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CLARA FACILITY LAYOUT AND FEL SCHEMES

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Abstract

CLARA is a new FEL test facility being developed at STFC Daresbury Laboratory in the UK. Commissioning has started on the front-end (photo-injector and first linac) while the design of the later stages is still being finalised. We present the latest design work, focusing on the layout and specification of components in and around the undulator sections. We give an overview of the design and modelling of the FEL schemes planned to be tested.

INTRODUCTION

The UK is constructing a new FEL test facility called CLARA [1] which will be a dedicated accelerator R&D facility focused around demonstrating FEL schemes that can be applied to enhance the capabilities of X-ray FEL facilities - including a potential UK XFEL [2]. It will operate with 250 MeV maximum energy and λ_r=100-400 nm fundamental FEL wavelength (see Fig. 1 for layout). The front end (up to 50 MeV) is being commissioned and the second phase (up to 150 MeV) is being assembled while design of the later stages continues - aiming for FEL lasing in 2022.

While CLARA will serve as a test-bed for various accelerator technologies, the focus of this paper is on the FEL schemes and the implications for the layout of the FEL section. The design of the FEL section will be finalised in September 2017 prior to initiating purchasing of the undulators. The main aims dictating design choices for the CLARA FEL section are:

- To demonstrate novel FEL capabilities that could be applied at X-ray FEL facilities, specifically ultra-short pulses, improved pulse quality, stability and synchronisation. For ultra-short pulses the aim is for pulse durations in the 1-100 fs range, which would correspond to 1-100 as when translated from the 100 nm minimum wavelength of CLARA to ~0.1 nm facilities.
- To gain experience with schemes for a future UK XFEL including those already demonstrated elsewhere.
- To produce a flexible design that can accommodate new ideas and future upgrades.

Given the above we aim to keep the focus on energy/wavelength-independent aspects of the FEL concepts and so minimise energy/wavelength-specific difficulties so far as possible. Key drivers for the wavelength choice were therefore the availability of single-shot diagnostic techniques for the characterisation of the output and availability of suitable seed sources for interacting with the electron beam. To suit single-shot temporal diagnostics it is proposed to study short pulse generation for FEL wavelengths in the range 250-400 nm, where suitable non-linear materials are available. For schemes requiring only spectral characterisation the operating wavelength range will be 100-266 nm. While it was previously planned to use seed/modulating laser sources throughout the range from 800 nm-100 µm [1], on further consideration it is more straightforward (i.e. requires less laser R&D) to avoid the range from 20 µm$\lesssim \lambda_{\mathrm{mod}} \lesssim$70 µm and to cluster FEL schemes around a few select wavelengths.

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FEL SCHEMES

The CLARA FEL team maintains an ongoing review of FEL schemes that have been proposed and demonstrated worldwide and assesses their compatibility with the aims and layout of CLARA. Some of these are listed below, categorised into what is foreseen to be the initial/major CLARA projects and others that impact the layout through maintaining as options of high interest.

Initial Projects

Schemes under consideration for the early stages of CLARA are those that are expected to be relatively less demanding at least in not requiring external laser modulation or synchronisation. This includes single-spike SASE [3], tapering (assessed for CLARA in [4]), two-colour schemes via undulator tuning and testing novel undulator technology [5] in a designated afterburner section.

Major Projects

These are listed in a potential running order where elements of the layout would be introduced incrementally:

High-brightness SASE The high-brightness SASE scheme [6] employs chicanes between undulator modules to increase the slippage of the radiation relative to the electron bunch and so improve the temporal coherence of the emitted radiation pulse. In simulations the scheme has been shown to perform more effectively for undulator modules shorter than the FEL gain length. It requires no laser seeding/modulation.

Mode-locked FEL The mode-locked FEL concept [7] uses chicane delays between undulator sections to allow pulses with duration much shorter than the FEL co-operation length, $l_c = \lambda_r/4\pi\rho$ (where the FEL parameter $\rho \approx 10^{-4} - 10^{-3}$), which is a lower limit for many schemes. The number of cycles per pulse can be reduced from hundreds to approximately the number of periods in an undulator module, N. For demonstration on CLARA the number of periods per undulator module should therefore be minimised, without negatively impacting other schemes: this has been set to 27 periods. While preliminary results could be achieved

