START-TO-END SIMULATIONS OF SASE AND HHG-SEEDED MODE-LOCKED FEL

D.J. Dunning, N.R. Thompson and P.H. Williams,
ASTeC, STFC Daresbury Laboratory & Cockcroft Institute, UK
B.W.J. McNeil, SUPA, Department of Physics, University of Strathclyde, Glasgow, UK

Abstract

Start-to-end modelling of a SASE mode-locked FEL amplifier scheme [1] is presented using a superconducting re-circulating linac design [2]. Locking of the modes is achieved by modulating the electron beam energy at the mode frequency spacing. Previous studies [3] have shown that in a High Harmonic Generation (HHG) seeded mode-coupled FEL amplifier scheme (no electron beam energy modulation), although the attosecond pulse train structure of the seed is amplified through to saturation, a temporal broadening of the individual pulses occurs. An HHG seeded mode-locked FEL amplifier scheme is modelled and it is seen that the temporal spikes of the HHG seed must be correctly phase-matched with the electron beam energy modulation for successful operation. By using a filtered HHG seed, which removes the seed's attosecond pulse train structure, no such phase matching is required. Despite the absence of an initial attosecond pulse structure, a modal structure develops and is subsequently amplified to generate an attosecond pulse train with the good temporal coherence properties of the seed, significantly shorter individual pulse widths and higher peak powers than may be achieved in any of the other schemes.

START-TO-END SIMULATION OF MODE-LOCKED SASE FEL

In the drive towards attosecond science many schemes have been proposed to generate short radiation pulses from an FEL amplifier (see e.g. [4, 5, 6] and references therein). In these schemes single pulses are generated with widths the order of the coherence length $l_{coh} \approx l_c$ where $l_c =$ is the cooperation length of the interaction [7]. In [1], a modular undulator-chicane system allows synthesis and phase-locking of longitudinal modes to generate a train of short, uniformly spaced pulses. In this mode-locked amplifier technique, pulses may be generated with lengths significantly less than l_c.

Mode Generation in an Amplifier

The equally spaced modal structure in the amplifier spectrum is generated by periodically delaying the electron bunch using magnetic chicanes between undulator modules [1]. The total relative slippage of the radiation with respect to the electron bunch per module is $s = l + \delta$, where l is that occurring in the undulator and δ that within the chicane. The slippage enhancement factor is defined as $S_e = s/l$. For $S_e > 1$ the spectrum takes the form of a frequency comb modulated by the sinc-function envelope of the single undulator module spectrum centered at the resonant FEL frequency, ω_r. The mode separation of the frequency comb is $\Delta\omega = 2\pi/T_s$ where $T_s = s/c$ is the time taken for radiation to propagate the slippage length. The number of modes under the central envelope of the spectrum is $N_0 = 2S_e - 1$.

Accelerator Modelling

The electron distribution used in the FEL simulations was generated as part of ongoing start-to-end simulation studies of a superconducting re-circulating linac design [2, 8]. The design utilises 1.3 GHz superconducting CW accelerating structures to deliver longitudinally compressed electron bunches with repetition rates of 1 kHz. Tracking is performed from a normal conducting RF photocathode gun, accelerating and compressing in three stages to obtain peak current greater than 1 kA at 2.2 GeV. This is achieved through injection at 200 MeV, then recirculating twice in a 1 GeV main linac. A laser heater is used to mitigate the effects of CSR-induced microbunching. Figure 1 shows the longitudinal phase space and current profile for the bunch after the final bunch compressor.

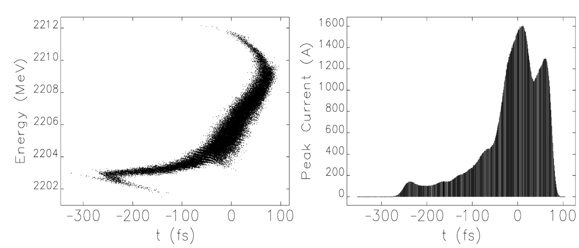

Figure 1: Longitudinal phase space (left) and current profile (right) after the final compressor.

