PARAMETER STUDY OF AN X-RAY FEL OSCILLATOR*

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Abstract

An x-ray radiation source based on a free-electron laser (FEL) oscillator was recently proposed as a complementary facility to those based on self-amplified spontaneous emission [1]. Such a source uses narrow-bandwidth Bragg mirrors and a low-emittance, high-brightness electron beam to produce coherent, intense pulses of hard x-ray radiation. We present a study of the FEL oscillator performance and radiation characteristics at several wavelengths using a variety of electron beam and undulator parameters. Our simulations include realistic complex mirror reflectivities calculated from dynamical diffraction, and demonstrate the feasibility of a four-mirror cavity that can provide tunable FEL radiation. We comment on how this concept may be extended to soft x-rays using dielectric multilayer mirrors.

INTRODUCTION

The basic principles of a free-electron laser (FEL) oscillator are well-known (see, e.g., [2]), involving the successive FEL gain of radiation confined in an optical cavity. The first extension of the oscillator scheme to x-rays was suggested by Collela and Luccio over 25 years ago [3], although at that time the electron beam requirements were not well understood, and the scheme remained largely speculative. Recently, a concrete FEL oscillator design for hard x-rays was proposed [1], for which the electron beam has a low emittance ~ 0.1 mm · mrad, while the resonator cavity uses Bragg mirrors that have high reflectivities for x-rays over very narrow bandwidths [4]. Typically, the per pass linear FEL $g \gtrsim 0.3$, while the total power losses in an optimized cavity can be 0.15-0.25. Such a device is predicted to provide Fourier-limited, picosecond x-ray pulses of MW power at repetition rates ~ 1 MHz, thereby serving as a complementary source to those based on self-amplified spontaneous emission, such as LCLS [5].

This paper presents the radiation characteristics for several potential x-ray sources using the 2D FEL code GINGER [6], modified to include the Bragg mirror reflectivity obtained from the dynamical diffraction theory[1]. We present results covering the photon spectral range from 5-20 keV, and also show that a 4-mirror geometry can be used to tune the radiation energy over a range on the order of 5% by adjusting the x-ray angle of incidence on the four mirrors. We remark on using multilayer mirrors to extend the oscillator scheme to produce soft x-rays and then conclude.

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FEL OSCILLATORS FOR HARD AND SOFT X-RAYS

Two-Mirror Cavity

The simplest FEL oscillator design (both conceptually and practically) uses two Bragg crystal mirrors in a near-backscatter geometry, as diagrammed in Fig. 1(a). The thickness of one mirror is tailored so as to couple $\sim 4\%$ of the radiation out of the cavity for use. Typically the single-pass FEL gain is small, so we consider a stable resonator cavity where the focusing is provided by two grazing incidence mirrors. For this study we assume each mirror reflects 95% of the incident radiation in the specular direction. We take the electron beam to be spatially Gaussian, with a longitudinal rms width $\sigma_e = 1$ ps, and a cylindrically symmetric transverse profile described by the normalized emittance $\varepsilon_x = 0.2$ mm · mrad. Additionally, the beam energy spread $\sigma_{\rm E} = 1.4$ MeV and the undulator gap is fixed to be 5 mm; the remaining parameters are chosen to provide sufficient gain to overcome the cavity losses at the central wavelength of the Bragg mirrors, and are listed in Table 1.

The bottom portion of Table 1 list the x-ray properties of the small fraction of the radiation that is transmitted through the thin mirror. Each source provides 10^8-10^9 pho-

