High-gain harmonic generation free-electron laser with variable wavelength

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The external seed of the high-gain harmonic generation (HGHG) free-electron laser (FEL) determines the wavelength of the output radiation. Therefore, the tunability of such a laser depends upon the tunability of the seed. In this paper, we present and discuss an alternative scheme for the tunable HGHG FEL wherein the seed's wavelength is fixed and the variations in the wavelength of radiation are achieved by tuning the accelerator. As an illustration, we apply our proposed scheme to the deep ultraviolet free electron laser (DUV FEL) at Brookhaven National Laboratory demonstrating the ability to attain about a $\pm 10\%$ variation in the wavelength's tuning range.

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I. INTRODUCTION

Storage ring synchrotron light sources have been very successful with respect to stable accelerator operations and generated scientific output. Insertion devices of low emittance electron storage rings provide high brightness and flux of the spontaneous emission. The broad spectrum of synchrotron radiation covers many decades in wavelength enabling broad range of user applications.

The next step in brightness increase is due to lasers and laserlike sources. Nowadays conventional lasers are capable of providing high-brightness radiation in infrared to soft x-ray range.

High-gain free-electron lasers have been proposed as powerful light sources for the short-wavelength range. Ultrashort radiation pulses from vacuum ultraviolet (VUV) to x-ray provide a unique possibility for studying fast processes in a large variety of scientific applications. Output radiation tunability and coherence are important measures of the free-electron laser (FEL) performance. High-gain FELs based on the self-amplified spontaneous emission [1,2] (SASE) and high-gain harmonic generation (HGHG) principles [3,4] deliver short radiation pulses with full transverse coherence.

In the HGHG scheme, a coherent seed at a subharmonic wavelength of the desired output radiation interacts with the electron beam in an energy-modulating section. The energy modulation is then converted into spatial bunching as it traverses a dispersive section. In the second undulator (the radiator), which is tuned to a higher harmonic of the seed radiation, the microbunched electron beam first emits coherent radiation and then amplifies it exponentially until reaching saturation.

The HGHG FEL has several advantages compared with the SASE. Since the HGHG FEL utilizes external seed, the output radiation takes off from a premodulated electron bunch, not from noise, as in the SASE case. This configuration insures longitudinal coherence, high spectral purity, and shorter saturation length.

In the HGHG FEL the seed controls the wavelength of the FEL output. Therefore, as it is generally understood, to alter the wavelength of the HGHG laser, the seed laser must be tunable.

The laser community provides a variety of lasers, which can be used as a seed for an HGHG FEL. For instance, the tuning range of Ti:sapphire laser system [5] is limited to 3.5%. For a GaAs diode-pumped laser [6] a tunability of 10% can be achieved (780 nm–870 nm).

Broadband VUV light generation has been demonstrated through cascaded nonlinear wave mixing in a gas. Using a hollow-fiber geometry, frequency conversion of ultrashort Ti:sapphire laser pulses from the visible into the deep UV around 200 and 160 nm is achieved [7].

Tunable high harmonic generation (HHG) lasers employ high harmonics [8,9], achieving 10^{10} photons per pulse. The tunability of argon or xenon HHG lasers is determined by a seed and can be extended up to a few percents for high harmonics in the range from 114 to 32 nm. Recently narrow band continuously tunable x-ray ultraviolet (XUV) laser radiation (100–40 nm), based on high harmonic generation, is demonstrated [10,11]. An unprecedented spectral purity of 2.5×10^5 covers the entire 40–100 nm region with continuous tunability, but number of photons per pulse ($\sim 10^5$) is still relatively small [10].

Optical parametric amplification (OPA) is a laser system to generate near-transform-limited femtosecond pulses that are tunable over the visible spectrum and into the NIR. The OPA is pumped by a harmonic of an amplified Ti:sapphire laser system. The conversion efficiency of the UV-pumped OPA is greatly increased by using noncollinear geometry to compensate group velocity mismatch between the pump, signal, and idler pulses. With OPA wavelength-tuning range can be extended from 700 nm to 400 nm [12].

