HIGH-GAIN FREE-ELECTRON LASERS AND HARMONIC GENERATION

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Abstract. We consider a free-electron laser (FEL) operating in the high-gain regime including the mechanism of self-induced harmonic generation (SIHG). We discuss the mechanism leading to saturation at these higher harmonics and analyze the effect of beam quality variations. Finally, we study an undulator configuration that allows the saturated harmonic power to become comparable with that of the fundamental.

INTRODUCTION

The mechanisms behind coherent, self-induced harmonic generation (SIHG) in free-electron laser (FEL) devices has been the subject of both older and more recent theoretical [1-7] and experimental activity [8-9]. SIHG is a promising method to obtain shorter wavelengths in, for an example, self-amplified spontaneous emission (SASE) FELs, since not only the fundamental but the higher harmonics achieve saturation nearly simultaneously. This occurs in all single-pass, high-gain, free-electron lasers configured with planar undulators. The sinusoidal electron beam traversal through these undulators naturally forces the odd harmonics to be favored.

The possibility of exploiting SIHG to coherently generate higher-order harmonics, which eventually may be exploited to 1) themselves serve as a radiation source or 2) serve as a seed for FEL operation at shorter wavelengths, has been a leitmotif for the design of devices operating in the VUV-X region of the spectrum [4-7,9-14].

In this contribution we discuss several schemes of high-gain FELs exploiting SIHG and, in particular, we will deal with the effect of the beam quality on higher harmonics and possible methods to enhance the output power of the higher harmonics.

Let it be known that we are merely stating what has been discussed in the September 2000 Arcidosso Workshop, “The Physics of, and Science with, the X-ray Free-Electron Laser” in Arcidosso, Italy; in a follow-up meeting held in November at the Advanced Photon Source (APS) at Argonne National Laboratory (ANL); and in many subsequent other forms of contact. We do not make any attempt to provide an unanimous conclusion as some of us still have a difference in opinion.

DISCUSSION OF THE NUMERICAL RESULTS

We will consider an FEL operating in the SASE regime with the parameters listed in Table 1. The undulator and electron beam parameters have been chosen in accordance with those of Ref. [3] and we have checked that the numerical method employed in the present investigation, based on a one-dimensional macroparticle code, PROMETEO, is capable of reproducing results similar to the three-dimensional simulation analysis of Ref. [3] after an appropriate choice of the electron beam current density (see Table 1).

In Fig. 1 (a-d) we plot the evolution of the first three odd harmonics for different values of the electron beam relative energy spread. In the case of Fig. 1 (a) ($\sigma_\varepsilon = 5 \times 10^{-4}$), all harmonics reach saturation and the saturated power of the fundamental is larger than the SIHG by one to two orders of magnitude.

It is well known that less desirable electron beam quality affects the fundamental and, therefore, harmonic evolution. The linear harmonics have been previously shown to be significantly affected by a degraded electron beam quality [15]. The nonlinear harmonics appear to be less sensitive to energy spread with respect to the fundamental as shown in Fig. 1 (b, c, d), where we have considered $\sigma_\varepsilon = 10^{-3}$, 1.5×10^{-3}, 2×10^{-3}, respectively. The numerical results clearly display that, while the evolution of the first harmonic (fundamental) is not significantly distorted by an increase of the energy spread, the SIHG exhibits a mild reduction of the saturated power. Using PROMETEO, the saturation of the fundamental is always followed by that of SIHG, at least for the range of parameters we have explored.

TABLE 1. List of parameters

E (MeV) = 219.5
I (A) = 150
e-beam transverse area (m^2) = 3.8×10^{-7}
Current density (A/m^2) = 3.95×10^8 A/m^2
ε_n (mm-mrad) = 5π
λ_u (cm) = 3.3
K = 3.1