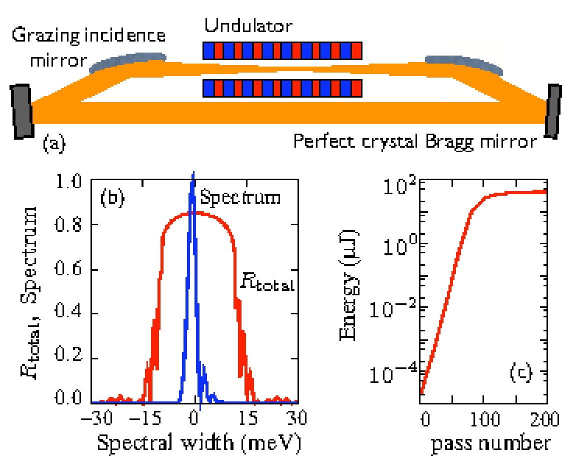

Figure 1: Panel (a) shows a schematic of the FEL oscillator in near-backscatter geometry. Panel (b) shows the band-pass of the diamond mirror near 12-keV (red) and the saturated radiation spectrum (blue) that is transmitted through the thin mirror. These spectra are representative of the various parameters listed in Table 1. Panel (c) shows the initial exponential gain for the 12 keV oscillator, with saturation after 50-200 passes being typical for the FEL configurations listed in Table 1.

Table 1: Possible undulator, beam, and optical cavity parameters. For all cases the transverse emittance $\varepsilon_x = 0.2\,\text{mm}\cdot$mrad, energy spread $\sigma_\text{E} = 1.4\,\text{MeV}$, the rms beam length $\sigma_e = 1$ ps, while the undulator gap is 5 mm. The radiation characteristics in the lower box are for the x-ray pulses that are coupled through the thin mirror out of the FEL cavity.

Parameter	**4.9156 keV**	**5.591 keV**	**12.04 keV**	**14.326 keV**	**19.936 keV**
λ_u (cm)	2.244	1.96	1.76	1.656	1.50
N_u	1000	1500	3000	3000	3000
FEL K	2.50	1.53	1.51	1.322	1.05
E_beam (GeV)	7.0	5.0	7.0	7.0	7.0
I_peak (A)	10.0	20.0	10.0	20.0	20.0
Z_β (m)	4.5	6.0	10.0	10.0	10.0
g_linear	0.32	0.60	0.36	0.55	0.32
R_total	0.84	0.66	0.85	0.80	0.85
Bragg crystal	C(2 2 0)	Si(2 2 4)	C(4 4 4)	Al_2O_3(0 0 0 30)	C(5 5 9)
P_sat (MW)	99.0	22.7	25.8	25.2	12.9
spectral width (meV)	2.89	2.16	1.29	2.54	0.80
$\Delta t\Delta\omega$	2.25	1.38	1.01	2.90	1.14
photons/pulse	4.6×10^9	6.0×10^8	1.1×10^9	6.2×10^8	3.6×10^8

tons with a peak power $P_\text{peak} \sim 1$ MW, corresponding to FEL saturation at a peak intercavity power $P_\text{sat} \gtrsim 10$ MW. Furthermore, the spectral width of the radiation is of order a few meV, which is much smaller than the bandwidth of the Bragg mirrors as shown in Fig. 1(b); while this plot uses data from the 12-keV oscillator, the results are typical. Additionally, the time-spectral product $\Delta t\Delta\omega$ is close to the Fourier limit $1/2$, and the peak spectral brightness is 0.6-2.7$\times10^{32}$ photons/[s(mm $\cdot$ mrad)^2(0.1% bndwth)].

The oscillators in Table 1 explore three possible materials for the Bragg mirrors: diamond, silicon, and sapphire. While all of these materials appear to provide suitably high reflectivity to facilitate FEL gain, one must also consider the heat loading due to photoabsorption and the resulting differential crystal expansion and shifting of the peak Bragg reflectivity. The relatively high absorption in silicon may make the heat loading difficulties insurmountable, while the material properties of sapphire are more favorable. In this respect, the low absorption, high thermal conductivity, and low coefficient of thermal expansion make diamond an ideal candidate for the Bragg mirrors of an FEL oscillator, and we specialize to diamond cavities for the tunable, four-mirror source in the next section.

