TUNABLE SOFT X-RAY OSCILLATORS*

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Abstract

A concept for a tunable soft x-ray free electron laser (FEL) photon source is presented and studied numerically. The concept is based on echo-enabled harmonic generation [1] (EEHG), wherein two modulator-chicane sections impose high harmonic structure with much greater efficacy as compared to conventional high harmonic FELs that use only one modulator-chicane section. The idea proposed here is to replace the external laser power sources in the EEHG modulators with FEL oscillators, and to combine the bunching of the beam with the production of radiation. Tunability is accomplished by adjusting the magnetic chicanes while the two oscillators remain at a fixed frequency. This scheme eliminates the need to develop coherent sources with the requisite power, pulse length, and stability requirements by exploiting the MHz bunch repetition rates of FEL continuous wave (CW) sources driven by superconducting (SC) linacs. We present time-dependent GINGER simulation results for an EEHG scheme with an oscillator modulator at 43 nm employing 50% reflective dielectric mirrors and a second modulator employing an external, 215-nm drive laser. Peak output of order 300 MW is obtained at 2.7 nm, corresponding to the 80th harmonic of 215 nm. An alternative single-cavity echo-oscillator scheme based on a 13.4 nm oscillator is investigated with time-independent simulations that a 180-MW peak power at final wavelength of 1.12 nm. Three alternate configurations that use separate bunches to produce the radiation for EEHG microbunching are also presented. Our results show that oscillator-based soft x-ray FELs driven by CW-SC linacs are extremely attractive because of their potential to produce tunable radiation at high average power together with excellent longitudinal coherence and narrow spectral bandwidth.

INTRODUCTION

The last ten years have seen rapid experimental advances in short wavelength free electron laser operation at facilities such as FLASH [2] and LCLS [3]. Although single-pass FELs are unique tools for the exploration of matter, there are important classes of experiments that require high average flux but for which high peak power cannot be tolerated. Short wavelength FELs with high average power but lower peak power can meet this need by using electron bunches produced at MHz and higher repetition rates and accelerated in SC linacs operating in CW mode. At LBNL, we currently are investigating [4] a CW, soft x-ray FEL driven by a 2.4 GeV superconducting linac that feeds a suite of as many as ten FELs operated in either SASE mode or in alternative modes with high longitudinal coherence. The latter include short pulse, single spike operation [5] wherein the output pulse length needs to be comparable to the FEL coherence length, direct seeding (limited by the repetition rate of laser-driven high harmonic generation sources), multi-undulator self-seeding schemes [6], and seeded, harmonic upshift schemes [7].

However, there is an additional approach that produces excellent longitudinal coherence and high average power — an oscillator configuration — for which the multi-MHz repetition rate capability of SC linacs is an obvious match. Historically, short wavelength oscillators ($\lambda > 10$ nm due to lack of reflective mirrors at shorter wavelengths) were first extensively studied in the 1980's [8]. A number of harmonic generation schemes using oscillators, were also investigated [9, 10]. The results showed that while the FEL could produce the radiation power needed to modulate the electron beam, there was an over-bunching problem requiring an optical klystron configuration to reduce the intracavity power. Double-oscillator schemes for high harmonic radiation were also briefly considered [10]. However, overall interest in oscillators appeared to wane by the early 2000's with the success of UV and XUV SASE-based FELs such as LEUTL[11], TTF-FEL[12], and FLASH. More recently, there has been renewed interest [13] in an FEL oscillator operating directly at hard x-ray energies based on a cavity employing multiple Bragg crystal reflectors, but this technology cannot be readily extended to the soft x-ray regime.

Today, layered dielectric mirror technology has advanced greatly in performance [14] including mirrors with normal incidence reflectivity on the order of 50%-70% at several discrete wavelengths between 13 nm and 43 nm. Also, the recent invention of the echo-enhanced high harmonic generation (EEHG) scheme suggests it will be possible to reach harmonic upshift ratios well in excess of 20 without requiring excessively small incoherent energy spreads. In this paper, we propose a novel oscillator approach driven by a SC linac combining the EEHG scheme together with a cavity employing currently available dielectric mirrors in the $\lambda \geq 13$ nm region to produce high average power, longitudinally coherent output at $\lambda \sim 1$ nm. A schematic of our approach is shown in Fig. 1. In its