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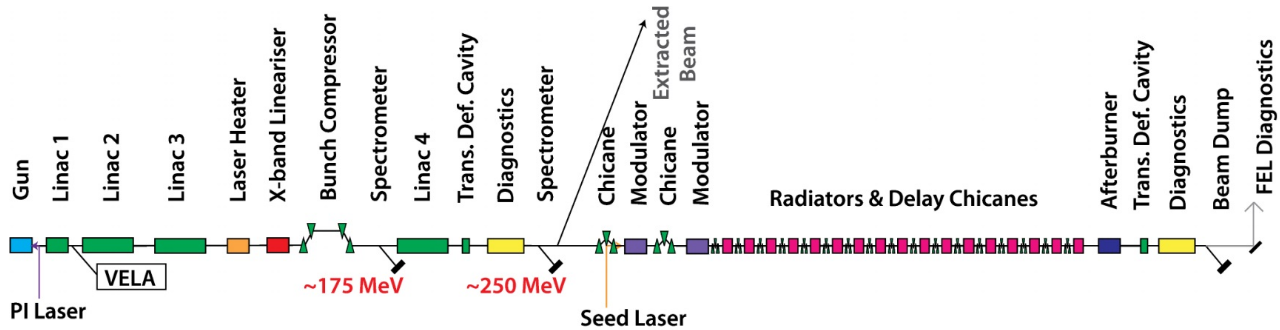

Figure 1: Schematic layout of CLARA. The total length is ~90 m.

without interaction with an external laser, the scheme ultimately requires the electron beam energy to be modulated with period $\lambda_{\text{mod}} = S_e N \lambda_r$, where the slippage enhancement factor [7] $S_e \sim 4 - 8$ has commonly been used in modelling. Latest studies indicate that a 20 µm source would be suitable.

Mode-locked afterburner The mode-locked afterburner [8] differs from the above by requiring chicane delays and short undulator modules only in a short afterburner section, without the constraint of maintaining performance of other schemes. N can therefore be reduced to ~8 periods and the modulation period can be reduced, e.g. to 3 µm at λ_r=100 nm [9] or ~8 µm at λ_r=266 nm.

Energy chirp with tapered undulator The energy chirp with tapered undulator scheme [10] uses a few-cycle laser pulse to modulate the electron beam energy and a tapered undulator to select a short region of the beam with a specific chirp for FEL lasing. In [10] a hard x-ray resonant FEL wavelength of λ_r=0.15 nm is used with an 800 nm modulating laser pulse to generate an isolated SASE spike with 200 as FWHM duration, corresponding to sub-cycle scale of the 800 nm modulation. For CLARA with λ_r=266 nm the optimum modulating wavelength should be approximately 40 µm [1], so operation with λ_r=400 nm and $\lambda_{\text{mod}} \approx$70 µm may be preferable to deliver a suitable modulating laser.

Other Schemes Impacting the Layout

Variable polarisation The relative advantages of planar undulators versus helical (with variable polarisation) undulators for CLARA has been considered in depth [11]. Given that the priority is not for significant investment in complex polarisation-preserving transport and diagnostics, the conclusion is that the flexibility and higher growth rate of helical undulators does not justify the increased complexity and cost. Nevertheless some flexibility is desirable to provide an extra degree of freedom for future developments. Hence the option of rotating the undulators about the beam axis has been specified provided the cost increase is not substantial. An example of a scheme enabled by this has been studied [12] and more complex variants can be envisaged.

EEHG Echo-enabled harmonic generation (EEHG) [13] is not presently a major project because detailed experimental studies have been carried out elsewhere. Nevertheless because of its utility and flexibility for a range of schemes it is considered essential to include components to allow this. EEHG on CLARA has been studied assuming 800 nm seed wavelength [1].

Frequency modulation Frequency modulation in FELs is a topic of research aiming to deliver output with very broad bandwidth [14]. Undulator tapering within modules is specified for CLARA to enable studies such as this.

Summary of Requirements

The conclusion from analysis of potential schemes is that the design of the FEL section should be suitable for the major projects but also flexible to enable a large number of other options. This can be achieved by choosing a layout that is fairly universal in the sense that it will feature a short modulation section, then a long radiator, then an afterburner region, with several features to maximise flexibility: (1) Including two modulator undulators with chicanes of suitable R_{56} to allow EEHG and to increase modulation amplitude applied in the first modulator by the optical klystron effect [15]. Upgrades to add extra modulators could be achieved by removing radiators. (2) Allowing sufficient transverse aperture to inject a large range of wavelengths from external lasers (up to 100 µm). (3) Utilising short radiator modules with chicanes between modules to study HB-SASE and mode-locking. (4) Using rotatable planar undulators to give a degree of freedom on polarisation, together with variable gap and tapering within modules. (5) Leaving space to interchange afterburner sections to test e.g. novel undulators, mode-locked afterburner. (6) Engineering approaches to ease re-configuring the layout (e.g. rail-mounting) have been proposed and will be considered in more detail.