The Four-Mirror Cavity: a Tunable X-ray Source

The near backscatter geometry of the previous section is relatively simple, requiring the careful alignment of only two Bragg mirrors. However, the tuning range in this geometry is limited to the few-meV range of the mirror bandwidth, since for $\theta \approx 0$ Bragg's law $\lambda = 2d\cos\theta$ is nearly independent of the incident angle θ. To increase the tuning range of the FEL, Ref. [7] proposed a four-mirror geometry as shown schematically in Fig. 2(a). By simultaneously tilting all the mirrors and adjusting the radiation path length, one can change the central wavelength of peak reflectivity while keeping the round-trip transit time constant. In this case, the total reflectivity of the four mirrors is narrowly peaked in the θ-λ plane as shown in Fig. 2(b). Thus, the Bragg mirrors filter the radiation in both frequency and angular space; to minimize the latter effect we use a collimating mirror after the FEL to decrease the angular spread of the x-rays from 1 μrad to 0.25 μrad, for which the Bragg crystal reflectivity is nearly constant. Then, the mirror to the left of the undulator in Fig. 2(a) focuses the beam back to 1 μrad divergence to maximize the FEL gain.

We list the parameters for three different tunable sources of 10-20 keV photons in Table 2. In this case, we have fixed the beam energy $E_\text{beam} = 7$ GeV, current $I_\text{peak} = 20$ A, and energy spread $\sigma_\text{E} = 1.4$ MeV, while the number of undulator periods $N_u = 3000$. Because the gain is reduced as the four-mirror bandwidth becomes comparable to that associated with the electron beam $\sim 1/\sigma_e$, we have chosen the emittance and other parameters to assure that the single-pass, steady-state gain g_lin is fairly large.

The transmitted radiation characteristics listed in the lower portion of Table 2 are quite similar to those from Table 1: the x-ray pulses contain $\sim 10^9$ photons in a nearly Fourier-limited spectral range ~ 1 meV. We observe net gain for a photon energy range $\pm3\%$ of that used in Table 2. Because the crystal planes are at an angle from the surface (i.e., asymmetric), however, the radiation can only be effectively out-coupled for variations of the photon energy $\sim\pm1\%$. One can increase this range by either varying the thickness of the thin mirror or by orienting the crystal planes to be more parallel to the surface.

Multilayer Mirror Cavity for Soft X-rays

The x-ray FEL oscillator can be extended to the extreme ultraviolet/soft x-ray regime by replacing the Bragg crystals with multilayer mirrors[2] whose reflectivity is peaked between 50 and 500 eV. The manufacture of multilayer mirrors for this energy range is presently an area of ac-

[2] We thank E. Gulliksen for discussions on multilayer mirrors.

Table 2: Possible undulator, beam, and optical cavity parameters for the 4-mirror, tunable FEL. For all cases the electron beam energy $E_{\text{beam}} =$ 7 GeV, current $I_{\text{beam}} =$ 20 A, energy spread $\sigma_{\text{E}} = 1.4$ MeV, the rms beam length $\sigma_e = 1$ ps, while $N_u = 3000$ and the undulator gap is 5 mm. The cavity is chosen to be 100 m long and the focusing parameter Z_β = 10 m. The lower box contains radiation characteristics of the x-ray pulses that are couple through the thin mirror assuming 4% transmission.

Parameter	9.03 keV	14.23 keV	20.66 keV
λ_u (cm)	1.76	1.656	1.50
FEL K	1.51	1.322	1.05
ε_x (mm · mrad)	0.2	0.2	0.1
g_{linear}	0.86	0.58	0.56
R_{total}	0.85	0.80	0.85
Bragg crystal	C(4 4 4)	C(3 3 3)	C(3 3 11)
Tuning range	6.2%	6.0%	3.5 %
P_{sat} (MW)	88.2	59.7	33.3
Spectral width (meV)	1.36	1.32	0.583
$\Delta t \Delta\omega$	1.35	1.19	0.65
photons/pulse	4.4×10^9	1.5×10^9	4.3×10^8
P_{peak} (MW)	3.5	2.4	1.4