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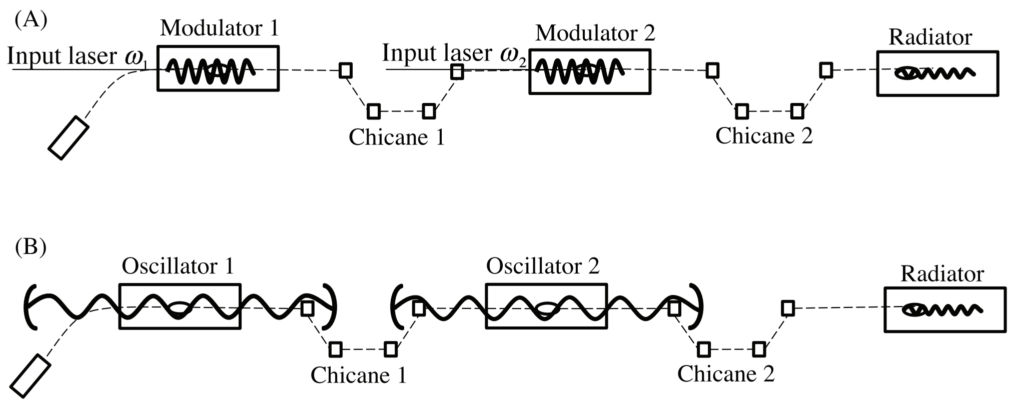

Figure 1: A schematic of the echo scheme as developed in Ref. [1] and the echo-oscillator scheme, in which the input lasers at ω_1 and ω_2 are replaced by FEL oscillators. The oscillator power is produced by the bunches even as they are modulated in the oscillators as part of the echo scheme.

simplest incarnation, there are two "modulator" oscillators in sequence operating at EUV wavelengths separated by a chicane with a large R_{56} value that produces the striped longitudinal phase space characteristic of the EEHG scheme. Following the second oscillator is a much weaker chicane that produces longitudinal microbunching with high harmonic overtones. Finally, there is a long "radiator" undulator operating in the exponential gain regime and which is resonant at a soft x-ray wavelength harmonically related to the resonant wavelengths of the upstream oscillators. The EEHG-oscillator combination offers at least five notable features: (1) It is easily tunable in wavelength and has large harmonic reach via adjustment of the chicane chromatic dispersion. (2) Its output has the longitudinal coherence and narrow bandwidth characteristic of oscillators. (3) It operates at very high repetition rate and does not require seeding by an external laser. (4) The final output peak power (and thus average power) is tunable via taper control of the final radiator undulator. (5) Taken as an ensemble, polychromatic output oscillator and radiator outputs are naturally synchronized temporally; there is also approximate synchronism with the electron bunches (downstream these could also be used to produce coherent THz or incoherent insertion device radiation for various pump probe experiments).

In the remainder of this paper we give some sample numerical simulation results to show that the qualitative promise of the EEHG-oscillator marriage appears to be successful to at least some degree quantitatively. Here we are not concerned with detailed specifications of a technical design; important technology questions, such as the specifics of cavity design and instantaneous and average power dissipation will be considered in a future publication. We anticipate that the mirror tolerances are within what is achievable now or in the near future, but admit this claim will have to be examined far more carefully in a real design. The electron beam parameters we use in our simulation examples are consistent with the state of the art, low-repetition-rate guns at low bunch charge of the order of 10 pC; the parameters have not yet been demonstrated for MHz-repetition-rate guns. We have chosen 2.4-GeV electron beam energy with a parabolic density profile, a peak current of 150 A, a bunch length of 115 fs (relevant only for time-dependent studies), an incoherent energy spread of 24 keV, and a transverse normalized emittance of 0.1 μm (we note that greater emittances and energy spreads would also likely work nearly as well). In what follows, we give two particular examples. First we study a 43-nm modulator oscillator followed by a strong chicane and then a 215-nm modulator (the latter wavelength is long enough that it could be produced by an external laser rather than a second oscillator). The final radiator operates at the 80th harmonic of 215 nm. A second example consists of a single-wavelength EEHG double oscillator operating at 13.4 nm, a wavelength where robust mirror technology is available. Finally, we discuss some alternate EEHG oscillator geometry configurations that may be of interest.

