

REVIEW OF COHERENT SASE SCHEMES

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Abstract

A review is presented of some of the methods and their origins that have recently been proposed to improve the temporal coherence of SASE output. These methods do not require any external laser seed field, or the use of the so-called self-seeding methods, where the SASE radiation is optically filtered and improved at an early stage of the interaction before re-injection and amplification to saturation. By using methods that introduce an additional relative propagation between the electron beam and the radiation field, the localised collective interaction, which leads to the formation of the ‘spiking’ associated with normal SASE output, is removed. The result is output pulses which are close to the fourier transform limit without the need for any external seeds or intermediate optics.

INTRODUCTION

This review presents the work of several different authors and closely follows the oral presentation presented at the 36th International Free Electron Laser Conference, Basel, August 25-29, 2014. An historical perspective is given of some methods proposed to improve the temporal coherence properties of SASE output. It is hoped this perspective will demonstrate how some of the quite complex, perhaps non-intuitive, departures from a simple FEL interaction evolved.

SASE

The problem with normal SASE output from a FEL is that it has relatively poor temporal coherence. At shorter wavelengths, the electron pulse length can be significantly greater length than the relative propagation, or slippage, of a light wavefront through the pulse to saturation. As the SASE interaction starts from noise, this itself would limit the temporal coherence length to the slippage length. However, a more fundamental length that limits the temporal coherence length is the cooperation length l_c [1]. This is the length that a light wavefront propagates, or slips, through the electron pulse in one gain length l_g through the undulator. As each region of length $\sim l_c$ starts from noise, this leads to a spiking behaviour in the light intensity with spikes separated by $\sim 2\pi l_c$ [2]. A similar noisy spectrum results which gives a relatively large time-bandwidth product $\Delta\nu\Delta t \gg 1$ with typical simulated output in the X-ray shown in slide 3. A closer look at the phase of the light in slide 4, again from simulations, shows that the phase of each of the radiation ‘spikes’ is uncorrelated. i.e. each spike appears to have evolved independently from the others from noise.

DIRECT SEEDING

One method to improve this noisy output is to inject a resonant coherent seed light field coincident with the electron pulse at the start of the FEL interaction. If the seed is of sufficient intensity to dominate that due to the spontaneous noise, then the interaction can progress with a well-defined phase imposed by the seed through to saturation. This was first performed at short wavelengths at ~ 53 nm [3] as shown in slide 6. Unfortunately, no such seeds yet exist in the X-ray.

INDIRECT SEEDING

An alternative to direct seeding at the desired wavelength is to first prepare the electron beam by seeding at a longer wavelength where a suitable seed with good temporal coherence properties is available. The bunched electrons will inherit the coherence properties of the seed and will also have strong coherent bunching components at higher harmonic wavelengths. The electrons can subsequently be injected into an undulator resonant at these shorter harmonic wavelengths [4,5] where lasing may continue (slide 8) in a process sometimes called ‘High Gain Harmonic Generation’. The electron bunching may be enhanced between undulators by using a dispersive chicane. In principle this process can be ‘cascaded’ to shorter wavelengths as demonstrated experimentally [6] and shown in slide 9. Unfortunately (slide 10), the phase noise amplification is multiplied by a factor of the square of the frequency increase through the cascaded system, and with current seeds available this method cannot yet be used to reach X-ray wavelengths [7].

An alternative to HGHG is the Echo Enabled Harmonic Generation, first described in [8,9] and experimentally observed in [10] (slide 13). Interesting variations of the method are also being pursued [11] (slide 14), which may offer scope for further development. The EEHG method is described schematically in slide 15 and involves a preparation of the electron beam by: energy modulation - dispersion - energy modulation - dispersion. This introduces an electron bunching at an harmonic of the energy modulation period which will then emit radiation superradiantly on entering an undulator tuned to the electron bunching period. The limit as to how high the harmonic can be pushed probably remains unresolved, although good progress is being made experimentally with the 15th harmonic emission demonstrated [12]. The work of [13] suggests that the upper harmonic limit will be due to fluctuations in the modulating laser phase and intensity.

