MODE LOCKED OPTICAL KLYSTRON CONFIGURATION IN AN FEL CAVITY RESONATOR

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Abstract

Chicanes placed between undulator modules in a high-gain FEL amplifier have been shown to generate a set of axial modes that may be locked to generate attosecond pulse trains in the x-ray [1]. Using numerical simulations, it is shown here that a similar system may be used in a FEL cavity resonator to generate an equally spaced set of frequency modes with a spacing much greater than those of the cavity modes. As with the FEL amplifier case, these modes can lock to generate a pulse train. Also shown are simulations of a short-pulse RAFEL which generate stable, single attosecond pulses in the x-ray.

INTRODUCTION

Attosecond Pulse Trains (APTs) from High Harmonic sources have proven a valuable tool in atomic and molecular science. Examples include the study of single ionisation events, where the APT acts as a 'Quantum Stroboscope' [2], and as a tool to *control* electron wave packet localisation [3] and relativistic recollision dynamics [4] within atoms and molecules driven by lasers.

A method proposed to create and lock modes in a FEL *amplifier* system, that may generate high power APTs into the hard x-ray [1, 5, 6], considerably extends the potential of such APT methods to higher powers, shorter wavelengths and shorter attosecond pulses.

This paper extends the numerical simulations of the modular undulator/chicane method of mode generation in an FEL amplifier, which we call Mode Locked Optical Klystron (MLOK), to include a MLOK cavity-oscillator FEL configuration. This was carried out for both a high-gain FEL with low cavity feedback, a so-called Regenerative Amplifier FEL (RAFEL) which can operate to generate coherent pulses at short wavelengths with remarkably low feedback [7], and also for a lower-gain FEL with higher cavity feedback operating in the infrared with parameters similar to the IR-FEL of the ALICE facility [9] at Daresbury Laboratory in the U.K. In principle the MLOK method should also work for lower gain X-ray FEL Oscillators (XFELO - see e.g. [8]). In both the low and high gain cavity-oscillator cases simulations were carried out both with and without the MLOK configuration to allow comparison.

In a FEL amplifier operating at wavelength λ and for electron bunch lengths of $l_b \approx 2\pi l_c$, where ρ is the FEL parameter [10] and $l_c = \lambda/4\pi\rho$ is the cooperation length, the electron pulse tends to emit a relatively short single weak-superradiant 'spike' [11, 12]. In the x-ray this method has been proposed as a method of generating single coherent attosecond pulses of duration ~ 200as [13]. As no coherent seeds are yet available in the x-ray, the FEL amplifier starts from intrinsic spontaneous noise. This introduces significant jitter in the peak output power and saturation time [12] which can make the single pulses more difficult to phase with other drive lasers in pump-probe experiments. In addition to the MLOK simulations, interesting and potentially useful new results are presented here which show that when such short electron pulses are used in a RAFEL configuration these jitters are greatly reduced to give stable short-pulse output. Furthermore, when the MLOK RAFEL configuration is used, the short weak-superradiant pulse breaks up into a short APT containing relatively few individual pulses.

The first two sections first consider the short-pulse RAFEL configuration without and with the MLOK configuration. The next sections present results for a MLOK simulation for a lower gain cavity-oscillator FEL followed by conclusions.

The simulations use a version of the 1D code described in [14] modified to include a modular undulator and dispesive chicane lattice, and are carried out without any energy spread or emittance effects - i.e. assuming only cold electrons.

