# Schemes for Large Bandwidth Pulses

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The relative spectral width of X-ray Free-Electron Lasers, operating in the Self-Amplified Spontaneous Emission (SASE) mode, is defined by the FEL parameter, which is on the order of $10^{-3}$ to $10^{-4}$. While external seeded or self-seeding schemes aim to reduce this value further the enhancement of the spectral width requires different approaches. In this presentation various methods, where some have already been proven experimentally, are discussed and their advantages and disadvantages summarized.

*Keywords*: Free-electron Laser, Large Bandwidth.

## 1. Introduction

While the longitudinal coherence of a Free-Electron Laser (FEL) is often the figure of merit with the aim for the smallest radiation bandwidths, some user applications demand broader spectra. These include the possibility of compressing the FEL pulse further in analogy of chirped-pulse amplification (CPA) of classical lasers, to perform single shot X-ray absorption spectroscopy of various K-, L- or M-edges or to achieve a higher chance to fulfill the conditions for Bragg or Laue diffraction of nano-crystals that are not oriented properly, e.g. in liquid jet streams.

The reference bandwidth for hard X-ray FELs is defined by the FEL parameter and is on the order of $10^{-3}$ to $10^{-4}$. For the applications mentioned above the value should be increased to the few-percent level. While the resonant bandwidth remains unchanged some flexibility is achieved by the SASE process where parts of the electron bunch are amplifying the signal independently from each other, tuning themselves to different resonant wavelengths according to the local mean energy or undulator field. This variation can be larger than the intrinsic bandwidth and the spectrum of the full signal gets broader. This strategy is followed by most of the proposed methods described in this paper. One approach is different, where the spike length in the SASE pulse is modified to generate shorter spikes and thus broader spectra by means of mode-locked lasing with very short undulator modules. This method is described at the end of the paper before we conclude with a summary, in which we compare the different methods with their advantages and disadvantages.

## 2. Energy Chirp

For electron beams, whose bunch lengths are much longer than the slippage length, the FEL performance can be considered rather local and many independent radiation spikes occur in the radiation profile and spectrum. In particular a variation in the mean energy along the bunch will translate to variations of the resonance condition. Therefore a chirp in the energy along the electron bunch yields a chirp in the radiation profile, if the FEL operates in the SASE configuration. Therefore the first proposed method to generate a large bandwidth signal is to inject an electron beam with a similarly large energy chirp. The quadratic dependence of the energy in the resonance condition increases the relative FEL chirp by a factor of two with respect to the energy chirp in the beam.

The straightforward approach is to accelerate the electron bunch off-crest similar to generating the chirp for bunch compression. This is limited by the total accelerating gradient the RF structure can provide. If for the shortest FEL wavelength all RF stations must be operated on-crest then any off-crest acceleration would no longer allow reaching that wavelength. To a certain aspect it is also inefficient because the RF power consumption is larger than for on-crest acceleration to the same beam energy. Therefore it is convenient to utilize other mechanisms to induce a chirp. The most prominent candidates are the wakefields in the main linac, in particular in RF structures which are resonant to S-band frequencies or higher. In a standard design, these wakes are considered to actually remove any induced chirp, needed for compression, where the electrons at the head have a slightly

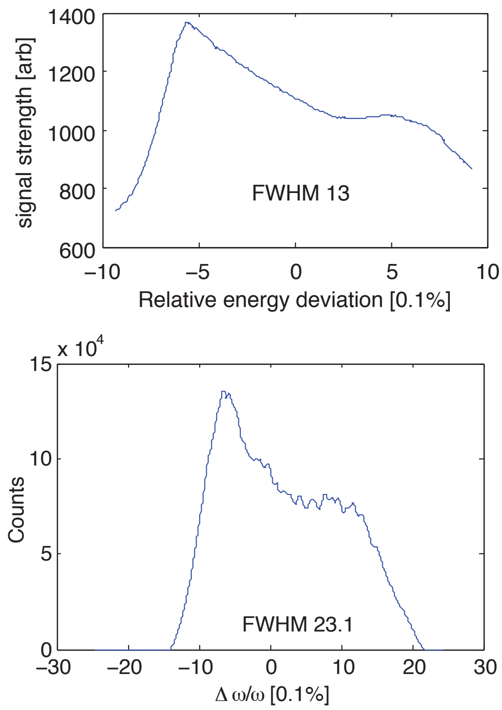


Fig. 1. Energy distribution of the electron bunch and envelope of the FEL spectrum (upper and lower plot, respectively) for an overcompressed bunch at LCLS [2].