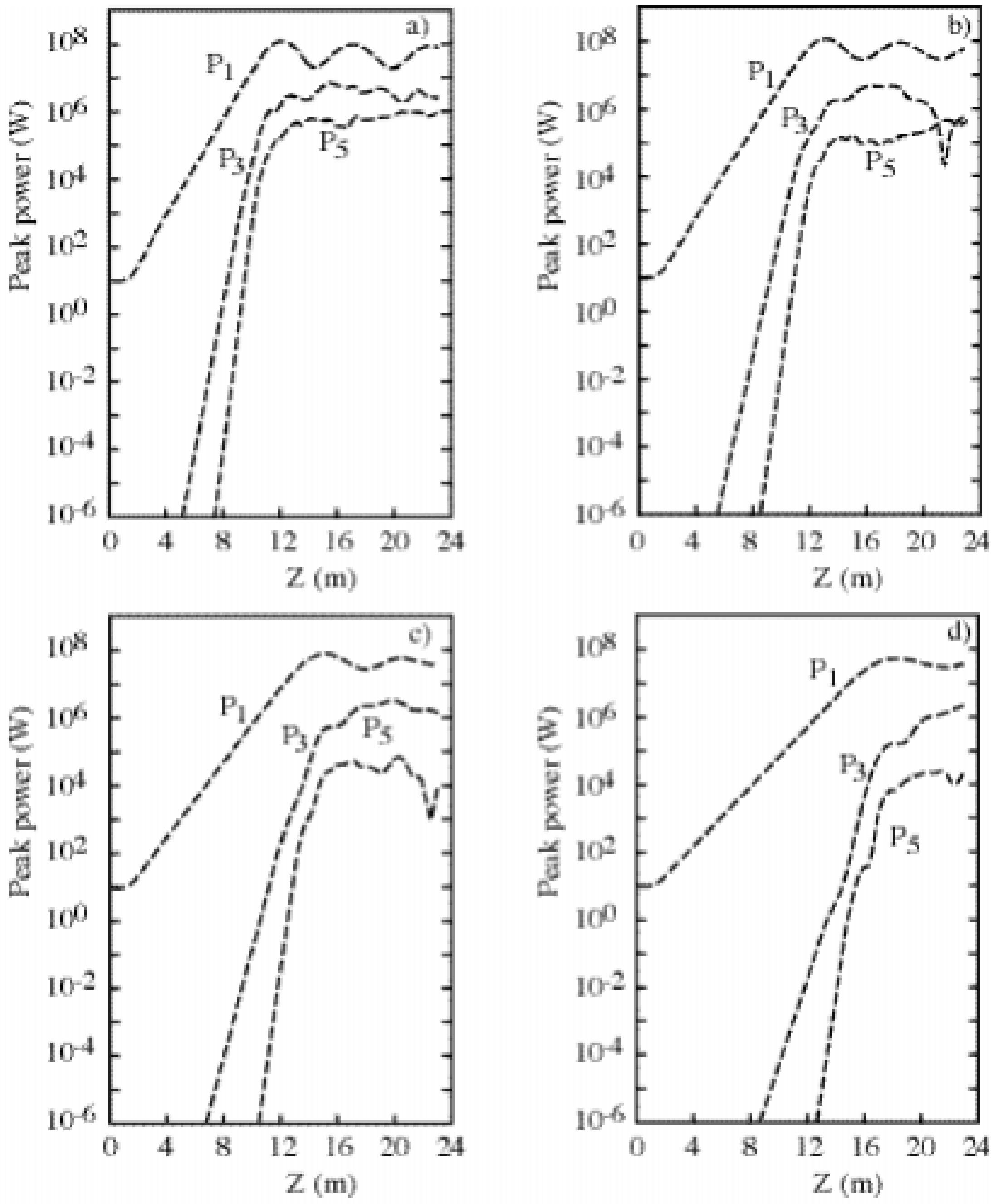

FIGURE 1. Evolution of first three odd harmonics vs z(m). a) $\sigma_\varepsilon = 5 \times 10^{-4}$, b) $\sigma_\varepsilon = 10^{-3}$, c) $\sigma_\varepsilon = 1.5 \times 10^{-3}$, d) $\sigma_\varepsilon = 2 \times 10^{-3}$.

To further analyze these results, we have performed parameter scans of the electron beam energy spread and emittance for the same parameter set as shown in Table 1 using the three-dimensional macroparticle computer code known as MEDUSA, as discussed in reference [3]. These scans were made using the fundamental and third harmonic only. In this analysis, the powers of the fundamental and third harmonic are chosen at the point of the fundamental saturation. In Figs. 2 and 3, the variation of both the fundamental and third harmonic output power is shown as a function of the energy spread and emittance, respectively. Note that as the energy spread or emittance degrades, the harmonic power decreases slightly more rapidly than that of the fundamental. This is not so much, however, that the harmonic power would become unusable.

The choice made for the current density in the one-dimensional code PROMETEO differs from that found in MEDUSA. MEDUSA follows the propagation of both the electromagnetic field and a matched beam self-consistently in three dimensions for a given emittance and, for the case under study, yields an rms beam radius of about 180 μm corresponding to a current density of about 1.5×10^9 A/m^2. Hence, the results may differ, and the comparison between the two codes may change if the higher current density would be applied in a PROMETEO simulation run.

