OPTIMIZATION OF THE NIJI-IV FEL SYSTEM FOR THE COHERENT HARMONIC GENERATION IN A Q-SWITCHED REGIME

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Abstract

The Coherent Harmonic Generation (CHG) in the VUV region at the storage ring NIJI-IV has been numerically investigated. The harmonic radiation is produced in an FEL oscillator with a hole-coupled resonator including a 6.3-m optical klystron ETLOK-II. The evolution of light pulses through Q-switched FEL process is simulated using the code GENESIS1.3 and its extended version. The parameters of the NIJI-IV FEL system were optimized for electron-beam energy and optical cavity configurations.

INTORODUCTION

Several works on harmonic generation in storage ring FELs (SRFELs) have been experimentally and theoretically performed [1-9]. In the previous work [9], we have made simulation code for investigation the harmonic generation with a hole-coupled resonator combined with a 6.3-m optical klystron ETLOK-II [10]. In this paper the optimization of the NIJI-IV FEL system is studied by means of the code.

OUTLINE OF SIMULTAION

The detail of simulation procedure was described in Ref.[9] and this section presents the outline: The FEL process in an optical klystron ETLOK-II is simulated using the code GENESIS1.3 [11]. In SRFELs the electron energy spread induced by the FEL interaction accumulates from turn to turn. This code includes the energy spread growth which was calculated by GENESIS1.3. The optical field emitted from ETLOK-II is reflected by a hole-coupled resonator. The paraxial wave equation

$$\left(\Delta_\perp + 2ik_s \frac{\partial}{\partial z}\right) a_s e^{i\phi} = 0 \qquad (1)$$

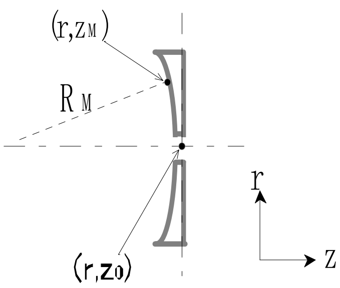

Figure1: Definition of mirror geometry

was used for the calculation. The reflected field $a_{ref}(r, z)\, exp(-ik_s z)$ can be expressed in the incident field $a_{inc}(r, z) exp(ik_s z)$ in approximation of $k_s R \gg 1$ as

$$a_{ref}(r,z_0) = \left[a_{inc}(r,z_0) - \frac{ird_r rd_r}{2k_s R_M} a_{inc}(r,z_0) - \frac{r^2}{R_M^2} a_{inc}(r,z_0) - \frac{r^3 d_r}{R_M^2} a_{inc}(r,z_0) + \frac{ik_s r^4}{R_M^3} a_{inc}(r,z_0) \right] \exp(2ik_s z_M) \qquad (2)$$

Here the surface of a spherical mirror with radius of curvature R_M was parameterized as $z_M = z_0 - r^2/2R_M$, as shown in Fig. 1, and the last four terms in Eq.(2) can be neglected for NIJI-IV. In this simulation, the reflection of a hole on the mirror axis was assumed a smooth-edge function as $R(r)=2(r/R_a)^4-(r/R_a)^8$. The effective radius of the hole, $R_{eff} = 0.74R_a$, is defined as the radial position where the reflection R becomes 0.5 [12].

The coherent emission from the number of electron N_e in the straightforward direction at the harmonic n [7,8] was evaluated by

$$\frac{d^2 I_n}{d\omega d\Omega} = \frac{1}{2} N_e^2 a_n^2 \frac{d^2 I_0}{d\omega d\Omega} \qquad (3)$$

where

$$a_n = 2J_n\left(4\pi n N_d \frac{\Delta\gamma_m}{\gamma}\right) f_n$$

is the enhancement factor of nth coherent harmonic emission and $d^2I_0/d\omega d\Omega$ is the emission from a single electron and J_n is Bessel function of the order n and f_n the modulation factor. The energy modulation $\Delta\gamma_m$ was estimated by GENESIS1.3.

OPTIMIZATION OF THE NIJI-IV FEL SYSTEM

Electron beam energy

The NIJI-IV is a compact storage ring whose circumference is 29.6m and is usually operated at the beam energy of ~310MeV for UV/VUV FEL experiments.

There is a possibility to increase harmonic radiation power in the higher electron-beam energy operation, since the average power of an undulator FEL is proportional to γ^4. Therefore the beam energy dependence of third harmonic radiation power was investigated.

