POSSIBILITY OF X-RAY FREE ELECTRON LASER WITH SINGLE CRYSTAL OPTICAL RESONATOR FOR BRAGG REFLECTION

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Abstract

Noting the X-ray reflection coefficient of a single crystal as high as 90 % at a Bragg angle, a possibility of X-ray free electron laser in a storage ring was investigated. An optical resonator composed of four Si single crystal mirrors with diffraction angle 45 degrees provides a light beam size in the optical resonator about 30 μm rms at a wavelength of 0.217 nm. Assuming an electron beam emittance of 46 pm-rad at a beam energy of 3 GeV, and a peak current of 1200 A, we obtain an FEL gain of 39 % for an undulator with a number of periods of 300, which is slightly higher than the radiation loss in the mirrors. At the same time a conceptual design of a storage ring with such a small emittance beam is presented.

1 INTRODUCTION

Free electron laser using an electron beam has attracted a strong concern to produce an intense coherent radiation in a wide range of wavelength. Many efforts have realized FEL's in the wavelength longer than about 200 nm with the aid of a high reflective optical resonator, but not in a shorter wavelength. This is because the reflectivity of light with mirrors is very low in the shorter wavelength. Thus, efforts have been made to develop high reflective mirrors made of multilayers. One of the ways to avoid this difficulty is a high gain single pass FEL or SASE [1]. A rapid progress of RF photo-cathode gun made it possible to produce a high quality electron beam, and a SASE even in X-rays has become a realistic subject, for which, however, a high quality linac with an energy about 10 GeV equipped with a bunch compression system is needed to produce an electron beam emittance compromising a diffraction limit in the order of 10^{-11} rad-m.

Meanwhile, recent progress in storage rings for synchrotron radiation has realized a beam emittance around several nm-rad at an energy of 6~8 GeV. Discussions have started as for the next generation light source with an emittance of sub nm-rad [2, 3]. Such a light source equipped with a number of insertion devices is expected to become a practical tool in a near future. It is noted that the gap height of insertion devices has already been reduced to 10 mm in X-ray storage rings, so that X-rays can be generated with insertion devices at a beam energy about 3 GeV. In addition, it is noted that X-rays can be reflected by 90 % at a Bragg angle with a single crystal [4], which is much stronger agaist heat load than multilayers. Thus, a possibility of an X-ray FEL using a single crystal resonator was first investigated. Apart from the FEL issues discussed here, a storage ring with an emittance smaller than the diffraction limit is in itself very interesting, because the brilliance of undulator radiation increases quadratically as for the number of undulator periods.

In this paper, a crude discussion is presented as for a possibility of an X-ray FEL equipped with a single crystal resonator for Bragg reflection, including a design of a small emittance ring.

2 OPTICAL RESONATOR

By the improvement of crystal perfectness, a single crystal can have a reflection coefficient of 90% at a Bragg angle for X-rays shorter than a few nano-meters. Suppose an optical resonator composed of four Si single crystals (unit cell length is 0.5431 nm) facing each other at 45 deg and separated by 1 and 29 m as shown in Fig.1. The mirror center on the beam axis is away from the electron beam orbit by about 50 cm in the case of a storage ring discussed later. The wavelength λ=0.217 nm is well reflected by the crystal plane (222). Assuming a confocal type of mirrors, we obtain a radiation size ω_0=32 μm at the center between the mirrors and 46 μm at the mirror surfaces. Horizontally polarized radiation generated by the undulator or by the FEL interaction in the optical resonator is reflected in the vertical direction, so that the electric field vector of the radiation is parallel to the mirror surfaces to give the high reflectibity. The reduction of the light pulse intensity per one circulation in the resonator is 34%, so that the FEL gain should be higher than this value. Practically, a high stability of the mirrors is required since the sizes of the radiation and electron beams are very small. To make a confocal mirrors with single crystals might not be easy. Combination of two pairs of mirrors, toroidal and plane, in two directions relaxes this difficulty. Possibly, two-mirror system is better than the four-mirror system.

