A Single-Pass Free-Electron Laser for Soft X-Rays with Wavelengths ≤ 10 nm*

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Abstract

We consider a single-pass FEL amplifier, driven by an rf-linac followed by a damping ring for reduced emittance, for use in generating intense coherent light at wavelengths < 10 nm. The dependence of the optical gain on electron beam quality, studied with the 3-D FEL simulation code FELEX, is given and related to the expected power of self-amplified spontaneous emission. Design issues for the damping ring to achieve the required electron beam quality are discussed.

Introduction

The free-electron laser appears to be a promising source of intense, coherent, short-wavelength optical radiation. A substantial amount of theoretical work has been done on laser oscillators driven by either electron storage rings [1], [2] or rf-linacs [3], [4] in order to define the electron beam quality required for generation of light in the extreme ultraviolet (XUV: 10 nm - 100 nm) and the vacuum ultraviolet (VUV: 100 nm - 200 nm). These laser oscillators will operate in spectral regions where mirrors with appreciable (≥50%) reflectivity are available [5]. For wavelengths less than about 10 nm, it appears that no such mirrors are available, and therefore one cannot conceive of operating an FEL oscillator.

An alternative scheme which involves no mirrors has been suggested [6], [7], [14]. In this scheme, electrons are injected into one end of a very long wiggler magnet. The electrons radiate spontaneously and that radiation is itself further amplified by the same electrons as they propagate down the wiggler. This process is termed self-amplified spontaneous emission (SASE). Useful amounts of short-wavelength radiation can be generated if the electron beam quality is high enough.

Previous studies of this generation method [6]-[9] have treated SASE and FEL high-gain amplification phenomena for a zero emittance electron beam. While most results have been derived for an electron beam with no energy spread, some results are available for rectangular [10] (1-D theory) or Lorentzian [8], [9] (2-D theory) energy spreads.

In the present work, we make use of analytical results and numerical 3-D FEL gain calculations to arrive at approximate requirements on electron-beam current, emittance, and energy-spread values needed to obtain useful amounts of radiation via SASE in the wavelength region < 10 nm. Then, the design of a damping ring to achieve these beam quality requirements is discussed. In general, our conclusion is that it may be very difficult to design an electron damping ring which achieves the beam quality needed for the generation of ~5 nm radiation via SASE using conventional magnetic undulator technology.

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Beam quality for SASE at 4-6 nm

We now discuss our procedures to determine the required electron-beam quality. The theory leads to an expression for the power spectrum $dP/d\omega$ of the light generated (Eq. (7) of Ref. 7)

$$\frac{dP}{d\omega} = e^{\tau} S(\Delta\omega/\omega_m)\left[g_A \left.\frac{dP}{d\omega}\right|_0 + g_S \frac{\rho E_0}{2\pi}\right] \quad , \tag{1}$$

where ω_m is the frequency of maximum gain, $\Delta\omega = \omega-\omega_m$, $S(x) = \exp(-x^2/2\sigma^2)$, $\tau = 8\pi\mu\rho N$, and g_S and g_A are quantities of order unity. The first term represents the amplification of a coherent signal at frequency ω with initial power spectrum $\left.\frac{dP}{d\omega}\right|_0$, and the second term represents the effective noise source for SASE (E_0 is the initial energy of a single beam electron). If there is no coherent light present at the entrance of the amplifier, then $\left.\frac{dP}{d\omega}\right|_0 \equiv 0$ and integration of (1) leads to the following expression for the SASE power ($P_{eb} = I E_0/|e|$)

$$P_{SASE} = \rho P_{eb} \frac{g_s e^{\tau}}{N_\lambda} \quad , \tag{2}$$

where

$$N_\lambda = \frac{2(I/|e|c)\lambda}{\sqrt{\pi}\ (\Delta\lambda/\lambda)} \quad . \tag{3}$$

Here I is the electron current, $|e|$ is the magnitude of electron's charge, c is the velocity of light, $\lambda = 2\pi c/\omega_m$ is the radiation wavelength, and $\Delta\lambda/\lambda$ is the fractional full width at e^{-1} of the gain spectrum. The gain e^{τ} is expressed in terms of the number of periods N of the constant period wiggler, a numerical constant μ, which is $\sqrt{3/2}$ in 1-d, and a characteristic dimensionless parameter ρ which can be written as

$$\rho = \left\{ \frac{G^2}{32\pi} r_e n_0 2^{3/2} \right\}^{1/3} \lambda^{1/2} \lambda_w^{1/6} \left[\frac{a_w^{4/3}}{1+\frac{1}{2}a_w^2}\right]^{1/2} \tag{4}$$

Here λ_w is the wiggler wavelength, $a_w = |e|B_w\lambda_w/(2\pi mc^2)$ is the dimensionless vector potential for peak wiggler field B_w, r_e is the classical radius of the electron, and n_0 is the electron density of the beam. G is the Bessel function coupling constant for a plane-polarized wiggler: $G = J_0(\xi) - J_1(\xi)$ with $\xi = a_w^2 / (4 + 2a_w^2)$. For a beam of peak current I with a Gaussian transverse phase space distribution and a normalized transverse emittance [3] ϵ_n, the peak on-axis electron density n_0

can be written as

$$n_0 = I\,B_w/(\epsilon_n mc^3) \quad , \qquad (5)$$

where m is the mass of an electron, and we have assumed a curved-pole-face wiggler [11] with equal focusing in the two transverse coordinates.