FEL Modelling

Modelling of a SASE mode-locked FEL amplifier scheme operating in the extreme ultraviolet (XUV) has been carried out using the 3-D code, Genesis 1.3 [9]. The resonant wavelength of the FEL is set to 12.4 nm, although previous results show that the method scales into the x-ray [1]. Undulator modules of 8 periods are chosen and the slippage in the chicanes is set to $\delta = 23 \times \lambda_r$ (where λ_r is the resonant FEL wavelength) so the slippage enhancement factor $S_e = 3.9$. A sinusoidal electron energy modulation is introduced of period s and amplitude $\pm 0.5\%$. The modulation has been manually added in this case, but future work will include full modelling of this step. The radiation power output close to saturation (55 modules) is shown in Fig. 2 for a $\sim$200 fs region corresponding to the highest current region in the electron bunch. While the peak of the radiation power occurs in the region of highest current, the envelope of the radiation is also dependent upon the SASE noise. Peak powers of $>$1 GW and pulse widths of 250 as FWHM are observed.

The regions of minimum electron bunch energy gradient, at the maxima and minima of the energy modulation, preferentially support the FEL interaction. Discrete radiation pulses develop so that they are aligned at the zero gradient positions of the energy modulation as they pass the centre of the undulator modules: this is shown in Fig. 3. Two pulses therefore develop per modulation period; the minima and maxima of the energy modulation effectively support two separate sets of modes with the higher electron energy set centred about a shorter wavelength than the lower electron energy set. This can be seen in the radiation spectrum of Fig. 2.

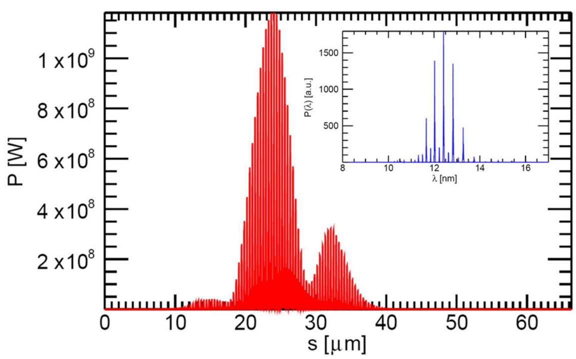

Figure 2: Radiation power output close to saturation (55 modules) for a $\sim$200 fs region corresponding to the peak current region of the electron bunch, and the corresponding radiation spectrum (inset).

MODE-COUPLED CONFIGURATION

Modelling Method

The results of HHG seeded simulations, using a 1-D code similar to that described in [10], are presented. The notation follows that of [1], with the scaled units of [7, 11] being used. A uniform electron bunch current is assumed. The total slippage of the radiation with respect to the electron bunch per module, scaled by l_c, is $\bar{s} = \bar{l} + \bar{\delta}$, where $\bar{l}$ is the slippage occurring in the undulator ($\bar{l} = N\lambda_r/l_c$) and $\bar{\delta}$ is the slippage within the chicane. The scaled resonant FEL frequency is $\bar{\omega} = (\omega - \omega_r)/2\rho\omega_r$. The slippage enhancement factor may be written as $S_e = \bar{s}/\bar{l}$.