SHORT PULSE RAFEL

The Regenerative Amplifier FEL offers the prospect of high-gain FEL lasing, self-seeded by a small fraction of the radiation generated by a preceeding electron bunch. RAFEL simulations predict excellent temporal coherence into the x-ray using a very low-Q cavity with fractional feedback of output radiation powers as low as $\sim 10^{-5}$ [7]. Cavity mirrors can then be of much lower reflectivity than required by low-gain cavity FELs. A RAFEL using short electron pulses was simulated to demonstrate the principle. In a SASE FEL amplifier, short electron pulse lengths have been proposed to generate single attosecond pulses in the x-ray. Here it is demonstrated that the output from a RAFEL generates similar short radiation pulse output, but without the associated power and temporal jitter associated with SASE. The parameters used are typical of an x-ray FEL: $\rho = 5 \times 10^{-4}$, electron bunch gaussian current profile of width $\sigma_b = l_c$ and charge $Q = 20pC$; undulator length $l_u = 6l_g$; a cavity power feedback factor of $F = 4\times10^{-3}$; cavity detuned by lengthening it by l_c above its synchronous length where the round-trip time of a pulse of light equals the electron bunch repetition-rate. Saturation is attained after $\approx$ 25 passes to generate stable temporal power output with negligable visible variation pass-to-pass. The radiation and electron beam parameters are shown in Fig. 1 at the start of the 48th pass through the undulator. The scaled radiation power $|A|^2 \approx P_{rad}/\rho P_{beam}$, the current weighted bunching parameter $\chi|b|$ due to the initial shot-noise, where $\chi = I/I_{pk}$ is the scaled current, and the scaled Power Spectral Density (PSD) are plotted as a function of the scaled distance $\bar{z}_1 = (z - v_z t)/l_c$ and frequency $f = 2\rho\bar{\omega} = (\omega - \omega_r)/\omega_r$. The output at the undulator end is shown in Fig. 2 showing strong electron bunching and a single, short pulse with scaled power close to that of the usual steady-state value of $|A| \sim 1$. The pulse is close to Fourier transform limited with a time-bandwidth product $\Delta\nu\Delta t$ calculated by taking the FWHM values from the output plots of Fig. 2 and using the relation $\Delta\nu\Delta t = \Delta f \Delta\bar{z}_1/4\pi\rho \approx 0.5$.

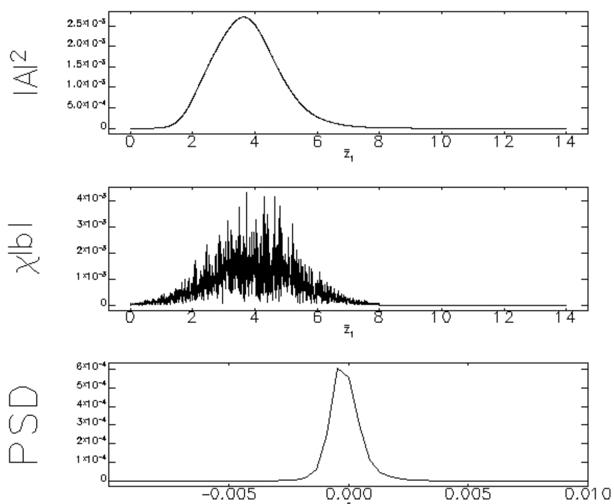

Figure 1: Short pulse RAFEL simulation - showing saturated evolution at the undulator entrance. From top: scaled power at the beginning of the interaction at saturation; the current-weighted bunching; the scaled spectral power as a function of scaled frequency.

SHORT PULSE MLOK RAFEL

Simulations of a RAFEL operating in a MLOK configuration are now presented. The parameters used are more typical of a soft x-ray FEL and a lower gain undulator was used: $\rho = 2 \times 10^{-3}$, an electron bunch gaussian current profile with $\sigma_b = l_c$ and of charge $Q = 200pC$. A total of 16 undulator/chicane modules were used with each undulator module of length $l_u = 0.25 l_g$, so that the total FEL interaction length was therefore $4l_g$, and each chicane adding an extra relative electron/radiation slippage of $1.25 l_c$. This gives a total relative slippage per module in units of $\bar{z}_1$ of $\bar{s} = s/l_c = 1.5$ so that the scaled frequency spacing of the modes is $\Delta f = 4\pi\rho/\bar{s} \approx 1.68 \times 10^{-2}$. The

