X-ray FEL in a Small Emittance Storage Ring

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Abstract

It is shown that an X-ray FEL using a single crystal optical resonator with a normal Bragg reflection in a storage ring endorsed with a small emittance and narrow energy spread electron beam can have an FEL gain of 24 % at a wavelength of 0.206 nm, which is higher than the cavity loss. It is also shown that the gain is enhanced by a factor of 4 in the SASE regime.

1 Introduction

By the recent progress of a photo-cathode RF gun to generate a very small emittance and highly intense electron beam, a single pass X-ray FEL(SASE) using a high energy linac, as high as 10~15 GeV, is becoming a realistic subject. The emittance decreases as the increase of the beam energy. Main cause of the trend is not only because of the progress of the RF-gun, but also because of the lack of a high reflective mirrors in X-ray region.

Previously, we have noticed that a high reflectivity of X-rays can be obtained by the Bragg reflection with a single crystal, and a high peak current and a small emittance, as small as 46 prad-m, of electron beam can be obtained in a storage ring fairly modified from the SPring-8 storage ring [1]. It was also shown that the FEL gain at a wavelength of 0.217 nm can be higher than the mirror loss at a beam energy of 3 GeV.

In the present paper, a further consideration on the optical cavity FEL in the X-ray region is discussed.

2 Optical resonator FEL with Bragg reflection

Previously, we have assumed a Bragg reflection at an angle of $\theta=\pi/4$ of a pure Si single crystal. The reflectivity at the FEL wavelength of 0.217 nm is expected as high as 90 %. The high reflectivity is, however, limited in a narrow angle region about 10 μrad, and the reflected wave suffers a phase change from $-\pi$ to π depending on the reflection angle in the full width of the high reflective angle region. Thus, the ring resonator with the Bragg reflection is not appropriate as the optical cavity for the FEL.

In the course of this study, it was noticed that the Bragg reflection at $\theta=\pi/2$ is also very high even in a much wider angle range about a few mrad. This property has already been investigated theoretically for an application to a high resolution X-ray monochrometer by the use of a Fabry-Pellow resonator [2, 3, 4]. It is expected that the phase shift of the reflected wave is π and nearly constant around the center of the normal reflection.

Table 1 X-ray FEL and undulator parameters

Wavelength	λ	0.2059	nm
Beam energy	E	2.94	GeV
Peak current	I_p	1200	A
Electron beam size	$\sigma_{x,y}$	11	μm
X-ray wave size	w_0	31	μm
FEL gain	G	24	%
Optical cavity loss	δ	20	%
Undulator			
Period	λ_0	13	mm
Gap height	g	8	mm
Peak field	B_0	0.248	T
K value	K	0.301	
Number of periods	N_u	300	
Total length	L_u	3900	mm

To stand against a high heat load of the X-ray FEL, we prefer the use of a diamond crystal (the unit cell length is a=0.356688 nm) because of a high thermal conductivity (1000~2000 W/m/K) and a small thermal expansion coefficient (0.8×10^{-6}/K). A reflection as high as 90 % can be obtained by the Bragg angle reflection in the wavelength region shorter than 0.3~0.4 nm, so we select tentatively (111) plane reflection at a wavelength λ=0.2059 nm. Figure 1 shows schematically the FEL system made of the single crystal optical resonator with a

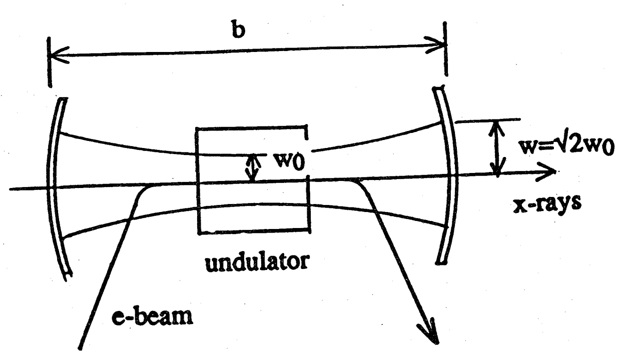

Fig.1 Schematic FEL system and radiation wave size.