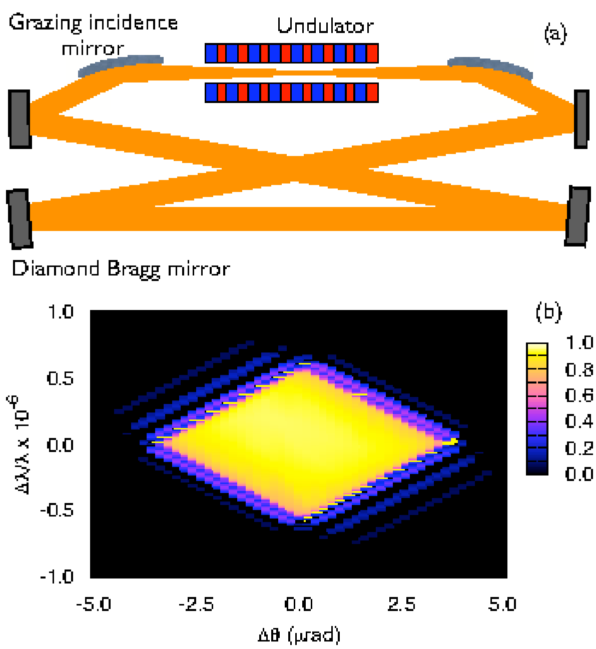

Figure 2: Panel (a) shows a schematic of the 4-mirror tunable FEL oscillator cavity. By simultaneously adjusting the incidence angle θ on all four mirrors one can change the FEL wavelength according to Bragg's Law $\lambda = 2d\cos\theta$. The resulting 4-mirror reflectivity is narrow in both energy and angular acceptance as shown in (b), which is an example taken at $\theta = 15^\circ$ for the C(3 3 7) reflection operating near 14 keV. Note that the angular acceptance is still significantly larger than that of the collimated beam, whose divergence ~ 0.25 μrad.

Table 3: Soft x-ray FEL oscillator using multilayer mirrors. Here, we fix $\lambda_u = 2$ cm, $N_u = 500$, $K \approx 1$, $\sigma_e = 50$ fs, and $\sigma_{\text{E}}/E_{\text{beam}} = 0.1\%$.

Parameter	100 eV	400 eV
ε_x (mm · mrad)	0.8	0.3
I_{beam} (A)	160.0	500.0
mirror material	Mo/Si	Cr/Sc
R_{total}	0.45	0.0225
P_{sat} (MW)	180	100
Spectral width (meV)	37.9	83.9
Temporal width (fs)	32.1	21.2

tive research, and current technologies have obtained peak reflectivities between 10% to 70%, depending on the material and energy range [8]. In order to overcome the higher losses, the single-pass FEL gain must be greater than one, so that the oscillator dynamics is closer to that of a regenerative amplifier. We sketch two possible soft x-ray sources using a 500-period, $\lambda_u = 1$ cm undulator and a 50 fs electron beam in Table 3. The near backscatter geometry resembles that of Fig. 1, although focusing multilayers may obviate the need for grazing incidence mirrors. The values in Table 3 indicate narrow bandwidth, fs pulses of soft x-rays, with peak intercavity power $\gtrsim 100$ MW.

CONCLUSIONS

We have detailed a number of possible electron beam, undulator, and Bragg crystal parameters that can be used to produce hard x-rays in the energy range 5-20 keV, based on a low-current, high-brightness beam. The resulting useful radiation provides $\sim 10^9$ photons in nearly Fourier-limited pulses whose spectral width is a few meV. Similar x-ray characteristics can also be produced with a four-mirror geometry that can tune the energy by a few percent. Finally, the oscillator concept can be extended to the 50- to 500-eV range by replacing the Bragg crystals with multilayer mirrors, to produce fs pulses of spectrally narrow soft x-rays.

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