It is interesting to note that the final electron bunching spectrum of the EEHG is a comb of modes about the final harmonic with mode separation of the initial modulation

frequency [14] and that emission from each of these modes can be obtained (slides 16-18) using a mode-locked amplifier FEL (see later slides 38-40).

SELF-SEEDING

Self-seeding is a method first proposed in [15] which allows the SASE interaction to develop from noise (slide 20). The light is then filtered pre-saturation to reduce the large noise bandwidth before re-commencing the FEL interaction to saturation. In this way the FEL ‘self-seeds’ from the clean, filtered spectrum. The method of [15], which uses an optical monochromator with grazing incidence optics, has been improved by using a much simpler filtering method [16] that utilises a coherent wake that occurs when X-rays are passed through a diamond crystal (slide 21) instead of the more complex grazing incidence optics. The use of the diamond crystal wake self-seeding has been shown to work successfully in experiments performed at the LCLS [17] (slide 22). While these results are very encouraging, the robustness of this method, e.g. to high rep-rates and re-tuning demands in a user facility such as the EU XFEL, remains to be tested.

HB-SASE, ISASE, PSASE (‘HIBP-SASE’)

The methods of improving the temporal coherence properties of SASE above all require either the use of an external coherent source to dominate the intrinsic noise of the SASE process (a coherent seed) and/or the filtering of the SASE light to remove the noise at some intermediate point between start-up and saturation. In this section, a description is given of methods that do not require either a seed or any filtering. These have been termed variously High-Brightness, Improved and Purified SASE [18–20] - see slide 23 for a conjoining of these terms. (For the authors of this paper, the process of arriving at such methods was mainly one of discovery using numerical experiments to see what could be achieved when ‘playing about’ with the FEL interaction. Some interesting, unexpected effects arose from this process and a short historical perspective is presented. Hopefully, students will be encouraged to similarly experiment and discover.)

The authors’ path towards HB-SASE [18] began by considering the effects of a series of relative phase shifts between the light and electrons as the FEL interaction progresses through the undulator [21].

Phase Shifting

A phase shift can be considered as a shifting of the electrons with respect to a resonant wavefront by a distance less than the resonant wavelength λ_r . This can be achieved by delaying the electrons in a chicane placed between undulator modules - slides 26 & 27.

If a π phase shift (electron delays of $\lambda_r/2$) occurs, electrons that were gaining energy from the field begin to lose energy to the field and visa-versa (slide 26). The effect is to reduce the electron energy spread induced by the interaction

while maintaining the electron bunching process. Note there is little net gain or loss in the field energy as the FEL interaction is being continually interrupted. This π -shifting process can be repeated along the undulator, bunching the electrons while keeping the energy spread relatively small. Slide 28 plots $|b|/\sigma_p$ as a function of the distance along the undulator, where $|b|$ is the bunching factor and $\sigma_p = \sigma_\gamma/\rho\gamma$ is the scaled energy spread. Without phase shifting it is seen the bunching-to-spread ratio saturates at $|b|/\sigma_p \approx 0.7$, whereas with the π phase shifting this is increased to $|b|/\sigma_p \approx 2.5$ demonstrating a larger bunching per unit energy spread.

If the interaction is in a planar undulator and the interaction is also considered at the 3rd harmonic say, then introduction of $2\pi/3$ or $4\pi/3$ phase shifts will disrupt the interaction at the fundamental wavelength. However, the 3rd harmonic will see no net phase shift and can continue an un-interrupted FEL interaction to saturation (slides 29 & 30). This effect of suppressing the fundamental while allowing an harmonic to lase has been termed ‘harmonic lasing’ [22, 23].

