THE RADIATOR-FIRST HGHG MULTI-MHz X-RAY FEL CONCEPT

M. Reinsch*, G. Penn, LBNL, Berkeley, CA 94720, USA
P. Gandhi, J. Wurtele†, University of California, Berkeley, CA 94720, USA

Abstract

A novel configuration for a high repetition rate X-ray FEL is investigated. In this scheme longitudinally coherent FEL pulses are obtained using a high gain harmonic generation (HGHG) system in which the seed power is generated in an FEL oscillator downstream of the HGHG section. The oscillator is powered by the spent beams that leave the HGHG radiator. Radiation from the oscillator is sent to the modulator of the HGHG section. The dynamics and stability of the 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 in which the oscillator operates at 13.4 nm and HGHG radiation is generated at 1.34 nm. This radiator-first configuration potentially solves (i) the challenge of finding sources to seed future FELs driven by multi-MHz superconducting RF linacs and (ii) the difficulty of producing X-ray radiation with a bunch that exits an oscillator in the more "natural" configuration in which the oscillator precedes the radiator.

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]. There is a strong interest in X-ray beamlines that can deliver pulses with a high average flux at a non-destructive peak flux. FEL oscillators can meet these goals and provide longitudinal coherence, but tunability and availability at specific wavelengths are limited by mirror technologies. In the soft x-ray regime, 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. The "radiator first" scheme makes further use of the electron beam after the target radiation has been generated in order to produce 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 requirements. It also allows for a straightforward analysis which 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 give examples of a simplified pass-to-pass 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.

A MODIFIED HGHG LAYOUT

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. The HGHG section is laid out as in the conventional scheme, but it is surrounded by a system for the production and transport of the modulating laser pulse, based on the electron beam after passing through the radiator. While the radiator delivers a stream of radiation pulses to the user, the electron beam coming out of the radiator is also used to drive an oscillator which is tuned to the same wavelength as the modulator. Each seed pulse has been outcoupled and transported from this oscillator during the previous pass or passes. The longitudinal coherence of the oscillator pulse should lead to longitudinal coherence of the pulse delivered to users.

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, 10]. This may seem like the simplest option since the combined modulator/oscillator produces its own field, but the oscillator tends to induce a large energy spread that significantly degrades the performance of the radiator. It is also difficult to prevent the beam from becoming overbunched out of the modulator at saturation. While using a transverse optical klystron configuration has been shown in simulations to help control

* mwreinsch@lbl.gov
† also at LBNL, Berkeley, CA 94720, USA

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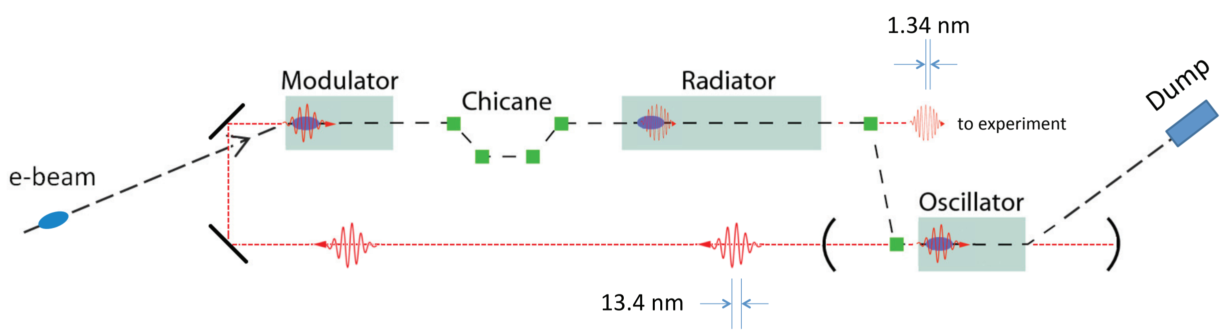

Figure 1: A schematic of a radiator-first configuration for oscillator seeding of a high gain harmonic generation FEL. Electron bunches are shown as blue ovals and the path of the radiation as dashed red lines. The power in the modulator seen by a bunch is generated in the oscillator by earlier bunches. 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.

the saturation power [3, 11], 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 oscillator, and thus are less constrained in oscillator design.

The radiator section and oscillator section each have a distinct energy bandwidth, and the energy spread will grow to some fraction of this bandwidth. To approach optimal performance, it is beneficial to have as large a difference between the FEL bandwidths as possible, and to have the bandwidth of the upstream elements be narrower than the downstream elements. Because the radiator wavelength is the shortest one, its FEL bandwidth is usually smaller than that of the oscillator. This is one major reason why it is convenient to arrange for the electron beam to pass through the radiator first, and then the oscillator. For simplicity, our simulations include a strong chicane between the radiator and oscillator to fully debunch the beam.

We consider an oscillator at 13.4 nm wavelength, where multilayer mirrors are available [12] that can achieve a round-trip reflectivity of 0.5, and a radiator tuned to the 10th harmonic.

SIMPLIFIED PASS-TO-PASS MAP

The generation and transport of radiation from the oscillator to the modulator forms a loop which leads to feedback from one pulse to the next. This has a significant impact on the dynamics, including the equilibrium state and its stability. Generally, if more (or less) radiation is extracted in the radiator, the energy spread of the beam will be increased (or decreased) as it enters the oscillator, which acts to decrease (or increase) the gain in the oscillator. This leads to a change in the modulation induced at a later pass, and thus in the power produced in the radiator.