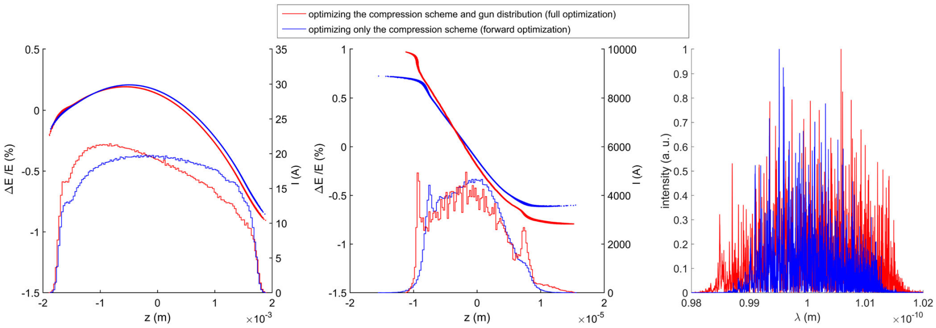


Fig. 2. Simulation for SwissFEL of initial and final current distribution, longitudinal phase space and the corresponding FEL spectrum (left, middle and right plot, respectively), with and without optimizing the laser profile at the cathode[5].

lower energy than those in the tail. While it avoids the inefficient off-crest acceleration, as described before, it makes the compression more sensitive to current profile and the explicit geometry of the RF structures. The basic idea is that in the last bunch compressor the beam is not compressed to the nominal bunch length but overcompressed to yield the same bunch length but a reverse profile[1]. If the design current profile is symmetric, e.g. a rather flat profile like at LCLS, then the FEL performance in SASE mode is unchanged, except that in this case the chirp direction after the last bunch compressor is reversed. In the succeeding linac the wakes now add to the chirp lowering further the energies of the electrons in the tail. This accumulation of chirp and the resulting broadening of the spectum has been demonstrated at LCLS[2]. Figure 1 shows the energy distribution and spectrum for a 250 pC bunch, where for various degrees of overcompression the spectral width has been maximized.

As a numerical example following the SwissFEL parameters, the full width of the energy chirp is 1.5% at 2 GeV, which is 30 MeV. Because this amount is normally removed by the wakes, the increase in the main linac is 30 MeV as well. With the reversal of the chirp both contributions add up, resulting in a total chirp of 60 MeV. At the maximum energy of 6 GeV the total chirp is 1%, which translates into a photon pulse chirp of about 2%. This approache favors machines with very large wakefield amplitudes such as SACLA or SwissFEL. In addition active dechirpers[3] can be used as a secondary source of wakefields.

The challenge is to preserve the beam quality for lasing. At a certain moment the bunch undergoes full compression in the bunch compressor, which can be the source of strong coherent synchrotron radiation. Besides a dent in the longitudinal chirp the beam experiences also strong transverse kicks introducing tilts. However with proper set-up of the compression and compensation with higher multipole magnets in the chicane these effects can be mitigated[4]. The compression scheme can further be enhanced by shaping the laser profile if the electron source is based on a photoelectron RF gun. That way it can straighten the induced electron chirp while flattening the current profile and increasing the wake amplitude. Enhancements of up to 50% are possible[5] before non-linear affects destroy the beam quality and thus the lasing. However the set-up of this is not easy and requires an iterative algorithm of prediction (forward tracking), correction (upscaling of the energy chirp) and reconstruction (backward tracking), as shown in Figure 2.

Similar to overcompression is full compression[6]. Instead of wake fields it is the longitudinal space charge which induces the chirp as seen in Figure 3. The difference is that in this method the pulses are shorter but provide more power due to the higher peak current. For very short pulses the slippage may prevent the amplification so that a linear taper is needed to amplify the shot noise signal up to saturation[7].

