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ALTERNATIVE ELECTRON BEAM SLICING METHODS FOR CLARA AND X-RAY FELS

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Abstract

Methods to generate ultra-short radiation pulses from X-ray FELs commonly slice a relatively long electron bunch to feature one (or more) short regions of higher beam quality which then lase preferentially. The slotted foil approach spoils the emittance of all but a short region, while laser-based alternatives modulate the electron beam energy, improving potential synchronisation to external sources. The CLARA FEL test facility under development in the UK will operate at 100-400 nm, aiming to demonstrate FEL schemes applicable at X-ray wavelengths. We present laser-based slicing schemes which may better suit the wavelength range of CLARA and provide options for X-ray facilities.

INTRODUCTION

CLARA is a new FEL test facility being developed at STFC Daresbury Laboratory in the UK [1], which will operate with 250 MeV maximum energy and λ_r=100-400 nm fundamental FEL wavelength. Commissioning is underway on the front-end while design of the later stages is still being finalised. An overview of the facility layout and FEL schemes is given in [2] but briefly the aim is to demonstrate novel FEL capabilities that could be applied at X-ray FEL facilities such as high-brightness SASE [3], mode-locking [4], mode-locked afterburner [5], optically slicing a single SASE spike [6] and others. It will have a flexible design that can accommodate new ideas and future changes.

A common feature of many FEL schemes including [4–6] is so called 'slicing' of the electron beam. It refers to applying a longitudinal variation in electron beam properties such that one (or more) short regions of the bunch lase preferentially, thereby generating shorter photon pulses for use in experiments. For example, the slotted foil method [7, 8] spoils emittance in all but a short section of the beam, while [6] defines the lasing part of the beam via a specific energy chirp.

Given the aims of CLARA it is desirable to keep the focus on wavelength-independent aspects of the FEL concepts and so minimise wavelength-specific difficulties where possible. For example, to suit single-shot temporal diagnostics it is proposed to study short pulse generation for FEL wavelengths in the range 250-400 nm. A similar argument applies for the seed/modulating lasers. Initially it was planned that both mode-locking and slicing with chirp/taper would be carried out with an applied energy modulation of period $\lambda_{\mathrm{mod}} \approx 50\,\mu\mathrm{m}$ [1]. However it has since been recognised that wavelengths outside the range $20\,\mu\mathrm{m} \lesssim \lambda_{\mathrm{mod}} \lesssim 70\,\mu\mathrm{m}$ would require less laser R&D to deliver suitable sources.

Modeling shows that mode-locking can be achieved with $\lambda_{\mathrm{mod}} = 20\,\mu\mathrm{m}$ while the transverse apertures of the modulation section have been specified to transport wavelengths up to 100 µm to retain these options. However, another option could be to use a shorter wavelength seed (e.g. 800 nm) to replace some of the functionality of the $20\,\mu\mathrm{m} \lesssim \lambda_{\mathrm{mod}} \lesssim 100\,\mu\mathrm{m}$ range - this paper reports studies of two such methods.

MODE-LOCKING WITH BEAT MODULATION

The mode-locked FEL concept [4] 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 optical cycles in the pulse can be reduced from hundreds to approximately the number of periods in an undulator module, $N = 27$ for CLARA. The electron beam energy (or other electron-beam properties [9] such as current [10]) needs to be modulated with period $\lambda_{\mathrm{mod}} = S_e N \lambda_r$, where a slippage enhancement factor [4] $S_e \approx 4$–8 has commonly been used, corresponding to ~30–60 µm for CLARA. While it might not be straightforward to deliver a suitable laser source operating in this range, it might nevertheless be possible to modulate the electron beam energy on this scale through a laser induced beating modulation, as has already been demonstrated for various purposes at the FERMI FEL [11].