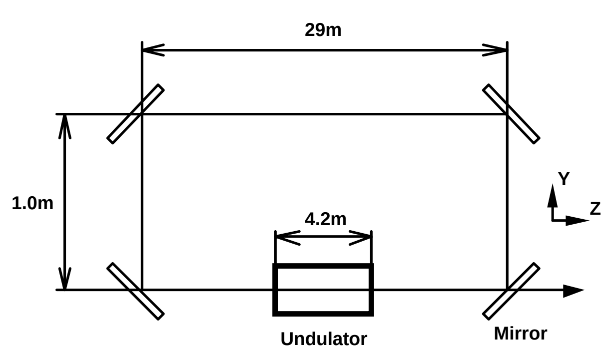

Fig.1 Optical resonator made of single crystals for FEL

3 UNDULATOR

The peak field of the Halbach type undulator is expressed as

$$B_p=2B_r \frac{\sin(\pi/4)}{\pi/4} \exp\left[-\frac{\pi g}{\lambda_0}\right]\left[1-\exp\left(-\frac{2\pi h}{\lambda_0}\right)\right]$$

We get B_p=0.284 T for the remanent field B_r=1.2 T with the gap height g=8 mm, the undulator period λ_0=1.4 cm and the block height $h=\lambda_0/4$, so that $K=0.934B_p\lambda_0$ =0.371. This undulator generates the radiation wavelength λ=0.217 nm at a beam energy of 3.0 GeV. Higher harmonic components of the undulator radiation are weak because of the smaller value of K than 1.

4 FEL GAIN

The FEL gain in the small signal regime is given by

$$G=32(2)^{1/2}\pi^2(\lambda^3 \lambda_0)^{1/2} \zeta(K)\frac{I_p}{I_A}\frac{N_u^3}{\Sigma\eta}F(\xi)$$

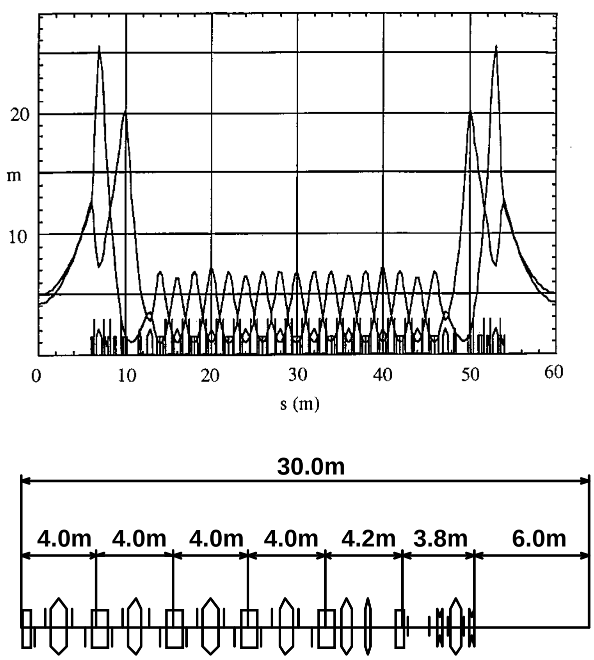

Fig.2 Half unit cell (bottom) and lattice function in a unit cell of the storage ring