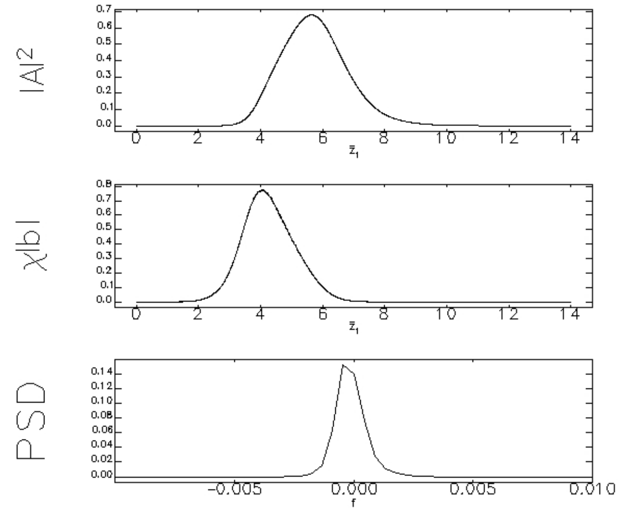

Figure 2: Short pulse RAFEL simulation - showing saturated evolution at the undulator exit.

shorter FEL interaction length than the previous short pulse RAFEL case requires a larger cavity power feedback factor of $F = 3.5 \times 10^{-2}$ - the shorter interaction is not a requirement for successful operation but is simply used to demonstrate a different set of operating parameters. In order to couple the modes generated by the MLOK configuration an energy modulation of amplitude $(\gamma_{mod} - \gamma_r)/\rho\gamma_r = 1$ at the mode spacing frequency $\Delta f = 1.68 \times 10^{-2}$ was introduced. The cavity was detuned by lengthening it by $3l_c$. Note this cavity detuning is larger than the previous RAFEL case as the radiation pulse is extended in duration due to the extra relative slippage introduced by the chicanes. This extra slippage also has the effect of increasing the effective cooperation length [1, 16] thereby shortening the effective length of the electron bunch. The output saturates after $\approx$ 15 cavity round trips to give stable, almost jitter-free output as shown at the beginning and end of the cavity in Figs. 3 and 4 respectively.

The modal structure and pulse train output are as expected. Also evident is a similar structure in the current weighted bunching which, perhaps unsurprisingly, occur synchronously with the radiation pulse trains. Not shown are the early pre-saturation stages of evolution in the cavity where the radiation and bunching modes evolve rapidly from the electron bunch noise and a clear modal structure is apparent at the end of the first cavity pass. The spontaneous spectrum of a MLOK configuration is given by a set of uniformly spaced modes of spacing $\Delta f = 4\pi\rho/\bar{s}$ and modulated by the envelope of the single undulator module spectrum [1] of $\Delta f_{FWHM} = \Delta\omega_{FWHM}/\omega_r \approx 1/N_u$ where N_u is the number of undulator periods in a module. Here, $N_u \approx 10$ and it is seen that the modal envelope agrees well with value $\Delta f_{FWHM} \approx 1/N_u = 0.1$. The individual pulses in the train are estimated at $\sim 0.3 l_c$ in length corresponding, for the value of ρ used here, to 12 radiation wavelengths. In the soft x-ray of, say $\lambda = 3$nm,

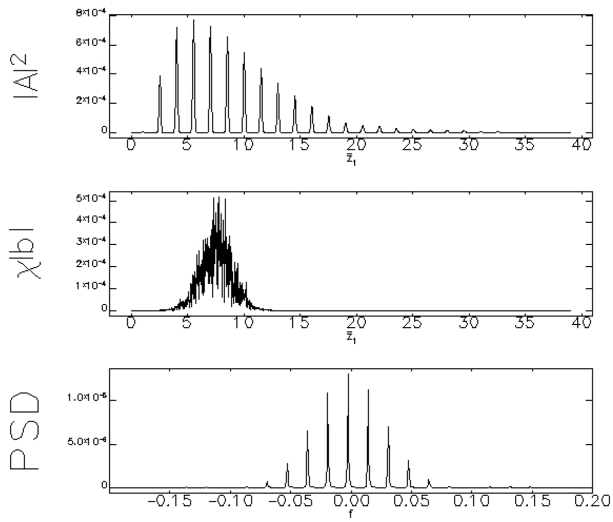

Figure 3: Short pulse MLOK RAFEL simulation - showing saturated evolution at the undulator entrance. From top: scaled power at the beginning of the interaction at saturation; the current-weighted bunching; the scaled spectral power as a function of scaled frequency.