Modulation Stage

For initial studies the modulation stage was approximated by directly applying a superposition of two sinusoidal energy modulations of different period to the electron beam. Wavelengths of $\lambda_1 = 800$ nm and $\lambda_2 = 816$ nm were used to give a beat modulation period $\lambda_{\mathrm{beat}} = 40\,\mu\mathrm{m}$ as shown in Fig. 1. This is plotted alongside a typical sinusoidal energy modulation (with $\lambda_{\mathrm{mod}} = 40\,\mu\mathrm{m}$) as would normally be used. In both cases it would be expected for FEL pulses to develop at $s = 20/60/100\,\mu\mathrm{m}$, etc. where the energy variation is minimised. The beat modulation case can in fact be anticipated to give cleaner output since the normal sinusoidal modulation generates secondary spikes at the maxima of the energy modulation where the energy chirp is also minimised [9].

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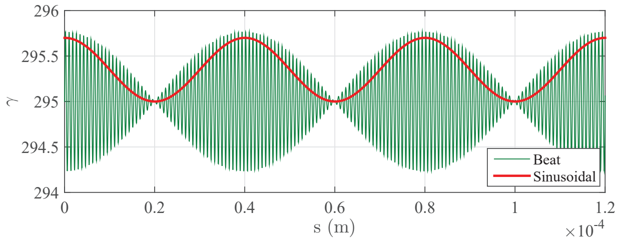

Figure 1: Electron beam energy variation with longitudinal bunch position for a beat modulation case comprising two sinusoidal wavelengths of $\lambda_1 = 800$ nm and $\lambda_2 = 816$ nm to give $\lambda_{beat} = 40$ µm and a sinusoidal modulation with $\lambda_{mod} = 40$ µm as typically used in mode-locked FEL simulations.

Mode-Locked FEL Simulation Results

The modulated electron beam was entered into a mode-locked FEL simulation using the 'beamfile' method (a list defining electron beam slice properties) in Genesis 1.3 [12]. The electron beam parameters of the CLARA long-bunch mode [13] were used and the undulator parameters were set for $\lambda_r = 266$ nm. In addition to an undulator slippage of $27\lambda_r$, chicane slippage of $123\lambda_r$ was applied (assuming no dispersion), such that the total slippage per undulator-chicane module matched the modulation period. The modulation amplitude was scanned and the temporal profile and spectrum of the FEL radiation near to saturation (at the end of the 15^{th} radiator module) are shown in Fig. 2 for the optimum case, alongside the current profile.

The beat modulation on the electron beam energy is seen to work well in giving a well defined temporal pulse profile and discrete modes in the spectrum. Individual pulse durations of ~30 fs FWHM correspond to ~27 cycles as expected from the earlier discussion. The envelope of the temporal profile and noise in the spectrum show the usual effects of SASE. As anticipated there are no sub-spikes (i.e. interleaved pulses at the minima/maxima) as is observed in the normal energy modulation case [1].

Studies are underway to model the modulation stage using Genesis 1.3 with a simple two-colour seed. Preliminary results indicate that the peak power for the modulating laser should be of the order 10^{8-9} W and that a suitable variation in energy spread can be achieved while the fine structure of the energy modulation appears washed out.

SLICING A SINGLE SASE SPIKE

In [6] simulations of the chirp and taper method were carried out at a hard x-ray resonant FEL wavelength of $\lambda_r = 0.15$ nm in combination with an 800 nm modulating laser pulse and an isolated SASE spike with 200 as FWHM duration was predicted, corresponding to sub-cycle scale of the 800 nm modulation. For operation on CLARA at $\lambda_r = 266$ nm the modulating laser should be approximately 40 µm [1] though $\lambda_r = 400$ nm and $\lambda_{mod} \approx 70$ µm may be preferable to deliver a suitable modulating laser. In both cases this is a less straightforward source to generate and requires much larger apertures for transport than for 800 nm.