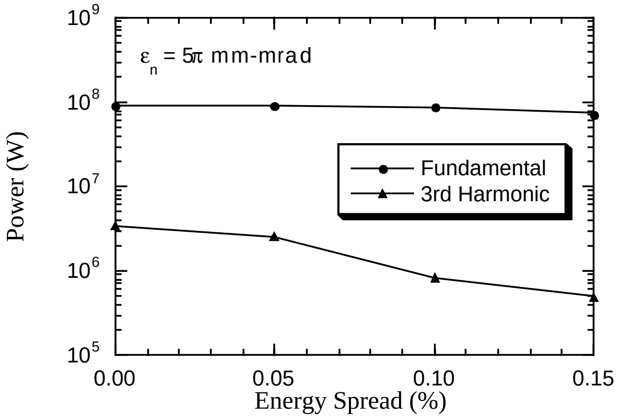

FIGURE 2. Power (W) of fundamental and third harmonic as a function of the electron beam energy spread (%).

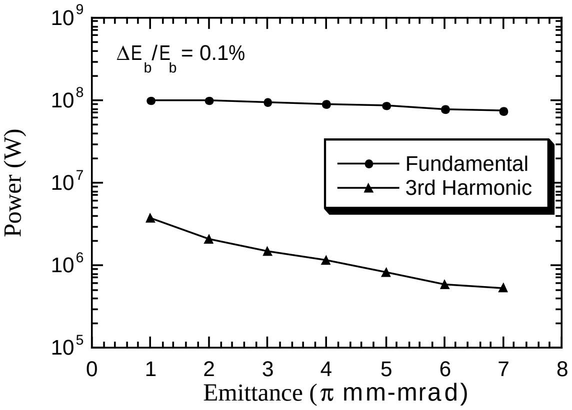

FIGURE 3. Power (W) of fundamental and third harmonic as a function of the electron beam emittance (π mm-mrad).

A more effective method of comparing this deviation is to examine the ratio of the harmonic power to the fundamental. For the PROMETEO analysis, this is shown in Fig. 4. For the MEDUSA analysis, the data for the harmonic-to-fundamental ratios as a function of energy spread and emittance are shown in Figs. 5-6.

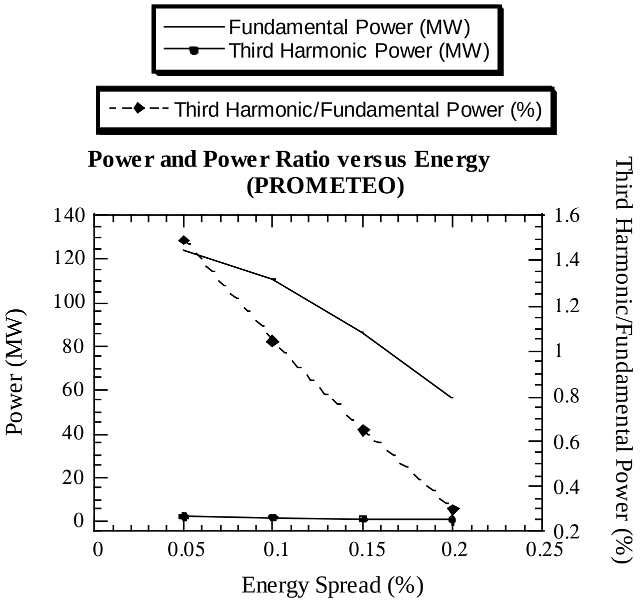

FIGURE 4. Fundamental and third harmonic power (W) and power ratio (%) of the third harmonic to the fundamental as a function of the electron beam energy spread (%) for the 1-dimensional macroparticle case.

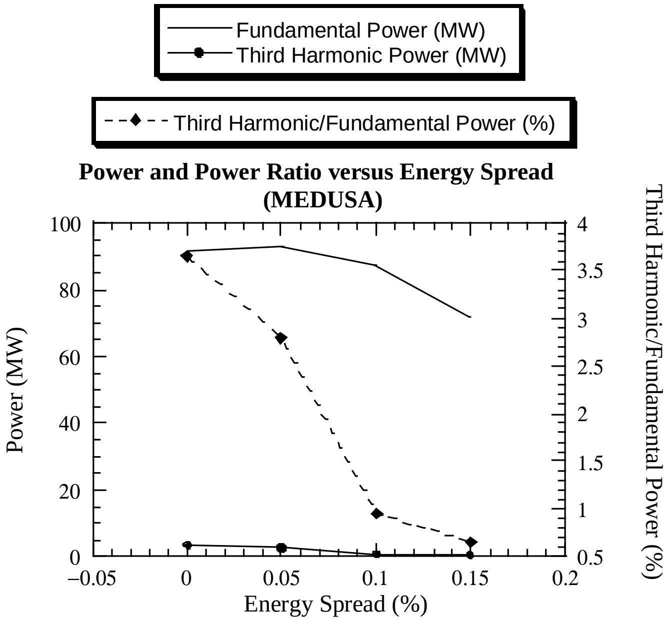

FIGURE 5. Fundamental and third harmonic power (W) and power ratio (%) of the third harmonic to the fundamental as a function of the electron beam energy spread (%) for the MEDUSA analysis.