Let us discuss some of the implications of seeding that are specific for FELs. Since most of modern high-gain FELs utilize a photocathode radio frequency (RF) gun, the gun laser system may serve as a source of the seed for an FEL. At the DUV FEL [13,14] the portion of the drive laser radiation is split in two beams. One of them is being used to drive photocathode RF gun and the other as a seed for HGHG FEL. This approach naturally allows accurate synchronization between the electron beam and the seed laser. Under such circumstances, varying the wavelength would cause retuning of the laser oscillator, thus retuning the laser's wavelength. In turn, this affects the number of electrons derived from the gun, since cathode quantum efficiency depends on the laser's photon energy and spot size.

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Another consideration is the alignment of the seed laser. For reliable HGHG performance, the seed laser and electron beams must be very accurately overlapped inside the modulator. Changing wavelength affects size of the seed laser's beam and its trajectory along the transport line, as well as in the coupling region. It also affects the relative timing of the electron and seed laser beams if dispersive optics is used. Since laser optics are naturally chromatic, they must be retuned for any particular wavelength.

In general, retuning the seed laser's wavelength is usually a time and effort consuming procedure. Making tuning range of tens of percents and maintaining the alignment, intensity and timing is a complicated problem. Turning the seed source into a "one-knob" tunable system will require extensive research and development.

Nonetheless, so far the tunable seed is the only known way to alter the HGHG output wavelength. The discussed arguments motivated us to look for an FEL configuration wherein the wavelength of the output radiation could be altered without changing the seed's wavelength.

It was previously proposed to "shift" the FEL output wavelength using combined acceleration and multiple chicane compression of microbunched beam [15]. "Wavelength shifting" scheme in Ref. [15] has two accelerator sections sandwiched between two chicanes located after an undulator where the laser seeding takes place. The wavelength of seed-laser-induced energy modulation is expected to shift to a shorter scale by (a) "overrotation" of the beam in the first chicane; (b) compression along with conversion of energy modulation into microbunching in the second chicane. Since microbunching wavelength is now much shorter, the authors assumed that the electron beam energy must be increased before entering into a second undulator system. Then, after acceleration, the microbunched beam is injected into undulator, two-undulator HG system or HGHG cascade. As an aside, the authors pointed out a possibility of altering the FEL output wavelength by changing the amount of compression in the "wavelength shifting" scheme.

However, careful analysis of the proposed scheme shows that the second chicane would not be able to provide the desired microbunching. In fact, density distribution in the electron beam in this scheme would have almost no bunching content, in opposite to the presented result. This would happen because the "overrotated" phase space of electron beam would evolve towards being even more "overrotated" after the second chicane. Besides, the proposed concept exhibits various feasibility issues. Special attention must be paid to a number of collective effects and aberrations that would destroy useful microbunching in the complicated transport line between undulator systems.

In our paper we present and analyze a different idea of tuning the FEL output wavelength based on a single HGHG cascade [16]. In our scheme, seed-laser-induced energy modulation at a fixed wavelength is compressed in the HGHG dispersion section. Varying amount of energy chirp, one can alter the FEL output wavelength around discrete values given by harmonics of the seed laser. Thus, modulator and radiator are always tuned to harmonically related resonant wavelengths and we do not consider wavelength shift, but smooth wavelength tuning. The wavelength shift to a significantly shorter one in our scheme is realized by amplification of a higher harmonic of seed in the radiator, as in the standard HGHG scheme. However, even though we tune the FEL output wavelength via compression of premodulated electron bunch in the same way as in Ref. [15], we do not use acceleration to shift the wavelength, and, in particular, we avoid "overrotation." In our opinion, this is essential in making the scheme viable.