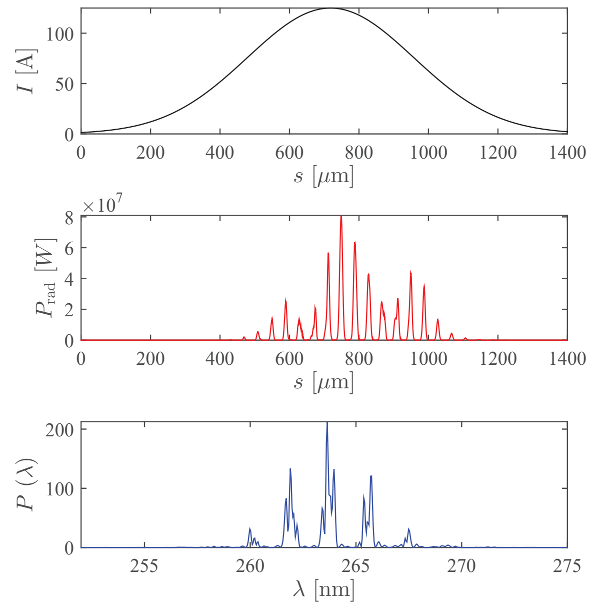

Figure 2: Current profile (top), temporal profile of the FEL power after 15 undulator modules (middle) and corresponding spectrum (bottom).

Another approach has recently been demonstrated [14,15], in which the temporal profile of the laser pulse used in the laser heater is shaped to have a short dip in intensity, such that the laser heater increases the energy spread of the beam everywhere except a short region. Compression of the bunch downstream of the laser heater and prior to the FEL means that the region of the bunch for lasing is further shortened compared to the feature imposed by the laser. This optical pulse shaping is expected to have advantages over the slotted foil method in terms of applicability at high repetition rates and in terms of flexibility and is an area that could be studied in detail on CLARA - here we report the first studies.

Modulation Stage

A laser heater is not included in the baseline design for CLARA since microbunching studies indicate it is not essential for FEL lasing, however space is reserved as it may enable useful experiments in future [16]. The FEL scheme has therefore been assessed for CLARA using modulator 1 tuned to be resonant with an 800 nm seed. Further studies in combination with start-to-end simulations would be of interest to determine the optimum location in terms of achievable pulse duration, synchronisation etc.

The long-bunch mode of CLARA [13] was again used for simulations but with the energy increased from 150 MeV to 190 MeV to allow the modulator to be resonant at 800 nm while operating at 266 nm in the radiator (this will also apply to the mode-locked FEL study). A preliminary study was

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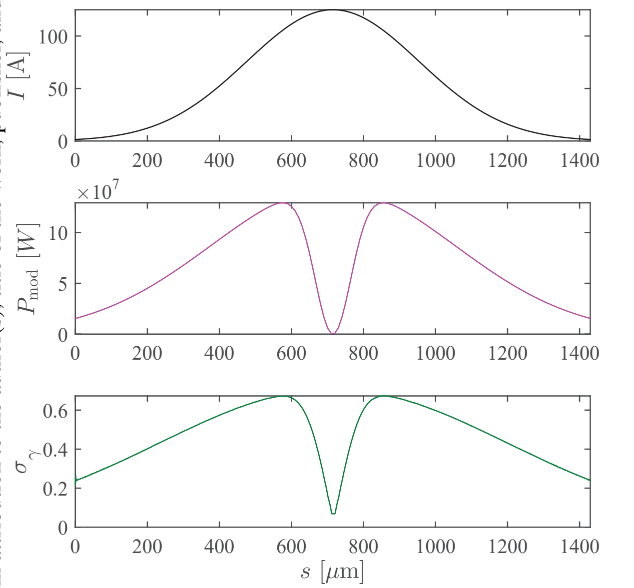

Figure 3: Current profile (top), temporal profile of the modulating laser pulse (middle) and corresponding induced energy spread at the end of the modulator (bottom).

carried out to determine how increasing the energy spread reduces the FEL power at the nominal saturation point. An energy spread of $\sigma_\gamma = 0.7$ was selected in order to reduce the maximum output power by around 3 orders of magnitude compared to the nominal $\sigma_\gamma = 0.05$. The modulation step was then modeled in Genesis 1.3 using the 'radfile' input method (a list of temporal slice properties of the laser pulse). The Gaussian temporal envelope of the modulating laser pulse was set to have duration slightly longer than the electron bunch. The peak power of the laser pulse was set to deliver the required energy spread increase from the earlier study. The width of the Gaussian dip in the radiation power was optimised to pick out a single SASE spike. The radiation power profile and the resulting energy spread profile are shown in Fig. 3 alongside the current profile. The modulating laser pulse energy should be ~300 µJ. Similar results were found assuming a 3 µm modulating laser, however 800 nm is preferable.