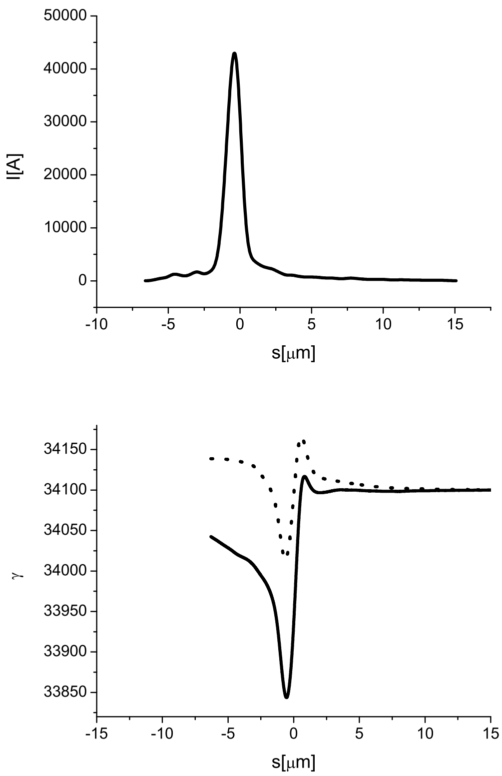


Fig. 3. Simulation for the European XFEL beamline SASE3 for a fully compressed bunch with its current profile and correleated energy distribution (upper and lower plot, respectively)[6].

## 3. Transverse Gradient Undulators

The idea is similar to an energy-chirped electron beam but in this approach the undulator field is chirped transversely. This field property can be provided by a transverse gradient undulator (TGU), available as a possible configuration in APPLE-type undulator modules or as dedicated TGU undulators with fixed gap in the form of a wedge. The latter is used as an example in the LCLS beamline to provide some tunability of the undulator field by the transverse position of the modulator[8]. In the former case the transverse gradient can be configured "on-demand" by a specific configuration of the four arrays of undulator magnets. In comparison to the standard APPLE-I and -II designs the proposed concept of the APPLE-III (also called APPLE-X) design[9] uses a lateral and radial motion of the magnet arrays, which provides much more flexibility and independence of the transverse gradient with respect to the average undulator field strength and polarization.

Converting the transverse gradient to a chirp in the photon beam requires ma-

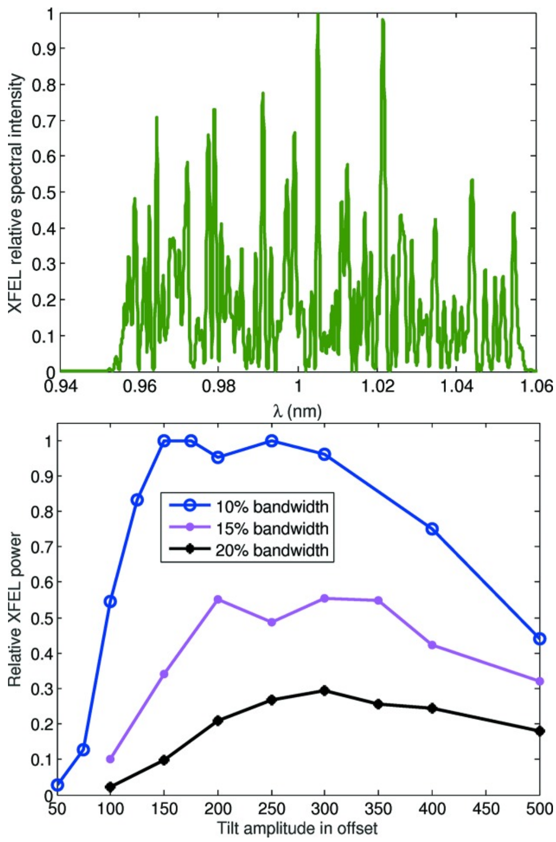


Fig. 4. Simulated spectrum for the SwissFEL soft-X-ray beamline Athos with an injected tilted beam and transverse gradient in the undulator field (upper plot). Optimization of tilt amplitude and gradient for various values of bandwidth in the FEL spectrum[10].

nipulating the electron beam prior to injection into the undulator by applying a spatial tilt[10]. This can be done by leaking out dispersion from a preceding dispersive section, by applying a time-dependent RF kick with a transverse deflecting structure, or by transverse wake fields. The last option has the disadvantage that the induced tilt is not linear. Between the source of the tilt and the entrance of the undulator there has to be a specific betatron phase advance of 90° plus a multiple of 180°. That way the beam enters with a spatial tilt but preserves its orientation along the undulator. Therefore the effective field of the undulator is different for each slice and a correlated chirp is generated under the condition that the slippage length is much shorter than the bunch length. Otherwise the radiation field slips out of the tilted beam and the amplification stops.

