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GENERATION OF COHERENT SOFT X-RAYS USING A SINGLE-PASS FREE-ELECTRON LASER AMPLIFIER*

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Abstract

We consider a single-pass free-electron laser (FEL) amplifier, driven by an rf-linac followed by a damping ring for reduced emittance, for use in generating coherent light in the soft x-ray region. The dependence of the optical gain on electron-beam quality, studied with the three-dimensional FEL simulation code FELEX, is given and related to the expected power of self-amplified spontaneous emission. We discuss issues for the damping ring designed to achieve the required electron beam quality. The idea of a multipass regenerative amplifier is also presented.

Introduction

In recent years, there has been a growing interest in using a free-electron laser (FEL) for generating intense, coherent, short-wavelength optical radiation [1]-[12]. For optical wavelengths in the extreme ultraviolet (XUV: 10 nm - 100 nm) and the vacuum ultraviolet (VUV: 100 nm - 200 nm) regions, where mirrors with appreciable (>50%) reflectivity are available [5], one may conceive of operating an FEL oscillator in conjunction with either an electron storage ring [1], [2] or an rf-linac [3], [4]. For wavelengths less than about 10 nm, it appears that no such mirrors are available; therefore, the laser oscillator approach is not viable.

An alternative scheme that utilizes the process of self-amplified spontaneous emission (SASE) and involves no mirrors has been suggested [6], [7], [12]. In this scheme, electrons are injected into one end of a long undulator magnet and spontaneous radiation is produced. As the electrons and the radiation propagate together down the undulator, the radiation is then further amplified by the same electrons that emitted the spontaneous radiation. If the electron beam quality is high enough, useful amounts of short-wavelength radiation can be generated. This

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kind of generation method, including SASE and FEL high-gain amplification phenomena, have been previously studied theoretically by assuming zero emittance in the electron beam [6]-[10]. Except for a few studies that assume rectangular [11] (one-dimensional theory) or Lorentzian [8], [10] (two-dimensional theory) distributions among electrons, most results were derived for an electron-beam without energy spread.

In the present work, we make use of analytical results and numerical three-dimensional FEL gain calculations to arrive at approximate requirements on electron-beam current, emittance, and energy-spread values needed to obtain useful amounts of SASE radiation in the soft x-ray wavelength region. Then, the possibility of using a damping ring to achieve these requirements on beam-quality is discussed. Our conclusion is that, in general, it may be very difficult to design an electron damping ring that achieves the beam quality needed for the generation of a 5 nm radiation through SASE using conventional magnetic undulator technology.

Beam Quality Requirements for SASE at 4-6 nm

In Ref. 7, we find that for the initial energy of a single electron E_o and the initial light power spectrum $dP/d\omega|_o$, the power spectrum $dP/d\omega$ of the light generated is

$$\frac{dP}{d\omega} = e^{\tau} S(\Delta\omega/\omega_m)\left[g_A \frac{dP}{d\omega}\Big|_o + g_s \frac{\rho E_o}{2\pi}\right] , \tag{1}$$

where e^{τ} is the gain factor, ω_m is the frequency of maximum gain, $\Delta\omega = \omega - \omega_m$, $S(x) = \exp(-x^2/2\sigma^2)$, g_s and g_A are quantities of order unity and ρ is a characteristic dimensionless parameter to be described in the following paragraph.

In the gain factor, $\tau = 8\pi\mu\rho$N, where N is the number of periods of the constant period undulator, μ is a numerical constant that has the value of $\sqrt{3}/2$ in the one-dimensional case, and the parameter ρ is defined as

$$\rho = \left[\frac{G^2}{32\pi} r_e n_o 2^{3/2}\right]^{1/3} \lambda^{1/2} \lambda_w^{1/6} \left[\frac{a_w^{4/3}}{1+\frac{1}{2}a_w^2}\right]^{1/2} . \tag{2}$$

Here λ_w is the undulator wavelength, r_e is the classical electron radius, n_o is the density of beam electrons, λ is the radiation wavelength at the frequency ω_m, and $a_w = |e| B_w \lambda_w/(2\pi mc^2)$ is the dimensionless vector potential for peak undulator field B_w, where $|e|$ is the electron charge, c is the speed of light, and m is the electron mass. The quantity G in Eq.(2) is the coupling constant for a plane-polarized undulator, which is given by Bessel function factors through the relation $G = J_0(\xi) - J_1(\xi)$ with $\xi = a_w^2/(4 + 2a_w^2)$.

