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ISOLATED FEW-CYCLE PULSE GENERATION IN X-RAY FREE-ELECTRON LASERS

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Abstract

X-ray free-electron lasers (FELs) are promising candidates to deliver high-brightness radiation pulses with duration significantly shorter than the present leading technique, high harmonic generation (HHG). This would extend attosecond science to probe ultrafast dynamics with even finer resolution. To do so requires breaking below a characteristic FEL timescale of typically a few hundred optical cycles, dictated by the relative slippage of the radiation and electrons during amplification. The concept of mode-locking enables this, with the mode-locked afterburner configuration predicted to deliver few-cycle pulses (~ 1 attosecond at hard X-ray). However such techniques would produce a train of closely separated pulses, while an isolated pulse would be preferable for some types of experiment. Building on previous techniques, a new concept has been developed for isolated few-cycle pulse generation and it is presented alongside simulation studies.

INTRODUCTION

The motivation for generating short photon pulses is to study and influence ultra-fast dynamic processes, with the photon pulse duration dictating the temporal resolution of an experiment utilising it. High harmonic generation (HHG) [1, 2] in a laser-driven gas is the present leading source in this respect, having demonstrated pulse durations down to 53 as [3], and so has enabled study of electron dynamics on unprecedented timescales. In simple terms the minimum duration of a pulse of light is a product of the central wavelength, λ_r, and the number of optical cycles, N. HHG has made a significant advance in terms of shortest pulses through operating at significantly shorter wavelength ($\lambda_r \gtrsim 5$ nm) over conventional lasers ($\lambda_r \gtrsim 150$ nm). By the same argument amplifier FELs ($\lambda_r \gtrsim 0.05$ nm) have the potential to make significant further advances. However it is difficult to reduce N due to temporal slippage of the light relative to the electrons during the FEL amplification process. This effect results in a characteristic scale of the output, termed the co-operation length, $l_c = \lambda_r/4\pi\rho$, where the fundamental FEL parameter $\rho \sim 10^{-4} - 10^{-3}$, hence $N \sim 10^2 - 10^3$. The most advanced FEL short pulse schemes presently deliver pulse durations down to ~200 as at ~0.2 nm [4, 5], corresponding to $N \sim 300$.

Many techniques have been proposed to significantly reduce N in amplifier FELs and they can be roughly categorised as follows: (i) Schemes to attain pulses on the scale of the co-operation length through e.g. slicing [6, 7], including those recently demonstrated [4, 5]; (ii) Schemes to go moderately below the co-operation length, often with increased peak power, e.g. superradiance [8–10] or through stacking emission from separate regions of the bunch [11, 12]; (iii) Schemes to go significantly below the co-operation length - down to few-cycle or even single cycle.

Of the schemes in (iii), there are those that rely on FEL microbunching ($b = \langle e^i\theta_j \rangle$, where θ_j is the ponderomotive phase [13] of the j^{th} electron), e.g. mode-locking [14], mode-locked afterburner (ML-AB) [15], which give potential to reach shortest wavelengths but with pulses necessarily delivered in a train of fairly closely separated pulses (the FEL co-operation length limit can be consider to be discretised rather than fully avoided [16]). The alternative to using FEL-induced microbunching is to use externally-induced microbunching, e.g. through interacting an external laser with the electron beam in an undulator. Some such schemes work through microbunching a single short region of the electron beam and using a single/few-period undulator [17, 18], which generally limits the power to below FEL saturation. Alternatively, bunching can be imposed in multiple regions and then stacked to reach higher power [19, 20]. For schemes with externally-imposed microbunching there is generally considered to be difficulty associated with achieving this at the shortest FEL wavelengths, except perhaps if the external source is itself a FEL, e.g. [21].

A new concept is outlined here that uses FEL-induced microbunching to generate isolated few-cycle pulses. This would extend the wavelength reach beyond externally-induced options and potentially allow shorter pulses.