II. SCHEME OF TUNABLE HGHG FEL EMPLOYING SEED WITH A FIXED WAVELENGTH

Many proposed high-gain FEL schemes utilize a chirped electron beam, i.e., a beam with nonzero energy-time correlation along the bunch. This kind of beam generates chirped output, which can be further compressed using gratings [17] or a monochromator [18]. Recent studies at the DUV FEL [19] demonstrated widening of the HGHG spectrum for a chirped beam without a substantial decrease in the detected power.

For a chirped beam propagating through the HGHG FEL system, we would expect bunch compression in the dispersive section (DS), where the laser-induced energy modulation is translated into density bunching. We describe the motion of the electron with energy deviation ΔE from the beam average energy E (or normalized energy γ and energy deviation $\Delta\gamma$) relative to the light wave by the phase ψ. While passing the DS electron accumulates the phase advance $\Delta\psi = (\partial\psi/\partial\gamma)\Delta\gamma$. Denoting the DS strength as $\partial\psi/\partial\gamma$ (Ref. [4]) and energy chirp as $h=(1/E)(\partial E/\partial z)$, we write for the compression ratio

$$C = \frac{\sigma_{\rm out}}{\sigma_{\rm in}} \approx 1 - R_{56}h, \tag{1}$$

where the DS transport matrix element $R_{56}=(\gamma/k_n)(\partial\psi/\partial\gamma)$, and k_n is the FEL output radiation wave number at the nth harmonic of the seed. We neglected the intrinsic energy spread in Eq. (1), assuming it is small in comparison with the chirp-induced energy spread. Since the whole beam undergoes compression, the laser-induced modulation along the bunch also must be compressed with the same compression factor. Therefore, the prebunched electron beam enters the radiator with a new bunching wavelength $\lambda_C=\lambda_0/C$. Now, having adjusted the beam's energy to a value of $\gamma_C=\gamma_0/\sqrt{C}$ to keep radiation in resonance, we can observe the FEL output after passing through the radiator at a new wavelength λ_C.

For the HGHG tuning range we get

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_C - \lambda_0}{\lambda_0} = R_{56}\cdot h, \tag{2}$$

where, for simplicity, both chirp and R_{56} are assumed to be independent of the energy.

Our recent beam modulation studies [20,21] illustrate the described phenomena. We demonstrated that the space-charge-induced modulation (wavelength of few hundreds of femtoseconds) contracts roughly in compression ratio times during the compression process (Fig. 1). Since a strong mag-