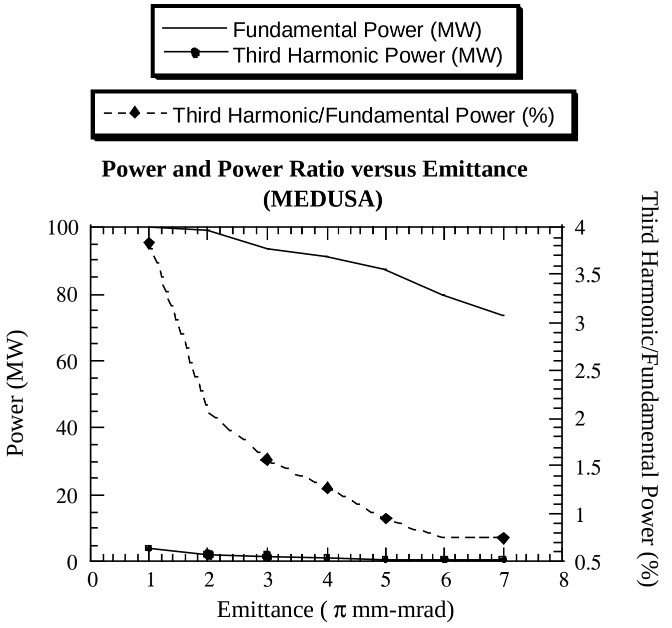

FIGURE 6. Fundamental and third harmonic power (W) and power ratio (%) of the third harmonic to the fundamental as a function of the electron beam emittance (π mm-mrad) for the MEDUSA analysis.

In the previous simulations, only the nonlinear harmonics produced by SIHG using a single undulator were followed. In such SIHG, the power of the fundamental is always significantly larger than that of the harmonics. Generally speaking, the third harmonic power at saturation is in the range of one percent of the fundamental.

We now will analyze an undulator configuration to enhance the power of the SIHG. The undulator consists of two parts: the first with the parameters given in Table 1, the second with a period exactly 1/3 of that of the first section but with the same K parameter. In this example the third harmonic of the first undulator corresponds to the fundamental of the second undulator and the electron beam prebunching induced in the first part may provide the condition for the growth of the power at $\lambda/3$ in the second section.

Figure 7 shows the results for different values of the energy spread. We have considered different lengths of the first section and have found that the *higher harmonics* may reach power levels comparable with those of the fundamental for small values of the energy spread. When σ_ε exceeds 10^{-3}, the gain length becomes prohibitively long in the second section. The case not presented here places the second undulator just after the third harmonic reaches saturation. Also note that the amount of power that can be generated by tuning the second undulator to the third harmonic is due to the coefficient of the bunching parameter, the coupling parameter, that goes as $(K_1/K_h)^2$, where $K_h = K(-1)^{(h-1)/2}\left[J_{(h-1)/2}(h\xi) - J_{(h+1)/2}(h\xi)\right]$ and $\xi = K^2/(4+2K^2)$. So, since the desired SIHG wavelength is now the fundamental of the second undulator, the amount of power available increases because the ratio becomes one.