Large Integer Wavelength Shifts

The ideas of phase shifting were then extended as part of post-graduate research [24] (slide 32) to introduce much larger relative phase shifts of $n2\pi$, where the integer $n \gg 1$ - i.e. multiple resonant wavelength shifts. By adding these extra integer resonant wavelength shifts, the simplistic idea was that light temporal phase profile and so the SASE spiking would be extended temporally so increasing the temporal coherence (slide 33). As above, the shifts can be achieved using chicanes placed between undulator modules as shown in slide 34. Note that near dispersionless chicanes can be designed so that the electrons receive the same relative shift with respect to the light field irrespective of their energy [25]. The slippage in units scaled with respect to the cooperation length l_c , of a resonant wavefront through the electron pulse within an undulator module is \bar{l} and that in the chicane $\bar{\delta}$. The total slippage in one undulator-chicane module is then $\bar{s} = \bar{l} + \bar{\delta}$. The bottom of slide 34 shows schematically the light field propagation (colour-coded with respect to the undulators above) through the electrons at the end of each undulator-chicane section. The enhancement in the slippage introduced by the chicanes is measured by the enhancement factor $S_e = \bar{s}/\bar{l}$ defined in slide 35. Initial results in slide 35 plot the mean separation of the light spikes as a function of S_e . It is seen that the separation of the spikes Δs , increases from the SASE value of $2\pi l_c$ in a quasi-linear way for the case of dispersionless chicanes ($D = 0$), and it is concluded that the cooperation length of the FEL interaction, and so the temporal coherence of the light, has increased by the slippage enhancement factor S_e . This is seen more clearly in slide 36 which shows the spike separation increasing as increasing $\Delta s \approx S_e \times 2\pi l_c$. Note that for values of $S_e > 2$ (written as S^* in the slide), there is a modulation in the light intensity. This is due to the formation of light modes directly analogous to the modes formed in a ring cavity and discussed in the following section.

It should be noted that around the same time as this research was being conducted, that other researchers hypothesised a similar approach [26] (slide 37).

Mode Generation

The modulations in the light intensity observed in slide 36 can be explained by considering the repeated equal extra slippages introduced by the chicanes - slide 39. The undulator-chicane slippage length s defines a characteristic length within which the light-electron interaction must evolve. Only wavelengths which have an integer number fitting into this length will survive the interferences caused by the repeated chicane slippage. This then defines a set of modes which are calculated in slide 39. The modal spectrum is the formally identical to that of a ring cavity of length s , the total slippage in each undulator/chicane module. This length, in units of the resonant wavelength, is of the order of a few times the number of undulator periods in a module, and can be very small, so that the mode spacing $\Delta\omega_s = 2\pi c/s$, can be much larger than that normally associated with a conventional cavity laser. Similar to mode-locking in conventional cavity lasers, the modes can be locked by introducing a modulation (here to the electron beam) at the mode spacing [27, 28] and may be able to generate few-cycle pulses in the hard X-ray and beyond [29].

HB-SASE

The introduction of extra equal slippage between undulator modules was seen to increase the cooperation length (and so temporal coherence and hence spectral brightness), but also to introduce a set of modes into the light output. If the modes surrounding the fundamental wavelength can be removed or suppressed, so that only the fundamental remains, and the increase in the cooperation length remains, then the objective of increasing the temporal coherence of the SASE output will have been met. This was achieved and then improved upon in two stages.

The first stage removed the modes about the fundamental by changing the total slippage for each undulator-chicane module. This causes the mode separation $\Delta\omega_s$ to change for each undulator-chicane module (slides 42 & 43) so that only the fundamental, central mode, receives sustained amplification. In the first stage, the chicanes introduced a slippage randomised about a mean value [30]. Slide 43 shows how the SASE spike-to-spike separation varies proportionally to, and the light bandwidth is inversely proportional to the mean slippage enhancement factor S_e . This now occurs without any modes evolving.