In Eq.(1), the first term represents the amplification of a coherent signal at frequency ω, and the second term represents the effective noise source for SASE. If there is no coherent light present at the entrance of the amplifier, then $\frac{dP}{d\omega}\big|_o = 0$ and integration of Eq.(1) leads to the following expression for the SASE power

$$P_{SASE} = \rho P_{eb} \frac{g_s e^{\tau}}{N_\lambda} \quad , \tag{3}$$

where

$$P_{eb} = I E_o / | e | \quad , \tag{4}$$

and

$$N_\lambda = \frac{2(I / | e | c)\lambda}{\sqrt{\pi}(\Delta\lambda/\lambda)} \quad . \tag{5}$$

In the above equations, I is the peak electron current and $\Delta\lambda/\lambda$ is the fractional full width at e^{-1} of the gain spectrum.

Our procedure for determining the required electron-beam quality proceeds by numerically calculating the gain $g_A e^{\tau}$ and fractional linewidth $(\Delta\lambda/\lambda) = 2\sqrt{2}\sigma$ for a small-amplitude initial coherent optical field using the three-dimensional FEL simulation code FELEX [13]. The SASE power is then evaluated by using Eq.(3) and the assumption $g_s = g_A$. The emittance and energy spread of the electron beam are modeled in FELEX by propagating in three dimensions a large number of simulation electrons whose initial positions and velocities are chosen to statistically sample the beam's initial phase-space volume. FELEX includes the betatron motion of electrons and optical refraction as well as diffraction. The gain spectrum is obtained from a series of calculations for different wavelengths.

In the present work, we assume that the beam electrons have a Gaussian transverse phase-space distribution and the electron beam is "matched" to a curved-pole-face undulator [14] with equal focusing in the two transverse coordinates. For simplicity, we also assume an ideal undulator magnetic field in which field errors have been neglected. Under these assumptions, the peak on-axis electron density n_o is related to the normalized transverse beam emittance [3] ϵ_n by

$$n_o = IB_w/(\epsilon_n mc^3) \quad . \tag{6}$$

Because the expected behavior of this system is dominated by the magnitude of ρ [6], [7], Eq.(1) suggests that high values of ρ will be needed to obtain significant

SASE power. Smaller ρ values not only lower the SASE power but also require longer undulators in which random magnetic field errors may become intolerably large [15]; the amplifier's performance could be further degraded. To allow SASE to reach saturation, one needs an undulator with $N \sim \rho^{-1}$ periods (for a perfect e-beam in 1-D) [6], [7]. This requirement might be reduced if an initial input signal were generated by harmonic emission from a simultaneously operating long wavelength FEL oscillator. With typical undulator parameters and electron energy between several hundred MeV and one GeV, the peak current should be about 200 A and a normalized emittance around $4\pi \times 10^{-4}$ cm·rad for ρ to be in the range of 5×10^{-4} to 10^{-3}.

Following previous work on the properties of an rf-linac-driven XUV oscillator [3], [4], we focused upon a curved-pole-face undulator with the following parameters: wavelength $\lambda_w = 1.6$ cm, peak on-axis magnetic field $B_w = 0.75$ T, dimensionless vector potential $a_w = 1.12$, and coupling constant $G = 0.895$. Hence, we first consider generating radiation at 4 nm using this undulator and an electron beam with $I = 200$ A, $\gamma = 1804$ (921.84 MeV), and $\epsilon_n = 3.9\pi \times 10^{-4}$ cm·rad. With 1000 undulator periods, we could not obtain any useful radiation output at 4 nm. However, increasing the number of periods to 1500 yielded the results shown in Table I in which the performance was calculated as a function of the full width at e^{-1} of the (Gaussian) energy spread $\Delta\gamma/\gamma$.