The temporal profile of the HHG seed is a comb of attosecond pulses separated by half the wavelength of the

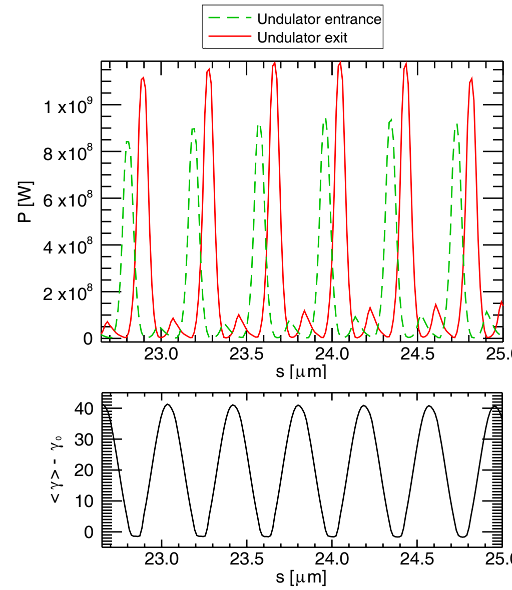

Figure 3: Radiation power at the entrance and exit of the 55th undulator module (above), and the slice-averaged energy offset from resonant energy (in terms of electron rest mass) of the beam (below).

drive laser, λ_d. The HHG seed was modelled in a similar way to that described in [12] with the resonant FEL wavelength chosen to be the 65th harmonic of the drive laser, i.e. $\lambda_r = \lambda_d/65$. The Nyquist theorem then limits the frequencies that can be modelled in the code to harmonics 33 to 97. For a typical HHG drive laser wavelength of λ_d = 805 nm (e.g. Ti:Sapphire), the 65th harmonic is 12.4 nm: with an FEL parameter of $\rho = 2 \times 10^{-3}$ (typical for an FEL operating in the XUV), and with 8 periods per undulator module, the scaled slippage is $\bar{l} = 0.201$. The temporal and modal structure of the seed is shown in Fig. 4. The spectral and temporal structure of the radiation generated by the undulator-chicane system is matched to that of the HHG seed by setting the scaled chicane slippage to be $\bar{\delta} = 0.616$ such that $\bar{s} = \bar{\lambda}_d/2$, where $\bar{\lambda}_d = \lambda_d/l_c$ is the scaled drive laser wavelength.

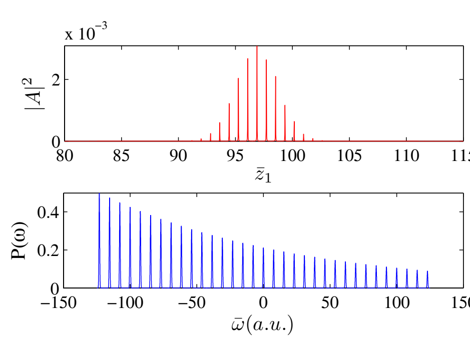

Figure 4: Scaled longitudinal intensity profile (above) and spectral power distribution (below) for the HHG seed.

Pulse Broadening in Mode-coupled Amplifier

In previous studies [3], it has been shown that the attosecond structure of an HHG seed can be amplified to saturation in the mode-coupled amplifier FEL of [1] (i.e. without any energy modulation of the electron beam). However, the lack of modulation at the mode spacing does not allow the modes to lock and consequently the individual pulses broaden as the FEL interaction progreses. The variation of the peak intensity and pulse width with scaled distance through the undulator are plotted in Fig. 5 for different frequency ranges of the HHG seed. The Nyquist theorem limits the frequencies that can be modelled in the code to harmonics 33 to 97. When the full spectral range of the HHG seed is used only the $N_0 = 2S_e - 1$ modes that fall under the envelope of the single undulator spectrum are amplified. The reducing modal content causes the duration of the individual pulses to broaden rapidly. The individual pulse durations continue to increase during further amplification for $\bar{z} > 1.7$, with the uniformly spaced temporal structure breaking up as $A^2 \approx 1$.