The second stage [18], slides 44-51, developed this method by introducing a series of increasing chicane slippages. Furthermore, the length l of each undulator module is chosen so that $l < l_g$, the gain length of the FEL interaction. The increasing slippage of each successive chicane should increase the temporal coherence in a non-linear way. The choice of undulator length $l < l_g$, ensures that a wavefront of the light never propagates through the electron pulse further than one cooperation length before being slippaged

by a chicane to another part of it. With the successively increasing slippage, this ensures a wavefront never interacts within a cooperation length range of any part of the electron pulse following a chicane slip. In this way, the localised FEL interaction that causes the spiking in the SASE output should be eliminated. The FEL interaction is de-localised.

In [18], the sequence of prime numbers was used to successively increase the slippage (slide 44 & 45). This ensures that the sideband modes associated with each successive chicane never repeat and only the fundamental mode receives gain. Slide 45 shows a schematic of a wavefront as it propagates through the series of undulators ($l < l_g$) and chicanes of increasing strength.

The rate at which the temporal coherence increases is determined by the rate at which a common phase ϕ of the light field is established throughout the interaction. slide 46 demonstrates how the rate of change of the light phase effectively evolves as $|b|/a$ where b is the electron bunching and a is the scaled field magnitude (see e.g. [31]). In the pre-saturation, linear region of evolution $|b| \sim a$, so that the phase can evolve rapidly from one undulator-chicane module to the next. A common phase can therefore propagate throughout the interaction to establish good temporal coherence and hence high spectral brightness.

Slide 47 shows the results of simulations for an electron pulse of length 4000 cooperation lengths and undulator modules of one half a gain length with the prime number sequence of increasing chicane shifts. Comparison is made against an equivalent SASE interaction (i.e. without chicanes). A relatively small increase in the saturation length is observed from 12 gain lengths for SASE to 14.5 gain lengths for HB-SASE, with no effective difference between the saturation intensities $|A|^2$. The difference between the coherence lengths though is significant, with the HB-SASE coherence length (red-squares) being just over two orders of magnitude greater than that of the SASE case (black-diamonds). Notice that at saturation, the coherence length is approximately half that of the total slippage of a light wavefront through the interaction, the maximum possible coherence length due to causality. Furthermore, in slide 48 summarising this result, it is seen that the coherence length growth rate is exponential in the linear regime prior to saturation.

A comparison of the numerical simulations to linear theory shows that the spectra at excellent agreement (slide 49) for a system operating at a wavelength of 1.24 nm. The modal structures are removed by the increasing prime slippages and the spectrum narrows as the phase information propagates through the pulse as the interaction progresses. (Note the change in frequency scale between the two plots.) Slide 50 shows a comparison between a SASE and an equivalent HB-SASE 3D simulation operating in the hard X-ray. It is seen the the HB-SASE output is close to being fourier transform limited. More detailed plots of the 1.24 nm simulations are shown in slide 51 which compare the SASE and HB-SASE output, with the notable difference being the relatively slowly changing radiation phase over the pulse in the HB-SASE case resulting in the much narrower spectrum.

iSASE

Contemporaneous research to that of HB-SASE [18], called iSASE [19], developed a similar method by using a geometrically increasing series of chicane induced slippages between the co-propagating electrons and light instead of the prime number increase as discussed above (slide 52). Undulator modules were also assumed to be greater than a gain length so that localised cooperative effects occur. The improvements in coherence that was observed in simulations was attributed to a ‘mixing’ of the light amplitudes and phases rather than the de-localisation of the FEL interaction and propagation of phase information throughout the interaction as discussed above. The authors highlight the increased stability of the iSASE method over that of self-seeding (slides 20-22) and the potential problems with crystal vibration and heating in self-seeded high rep-rate facilities. The iSASE method was extended into a tapered undulator. The tapered interaction with improved temporal coherence light enables hard X-ray powers towards TW levels to be extracted.