We then reduced the electron energy to 750 MeV, still retaining the same beam emittance and peak current. The calculated SASE results for the undulator with 1000 periods and 1500 periods are shown in Table II, where L_w is the undulator length.

For the three sets of data presented in Tables I and II, the damping ring design would be strained to achieve even the largest quoted energy spreads. If we solve the FEL resonance condition for λ_w, keeping $B_w = 0.75$ T, $\lambda = 6$ nm, and $\gamma = 1804$, we find that $\lambda_w = 1.986$ cm ($a_w = 1.39$ and $G = 0.863$). This increases the value of ρ to 7.4×10^{-4}, and we obtain the results shown in Table III, where the same beam emittance and peak current as before were used, and the energy spread was varied.

TABLE I

SASE at 4 nm for N = 1500 and $\rho = 5.684 \times 10^{-4}$

$\Delta\gamma/\gamma$	Peak Gain	P_{SASE} (watts)
0	2.4×10^5	2.05×10^6
5×10^{-4}	7.2×10^4	6.26×10^5
1×10^{-3}	5.3×10^3	5×10^4
2×10^{-3}	79	10^2

TABLE II

SASE at 6 nm for $\rho = 6.99 \times 10^{-4}$

$\Delta\gamma/\gamma$	Peak Gain	P_{SASE}(watts)
N = 1000 periods ($\mathbf{L_w}$ = 1600 cm)		
0	2.12×10^4	1.72×10^5
6.5×10^{-4}	7.26×10^3	5.87×10^4
1.3×10^{-3}	7.75×10^2	6.27×10^3
N = 1500 periods ($\mathbf{L_w}$ = 2400 cm)		
0	6.[illegible]8 $\times 10^6$	4.0×10^7
6.5×10^{-4}	1.12×10^6	6.7×10^6
1.3×10^{-3}	2.63×10^4	1.57×10^5

TABLE III

SASE at 6 nm for $\rho = 7.4 \times 10^{-4}$

$\Delta\gamma/\gamma$	Peak Gain	P_{SASE}(watts)
N = 1000 periods (L_w = 1986.08 cm)		
0	4.84×10^4	4.28×10^5
8.5×10^{-4}	8.45×10^3	7.47×10^4
1.7×10^{-3}	3.76×10^2	3.32×10^3
N = 1500 periods (L_w = 2979.12 cm)		
0	2.42×10^7	1.75×10^8
8.5×10^{-4}	1.34×10^6	1.21×10^7
1.7×10^{-3}	7.39×10^3	6.65×10^4

These results show that useful power levels ($\sim 50 - 150$ kW) can be obtained with a 1500-period undulator and an electron beam of 200-A peak current, $3.9\pi \times 10^{-4}$ cm·rad normalized emittance and a fractional energy spread $\Delta\gamma/\gamma$ equal to or slightly larger than twice the value of ρ. However, these conditions, including the long undulator, appear to be very difficult to achieve.

Damping Ring Design Studies

Because existing linac technology for providing the high-quality beam required by an SASE amplifier at 4-6 nm is inadequate, we considered using a damping ring in conjunction with an rf linac. A damping ring is able to reduce the emittance and energy spread of the stored beam without reducing the peak current. However, two major limitations must be overcome to obtain a low emittance, low energy-spread beam with high peak current: first, the microwave instability and second, intrabeam scattering.

We have examined a large range of possible lattice designs for the damping ring, including FODO lattices from 50 to 70 bends and triple-bend-achromat lattices [16] from 8 to 12 periods. All these designs have the property that, to reach a very small emittance, they also have small values of the momentum compaction factor α. Specifically, the lattices that can achieve $\epsilon_n \sim 4\pi \times 10^{-4}$ cm·rad all have a value of α between $5 \cdot 10^{-4}$ and 3×10^{-3}. The Keil-Schnell criterion [17] shows that the threshold current for the microwave instability is proportional to the quotient of α divided by the longitudinal impedance of the damping ring. With the required energy spread of 0.2% and a realistically assumed longitudinal impedance of 1 Ω, the value of α needs to be above 0.04 in order to circulate 200-A peak currents in the ring as required by the FEL physics. Thus, the requirements of small emittance and large current are difficult to achieve simultaneously.

