# OSCILLATOR SEEDING OF A HIGH GAIN HARMONIC GENERATION FEL IN A RADIATOR-FIRST CONFIGURATION *

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*Abstract*

A longitudinally coherent X-ray pulse from a high repetition rate free electron laser (FEL) is desired for a wide variety of experimental applications. However, generating such a pulse with a repetition rate greater than 1 MHz is a significant challenge. The desired high repetition rate sources, primarily high harmonic generation with intense lasers in gases or plasmas, do not exist now, and, for the multi-MHz bunch trains that superconducting accelerators can potentially produce, are likely not feasible with current technology. In this paper, we propose to place an oscillator downstream of a radiator. The oscillator generates radiation that is used as a seed for a high gain harmonic generation (HGHG) FEL which is upstream of the oscillator. For the first few pulses the oscillator builds up power and, until power is built up, the radiator has no HGHG seed. As power in the oscillator saturates, the HGHG is seeded and power is produced. The dynamics and stability of this radiator-first scheme is explored analytically and numerically. A single-pass map is derived using a semi-analytic model for FEL gain and saturation. Iteration of the map is shown to be in good agreement with simulations. A numerical example is presented for a soft X-ray FEL.

## INTRODUCTION

Superconducting linear accelerators (sc linacs) operating in continuous wave (cw) mode have the ability to produce high quality electron beams with bunch repetition rates of MHz and above [1]. A free electron laser (FEL) facility based on such a linac could allow users to complete experiments in orders of magnitude less time than required at current X-ray FELs. Furthermore, many experiments desire the longitudinal coherence and high average flux, but non-destructive peak flux that a cw sc FEL can provide. FEL oscillators could provide a tunable solution where broadband mirror technology has been developed. In the soft x-ray regime, however, the state of the art multilayer mirrors can only be made to reflect at certain wavelengths. Many seeding schemes have also been proposed to provide longitudinal coherence and allow for tunability, but rely on high power external lasers [2] that would limit the repetition rate at which they can operate.

Wurtele, *et al.*, [3] have proposed various schemes for producing longitudinally coherent light at high repetition rates by modifying these seeding schemes to remove the need for external lasers. The underlying idea is to use the electron beam to generate the required radiation instead of using a laser. A much simplified version of one of the more promising of these schemes is considered in this paper. The “radiator first” scheme makes use of the electron beam after the target radiation has been generated in order to provide the seed radiation for a harmonic generation scheme [4, 5]. Wurtele et al originally proposed this in conjuction with echo-enabled harmonic generation (EEHG) [6]; here we consider a high gain harmonic generation (HGHG) [7] scheme. The current configuration is less technically challenging in terms of hardware and simpler to analyze. Our analysis confirms simulation results, yields useful expressions for quickly finding workable parameters, and provides insight into the operation of coupled radiator-oscillator FEL systems.

In this paper, we first provide a description of the HGHG radiator-first scheme, and then present a simplified one-dimensional map which models the evolution of this system. The dynamics predicted from this map are compared to time-independent, one-dimensional simulations for a soft x-ray case.

## THE RADIATOR-FIRST SCHEME

The major motivation for considering the type of scheme diagrammed in Fig. 1, as was mentioned in the introduction, is that it eliminates the need for an external seed laser. Since the electrons are doing all the work of generating the seed and target radiation, the limiting factor on the repetition rate is now the electron source and accelerator. This comes at the cost of adding any complications associated with the oscillator and the transport of radiation from the oscillator back to the modulator. Others have considered similar schemes in which the oscillator is used in place of the modulator, but only with the oscillator placed before the radiator [8, 9]. This may seem like a more attractive option since there is no need to transport radiation or worry about timing it to overlap the beam. The downside to this approach is that the oscillator induces so much energy spread that the radiator performance is degraded. It is also difficult to tune the oscillator so that the beam does not come out overbunched at saturation. While using a transverse optical klystron configuration has led to limited success in simulations at controlling the saturation power [3, 10], there is no need for this in the radiator-first scheme as we are not interested in the phase space of the electron beam after the