SIMULATION RESULTS

43+215 nm → 2.7 nm Radiator System

To examine performance of the scheme with an oscillator modulator at 43 nm and a second modulator employing an external 215-nm drive laser, we used the GINGER [15] FEL simulation code in fully time-dependent mode. The 43-nm oscillator, which included an interior transverse optical klystron, was run past saturation (with roughly a 5% fluctuation in output power). The particle output from the GINGER simulation was then analytically moved through a chicane using a JAVA implementation of the chicane routine from the GENESIS code [16]. Some rebinning was performed to prepare the bunch for the modulator simulation since the particles moved across several time slices in the chicane. The rebinned particles were then injected into the 215-nm modulator section (simulated with GINGER) and passed through another chicane, before entering the radiator. The parameters for these runs are given in Table 1, and the final power output from the GINGER simulation of

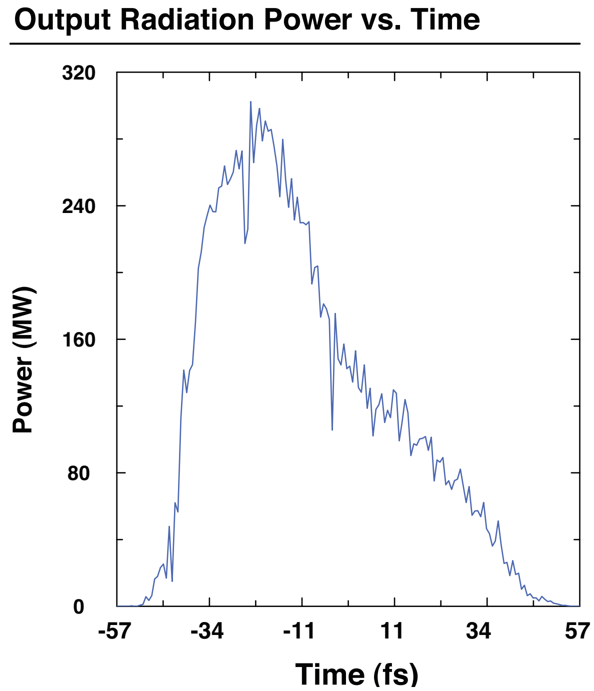

Figure 2: Output power versus time from a GINGER simulation from the first stage 43-nm oscillator in a hybrid EEHG scheme that also uses a second stage seeded by an external laser at $\lambda = 215\,\mathrm{nm}$. $t = 0$ corresponds to the temporal center of the electron bunch.

the radiator is shown in Fig. 2.

The purpose of optical klystron configuration in the 43-nm oscillator was to limit the size of the induced energy modulation, which in turn limits the energy spread of the beam at the entrance of the radiator. The GINGER simulation utilized an overall desynchronism of 24 fs between the electron bunch separation and transit time for the laser pulse in the optical cavity. The mirrors were assumed to be broadband; narrow band mirrors would act to further increase longitudinal coherence, but have yet to be simulated. Wide bandwidth in the mirror response allows for greater flexibility in tuning, but its impact on sensitivities and longitudinal coherence needs to be further explored.

Single Cavity Echo-oscillator at 13.4 nm

The conventional echo scheme also allows for equal frequencies in each modulator. It should, therefore, be possible to implement an echo-oscillator in a single cavity with the appropriately configured wigglers and dispersive sections. We considered such a single-frequency echo scheme using 13.4 nm mirrors (a robust frequency for dielectric mirror technology), as shown in Fig. 5.

As noted earlier, the use of FEL oscillators in optical klystron (OK) configurations can produce stable output of electron bunches with a smaller energy modulation than possible with a standard oscillator. In the single cavity EEHG we take a similar approach. The first energy modulation of the echo (both are within the single cavity) is produced with a standard OK type configuration of two undulator sections of equal length, separated by a small dispersion section. A large dispersion section follows to create the horizontally (i.e., energy) shredded phase space of the echo scheme. The bunch then passes through a third undu-

Table 1: Main parameters for a 43 nm oscillator and a 215 nm modulator EEHG FEL radiating 300 MW at 2.67 nm.