The electron-beam parameters for different energies were estimated as follows: The bunch length was calculated by $\sigma_l=(\sigma_{lp}{}^2+\sigma_{lM}{}^2)^{1/2}$. The bunch lengthening under the influence of the potential well distortion σ_{lp} was evaluated by

$$I=\frac{\sqrt{2\pi}E}{e\alpha R^3}\left(\frac{f_s}{f_{rev}}\right)^2\frac{\sigma_{lP}^3-\sigma_{l0}^2\sigma_{lP}}{(Z/n)_{eff}}\ . \quad (4)$$

Here f_s and f_{rev} are synchrotron oscillation frequency and ring revolution frequency, α and R are momentum compaction factor and ring average radius, σ_{l0} and $(Z/n)_{eff}$ are natural bunch length and the effective longitudinal coupling impedance, η is the phase-slip factor defined as $\eta=\alpha-1/\gamma^2$. The bunch lengthening due to microwave instability occurs above the threshold current

$$I_{th}=\frac{(2\pi)^{3/2}\eta f_{rev}\sigma_l E}{ec|Z/n|_{bb}}\left(\frac{\sigma_\gamma}{\gamma}\right)^2\ . \quad (5)$$

The bunch length σ_{lM} is described as

$$\sigma_{lM}=\left(\frac{\eta R^3 I|Z/n|_{bb}}{\sqrt{2\pi}(E/e)(f_s/f_{rev})^2}\right)^{1/3} \quad (6)$$

where $|Z/n|_{bb}$ and σ_γ/γ are longitudinal broad-band impedance and relative energy spread, respectively. The natural energy spread and emittance are proportional to E and E^2, respectively, which causes the decreases of FEL gain and power of harmonics at high energies. The emittance growth via intra-beam scattering (IBS) was estimated using the code ZAP of which the influence is remarkable at low energies.

The simulation has been performed at the energy of 310, 350, 380, 400 and 450MeV in a single-bunch operation at 30mA.The electron-beam parameters at 310MeV are listed in Table 1. In this study, the designed values of natural energy spread and emittance were used for simulation. The optical resonator parameters are listed in Table 2. The fundamental at 300nm was calculated at R_M=8m with an effective hole diameter of 0.2mm in a

Table 1: Parameters of NIJI-IV at the electron-beam energy of 310MeV

Natural relative energy spread	2.4×10^{-4}
Natural emittance	5.6×10^{-8}
Revolution frequency	10.1MHz
Momentum compaction factor	0.0884
Beam current	30 mA

Table 2: Parameters for ETLOK-II and optical resonator

Magnetic period	
Undulator section	72mm
Dispersive section	216mm
Total length	6.288m
Number of period	42×2
Cavity length	14.8m
Cavity loss	1.0%

Q-switched regime. In this condition, the intra-cavity peak power of third harmonic at 100nm was obtained as maximum intensity when the beam energy was 380MeV.

Asymmetric resonator

In the previous section, the calculation was performed with symmetric resonator, while there are some advantages of making use of asymmetric resonator: i) the spot size on the downstream mirror can be larger so that the cavity loss becomes smaller. ii) the beam waist position can be near the center of the upstream undulator so that the energy modulation $\Delta\gamma_m$ could be larger. Hence, in this section, asymmetric resonator is considered at the beam energy of 380MeV.

The intra-cavity power of third harmonic at 100nm was calculated by changing the radius of curvature of downstream mirror R_d with a 0.2mm effective hole diameter as shown in Fig.2. (The radius of curvature of upstream mirror R_u was fixed at 8m.) The third harmonic power of asymmetric resonator with R_d =9 and 10m is larger than that of symmetric resonator with R_d =8m. The value of R_d is optimized at 10m and the power decreases more than R_d =11m.

In order to understand the tendency in Fig.2, spot size on upstream w_u and downstream mirror w_d were calculated, as shown in Fig.3, by

$$w_d=\sqrt{\frac{\lambda_s R_d}{\pi}}\left(\frac{L_c(R_u-L_c)}{(R_d-L_c)(R_u+R_d-L_c)}\right)^{1/4}$$

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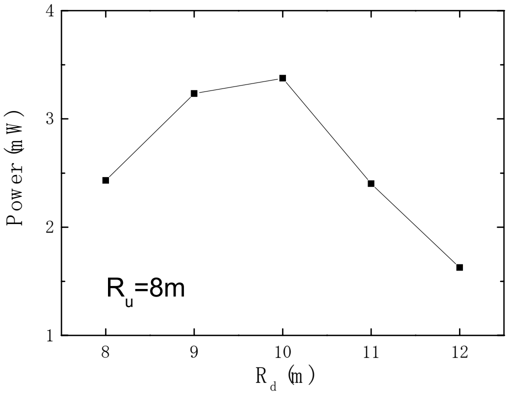

Figure2: Dependence of intra-cavity peak power for third harmonic on the radius of curvature of downstream mirror R_d with R_u=8m.