Table 2 Small emittance storage ring parameters

Beam energy	E	3	GeV
Circumference	C	1440	m
Periodicity	p	24	
Natural emittance	ε_{x0}	46	pm-rad
Compaction factor	α_p	5.68x10-5	
Radiation energy	U_0	235	keV
Energy spread	ε_E/E	6.23x10-4	
Tune	ν_x	84.40	
	ν_y	68.45	
	ν_s	1.39x10-3	
Natural chromaticity	ξ_x	-124.9	
	ξ_y	-106.0	
Damping time	τ_x	65	ms
	τ_y	123	ms
	τ_ε	111	ms
Revolution frequency	f_0	208.2	kHz
Harmonic number	h	2442	
RF frequency	f_{RF}	508.42	MHz
RF voltage	V_{RF}	351	kV
Bucket height	$\Delta E_{max}/E$	1.0	%
Bunch length	σ_τ	20	ps
Average current	I_0	10	mA/bunch
Number of bunches	N_b	48	
Bending magnets (per cell)			
Bending field	B	0.3272	T
n-value	n	1041.96	
Bending radius	ρ	30.558	m
Magnets length (number)	l_B	0.8(9), 0.4(2)	m
Number of bends	N_B	264	
Quadrupole magnets			
Field gradient	B_y'	≤ 16	T/m
Magnet length (number)	l_Q	0.8(8), 0.6(4), 0.3(6)	m

confocal radius R=b=30 m, where b is the mirror distance. The radiation wave size of the Gaussian distribution of intensity is $w_0=(\lambda b/2\pi)^{1/2}=31.4$ μm at the center of the cavity and $w=\sqrt{2}w_0=44.3$ μm at the surface of the mirror. Thus, the divergence of the radiation at the position of the mirror is only about 1.4 μrad, which is much smaller than the width of the high reflection angle range. Table 1 represents the parameters of the FEL and undulator, which was estimated from the parameters of the storage ring described below.

We have previously made a design consideration of a small emittance storage ring, which is modified from the SPring-8 storage ring in such a way that the beam energy is reduced from 8 GeV to 3 GeV, and the number of bending magnets is increased from 88 to 264. This modification reduces the emittance from 6 nrad-m to 46 prad-m. The storage ring parameters are given in Table 2. The emittance $\varepsilon_{x,y}(=\varepsilon_{x0}/2)$ is close to the diffraction limit $\lambda/4\pi$(=16 prad-m), and the energy spread is much smaller than the undulator radiation width $1/(2N_u)$ (=1.7×10^{-3}), which are the necessary conditions for the FEL oscillation as well as the gain>loss relation.

3 Gain enhancement

In the previous section, the gain was estimated on the assumption that the increase of the radiation power is very small, so that the power is almost constant in one pass through the undulator. This is the so called Compton regime. However, the estimated gain is 24 %. Therefore, it is necessary to take into account the increase of the radiation power. The SASE theory [5] can be applied when the emittance of the electron beam is approximately smaller than the radiation limit, which is satisfied in the present case as mentioned before. In this case the power increases as $P=P_0\exp(4\pi N_u\rho)$, and the gain is given by $G_s=\exp(4\pi N_u\rho)-1$. Here, ρ is the Pierce parameter given by

$$\rho=[(K/4)(<\gamma_0>/\gamma_r)^2(\Omega_p/\omega_0)]^{2/3}$$

where $<\gamma_0>$ and γ_r are the average and resonance energy of the electron beam, Ω_p is the plasma frequency and $\omega_0(=2\pi c/\lambda_0)$ is the undulator frequency. The plasma frequency is given by

$$\Omega_p=[n_0e^2/\varepsilon_0 m_e<\gamma_0>^3]^{1/2}$$

with n_0, the electron density, e, the electron charge, ε_0, the dielectric constant in vacuum and m_e, the mass of electron. Using the same parameters of the undulator and the electron beam given in Tables 1 and 2, we obtain the parameters for the FEL in the SASE regime shown in Table 3, and the gain is G_s=0.95 %. Thus, the gain is enhanced about 4 times. We cannot, however, expect a higher gain with a longer undulator since the energy spread is larger than the Pierce parameter.

Table 3 Parameters for SASE regime

Wavelength	λ	0.20	nm
Number of electrons per bunch	N_e	3.0×10^{11}	
Electron density	n_0	1.3×10^{23}	
Plasma frequency	Ω_p	4.4×10^{7}	Hz
Undulator frequency	ω_0	1.4×10^{12}	Hz
Pierce parameter	ρ	1.8×10^{-4}	
Enhanced gain	G_s	95	%

4 Conclusion

In the present paper, we have investigated the possibility of X-ray FEL at a wavelength of 0.206 nm on the assumption of a storage ring with a small emittance and a small energy spread of the electron beam. We have assumed an optical resonator with a normal Bragg reflection by a single crystal, with which a high reflectivity in a wide angle range can be expected. Estimated FEL gain is 24 % in the Compton regime, and enhanced to 95 % in the SASE regime, which is much higher than the mirror loss. In spite of the crude estimation, the present investigation is very encouraging for promoting detailed investigations of the storage ring FELs.

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