We have developed an analytic map for the dynamics of the radiator-first HGHG configuration based on a one-dimensional FEL model which includes a correction for the effect of energy spread [13]. The full details of the map analysis will be found in Ref. [14]. This map can be used to estimate and understand the output levels and dynamics of this configuration, including whether or not a stable equilibrium point will be reached.

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 total power reflection coefficient for the radiation after one pass around the oscillator, σ_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. The energy spread σ_k depends on both the final oscillator power from the previous pass and the parameters of the HGHG stage [16].

This expression incorporates a decrease in growth rate as the intensity approaches the saturation value [15] (hence the factor $I_{k-1}/I_{\rm sat}$ in the denominator) and the effect of energy spread to reduce both the linear growth rate and saturation intensity [13]. The dependence of the equilibrium point on the choice of R_{56} is shown in Fig. 2. The oscillator is taken to have $R = 0.5$ and $G(\sigma = 0) = 9.5$. Note that the slope, which is the multiplication factor for small deviations from the equilibrium point, always has magnitude less than unity, corresponding to stable dynamics. At the optimum choice of R_{56}, the oscillator intensity is 0.70 of the maximum possible saturation value, while the radiator intensity is 0.16 times the equivalent maximum output at 1.34 nm. Also of interest is that, based on estimates of shot noise, the system always reaches its saturation value after less than 20 bunches have passed through, although for a poor choice of R_{56} that saturation value will be es-

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sentially zero. This rapid convergence arises naturally from optimizing the power coming from the radiator, but is not necessarily the best choice if stability is the predominant concern.

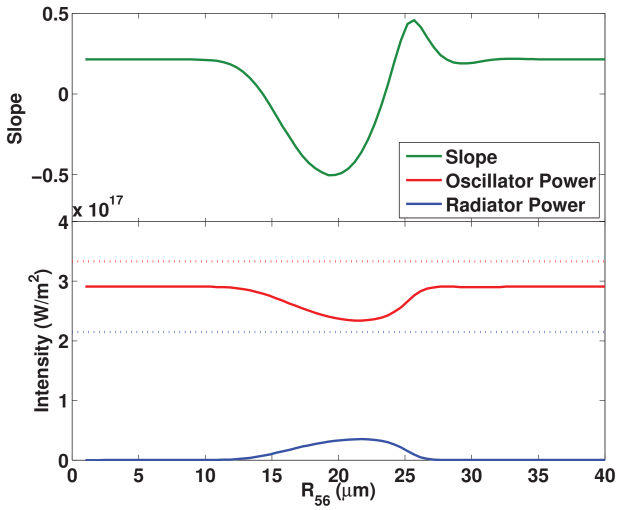

Figure 2: Bottom plot: Equilibrium intensity of oscillator (red) and radiator (blue); dashed lines show nominal saturation values. Top plot: Slope of transfer map from one pass to the next; values with magnitude >1 would correspond to unstable dynamics, leading to oscillations.

We can also use this analysis to consider the sensitivity to drift in electron beam parameters. For example, changes in peak current or energy spread will modify the gain and saturated intensity levels in both the radiator and oscillator. If we consider only variations to energy spread for a fixed beamline configuration (including the value of R_{56}), the resulting changes in the dependence of oscillator power on oscillator power in the previous stage are shown in Fig. 3. Here the intensity X is scaled to $I_{\rm sat}(\sigma=0)$. We note that a reduction in energy spread by roughly 15% increases the gain sufficiently to lead to an unstable equilibrium point. Even before the fixed point becomes unstable, the value of the equilibrium point shows a strong sensitivity to the energy spread, as shown by the shift in position of the intersection of the curve with the line $X_k = X_{k-1}$. Note that higher energy spread leads to higher equilibrium power in the oscillator, because it reduces the bunching at the start of the radiator, and thus the final power and energy spread coming out of the radiator.

Overall, the model considered here agrees well with simulations using time-independent, one-dimensional dynamics including energy spread. However, both the model and simulations should be extended to include pulse propagation in time and multi-dimensional effects. More sophisticated treatments of both the oscillator and radiator should be incorporated in the future.

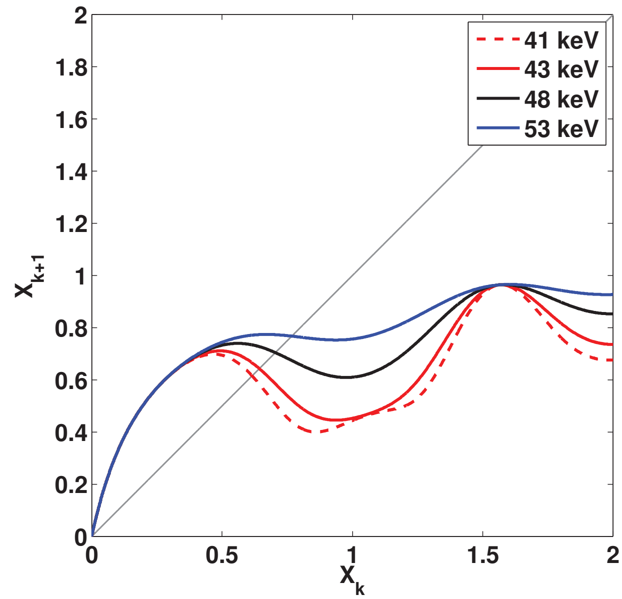

Figure 3: A selection of maps characterizing the dependence of oscillator power on the oscillator power from the previous pass. The nominal energy spread and several perturbations from this value are shown.

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