Parameter	Oscillator 43 nm	Modulator 215 nm
Undulator period	7 cm	18 cm
a_w	7.2	10.2
Length, first section	10 m	4 m
Length, break	1.4 m	N/A
Length, second section	2.6 m	N/A
R_{56} in break	10.5µm	N/A
Radiation waist	500 µm	500 µm
Power	65 MW	74 MW
Losses/reflection	50%	N/A
R_{56} (Chicane 1)	1450 µm	
R_{56} (Chicane 2)	82 µm	

Table 2: Some key parameters for the steady-state GINGER simulations of a 13.4 nm single cavity echo-oscillator scheme radiating at the 12th harmonic. The configuration is shown in Fig. 5.

Optical Klystron component:	
Wiggler sections	2 identical
λ_w	7 cm
a_w	2.7
Section length	1.4 m
Chicane length	1.2 m
R_{56}	41 µm
Chicane 1:	
Length	1.2 m
R_{56}	100 µm
Second modulator:	
Wiggler sections	1 as above
Section length	1.4 m
Optical cavity:	
Cavity power	38 MW
Losses/reflection	32%
Chicane 2:	
Length	1.2 m
R_{56}	30 µm
1.12 nm radiator:	
λ_w	2.2 cm
a_w	1.1
Length	20 m
Power	180 MW

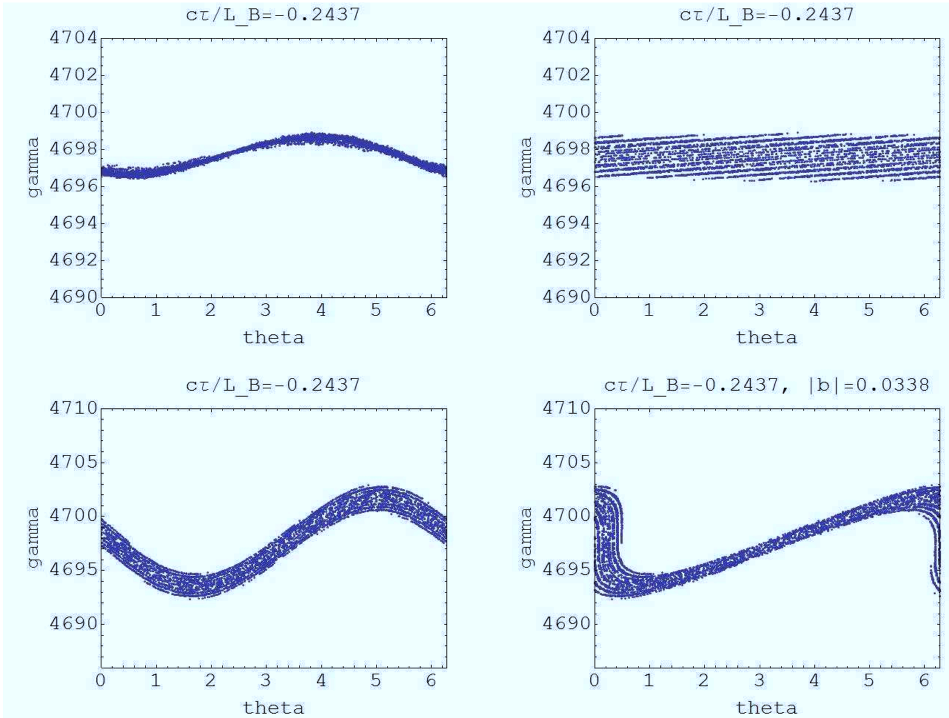

Figure 3: EEHG simulation results using GINGER showing the bunch phase space at a normalized distance of 0.24 from the tail of the bunch of a 43 nm oscillator followed by a 215 nm laser-driven modulator (replacing the second oscillator in Fig. 1). Plotted are the longitudinal phase space after the 43 nm oscillator (top left), the first chicane (top right), the 215 nm modulator (bottom left) and after the second chicane (bottom right). The bunching is over 3% at the 80th harmonic of 215 nm.

lator section to provide the needed second modulation. As it exits the cavity, it propagates through the second dispersion section before entering the radiator (see Fig. 5).