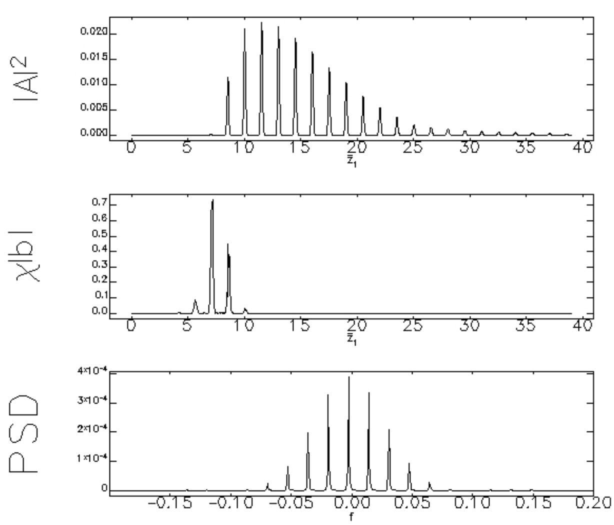

Figure 4: Short pulse MLOK RAFEL simulation - showing saturated evolution at the undulator exit.

this corresponds to a duration of 120as.

Peak powers of the pulses in the train are reduced by a factor of ~ 50 from that of the example of the short pulse RAFEL above. The scaled radiation energy, obtained when $|A|^2$ is integrated over $\bar{z}_1$, is similarly reduced by approximately the same factor. This may, in part, be explained by the larger proportion of the current weighted bunching for the non-MLOK case when integrated over $\bar{z}_1$ and also the effective shortening of the electron pulse due to an increased effective cooperation length. Research to establish the scalings for these factors is ongoing.

IR CAVITY OSCILLATOR MLOK

In this section results of simulations with parameters typical of an IR-FEL oscillator that include a MLOK undulator/chicane lattice are presented. The parameters used are derived from an on-going feasibility study of what may be available at the ALICE IR-FEL facility currently under development at the Daresbury Larboratory in the UK [9]. Typical scaled parameters are for a Gaussian electron bunch of length $\sigma_b = 2.4l_c$; $\rho = 2.3 \times 10^{-3}$; ten MLOK modules each consisting of an undulator module of length $l_u = 0.22l_g$ and a chicane that introduces a relative electron/radiation slippage of $0.88l_c$. An energy modulation of amplitude $(\gamma_{mod} - \gamma_r)/\rho\gamma_r = 1$ at the mode spacing frequency $\Delta f = 2.63 \times 10^{-2}$ was introduced. This is a relativelely low-gain system when compared with the RAFELs considered in the previous two sections and requires a larger feedback factor of $F = 0.9$ to lase. The cavity was detuned by lengthening it by $2.5l_c$. Output from such a low-gain MLOK IR-FEL operating at 4.5μm is shown in Fig. 5. As with the RAFEL simula-

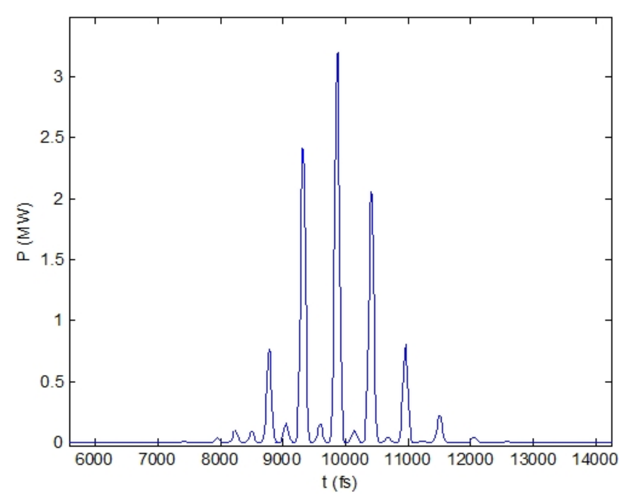

Figure 5: MLOK IR-FEL simulation - showing saturated power at the undulator exit in unscaled units.

tions above, the temporal pulse-train structure gives clear evidence of the mode-locking, each individual pulse being 7 optical periods or ~ 100fs duration. Here, however, the peak powers are only slightly reduced by a factor $\lesssim 2$ from the IR-FEL operating normally without MLOK. As with the MLOK RAFEL simulations above, the equi-spaced frequency modes are clearly visible in the spectrum (not shown.)