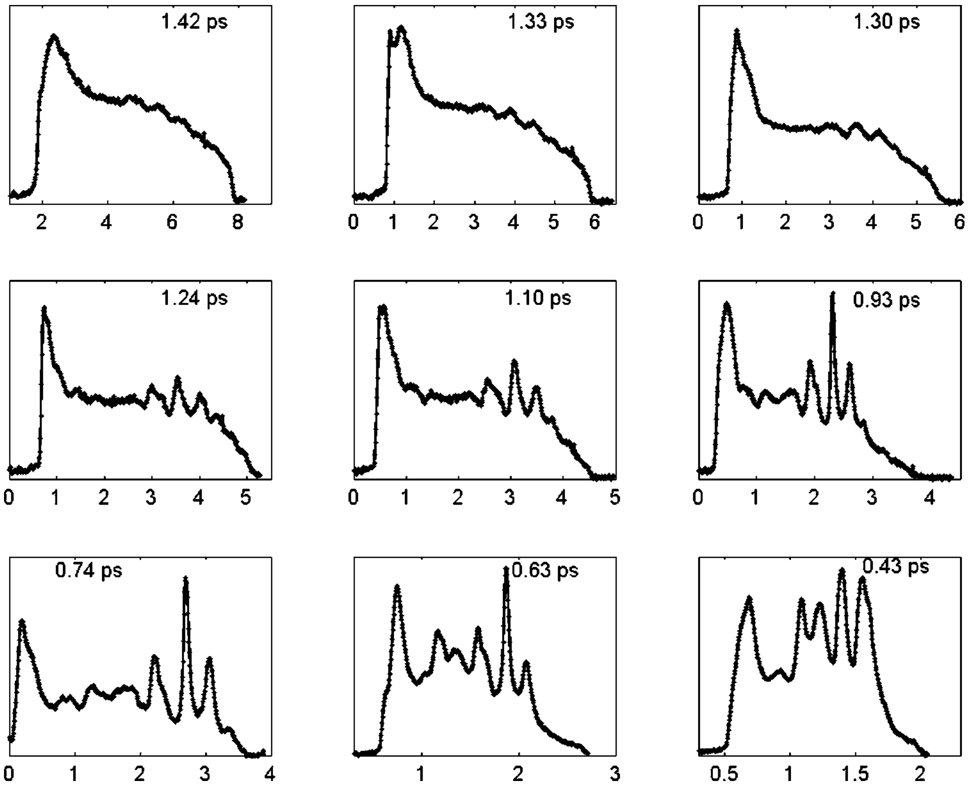

FIG. 1. Evolution of space-charge-induced energy modulation along the electron bunch during compression process [20]. A single plot represents an energy spectrum of the chirped beam (horizontal axis is scaled in picoseconds, vertical axis is in arbitrary units). The parameter printed on each plot is the RMS bunch length. While bunch gets compressed (from left to right and from up to down) the average modulation wavelength, or the average distance between two consecutive spikes, contracts in the compression ratio times (note the change in the time scale on the pictures). The amplitude of the modulation increases due to properties of space-charge force [21].

netic chicane is employed as a bunch compressor, the observed contraction was measured as about 350%. For an FEL, it would be sufficient to provide tunability of the order of a few percent. Using a weak dispersion in DS can complete this operation.

Next we estimate the various limitations of the suggested method, and discuss an optimized scheme that is free from most of them.

III. LIMITATIONS AND OPTIMIZED FEL SCHEME

First, DS strength must be maximized to achieve a large compression ratio. The density bunching after DS [4,22] is given by the following expression:

$$b_n = \exp\left[-\frac{1}{2}\left(\frac{\partial\psi}{\partial\gamma}\sigma_\gamma\right)^2\right]J_n\left(\left|\frac{\partial\psi}{\partial\gamma}\right|\Delta_\gamma\right), \tag{3}$$

where σ_γ stands for the intrinsic energy spread, Δ_γ is the energy modulation induced by the seed laser ($\Delta_\gamma \propto \sqrt{P_L}$), and J_n is the Bessel function of order n. According to (3), to maximize the DS strength, the energy's modulation amplitude must be lowered by decreasing the seed laser's power. Using one of the Bessel function properties we get

$$\left|\left(\frac{\partial\psi}{\partial\gamma}\right)_{\mathrm{opt}}\right| \approx \frac{n+1}{\Delta_\gamma}. \tag{4}$$

(The value of argument, corresponding to the maximum of Bessel function of the nth order, is roughly equal to $n+1$. This holds well for the values of n below 10.) Now, with the reduction in bunching of $\sqrt{e}$ times due to the exponent in (3) the criterion for a minimum value of energy modulation is obtained (5),

$$\Delta_\gamma \geqslant \sigma_\gamma(n+1). \tag{5}$$

This sets a particular limit on the minimum seed laser power in the HGHG scheme. Therefore, the intrinsic energy spread limits the energy modulation amplitude (5) and, in turn, the maximum value of the DS strength in (4). Note, that in the above derivation we neglected the dispersion due to the undulators.

The amount of available chirp is constrained by the beam's energy spread suitable for a FEL. FEL dynamics [23] require that the spread along a single slippage length ($N_u\lambda$) is less than FEL parameter (6),

$$|h_{\max}| < \frac{\rho_{\mathrm{FEL}}}{N_u\lambda}. \tag{6}$$

Also, a very large chirp along the bunch would significantly increase the projected energy spread, which creates difficulties in transporting the beam through the accelerator.