The major drawback is that no external focusing is permitted in order to preserve the tilt, therefore the beam has to drift along the total undulator length. While this lack of optimum focusing results in an overall reduction of the achievable radiation power, it is still tolerable with today's good emittance values of the driving electron beam. It has to be noted that a transverse gradient in the undulator field causes a kick and natural focusing. The former can be compensated with compensating coils, typically included in undulators with variable gap to compensate for the earth magnetic field. The latter can be a problem but for reasonable gradients the effect is less than the natural focusing in the perpendicular plane. As long as the phase advance of this focusing is significantly less than 90° over one gain length, the radiation field will try to follow and the changing tilt can be compensated by adjusting the initial tilt.

For each desired chirp there is an optimal gradient and a matched tilt. In one extreme of a strong gradient there is a significant change in the undulator field over the beam size of an electron slice so that locally electrons cannot contribute to the same wavelength. In the other extreme of a weak gradient and large tilt, the beam is effectively stretched transversely and the electron density reduced as well as the maximum length a radiation field can slip without leaving the beam. Figure 4 shows a scan for optimum performance for various bandwidth values.

## 4. Spectral Broadening

Another approach consists in actively increasing the spectral bandwidth of the FEL. The straightforward approach to increase the FEL parameter, which correlates directly to the FEL bandwidth, is rather limited due to the cubic-root dependence on the beam current. Lowering the beam energy has a stronger impact but to remain in the same resonance condition the undulator period or parameter needs to be lowered, which has a degrading effect on the FEL parameter.

A more promising approach is to generate radiation spikes that are shorter than the cooperation length. This can be done in an optical-klystron or mode-lock lasing configuration of the FEL[11], where after very short undulator modules the radiation field is advanced by means of delaying chicanes for the electron beam. A significant broadening occurs when the module length is shorter than the gain length [12]. In this regime the spectral width scales inversely with the number of undulator periods. Within the spectrum a modal structure is visible and not all frequencies within the broad bandwidth are excited. The spacing of these modes depends on the delay with respect to the slippage per module. And also, unlike in the previous methods, there is no correlation of the frequency with time. Therefore a post-FEL pulse compression is not possible.

This method is rather limited because the bandwidth is fixed by the length of the undulator and always present, unless the delays are turned off completely. In addition such a facility becomes long because the filling factor—the ratio between active undulator length and total length—is low due to the many intra-undulator break sections to host the delaying chicanes. This also results in difficulties to set up the lasing because wrong set values of phase shifters can completely destroy any FEL gain within one module. In contrast longer modules are more insensitive because there will always be some net gain even if the phase shifter is set to the worst value in terms of performance.

## 5. Conclusion

Several methods have been proposed to increase and control the bandwidth of a SASE signal. The solution with the least requirements for the hardware is by means of inducing a strong energy chirp with overcompression in the last compression stage. While the basic principle has been demonstrated it can be improved with tilt correction of the electron bunch and profile shaping. The disadvantage is a fixed chirp direction with the higher energy photons always arriving first. This is a fundamental drawback if the pulse is considered for optical pulse compression to shorten the pulse length and increasing the peak power. By the nature of wake fields, which always reduce the energy of electrons following the source of the wake

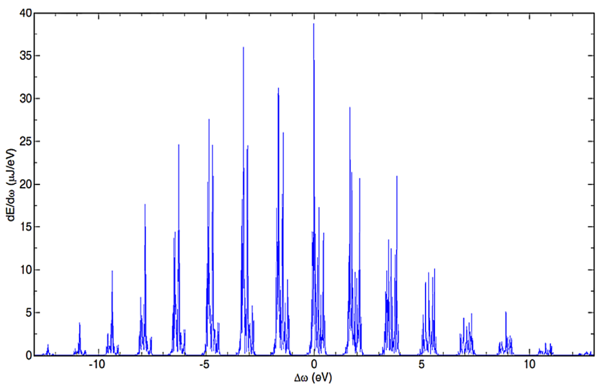


Fig. 5. Spectrum of a mode-locked configuration with module length of 12 undulator periods in the soft-X-ray regime [12].

fields, this cannot be changed.

Therefore alternative approaches offer more flexibility. The tilted beam, injected into a transverse gradient undulator, generates a chirped pulse, whose direction can be chosen by either the tilt or the gradient direction. Nevertheless the generation and propagation of a transverse tilt must be controllable and the FEL process must rely on the electron density within the undulator without proper external focusing.

Mode-lock operation offers also the benefit of a broad spectrum, which scales, after proper configuration, inversely with the number of periods per undulator module. Unlike the other schemes there is no correlation with FEL pulse frequency and time. Instead it is the interference of very short pulses, resulting in a modal structure in spectrum and time profile.

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