An interesting feature that appears in this low-gain case once into saturation is the appearance of some periodic breaking up of the pulse train structure, which then regenerates from the back of the electron pulse. Fig. 6 shows the radiation and electron parameters, as described for the RAFEL cases above, after many cavity round trips at the *beginning* of the MLOK lattice ($\bar{z} = 0$), before any interaction. The radiation power in the approximate region

$20 \lesssim \bar{z}_1 \lesssim 30$ forms part of the radiation of a few previous round trips before. This is now decaying in the cavity as it receives little gain propagating forward to larger values of $\bar{z}_1$ as the interaction proceeds - i.e. it is incorrectly aligned with the electron bunch to receive gain. The pulse train structure in the approximate region $\bar{z}_1 \lesssim 20$, while receiving significant gain for this pass through the cavity, will evolve into the cavity decay region $20 \lesssim \bar{z}_1 \lesssim 30$ in subsequent cavity round-trips. This may be a type of limit-cycle

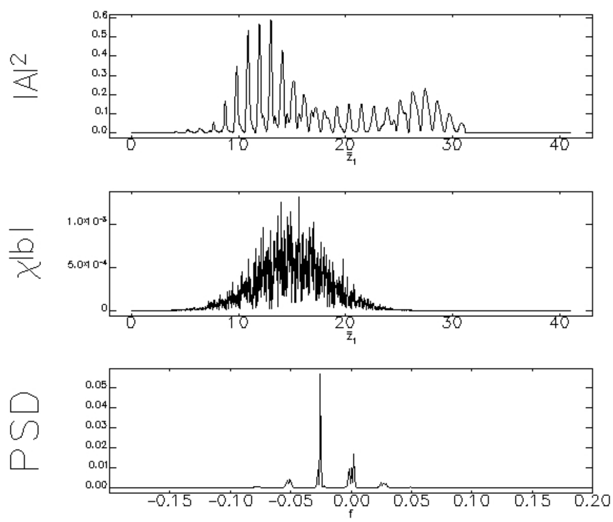

Figure 6: MLOK IR-FEL simulation - showing the beginning of the interaction at saturation, from top: scaled power; the current-weighted bunching; the scaled spectral power as a function of scaled frequency.

behaviour, perhaps due to insufficient cavity detuning optimisation, or may even be due to simulation issues e.g. regarding the use 'averaged' codes to model short radiation pulses [15]. This will be the subject of further research and optimisation.

CONCLUSIONS

The main results of this paper are twofold. Firstly, it has been demonstrated that a Regenerative Amplifier FEL may operate with short electron bunches of length the order of the cooperation length l_c using typical x-ray FEL parameters to generate a series of 'single' short spikes separated by the cavity round-trip time. Unlike a SASE amplifier operating in this short pulse mode, the output is stable in both its output timing and power making this short-pulse RAFEL a potentially very useful source where stable, single attosecond duration pulses are required. While a cavity feedback of 4×10^{-3} was used to demonstrate the principle here, the work of [7] suggests this factor may be reduced by up to a further factor of 10^{-3}. Such very small feedback factors should easily be within the reach of relatively broadband mirrors operating in the hard x-ray.

The second result of this paper extends the concepts developed for generating coupled frequency modes in an FEL amplifier [1] to a FEL cavity oscillator. When the frequency modes are coupled via a frequency modulation at the mode spacing of the electron beam (here an energy modulation was used, although a current modulation also works), the modes can lock to generate a well defined pulse train. The example of a RAFEL operating in the soft-x-ray gave individual pulses conservatively estimated at 200as duration at a wavelength of 3nm. Scaled to the x-ray with wavelength $\lambda = 0.15$nm and for $\rho = 5 \times 10^{-4}$ such pulses are 24as in duration. The reason for the lower peak powers generated are thought, in part, to be due to an effective increase in the cooperation length caused by the MLOK mechanism.

The potential to investigate the effects of MLOK FELs relatively inexpensively was also explored by simulation of a possible proof-of-principle experiment on an IR-FEL such as that at the ALICE IR-FEL in the UK. The potential appears very promising with simulations demonstrating clear evidence of mode generation and locking.

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