One technical limitation comes from the capabilities of the accelerator RF system. Since this method requires a strong energy chirp, the RF system must be able to provide more than the nominal value of power.

The broadening of the FEL output due to chirped bunch brings a serious disadvantage to this method. The large correlated chirp will generate large linewidth as follows:

$$\frac{\Delta\lambda}{\lambda} \approx 2|h|\sigma_z, \tag{7}$$

where σ_z is the bunch length.

As discussed in the preceding section, the beam energy must be adjusted for a new value of output wavelength $\lambda_C = \lambda_0/C$. This is necessary for providing resonance in the ra-

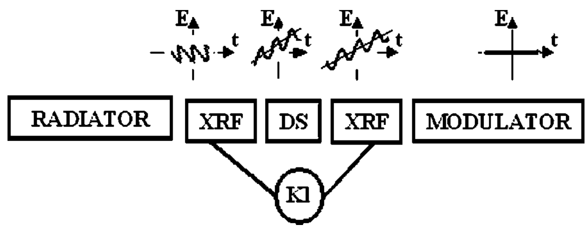

FIG. 2. Scheme of a tunable HGHG with a dedicated RF system. XRF stands for *X*-band RF section, and Kl for klystron(s).

diator. Using the new value of energy ($\gamma_C=\gamma_0/\sqrt{C}$) we calculate the resonance wavelength for the modulator $\lambda_M=\lambda_S C\neq\lambda_S$. Hence, the beam is out of resonance in the modulator. This is not a strong limitation since the modulator's bandwidth ($\Delta\lambda/\lambda\approx 1/N_{\mathrm{per}}$, where N_{per} stands for the number of modulator periods) is usually much wider than that of the radiator. (Usually a modulator has significantly fewer periods than a radiator.) Besides, we expect relatively small deviations in the resonant wavelength ($\Delta\lambda/\lambda\approx 1-C\leqslant 0.1$). However, if necessary, the modulator's gap can be adjusted. This will change K parameter of the modulator and, in turn, change the modulator resonance wavelength.

Thus, FEL dynamics constrains the available range of the dispersion strength and the energy chirp resulting in the limited wavelength tuning range. Most of these limitations can be bypassed in the following way (Fig. 2). A secondary RF system can be added, consisting of two accelerating sections, located before and after the DS. The first RF section imparts a chirp in the beam, which, being compressed in DS, gets unchirped in the second RF section. In this scheme, the chirp is provided only locally thus expunging most limitations for this configuration.

IV. APPLICATION TO THE DUV FEL

As a numerical example, we assume realistic parameters (Table I) for the operation of the DUV FEL [13]. First, we estimate the performance of the less efficient scheme that utilizes the initially chirped bunch.

Currently, the DUV-FEL RF system consists of four 3 GHz linac sections with a total energy gain of 185 MeV.

TABLE I. DUV FEL parameters.

Beam energy (MeV)	175.5
Seed laser wavelength (nm)	800
Seed laser Raleigh range (m)	2.4
Harmonic number	3
Radiator period (m)	0.0389
Radiator length (m)	10
Modulator length (m)	0.8
Modulator period (m)	0.08
Intrinsic energy spread (RMS)	3×10^{-5}
Projected energy spread (RMS)	1.6×10^{-3}
Bunch length (RMS) (ps)	0.5
HGHG pulse length (RMS) (ps)	0.5