DESCRIPTION OF THE SCHEME

The new scheme is developed from the ML-AB technique but incorporates the ideas of a chirped electron bunch modulation and uneven delays [12, 19]. In simulations of the ML-AB scheme it was demonstrated that the FEL interaction *can* support few-cycle structures during normal amplification in a long FEL amplifier undulator ('amplifier' stage) but that these structures are only prominent in the microbunching profile rather than the radiation. In the ML-AB concept these few-cycle microbunching peaks were realised by modulating the electron beam energy with period $\lambda_m \sim 30 \times \lambda_r$. Few-cycle peaks in the microbunching occurred equispaced at the electron energy minima. This structure in the electron beam was then used in combination with a mode-locked afterburner (periodic electron delays between few-period undulators) to produce equi-spaced few-cycle radiation pulses.

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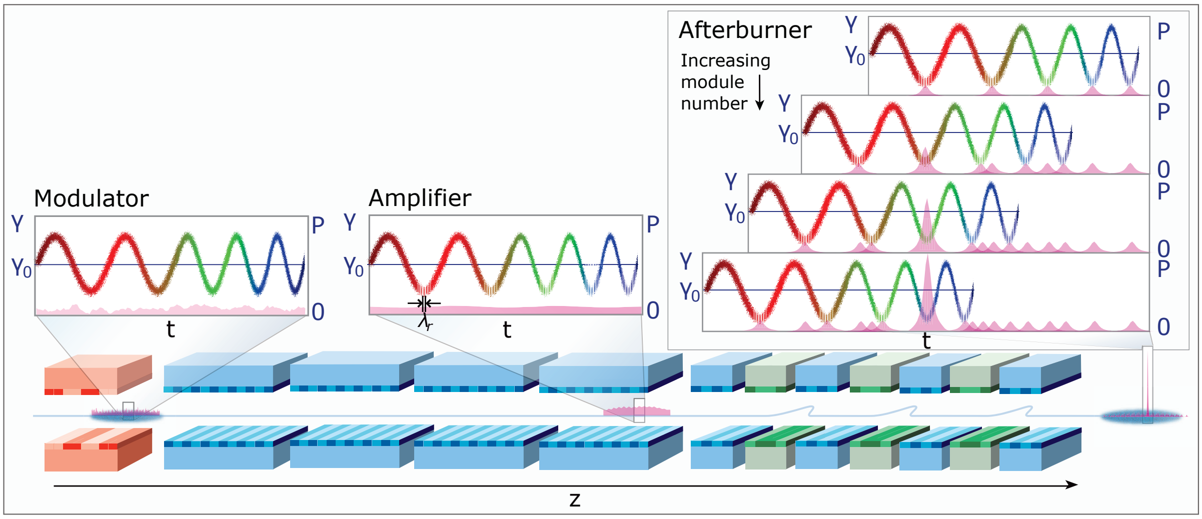

Figure 1: Schematic layout of the proposed technique for generating isolated few-cycle pulses. An electron beam is modulated (e.g. using an external laser and a short undulator to apply a chirped modulation of electron beam energy, γ (colours red-blue indicate longer to shorter wavelengths), such that a chirped comb structure develops in the FEL-induced electron microbunching in a long undulator (amplifier stage). Further amplification of the radiation power, P, with electron beam delays matched to the microbunching spacing (afterburner stage) generates an isolated few-cycle radiation pulse.

A key point underlying the new scheme is to recognise that FEL amplification in this way should be able to support arbitrary time-structures in the bunching profile (within constraints - there must be sufficient 'filling factor' of unspoiled beam to support amplification). Generating an isolated radiation pulse should therefore be possible through defining a none-equispaced (e.g. chirped) bunching structure and matching it to a series of electron beam delays (in the 'afterburner' stage) such that, of several initial radiation pulses in the first module, only one overlaps with microbunching peaks and therefore receives further amplification in all subsequent modules. This concept is illustrated in Fig. 1, and is referred to as a pulse-stacking afterburner (PS-AB).