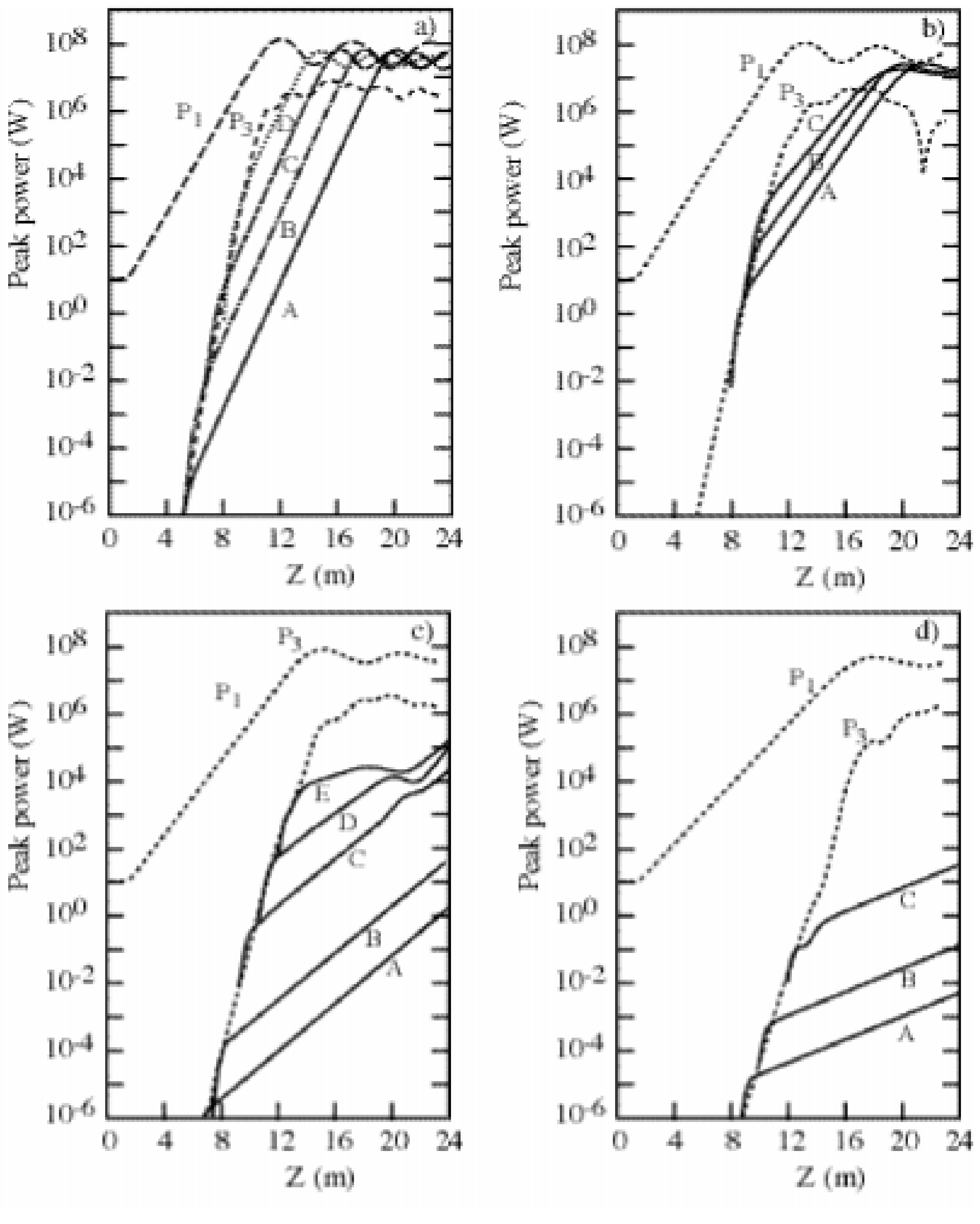

FIGURE 7. a) Evolution of the first and third harmonics as in Fig. 1 (a) ($\sigma_\varepsilon = 5 \times 10^{-4}$). The curves A, B, C, D refer to the case of composite undulator configuration, the section with $\lambda_u/3$ starts after a number of periods A) N = 120, B) N = 160, C) N = 200, D) N = 240. (b) Same as (a) ($\sigma_\varepsilon = 10^{-3}$), A) N = 240, B) N = 260, C) N = 280. (c) Same as (a) ($\sigma_\varepsilon = 1.5 \times 10^{-3}$), A) N = 180, B) N = 220, C) N = 280, D) N = 320, E) N = 360. (d) Same as (a) ($\sigma_\varepsilon = 2 \times 10^{-3}$), A) N = 260, B) N = 300, C) N = 360.

FINAL REMARKS

In this note we have explored some aspects of SIHG in high-gain FELs as were discussed in the Arcidosso workshop, in the follow-up meeting at the APS, and in subsequent communications. We have drawn the following conclusions:

- degrading electron beam quality produces a mildly worse effect on the SIHG power than on the fundamental but does not eliminate their overall usefulness,
- undulators with different period lengths can be exploited to enhance the power in a desired SIHG,
- a proper electron beam quality is crucial for the successful operation of an FEL scheme.

The reason why the two-undulator system cannot reach saturation in a reasonable length of the second undulator is under analysis and will be discussed more carefully elsewhere.

Finally, this group of individuals have agreed to continue meeting informally every few months to further discuss and critique exotic source schemes and issues regarding user facilities based upon FEL theory and experiment.

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