The above theoretical research led to an experiment at LCLS [32] which tested the basic concept of introducing extra electron-light slippage to increase temporal coherence. Instead of using chicanes to introduce the extra slippage, which were not available, alternate undulator modules were detuned far from resonance so that the light and electrons effectively propagated without interaction through these modules. The extra slippage introduced in these detuned undulator modules are approximately equal. In this respect, the experiment more closely models the earlier work of [30] than that of [18, 19] where the slippage increases in successive chicanes as the interaction progresses. Slides 53 & 54 show the undulator tunings and the output X-ray spectrum which clearly shows a narrowing in the ‘iSASE’ case. (Note that the detuned undulators in slide 54 are those with a small horizontal bar through the vertical yellow bar denoting the undulator parameter strength K .)

pSASE

A similar method of improving the temporal coherence of SASE to those described above is that of ‘purified SASE’ (pSASE). Instead of using chicanes to introduce extra slippage, pSASE (slide 55) replaces a few undulator modules in the middle of the exponential gain regime by ‘slippage boosted’ modules that are resonant at a sub-harmonic of the fundamental wavelength. The fundamental is then an harmonic in these modules and the slippage is increased by the harmonic factor. When planar undulators are used, the light also continues an harmonic gain process. This harmonic gain assists in the FEL guiding to reduce diffractive losses. Simulations demonstrating pSASE bandwidth reduction are seen in slide 55.

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HB-SASE Practical Issues

Some practical and limiting issues have been identified relating to the introduction of chicanes into the HB-SASE-type undulator module lattice (slide 56).

Firstly, the undulator modules should ideally be less than a gain length. As discussed above, this stops localised collective effects (spiking) and, as seen in the table enumerating the fractional increase in temporal coherence length l_{coh} of HB-SASE over SASE, is necessary to attain the large increases of $\sim 10^2$ that may be possible. Furthermore, use of near-isochronous chicanes [25] is also desirable. Simple dipole non-isochronous chicanes limit improvements to a factor $\lesssim 10$. Alternative electron delay methods, such as using simple chicanes together with some more complex types with negative R_{56} , may be an alternative but have not yet been investigated. Electron beam jitter may pose problems when used with isochronous chicanes. While the wavelength jitters, the electron delay due to the chicanes will remain constant and may cause phase mis-matching between undulator modules [33]. For example, for typical hard X-ray parameters, and for the largest chicane delay in an HB-SASE system to remain phase matched to $\lambda/4$, the relative electron beam energy jitter should be $\Delta\gamma/\gamma \lesssim 5 \times 10^{-5}$.

Further work with more detailed modelling of such effects is required. However, it is felt this is certainly justified given the potential benefits as summarised in slide 57.

CLARA

Finally, a proposed facility where many of the principles presented above may be tested was discussed. The CLARA proposal [34] (Compact Linear Accelerator for Research and Applications), is for a dedicated, flexible FEL Test Facility, operating with a maximum beam energy of ~ 250 MeV which will be able to test several of the most promising of the new FEL schemes, including those discussed here. The CLARA layout and outline of the methods that require testing is shown in slides 58 - 61. The wavelength range chosen for the CLARA FEL is 400 - 100 nm, which is appropriate for the demonstration of concepts on a relatively low energy accelerator. This wavelength range benefits from good diagnostics to allow characterisation and optimisation of the methods being tested. It is intended that CLARA will help inform the designs of a new generation of FEL facilities where the FEL interaction is pushed to its theoretical limits.

CONCLUSION

It is hoped that this review gives an insight into how research developed towards the concept of the title of this work ‘Coherent SASE Schemes’. The research route, at least for these authors, was not due to any single insight, but developed via collaboration over a decade of research that left some interesting concepts in its wake that may inform future FEL experiments and facility designs. Hopefully, some of these concepts may be able to be tested at a UK FEL test facility, CLARA. It is felt that the wait for such a facility

in the UK will have been worth it if such new concepts can be realised.

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