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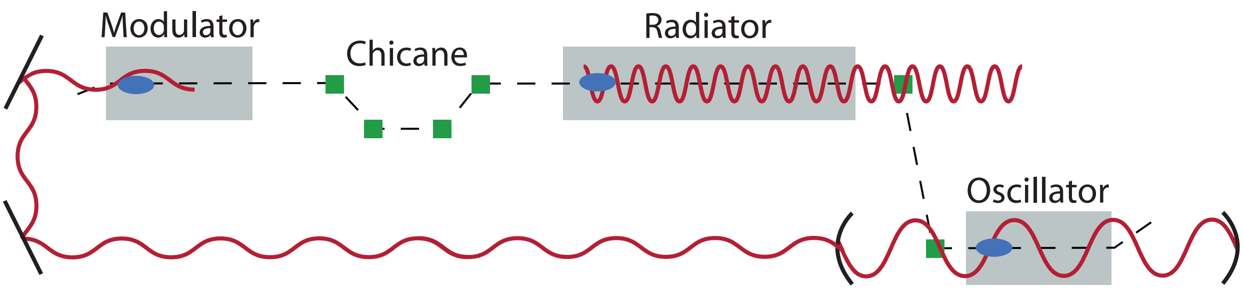


Figure 1: A schematic of a radiator-first configuration for oscillator seeding of a high gain harmonic generation FEL. Electron bunches are shown as blue ovals and the path of the radiation as wavy red lines. The power in the modulator seen by a bunch is generated in the oscillator by earlier bunches. The transfer line taking the electron beam from the radiator to the oscillator is not shown in detail because it has little effect on performance; the only requirement is that short-wavelength bunching should be suppressed.

oscillator, and thus are less constrained in oscillator design.

An electron bunch entering the HGHG radiator-first FEL encounters the modulator section and a chicane, followed by the radiator section and finally the oscillator. The seed radiation for the modulator section has been outcoupled and transported from the oscillator at the end of the system during the previous pass.

After exiting the modulator the electron bunch enters a chicane where a density modulation is produced, just as in the conventional implementation of HGHG. This density modulation results in bunching at harmonics of the seed radiation which, in turn, seed the FEL process in the radiator section. The radiator, which is tuned to a harmonic of the oscillator radiation, will deliver radiation to the user which is longitudinally coherent as a result of the coherence of the bunching imposed in the modulator.

The electron bunch, which would normally be discarded after the radiator, is instead transported to an oscillator tuned to produce radiation for modulation of a later bunch. Because of the harmonic upshift, the efficiency of the FEL process will be lower in the radiator than in the oscillator that follows. This means that the energy spread after the radiator will fall within the energy bandwidth of the oscillator and will be suitable to produce significant amounts of power in the oscillator, as confirmed by simulations and our simplified theory.

An increase in the harmonic upshift improves the beam quality entering the oscillator and increases its performance. Thus, it is beneficial to have as high a harmonic upshift as possible. The density modulation produced in the chicane before the radiator results in bunching at the frequency of the seed radiation. This modulation will be preserved through the radiator, and may also increase the performance of the oscillator. In our analysis, we do not attempt to make use of this effect and the bunching is assumed to be completely lost as the beam is transported from the radiator to the oscillator. Our simulations include a strong chicane between the radiator and oscillator to debunch the beam.

The beam is discarded at the end of the oscillator and the outcoupled radiation is transported back to the modulator for the next electron bunch, and the cycle is repeated. The map described in the next section provides an analytic method to determine if this process leads to a stable steady state for a given set of parameters. We consider an oscillator at 13.4 nm wavelength, where mirrors are available that can achieve a round-trip reflectivity of 0.5, and a radiator tuned to the 10th harmonic.

Depending on the parameters and actual layout of the device, it may not be possible to overlap the electron bunch with radiation produced during the previous pass. This can be resolved by having multiple radiation pulses within the oscillator cavity that each interact independently as if it were a sequence described by the map derived below.

