Computer Simulation of Stabilizing the Radiation Power of Storage Ring Free Electron Laser

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Abstract
It is known that the FEL radiation power in a storage ring becomes unstable because of a fluctuation of the FEL gain at a resonant frequency of the radiation power. This is demonstrated by a computer simulation with FEL power equation. To stabilize the radiation power, a slow rise of the gain and a negative feedback of the power are introduced in the FEL power equation. A computer simulation shows that the radiation power can be stabilized by the above method. Explicit parameter dependence of the radiation power at a steady state is obtained from the FEL power equation.

1 INTRODUCTION

Free electron laser has been realized in several electron storage rings in the visible light and ultraviolet regions [1]. The radiation power obtained is, however, very weak and unstable, so that efforts have been continued to increase and stabilize the radiation power.

It has been believed that the radiation power of storage ring FEL is determined by the ballance among the following four effects. The energy spread of the electron beam is increased by the FEL interaction or the interaction of the electron beam with the radiation field during the travel in wiggler field. The increase of the energy spread in turn reduces the FEL gain. In addition, the energy spread is increased or decreased by the quantum excitation and the radiation damping. Renieri and Dattori studied in detail the saturation mechanism of the radiation power with a Fokker-Planck equation, in which the stochastic process of the photon emission in the FEL interaction and bending radiation was taken into account [2,3].

Recently, the author has considered the saturation mechanism with the aid of the classical FEL theory [4]. As discussed later, the radiation power is determined by FEL power equation which simply considers the above four effects without the stochastic process in the FEL interaction [5].

Meanwhile, it has been noticed that the unstable or intermittent radiation power is induced by a perturbation of the FEL gain around a resonant frequency of the radiation power[6]. This is really demonstrated in computer simulation using the FEL power equation. It is shown that the unstable operation can be suppressed by a slow rise of the gain and a negative feedback of the radiation power[7].

2 FEL POWER EQUATION

From the FEL equation in the classical FEL theory , we get the following first integral

$$\dot{\phi}^2 - \dot{\phi}_0^2 = 2\Omega_L^2(\cos\phi - \cos\phi_0) \qquad (1)$$

where ϕ is the phase of an electron in the radiation and wiggler fields, and Ω_L is given by

$$\Omega_L = (4\pi e E_0 K_h/\lambda_0 m\gamma_r^2)^{1/2} \qquad (2)$$

with e : charge of the electron, E_0 : electric field of the radiation, K_h : K-parameter, λ_0 : wiggler period, m : mass of the electron, γ_r : resonant energy. Eq.(1) determines the trajectory of an electron in the phase space (ϕ, $\dot{\phi}$).

Because of the wavy trajectory, the energy spread σ_e increases when the electron beam passes the wiggler. Taking into account the radiation damping and quantum excitation, the change of the mean square energy spread per pass can be expressed as

$$\frac{d\sigma_e^2}{dn} = kP - 2\frac{T_0}{\tau_e}(\sigma_e^2 - \sigma_{e0}^2) \qquad (3)$$

$$k \simeq 130(eN_w\lambda_0 K_h/E_r\gamma_r)^2 \qquad (4)$$

with T_0 : revolution period, τ_e : longitudinal radiation damping time, σ_{e0} : initial energy spread, N_w : number of wiggler period, E_r : resonant energy.

The FEL gain is proportional to the peak current and gain function, and inversely to electron beam size. The peak current is inversely proportional to the energy spread. The gain function varies depending on the energy spread, and the average gain for a Gaussian distribution of the beam energy is expressed as

$$\langle P\rangle \simeq -0.0675\exp[-(N_w\sigma_e)^2/2\sigma_P^2], \quad (\sigma_P=0.15) \qquad (5)$$

If the wiggler is installed in a dispersion free region, the beam size is almost independent of the energy spread. Accordingly, the gain can be expressed as

$$G = G_0\langle P\rangle/\sigma_e \qquad (6)$$

where G_0 depends on various parameters except for the energy spread.

The change of the radiation power per pass is given by

$$dP/dn = (G - \delta)P \qquad (7)$$

where $\delta(=\delta_m+\delta_{ex})$ is the radiation loss coefficient with δ_m and δ_{ex} for intrinsic mirror loss and power extraction loss.