This system has been studied with *time-independent* numerical simulations using GINGER for a cavity tuned to take advantage of a peak in multilayer mirror reflectivity at 13.4 nm. The output radiation in this case is tuned for the 12th harmonic of 13.4 nm, where 180 MW was reached. This should be compared to an output of 300 MW from simulations where the beam proceeded directly from the OK into a dispersive section and radiator. The simulations here show that the system can be made to work, but do not yet demonstrate that a one-cavity EEHG can be an improvement over an OK cavity followed by a standard HGHG configuration. Further studies are in progress to understand the harmonic reach of the single cavity echo-oscillator scheme. The coupling between the components in the cavity during the start-up and at steady-state need further understanding, and simulations should be made with time-dependence.

ALTERNATE GEOMETRIES

We presented initial simulations of two possible echo-oscillator systems. Many other configurations of the can be imagined.

One of the major drawbacks of using an oscillator to create energy modulation in an electron beam is the lack of fine control over the magnitude of the modulation. The optimum modulations required for EEHG are approximately one to three times the initial energy spread. It is extremely difficult to produce this small of an energy modulation even with OK oscillators. The large modulation becomes an issue in the radiator because the final radiation production of the microbunched beam is limited by the energy spread. One way to avoid these difficulties and still not be limited by the repetition rate of a drive laser for the modulators is to use a fast kicker to send every other electron bunch to echo power source production. These bunches are sacrificed to reduce demands on the oscillator operation, at the cost of reduced overall efficiency.

The radiation from the sacrificial bunch could then be transported to the modulator inputs. The timing would work so that a standard echo scheme is implemented on those bunches that are not sacrificed. Only half of the electron bunches would produce output radiation in this scheme, but this would allow for much finer control of the energy modulation. Two flavors of this scheme are shown in Figs. 6 and 7. A way to recover the lost efficiency might be to first modulate the beam and radiate at short wavelengths via EEHG with a fresh, low energy spread beam; then, send the used bunches into oscillator cavities to pro-

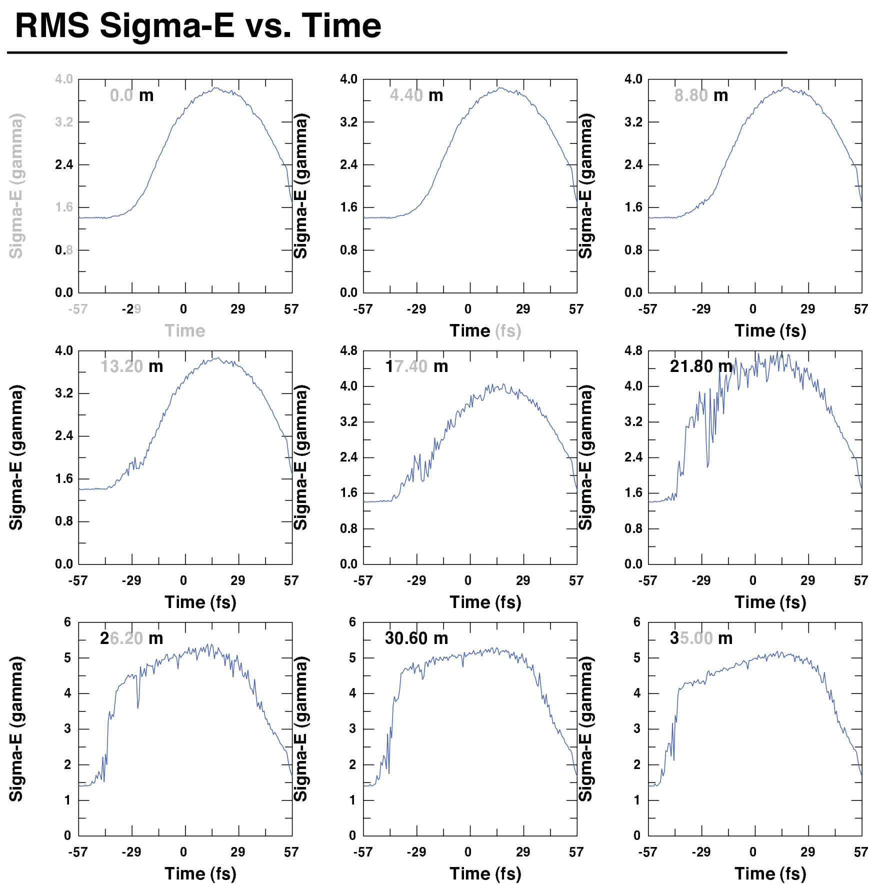

Figure 4: EEHG simulation results using GINGER showing the energy spread as a function of bunch position of a 43 nm oscillator followed by a 215 nm laser-driven modulator. Only the part of the bunch where the energy spread is small enough will radiate in the radiator. The limits on our ability to adjust the energy spread as a function of bunch position are currently being explored.

duce the seed power for the modulation of the next bunch. Since the seed power is at longer wavelengths, the heating of the bunch during the short wavelength EEHG production may not be so prohibitive for power production at longer wavelengths downstream. This scheme has not been studied numerically here.