For the PS-AB scheme, if microbunching increases substantially through the afterburner then emission from later modules will greatly exceed that from earlier ones (or vice versa), however to generate an isolated pulse requires approximately equal emission from each module. This requires roughly unchanging microbunching throughout the afterburner and so implies an extraction point for the PS-AB scheme close to saturation (maximum microbunching) together with some means of maintaining microbunching. The most obvious idea to achieve this is isochronous chicanes and that is what is assumed for this paper, though other methods have also been identified.

MODELLING

The PS-AB scheme has been modelled in Puffin [22–24] using parameters of the CLARA FEL test facility [25], as shown in Table 1. CLARA parameters are used for first tests of the scheme since it is faster to use parameters of a longer wavelength facility (λ_r=100 nm) in simulations, nevertheless the physics of the modelling is equivalent at x-ray wavelengths, and indeed the remit of CLARA is to test schemes applicable at x-ray facilities. For simple first tests of the concept the scheme is simulated in 1D (no radiation diffraction or electron beam transverse size effects) and with a seeded, flat-top current bunch. Results using energy modulation are reported, though modulation of energy spread has also been found to work, as should any modulation of electron beam quality [16, 26].

Table 1: CLARA Parameters for Modelling of the Amplifier Section

Parameter	Value
Electron beam energy	240 MeV
Electron beam current	400 A flat-top
Electron beam energy spread	0.1%
Undulator type	Planar
Field Orientation	Horizontal
Period, λ_u	25 mm
Module Length (total)	0.75 m
Inter-module gap length	0.5 m
Number of full periods	27
Active module length	0.675 m
Undulator parameter, a_u	0.8667
Resonant wavelength, λ_r	~100 nm

An energy modulation with relative amplitude γ_m/γ_0 was artificially applied to the electron beam, with chirped period starting at $\lambda_m = 50\lambda_r$ at the tail of the bunch, reducing linearly in period by $2\lambda_r$ per modulation period towards the head. The amplitude of the modulation was varied and simulations of the amplifier section were carried out, with the results plotted in Fig. 2. It is seen that increasing the modula-

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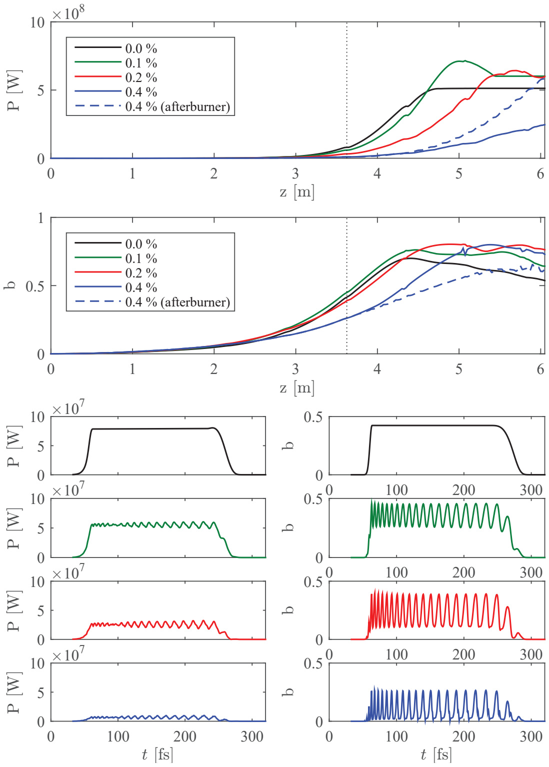

Figure 2: Optimisation of the amplifier stage and afterburner results. The top two plots show the maximum radiation power and electron beam microbunching with distance through a standard amplifier FEL, z, for different γ_m/γ_0. Break sections between undulator modules are collapsed to aid clarity. Results for the optimum afterburner case are also shown. The lower set of plots show temporal profiles of the radiation power (left) and electron beam microbunching (right) for the cases in the top plots (same colours). The lower plots are shown at z=3.625 m (dashed line in upper plots), which is the chosen extraction point for the afterburner.

tion amplitude increasingly restricts microbunching to those regions of the electron bunch around the energy minima (which is set to be resonant with the seed), i.e. generating a comb structure in terms of microbunching with chirped spacing. The amplification rate decreases with increasing γ_m/γ_0 because less of the bunch interacts. A corresponding fine-structure in the temporal profile of the radiation is largely washed out by slipping through the electron bunch.