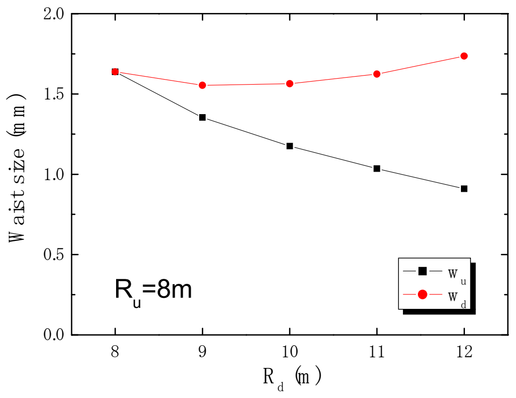

Figure3: Spot size on upstream w_u and downstream mirror w_d with R_u=8m.

$$w_u = \sqrt{\frac{\lambda_s R_u}{\pi}}\left(\frac{L_c(R_d-L_c)}{(R_u-L_c)(R_u+R_d-L_c)}\right)^{1/4}$$

where L_c is cavity length. The value of w_d is almost constant against R_d and that of w_u decreases with increasing R_d. The beam waist position was also calculated by

$$l_u = \frac{L_c(R_d-L_c)}{R_u+R_d-2L_c}.$$

The waist position for R_d =11 and 12m locates between the center and entrance of the upstream undulator. Therefore the filling factor for R_d =11 and 12m becomes small so that the power of third harmonic for R_d =11 and 12m is smaller than that for $R_d \leq 10$m. And the waist position for R_d =10m is found to be nearest the center of the upstream undulator. Hence the power of third harmonic for R_d =10m becomes maximum because the energy modulation $\Delta\gamma_m$ is largest.

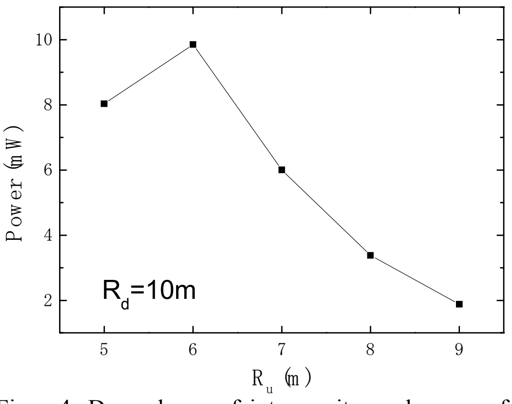

Figure4: Dependence of intra-cavity peak power for third harmonic on the radius of curvature of upstream mirror R_u with R_d=10m.

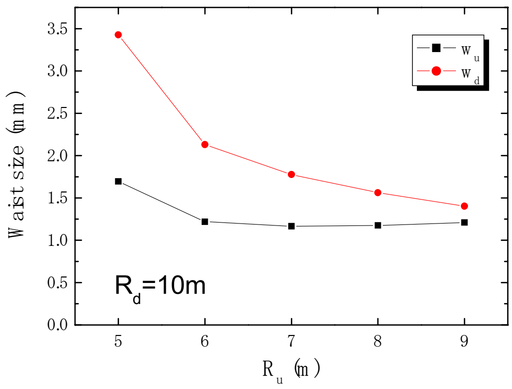

Figure5: Spot size on upstream w_u and downstream mirror w_d with R_d=10m.

The calculations have been also performed by changing R_u with R_d =10m. Figures 4 and 5 show dependence of power for third harmonic at 100nm and spot size on R_u, respectively. The optimized R_u was found to be 6m and the power of third harmonic was obtained as ~10mW which was much larger than the former one.

CONCLUSION

The generation of third harmonic in a Q-switched regime for the NIJI-IV FEL has been simulated using code GENESIS1.3 and its extended version. Optimization of asymmetric resonator has been performed by varying the radius of curvature for upstream and downstream mirror. The calculated intra-cavity peak power of third harmonic at 100nm was ~10mW with a hole-coupled resonator at the electron-beam energy of 380MeV.

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