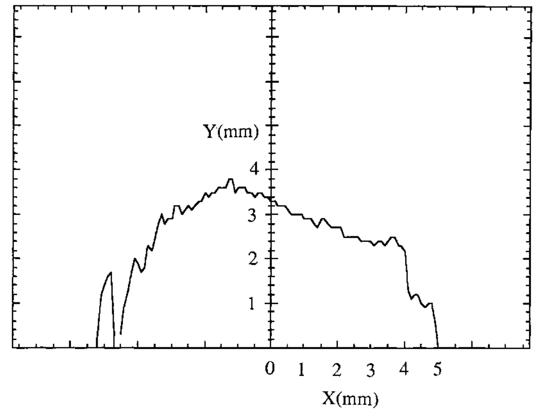

Fig.3 Dynamic aperture of the storage ring

where $\zeta(K)=K^2/2/(1+K^2/2)^{3/2}$, Ip is the peak current, I_A(=17000 A) is the Alfen current, Σ is the cross section of the electron beam, h is the filling factor, and $F(\xi)$ is the gain function. In the storage ring discussed later, we have the natural emittance of electron beam ε_x=46 pm-rad at 3 GeV and the beta function $\beta_x^* \approx \beta_y^* \approx 5$ m in the center of the straight section for the undulator. Assuming a full coupling of horizontal and vertical betatron oscillations, we have the beam size $\sigma_x \approx \sigma_y \approx 11$ μm, so that $\Sigma=\pi\sigma_x\sigma_y \approx 3.6\times10^{-10}$ m^2, and $\eta=(\omega_0/\sigma_{x,y})^2=8.5$.

To get a sufficiently high gain in the gain function, the number of the undulator periods should approximately satisfy the following relation, N_u $<1/(2\pi\sigma_E/E)$, where σ_E/E is the relative energy spread and given by $\sigma_E/E=6.23\times10^{-4}$. Therefore we assume N_u=300, with the undulator length L_u=4200 mm, for which we have $F(\xi)\approx0.06$. Substituting these values and Ip=1200 A into the gain equation, we obtain G=39%, which is slightly higher than the radiation loss.

5 SMALL EMITTANCE STORAGE RING

To fit to the tunnel of the SPring-8 storage ring with the circumference 1436 m and the periodicity 48, we considered a ring with almost the same circumference and a periodicity of 24. The unit cell of the ring consists of 8 normal cells sandwitched with dispersion suppressors and tune correctors as shown in Fig.2. Two bending magnets of rectangular type with defocusing field and a focusing quadrupole magnet constitute the normal cell, where focusing and defocusing sextupole magnets are installed to suppress the chromaticity. The field gradient in the bending magnets is rather weak as -11.16 T/m, which reduces the bending field as low as 0.327 T. The lattice function is shown in Fig.2. The dispersion function is less than 0.045, which produces the small emittance given above. The dispersion is suppressed to zero with two quadrupole magnets in the suppressor. The straight

Table 1 Storage ring parameters

Beam energy	E	3	GeV
Circumference	C	1440	m
Periodicity	p	24	
Natural emittance	ε_x	46	pm-rad
Compaction factor	α_p	5.68×10^{-5}	
Radiation energy	U_0	235	keV
Energy spread	ε_E/E	6.23×10^{-4}	
Tune	ν_x	84.40	
	ν_y	68.45	
	ν_s	1.39×10^{-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	24	
Peak current	I_p	1200	A
Bending magnets			
Bending field	B	0.3272	T
n-value	n	1041.96	
Bending radius	ρ	30.558	m
Magnet length	l_B	0.8, 0.4	m
Quadrupole magnets			
Field gradient	$B_{y'}$	≤ 16	T/m
Magnet length	l_Q	0.8, 0.6, 0.3 m	

section for insertion devices is as long as 12 m for a higher brilliance, which needs rather large peak values of the beta functions. The chromaticity is reduced to zero with focusing and defocusing sextupole magnets installed in the normal cells. The dynamic aperture is as narrow as several mm, as shown in Fig.3.

6 CONCLUSION

In the present paper, we have crudely discussed a possibility of an X-ray FEL in a small emittance ring equipped with a single crystal optical resonator for Bragg reflection. The estimated gain is slightly higher than the radiation loss. There are, however, several subjects such as bunch lengthening, intra-beam scattering and others not considered here yet, which might decrease the gain. Nevertheless, the results obtained here are encouraging to make a further optimization of the FEL system and storage ring, and it is also necessary to consider the beam dynamical issues.

Another important result of the present investigation is the design of the storage ring with an emittance as small as 46 pm-rad at a beam energy of 3 GeV, which is close to the diffraction limit of X-rays. Although the dynamic aperture is very small, it is not beyond practical operation. There are many things to be discussed further, which will be presented elsewhere.

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