A modulation amplitude of 0.4% and an extraction point of 3.625 m were chosen as the result of parameter scans targeting optimum performance in the afterburner. The parameters of the afterburner stage were the same as Table 1 but with 6 periods per undulator module and variable chicane delays between modules. Simulation results for the afterburner are shown in Fig. 2 (peak power averaged over λ_r and microbunching vs z) and Fig. 3 (temporal profiles of radiation power and electron beam microbunching). The electron beam delays were set such that one radiation pulse was optimally matched and it is seen that this pulse grows

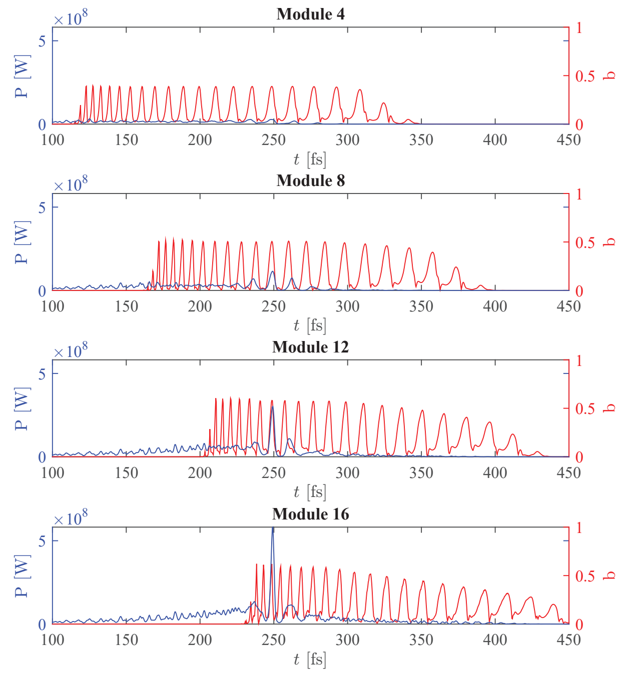

Figure 3: Simulation results for the afterburner stage. The temporal profiles of the radiation power and electron beam microbunching are shown with increasing module number. One radiation pulse is amplified preferentially to the rest.

preferentially compared to the rest. After 16 afterburner modules the peak power reaches 600 MW, which is similar to the normal FEL saturation level (through comparison with the $\gamma_m/\gamma_0 = 0$ case in Fig. 2) and the pulse duration is 2.4 fs FWHM, corresponding to $N = 7$. The contrast ratio between the peak power of the main peak and the adjacent sub-spikes is 4.3 and time-frequency analysis (not shown) indicates the possibility to improve this through filtering.

CONCLUSION AND OUTLOOK

A new technique has been developed to generate isolated few-cycle pulses and has been shown to deliver pulses of 7 cycles FWHM and with normal FEL saturation peak power in 1D simulations. Because the FEL interaction is used to form microbunching the scheme could potentially scale to hard x-ray wavelengths, where the pulse duration would approach ~1 as. However, further study is required to assess the performance of the scheme in 3D simulations and at shorter wavelengths. Additionally the methods of generating a suitable chirped modulation and of maintaining microbunching through the afterburner are major topics to resolve in order to realise such a scheme in practice. Given the large number of variables in the system the results to date can be considered to be only coarsely optimised - this could be a problem well-suited to machine-learning optimisation.

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