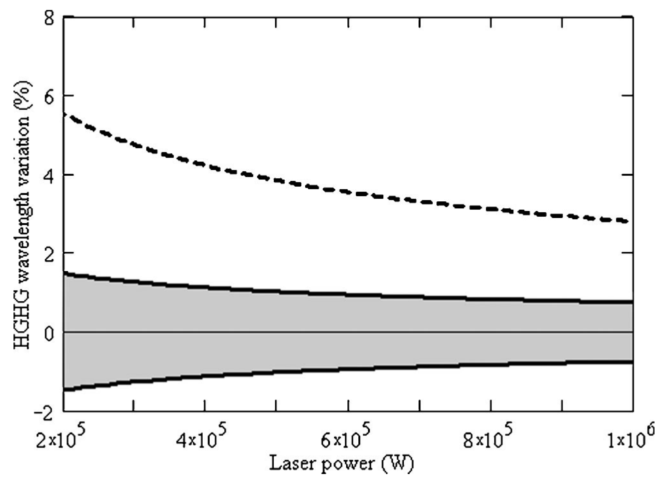

FIG. 3. The plot shows the variation in HGHG wavelength for the optimum strength of the dispersion section. The shaded area represents the range of tunability. The DUV FEL RF system can generate chirps of ± 11 m^{-1}. This determines maximum wavelength range of $\pm1.6\%$ at the minimum laser power of 200 kW. The dashed curve represents the maximum possible chirp (41 m^{-1}), determined by Eq. (6). The beam, seed, and radiator parameters are listed in Table I.

Shifting the beam off-crest in the last section (energy gain of 59 MeV) provides the necessary energy chirp. For FEL experiments with a 266 nm radiation, the electron beam energy should be 175.5 MeV. This constrains the available phase offset by $\arccos\{1-[(185-175.5)/59]\}=33$ degrees. Now, for the energy chirp we obtain

$$h=-\frac{2\pi}{\lambda_{\mathrm{RF}}}\frac{E_{\mathrm{ch}}\sin(\Delta\phi_{\mathrm{ch}})}{E+E_{\mathrm{ch}}\cos(\Delta\phi_{\mathrm{ch}})}=-\frac{2\pi}{0.105\ \mathrm{m}}\frac{59\ \mathrm{MeV}\sin(33°)}{175.5\ \mathrm{MeV}}\approx-11\ \mathrm{m}^{-1}. \quad (8)$$

The maximum DS strength of -0.34 mm is limited by the magnet's properties. The HGHG tuning range can be calculated as $\Delta\lambda/\lambda=hR_{56}=\pm11\ \mathrm{m}^{-1}\cdot-0.000\,34\ \mathrm{m}=\pm0.37\%$, or 0.74%.

Next we estimate the HGHG tuning range, given by Eq. (2), using the semianalytic solution, developed in Ref. [24]. Optimum value of the DS strength for any value of the laser power was found using the approximation of the result of Eq. (3) by the sixth order polynomial with harmonic number, intrinsic energy spread, and energy modulation amplitude as the parameters of the polynomial,

$$\left|\left(\frac{\partial\psi}{\partial\gamma}\right)_{\mathrm{opt}}\right|=\sum_{i=0}^{5}\sum_{j=0}^{5}D_{ij}n^i\frac{\sigma_\gamma^j}{\Delta_\gamma^{j+1}}, \quad (9)$$

where D_{ij} are numerical coefficients that are given in Ref. [24]. We used the optimum value of the DS strength for calculation of the HGHG tuning range, defined by Eq. (2).

Figure 3 represents the dependence of the tuning range on the laser's peak power. By decreasing the seed laser's power [and, consequently, Δ_γ in Eq. (9)], we must increase the strength of the DS to optimize bunching given in Eq. (3). In doing so, the tuning range of the HGHG is increased, as