OTHER FACTORS IMPACTING LAYOUT

Upstream of FEL Section

A number of electron beam operating modes, corresponding to FEL research topics, have been specified [16], with short-bunch and long-bunch modes both specified as 250 pC Gaussian bunches with target 0.5 mm-mrad normalised emittance and 25 keV energy spread but with differing peak currents (400 A versus 125 A) and nominal energies (240 MeV

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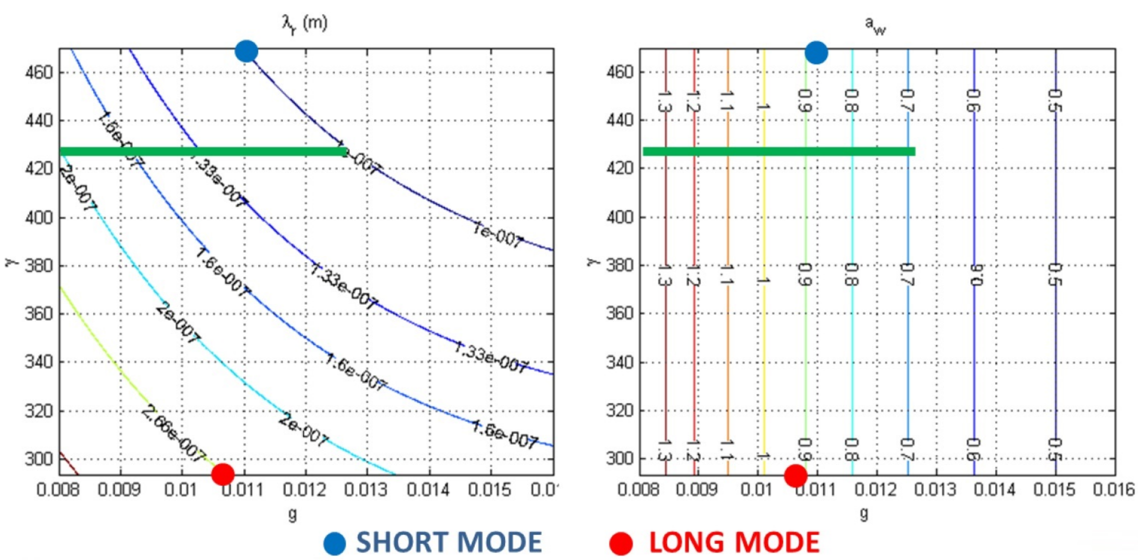

Figure 2: Wavelength and undulator parameter (a_w) tuning ranges for the CLARA radiator with λ_u =2.5 cm, in terms of undulator gap, g [m] and beam energy, γ. The green line shows a factor of 2 wavelength tuning from 100-200 nm. The maximum λ_r is 400 nm.

versus 150 MeV). The lower energy of the long-bunch mode brings the wavelength range in line with the temporal diagnostics (for short pulse schemes) and eases the seed laser power requirements by more than a factor of two compared to 240 MeV. Ultra-short and flat-top modes are also planned. The latest details of the accelerator layout to deliver the required beams for CLARA is given in [17]. The option of manipulating the beam using e.g. a dielectric wakefield element will be included in the layout to allow dechirping [18] and potentially more advanced FEL schemes [19]. While studies indicate that a laser heater will not be required for FEL lasing, space is reserved to add this as a future upgrade to enable e.g. microbunching studies [20].

Modulation Section

It has been concluded that the chosen FEL schemes can be achieved with a few selected seed/modulation wavelengths, listed in a potential order of implementation according to the FEL schemes above: 20 µm for mode-locking, 800 nm for EEHG and general purpose, 3–8 µm for the mode-locked afterburner, ~70–100 µm for chirp + taper. The transverse apertures have therefore been specified for a maximum 100 µm wavelength and it was identified that a seeding chicane would be preferable to a dog-leg for this [17]. To enable the chosen FEL schemes the modulators should be tuneable from 800 nm–100 µm, with sufficient transverse aperture and suitable modulator designs have been produced. Alternative modulation methods are presently under consideration that could potentially replace some of the functionality of the longer wavelength sources with e.g. an 800 nm source [21].

Radiator

A hybrid planar undulator type is chosen for the radiator modules, giving stronger on-axis field than a permanent magnet device. The choice of undulator period, λ_u, depends on the minimum operating gap (dependent on vacuum and wakes) and the required wavelength tuning range. Analysis of the former shows that for CLARA the vacuum benefits of NEG coated vessels are less important than the minimisation of wakefield effects by using aluminium or copper vessels [22], with 6 mm diameter aluminium/copper vessel specified (therefore 8 mm minimum undulator gap). For the tuning range we specify a factor of two in wavelength tuning at a fixed electron beam energy to enable e.g. harmonic cascade schemes. The combination of factors results in λ_u=2.5 cm, with tuning range as shown in Fig. 2.

While short undulator modules in the radiator are preferred for mode-locking and HB-SASE, there must also be consideration of the impact on normal FEL operation. The nominal module length of 0.75 m [15] has been compared against other options and found to be suitable in terms of transverse beam quality [23]. The break sections between modules are specified to be 0.5 m and the specifications of the break section components are being defined. Details of the FEL section beam-based alignment strategy using cavity BPMs are given in [24].

Radiation Extraction/Afterburner

Given the wavelength and expected transverse properties of the FEL light [23] it will be necessary to extract it before the afterburner section. Latest details of the mode-locked afterburner are given in [9].

SUMMARY

Design choices for the CLARA FEL section have been outlined and will be finalised in an upcoming internal review to initiate purchasing of the undulators.

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