We have also evaluated the effects of intrabeam scattering for particular ring designs by using the computer code ZAP[18]. The emittance growth rate due to intrabeam scattering is proportional to the luminosity of the beam. High luminosity beams need a short damping time and, hence, high damping rate to quench the emittance growth caused by the intrabeam scattering. For the great luminosity needed for soft x-ray SASE, we find that the ring's damping time has to be about 1 ms or less to achieve the required small emittance. In principle, such a short damping time can be achieved by increasing the amount of synchrotron radiation generated per revolution by using more bends and/or a higher bending magnetic field. Unfortunately, this also increases the final energy spread of the electron-beam and degrades the SASE gain.

We have found that the conventional FODO lattice or triple-bend-achromat lattice designs are unable to meet the stringent beam quality requirements of SASE. This conclusion was also the consensus at a recent workshop on low emittance beams [19]. It appears very difficult, if not impossible, to find a damping ring design that produces the required high-quality electron-beam. We are continuing these studies by looking at other possible lattice designs that may circumvent these problems. Meanwhile, we are evaluating the possibility of a multipass amplifier that may have less stringent requirements on the beam quality.

Multipass Soft X-Ray Regenerative Amplifier

The lack of mirrors with retroreflectance greater than 50% (180° redirection of the beam) for wavelength < 10 nm is one of the major reasons for abandoning the laser oscillator approach. The motivation for using a single-pass, high-gain SASE amplifier in the soft x-ray range is also prompted by the difficulty in producing an electron beam with both low emittance and sufficiently high repetition rate. The use of an electron damping ring to reduce the normalized emittance of high-current beams produced by an rf-linac from $\sim 25\pi \times 10^{-4}$ cm·rad to less than $10\pi \cdot 10^{-4}$ cm·rad is limited to pulse repetition rates of ~100 Hz by the damping time of the ring. In this case, even with adequate mirrors, a laser oscillator would require an unrealistically long spacing between resonator mirrors to match the low repetition rate. However, there is an intermediate mode of operation wherein the damping ring could produce bursts of two or three electron bunches at a time for use in a multipass amplifier (MPA). The attractive features of such an MPA would be higher output power and/or reduced undulator length to achieve the desired gain. One may also expect that the severe requirements on electron beams will be relaxed somewhat in an MPA so that the damping ring design can be eased.

The basic requirement for the "resonator" mirrors for a successful MPA would be that they return to the undulator entrance a large enough fraction of the radiation from the first electron bunch to obtain a substantial increase in output power from the second and, possibly, third electron bunches. Even with mirrors with retro-reflectance as low as 10%, the MPA would generate large increases in power over the single-pass device. For a large fraction of the spectral range from 1 to 10 nm, there appears to be a few mirror configurations that would provide this reflectance [20]. An example is a carbon mirror in a multifaceted configuration proposed by Newnam [5]. The output coupling of the radiation would be by a hole in one mirror or alternatively by use of a low-efficiency grating. The diameter of the hole coupler would be designed so that the fraction of radiation transmitted would be very small until stimulated emission caused the substantial spatial narrowing of the beam.

Conclusions

We have determined the required beam quality needed for SASE generation of 4 - 6 nm coherent radiation with a conventional constant-period undulator 1000 - 1500 periods long: $I = 200\ A$, $\epsilon_n = 3.9\pi \times 10^{-4}$ cm·rad, and $\Delta\gamma/\gamma \leq 2 \times 10^{-3}$. We have not yet found a suitable damping ring design that meets these requirements. We are examining new designs to overcome the limitations caused by the microwave instability and intrabeam scattering. We are also looking into possible methods to make a two-pass or three-pass amplifier. This might substantially loosen the requirements on the electron beam quality or undulator length.

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