Results from a time-independent GINGER simulation with power at the modulation wavelength equal to the oscillator production power at 13.4 nm (with additional reflection losses) produce radiation at the 25th harmonic (0.54 nm) with power of 220 MW. For comparison, a higher current (600 A) and higher energy spread (96 keV) (constant longitudinal emittance) yielded 900 MW at the 24th harmonic of 13.4 nm (0.56 nm).

CONCLUSIONS

We propose an EEHG scheme in which a pair of FEL oscillators and chicanes operate as an EEHG system. Such a system requires more of the FEL oscillator but does not require any other laser source for the EEHG. Initial time-dependent GINGER studies of a scheme with an oscillator at 43nm and an external drive laser at 215 nm show $\sim$ 300 MW can be obtained at the 80th harmonic of 215 nm. A single cavity echo-oscillator concept was described and implemented in a time-independent GINGER simulation. Simulated power levels of order 180 MW were obtained at the 12th harmonic of 13.4 nm. Various alternative configurations were presented.

The extent to which the assumed parameters can be relaxed, the wavelength reach can be extended and the specification of other accelerator constraints, such as on the energy chirp, timing, etc, remain to be explored.

Using the methods described above, we were able to model complicated FEL configurations with multiple oscillator, modulator, and chicane sections. The simulations reported here, while only beginning to explore the wide range of possibilities for soft x-ray oscillators, and likely far from optimal performance, indicate that oscillators in the soft x-ray regime should be given more serious study by groups considering CW FELs. There is potential for much more flexible and novel operating regimes to be reached when compared with seeding schemes widely pursued at present for single-pass FEL operation.

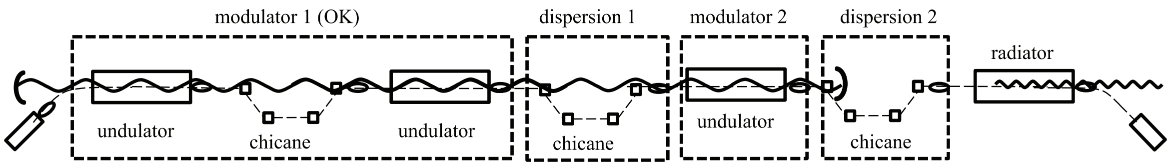

Figure 5: The echo-oscillator scheme implemented using a single oscillator cavity. Note that the first half of the oscillator, before Chicane 1, is in an optical klystron configuration to limit the energy modulation.

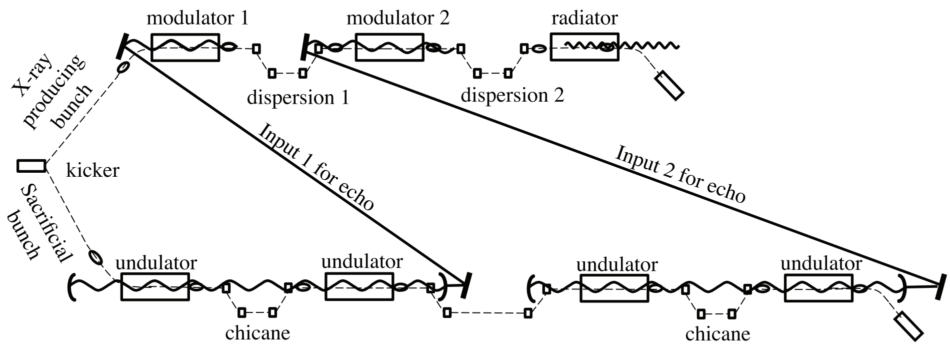

Figure 6: The sacrificial bunch scheme with separate beam lines for radiation generation and echo input power production. The EEHG then works as originally envisioned by Stupakov, but with the input power provided by alternate bunches propagating through FEL oscillators.