FEL Output

The modulated electron beam distribution was exported from the first stage and imported into a second Genesis simulation to model the CLARA radiator (initialising the shot noise at 266 nm). The FEL process starts up from noise so the scheme was first optimised for a single shot noise realisation then repeated for the optimum case using OCELOT [17] to automate runs. Several iterations of this process were carried out and the optimum results (temporal profile and spectrum at saturation) are shown in Fig. 4 and can be compared to a baseline case without any slicing effect shown in Fig. 5. An isolated pulse of duration ~200,fs FWHM is selected, corresponding to ~200 cycles at 266 nm. This is ~4 times longer than studies of the chirp and taper scheme

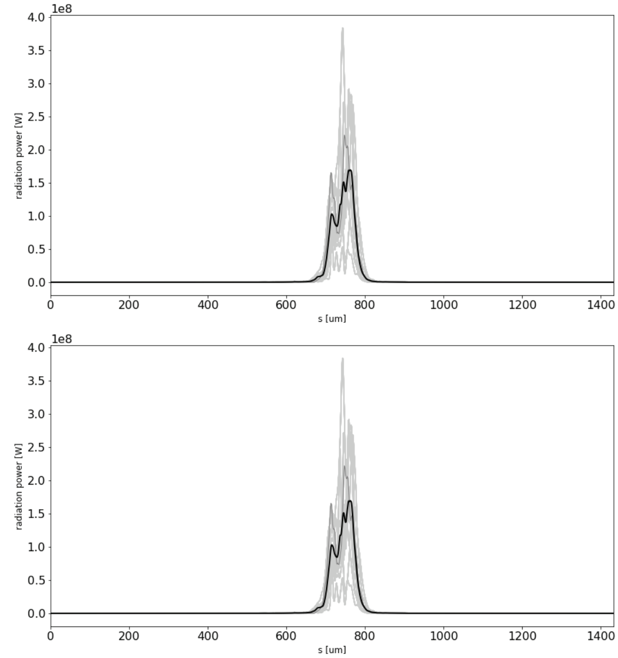

Figure 4: 800 nm sliced case power (top) and spectrum (bottom) for 10 shot noise cases (grey) and the average (black).

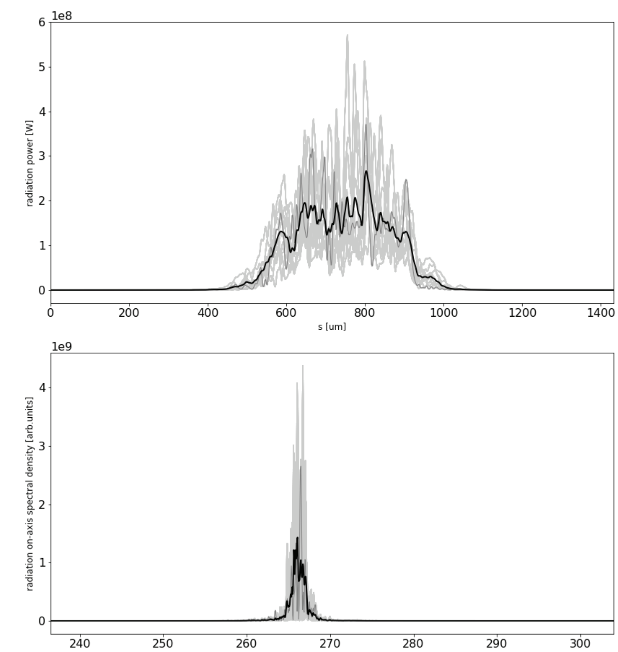

Figure 5: Nominal case power (top) and spectrum (bottom) for 10 shot noise cases (grey) and the average (black).

for CLARA [1], albeit with somewhat different parameters, indicating that further optimisation may be possible.

SUMMARY

Two methods have been investigated in which some functionality of difficult to realise longer wavelength sources required for CLARA could be replaced with a more readily available and configurable 800 nm source. The results of

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both are promising and will be considered in further studies. In particular, for the case of slicing a single SASE spike further work is required to assess how the ultimate potential of the temporal dip scheme compares to the chirp and taper scheme in terms of delivering short pulses at X-ray facilities.

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