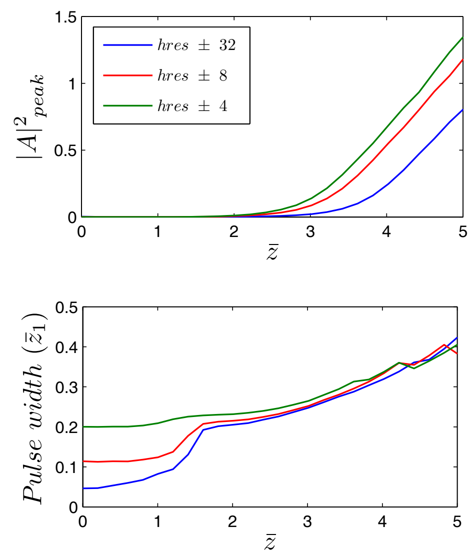

Figure 5: Peak intensity (top) and pulse width (bottom) plotted against $\bar{z}$ for different frequency ranges of the HHG seed. The plot 'hres±32' contains the full range (33 to 97) of HHG harmonics allowed to be modelled in the 1-D code.

MODE-LOCKED CONFIGURATION

An electron beam energy modulation is now introduced with period set equal to both the HHG pulse spacing and the slippage per undulator-chicane module. All HHG seed pulses then have the same initial longitudinal alignment relative to the beam modulation phase. The HHG seed pulses slip ahead of the electrons a distance $\bar{l}$ per undulator module and $\bar{\delta}$ in the chicanes; the slippage is shown in Fig. 6 for two different initial seed-modulation phases.

The system is modelled using the same 1D code, seed and undulator-chicane parameters of Figs. 4 and 5, but

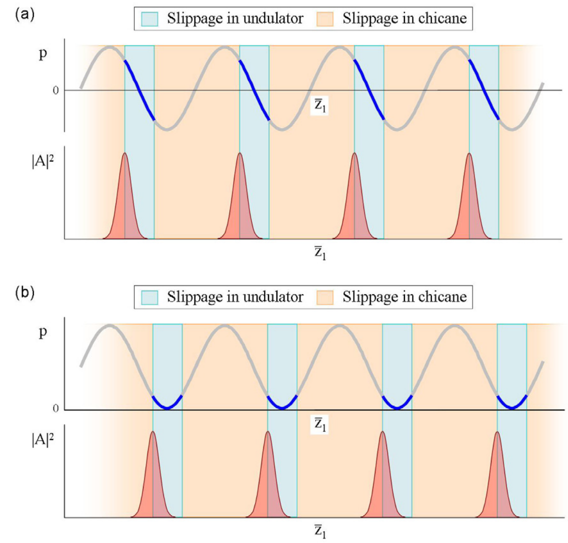

Figure 6: Initial alignment of the HHG seed pulses relative to the electron beam energy modulation for two cases (a) $\bar{l}/2$ behind the central energy of the modulation and (b) $\bar{l}/2$ behind the minima of the energy modulation.

with an electron energy modulation of period $\bar{s}$. The optimum amplification of the seed was found to occur when the seed pulses are aligned $\bar{l}/2$ behind the minimum and maximum energy positions at the beginning of the interaction, as shown in Fig. 6 (b).

The introduction of an energy modulation of sufficient amplitude and with frequency of the mode spacing 'locks' the modes of the HHG seed during amplification. The energy modulation also increases the number of modes that are amplified. This increase in mode number significantly

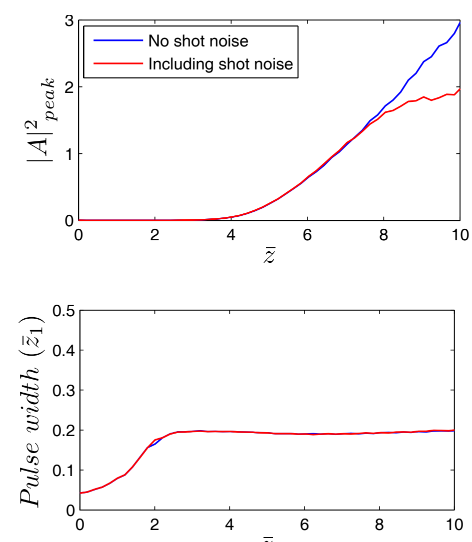

Figure 7: Peak intensity (top) and pulse width (bottom) plotted against $\bar{z}$ for the mode locked amplifier with an energy modulation of $\pm 0.5\%$.