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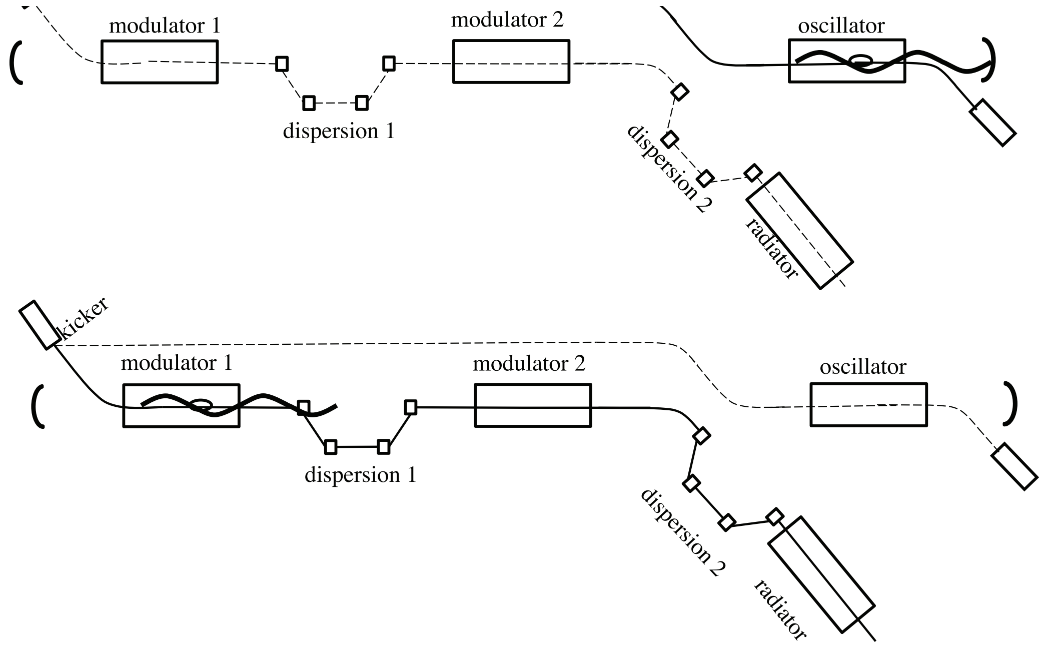

Figure 7: The sacrificial bunch scheme with a single oscillator. A variant of the idea in Fig. 6, where the radiation pulse within the oscillator alternately interacts with the "sacrifical" bunches and with the bunches that enter the radiator.

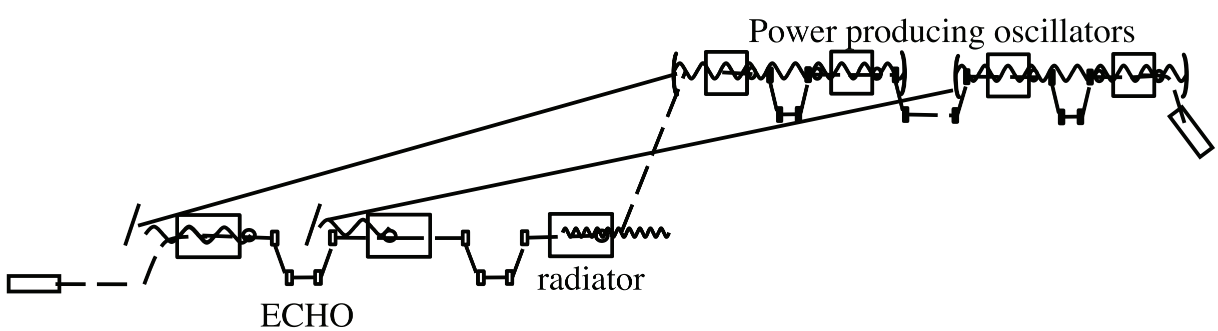

Figure 8: The "radiator-first" geometry, in which power production at short wavelengths precedes the production of input power for the modulators. The short wavelength EEHG FEL, more sensitive to energy spread, precedes the oscillators at longer wavelength that produce the input power for the EEHG. This has not yet been studied numerically.