## THE MAP

In order to understand the dynamics and stability of the radiator-first scheme, we must model the feedback between the oscillator and the harmonic generation scheme. Fluctuations in the power of the oscillator lead to fluctuations in the modulation amplitude of the beam as it enters the chicane. This causes variations in the initial bunching that seeds the radiator which, in turn, effects the amount of radiation extracted from the beam. If more (or less) radiation is extracted, the energy spread of the beam will be increased (or decreased) as it enters the oscillator. This variation in energy spread will then act to decrease (or increase) the gain in the oscillator for the the next pass.

The simplest result occurs for the case where each bunch receives the radiation produced by the preceding bunch (in turn affected, via the oscillator, by all earlier bunches as well). In this case, the peak intensity, $I$, in the oscillator satisfies the following nonlinear iterative map from bunch to bunch:

$$I_k = RI_{k-1}\frac{G(\sigma_k)}{1+[G(\sigma_k)-1]\,RI_{k-1}/I_{\rm sat}(\sigma_k)}, \qquad (1)$$

where $R$ is the transmission of the radiation after one pass around the oscillator, $\sigma_k$ is the relative energy spread of bunch $k$ going into the oscillator, $I_{\rm sat}(\sigma_k)$ is the nominal intensity at saturation, and $G(\sigma_k)$ is the linear gain through the undulator in the oscillator.

This expression takes into account both the decrease in actual gain as intensity approaches the saturation value (hence the factor $I_{k-1}/I_{\rm sat}$ in the denominator), and reductions in intensity at saturation and in linear gain as the energy spread is increased (following the formalism of M. Xie [11], both diminish as the energy spread approaches the FEL bandwidth). The behavior of this bunch-by-bunch map is shown in Fig. 2, where the intensity is scaled to $I_{\rm sat}(\sigma = 0)$. The oscillator is taken to have $R = 0.5$ and $G(\sigma = 0) = 9.5$. Note that the intensity reaches an equilibrium value at 0.70 which is stable, as evidenced by the slope of the curve having magnitude $< 1$. In the steady state, the power produced in the radiator is roughly $0.16$ times the ideal saturated power. The full details of the map analysis will be found in Ref. [12].

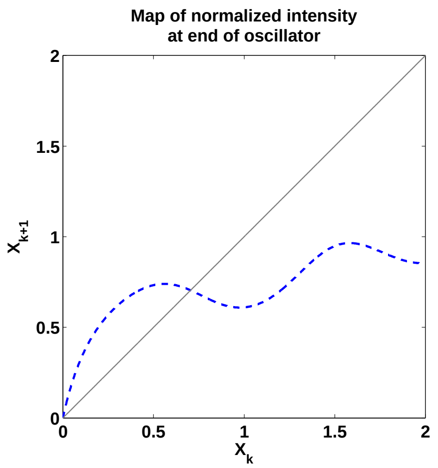


Figure 2: Normalized intensity at the end of the oscillator as a function of the normalized intensity at the end of the oscillator in the previous pass. The equilibrium point occurs at 0.70, and has a slope for the map of -0.44, indicating it is stable with damped oscillations.

This analysis captures the effects of variations in initial energy spread of the electron beam on the oscillator from pass to pass, and shows how the resulting power fluctuations impact the HGHG performance. We make use of a semi-analytical model of FEL gain and saturation based on the work of Dattoli et al. [13] to predict the output of the oscillator in a given pass based on the initial energy spread. By coupling this model to a simplified analysis of HGHG [14], we can produce a map that predicts the intensity at the end of the oscillator in one pass based on the the intensity of the previous pass.

This model is one-dimensional and does not include pulse propagation effects. More sophisticated treatments of both the oscillator and radiator should be incorporated in the future. These include an analytical theory for short-pulse FEL oscillators and multi-dimensional effects. We note that any limitation to short-pulse oscillators may not be so restrictive since high repetition rates limit the charge per bunch and high currents are desirable for improving the efficiency of the FEL process. Of course, once the bunch length of the electron beam is shortened to the cooperation length of the radiator, we reach the single spike SASE regime where longitudinal coherence will be guaranteed, but shot-to-shot fluctuations may be reduced by a feedback scheme such as the one used here. Thus, the short-pulse theory becomes applicable in the intermediary region where the bunch length is much less than the slippage length of the oscillator but longer than the coherence length in the radiator.

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