shortens the individual pulse widths compared to the case with no energy modulation. Furthermore, higher peak powers may be attained than can be generated using mode-locked SASE: the seed pulse envelope propagates into relatively 'fresh' electrons that have undergone SASE evolution from the lower spontaneous power. This effect reduces as the unseeded regions (starting up from noise) begin to saturate, as shown in Fig. 7. An obvious problem with such a scheme is the precise phase-matching between the HHG seed pulse train to the correct phase of the electron beam energy modulation.

An alternative method using a filtered HHG seed, which removes the seed's attosecond pulse train structure, negates the requirement for such precise phase-matching. The HHG seed of Fig. 4 is filtered to preserve only the central resonant mode, $\bar{\omega} = 0$, so that no attosecond structure remains and the seed has the simple gaussian envelope of the drive laser. An energy modulation of $\pm 0.5\%$ is used with seed frequency set to the resonant frequency of the electrons at the minimum of the modulated energy. The results are shown in Fig. 8. While seeding is only initially at the central mode, a modal structure nevertheless develops and is amplified to generate an attosecond pulse train while retaining the good temporal coherence properties of the seed. At saturation very similar pulse widths and powers to those of Fig. 7 are retained so that significantly shorter individual pulse widths than mode-coupled HHG amplification and higher peak powers than mode-locked SASE should therefore be possible.

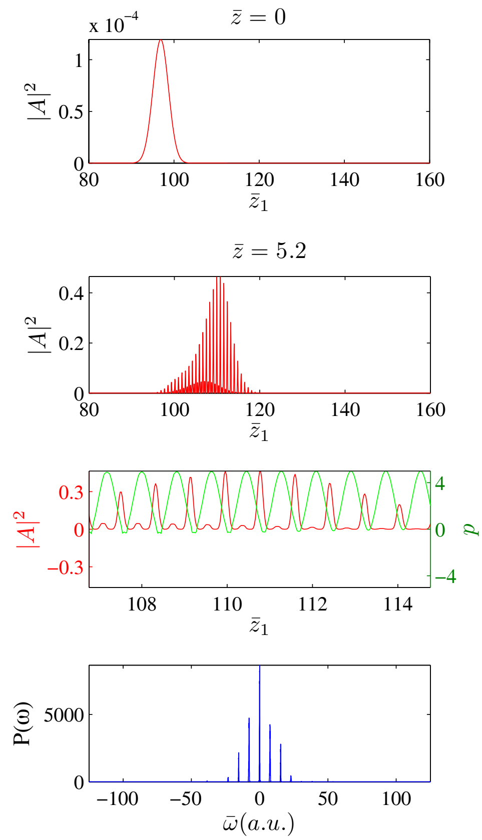

Figure 8: Simulation results for the mode-locked amplifier FEL with a filtered HHG seed. From top: scaled power at the beginning of the interaction, power near to saturation after 26 undulator-chicane modules, detail near to saturation, and the scaled spectral power, for $S_e = 4$ and an energy modulation of $\pm 0.5\%$

CONCLUSIONS

The first start-to-end modelling of mode-locked SASE has been performed and it is shown that the method remains valid with a realistic electron bunch. Amplification of HHG seed pulses has also been demonstrated and it has been shown that shorter individual pulses are retained in the case with an energy modulated electron beam than with no pre-conditioning of the beam. While it is shown that careful phase-matching of an (unfiltered) HHG pulse train structure to the modulated electron bunch is necessary to retain the structure during amplification, this is not required for the case with a filtered HHG seed, where a well defined set of locked modes and a pulse train are generated with the envelope set by the seed.

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