The expected behavior of this system is dominated by the magnitude of ρ [6], [7]. We require a peak current I = 200 A and a normalized emittance ϵ_n = 3.9π x 10^{-4} cm•rad for ρ to be in the range 5 - 10 x 10^{-4} (with typical wiggler parameters). Smaller ρ values would require longer wigglers in which random magnetic field errors may become intolerably large [12] and degrade the amplifier's performance. To allow SASE to reach saturation one needs [6], [7] a wiggler of N ~ ρ^{-1} periods (for a perfect e-beam in 1-D) although this requirement might be reduced if an initial input optical signal were available. Such an input signal might be generated by harmonic emission from a simultaneously operating longer wavelength FEL oscillator.

Our procedure is to numerically calculate 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 3-D FEL simulation code FELEX [13]. We then assume that $g_S = g_A$ and use Eqs. (2) and (3) to obtain the SASE power. FELEX models the emittance and energy spread of the e-beam by propagating in 3-D 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 electron betatron motion and optical refraction and diffraction, and a series of calculations for different wavelengths is needed to obtain the gain spectrum.

In previous work on the properties of an rf-linac-driven XUV oscillator [3], [4] we focused upon a curved-pole-face wiggler [11] with the following parameters: wavelength λ_w = 1.6 cm, peak on-axis magnetic field B_w = .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 wiggler and an electron beam with I = 200 A, γ = 1804 (921.84 MeV), and ϵ_n = 3.9π x 10^{-4}cm•rad. With a wiggler length of N = 1000, we could not obtain any useful radiation output at 4 nm. However, extending the length to 1500 periods yielded the results shown in Table I in which the performance is 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 ϵ_n and I. Table II shows the calculated SASE results for two wiggler lengths: 1000 periods and 1500 periods.

For the three sets of data presented in Tables I and II, the ring design would be strained to achieve the largest quoted energy spreads. If we solve the FEL resonance condition for λ_w keeping B_w = .75 T, λ = 6 nm, and γ = 1804, we find that λ_w = 1.986 cm (a_w = 1.39 and G = .863). This increases the value of ρ to 7.4 x 10^{-4}, and we obtain the results shown in Table III. The same ϵ_n and I as before were used and $\Delta\gamma/\gamma$ was varied.

TABLE I

SASE at 4 nm for N = 1500 and ρ = 5.684 x 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 ρ = 6.99 x 10^{-4}

$\Delta\gamma/\gamma$	Peak Gain	P_{SASE} (watts)
a) N = 1000 periods (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
b) N = 1500 periods (L_w = 2400 cm)		
0	6.78×10^6	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 ρ = 7.4 x 10^{-4}

$\Delta\gamma/\gamma$	Peak Gain	P_{SASE} (watts)
a) 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
b) 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 (~50 - 150 kW) can be obtained with a 1500-period wiggler and an electron beam of 200 A peak current, 3.9π x 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. These conditions, including the long wiggler, appear to be very difficult to achieve.

Multipass soft x-ray amplifier

Our initial motivation for a single-pass, high-gain SASE amplifier instead of a laser oscillator for wavelengths ≤ 10 nm was prompted not only by the lack of mirrors with retro-reflectance ≥ 50% (180° redirection of the beam), but also 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 ~$25\pi \times 10^{-4}$ cm•rad to $\leq 10\pi \times 10^{-4}$ cm•rad is limited to pulse repetition rates of ~100 Hz by the damping time of the ring. Even with adequate mirrors, this rate would require an unrealistically long spacing between resonator mirrors. 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 multiple-pass amplifier (MPA). The attractive features of such an MPA would be higher output power and/or reduced undulator length to achieve the desired gain.

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 retroreflectance 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 appear to be a few mirror configurations that would provide this reflectance [15]. 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.

Damping ring design issues

The function of the damping ring is to reduce the emittance and energy spread of the beam without reducing the peak current. Two major limitations must be overcome in order to obtain a low emittance, low energy spread beam with the large peak current required for SASE at 4-6 nm: the microwave instability and intrabeam scattering.

We have examined a large range of possible damping ring designs with the computer code SYNCH [16]. All of these designs have the property that, to achieve a very small emttance, they also need small values of the momentum compaction factor α. The Keil-Schnell criterion [17] shows that the threshold current for the microwave instability is proportional to the magnitude of α. Therefore, one needs a large value of α in order to propagate large peak currents, as required by the FEL physics, in the ring. Hence, the requirements of small emittance and large current are difficult to achieve simultaneously.

We have also used the computer code ZAP [18] to evaluate the effects of intrabeam scattering for particular ring designs. We find that the growth rate for intrabeam scattering is proportional to the luminosity of the beam, and very large growth rates result for beams of the great luminosity needed for soft x-ray SASE. One possible solution of this difficulty is to reduce the ring's damping time and so reduce the time available for this effect. One can reduce the damping time by increasing the amount of synchrotron radiation generated per revolution. Unfortunately, this also increases the final energy spread of the beam.

We have found it very difficult to find a conventional damping ring design that produces the required beam quality. We are continuing these studies by looking at other possible lattice designs which may circumvent these problems.

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