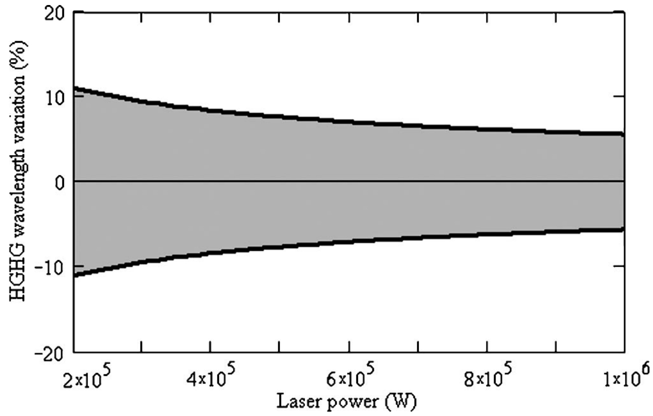

FIG. 4. Variation in HGHG wavelength for different seed laser power, using the scheme with *X*-band RF cavities incorporated into the DUV FEL magnetic system (Fig. 2). The two curves represent the positive (upper curve) and the negative (lower curve) chirps in the first *X*-band RF section. The beam, seed, and radiator parameters are listed in Table I.

shown in Fig. 2. As discussed earlier [Eq. (5)], the sliced energy spread (taken for this example as $\sigma_\gamma/\gamma = 3\times10^{-5}$, Ref. [25]) restricts the achievable value to R_{56}. Substituting $\Delta_\gamma = \sigma_\gamma(n+1)$ into Eq. (5) we get an expression for the maximum value of the DS strength $|(\partial\psi/\partial\gamma)_{\rm opt}| = 1/\sigma_\gamma$ (Ref. [26]). Using this expression we get the maximum value of R_{56} that is equal to -1.33 mm. This corresponds to a minimum laser power of 200 kW (Ref. [24]). Now, with this optimum value of R_{56} and the chirp given by Eq. (8), we obtain the HGHG tunability range of 3.2%.

For the second scheme, one should use the high frequency and high gradient RF structure to shorten the required length of the RF system. As an example, we refer to the NLC-type accelerating section [27–29] (11.4 GHz, 50–100 MV/m) or the CLIC section [30,31] at 30 GHz.

Assuming 1 m long sections with RF frequency of 11.4 GHz and an accelerating gradient of 60 MV/m, the energy chirp is ±82 m^{-1}. In this case, the phase offset is taken as $\Delta\phi_{\rm ch} = 90^\circ$. Using Eq. (2), we obtain a tuning range from -10% to $+10\%$ for positive and negative chirps, respectively. The next figure (Fig. 4) presents the HGHG tuning range for the scheme with *X*-band RF. Relative comparison between Figs. 3 and 4 shows order of magnitude improvement in the tuning range. Besides, in the last case the output HGHG bandwidth is not dominated by the energy spread in the electron beam. We also note that, since the *X*-band sections are short (the section length is less or comparable with the distance between DS and undulators in the existing DUV FEL layout), we do not expect reduction of microbunching while beam travels from modulator to radiator. Collective effects, even though its impact on the beam quality is expected to be negligible, are necessary to take into account in the real design.

V. CONCLUSION

In this paper, we discussed an alternative scheme for a tunable HGHG laser. It employs a separate RF system, located inside the FEL magnetic system. Applying this scheme, a wavelength region of few tens of percent could be covered. Narrow bandwidth, one of the important properties of the HGHG, is preserved. Furthermore, since modern RF technology delivers high-resolution low-level RF systems, the wavelength can be tuned using only “one knob,” and with a precision better than the natural bandwidth of the HGHG.

This technique can be combined with the conventional method of tuning the seed laser’s wavelength. Accordingly, the seed laser’s wavelength can be coarsely adjusted, and then finely tuned using the discussed method. In addition, we recall that in HGHG FEL one can change harmonic number. Thus, the tunability concept that we have developed can be used in combination with conventional methods to vary the wavelength around any harmonic. Assuming a third harmonic of the HGHG at DUV FEL, we get output at 266 nm. For the fourth harmonic, the resonant wavelength is reduced to 200 nm; therefore, harmonic separation is 25%. Now, having tunability of $\pm12.5\%$ around each harmonic, the HGHG FEL can be made completely tunable over a very large spectral range.

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