low charge diagnostics, and novel photocathode materials and preparation techniques.
- The enhancement of VELA, in terms of energy, beam power, and repetition rate, enabling additional industrial applications that are currently excluded.
- 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 wide ranging scientific research applications such as ultrafast electron diffraction experiments, plasma wakefield accelerator research (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.

OPERATING MODES

The approach we have adopted is to design a flexible, well-diagnosed facility that is appropriate for testing a variety of advanced FEL concepts. This flexibility will be built into the accelerator itself, and also incorporated into the systems specific to the FEL. 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 complete set of experiments will be discussed in the forthcoming Conceptual Design Report, one example currently under study is described in [3]. The parameters for the different operating modes are given in Table 1.

DESIGN AND LAYOUT

The design approach adopted for CLARA is to build in flexibility of operation, enabling as wide an exploration of FEL schemes as possible. A major aim is to be able to test seeded FEL schemes. This places a stringent requirement on the longitudinal properties of the electron bunches, namely that the slice parameters should be nearly constant for a large proportion of the full-width bunch length. In addition, CLARA should have the ability to deliver high peak current bunches for SASE operation and ultra-short pulse generation schemes, such as velocity compressed bunches. This flexibility of delivering tailored pulse profiles will allow a direct comparison of FEL schemes in one facility. An overview of the proposed layout is shown in Figure 1. The S-band RF photocathode gun is followed by a 2 m long linac, chosen such that it may be used in acceleration or bunching configurations. A second linac follows which is ~4m long and capable of accelerating up to ~150MeV. Space for a laser heater is reserved at this point. A fourth harmonic linearizing X-band cavity is situated before the magnetic compressor to correct for longitudinal phase space curvature. The variable magnetic bunch compressor is then followed by the first dedicated beam diagnostics section, incorporating transverse deflecting cavity and spectrometer, enabling measurement of emittance, bunch length and slice properties. Linacs 3 & 4 (each ~4m long) accelerate to 250MeV, these are followed by a second diagnostics section. The beam then passes through a dogleg section, offsetting the FEL from the linacs transversely to enable co-propagation of long wavelength laser seeds. Further details of the beam dynamics performance, including jitter studies, can be found in [4, 5].

The FEL requires interaction with seed lasers over a wide range of wavelengths in a short, four period, modulator undulator followed by amplification in seven 1.5 m long radiator undulators. 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.

Initially the existing VELA RF photoinjector will serve as the electron source for CLARA [6]. However, as this is limited to 10 Hz operation we are actively designing a bright high repetition rate, 400 Hz, RF gun which will be installed in the future [7].

Table 1: Main Parameters for the Five CLARA Operating Modes

Parameter	*Seeding*	*SASE*	*Ultra-short*	*Multibunch*	*Industrial*
Max Energy (MeV)	*250*	*250*	*250*	*250*	*100*
Macropulse Rep Rate (Hz)	*100*	*100*	*100*	*100*	*400*
Bunches/macropulse	*1*	*1*	*1*	*20*	*TBC*
Bunch Charge (pC)	*250*	*250*	*20 – 100*	*25*	*250*
Peak Current (A)	*125 – 400*	*400*	*1500*	*400*	*TBC*
Bunch Length (fs)	*250 – 850 (flat)*	*250 (rms)*	*<30*	*250*	*TBC*
Norm. Emittance (mm-mrad)	*<1*	*<1*	*<1*	*<1*	*<1*
RMS Energy Spread (keV)	*25*	*100*	*150*	*100*	*TBC*
Radiator Period (mm)	*27*	*27*	*27*	*27*	-

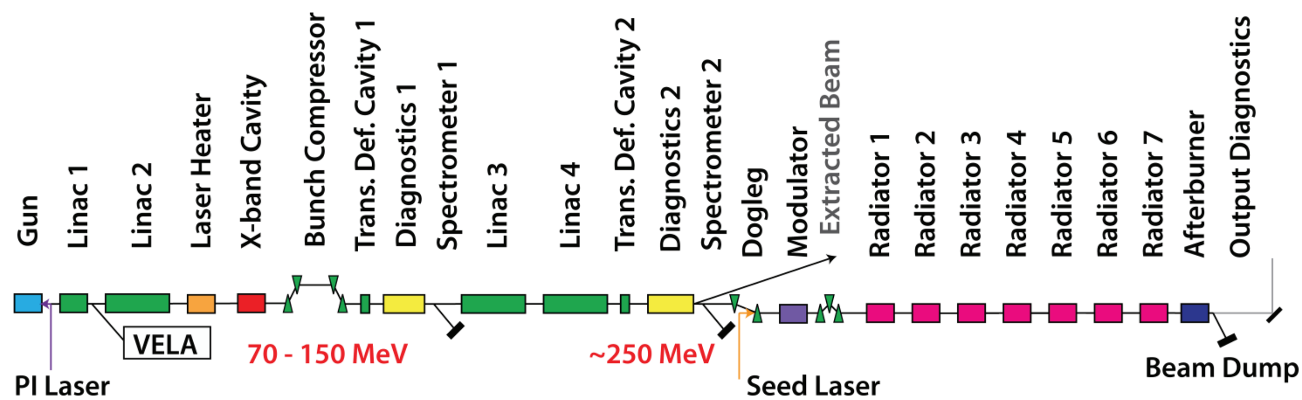

Figure 1: CLARA layout overview.

OTHER POTENTIAL APPLICATIONS

The primary motivation for CLARA is clearly as an FEL test facility but the availability of bright bunches of electrons will also enable other challenging areas of accelerator research to be developed which would otherwise not be possible. Possible areas which have been identified so far include:

- Plasma accelerator research, either electron driven or laser driven with an injected electron bunch [8].
- Ultrafast electron diffraction with the RF injector.
- Short pulse gamma beam generation using Compton scattering.
- Dielectric wakefield acceleration experiments.
- Non-equilibrium storage rings which store ultra-bright electron bunches for only a few thousand turns.
- Exotic storage ring concepts, perhaps to test optical stochastic cooling or integrable optics lattices.

To enable these opportunities to be feasible in the future, space has been reserved within the CLARA tunnel for a 250 MeV beam transport line parallel to the FEL and the option of taking additional beamlines into a new shielded area, large enough to house a small storage ring, is also practical within the confines of the existing building.

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