The radiation power can be determined by Eqs.(3),(6) and (7). At a steady state $dP/dn=d\sigma_e^2/dn=0$, we have $G=\delta$, which determines the energy spread as σ_{es}, and

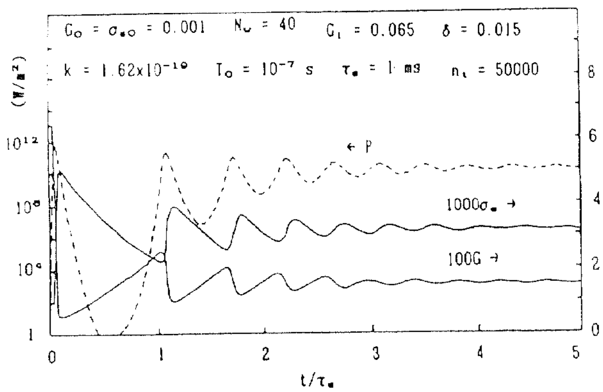

Fig.1 Computer simulation of FEL power equation for the radiation power P, the energy spread σ_ϵ and the gain G.

the radiation power at the staedy state is expressed as

$$P_s = \frac{2}{k}\frac{T_0}{\tau_\epsilon}(\sigma_{\epsilon s}{}^2 - \sigma_{\epsilon 0}{}^2) \qquad (8)$$

$$T_0/\tau_\epsilon \simeq U_0/E_r \qquad (9)$$

where U_0 is the radiation power per turn. From the average gain function $\langle F \rangle$, we have the maximum energy spread

$$\sigma_{\epsilon s} \simeq 1/2N_w = \delta\omega/\omega \qquad (10)$$

Therefore, we have the maximum power available in the storage ring FEL,

$$P_{max} = \frac{2}{k}\frac{U_0}{E_r}\left(\frac{\delta\omega}{\omega}\right)^2 \qquad (11)$$

which is almost independent of the beam current. The radiation power extracted from the mirror cavity is $W_s = \delta_{ex} S P_s$ with S the cross section of the extracted power. The above formula is rather different from the

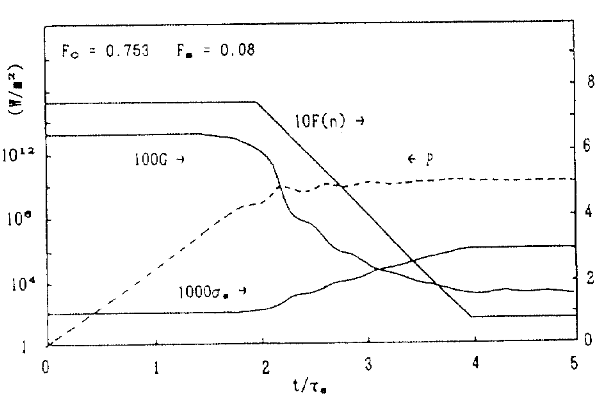

Fig.2 Simulation of FEL power equation with a slow rise of the gain.

result given by Renieri and Dattori.

$$W_s = (\delta\omega/\omega)U_0 I_p \chi, \quad (\chi \le 1) \qquad (12)$$

where I_p is the peak current.

3 STABILIZATION OF RADIATION POWER

3.1 Slow rise of the gain

Figure 1 demonstrates an example of the transient process of the energy spread, gain and radiation power obtained from the FEL power equation. Parameters used are shown in the Figure. We see that at the initial stage the power and energy spread increase rapidly and the gain decreases. Then these quantities vary periodically, and arrive at a steady state about five times later than the damping time.

The FEL power equation was derived on the assumption that the energy distribution of the electron beam is always a Gaussian. The rapid change at the initial stage, however, possibly deforms the distribution, and may introduce a fluctuation of the energy spread.

The rapid oscillation can be suppressed by reducing the gain as follows,

$$G_{eff} = G(1 - F(n)) \qquad (13)$$

An example of the simulation is shown in Fig.2, where the radiation power increases gradually and saturates without the oscillation.

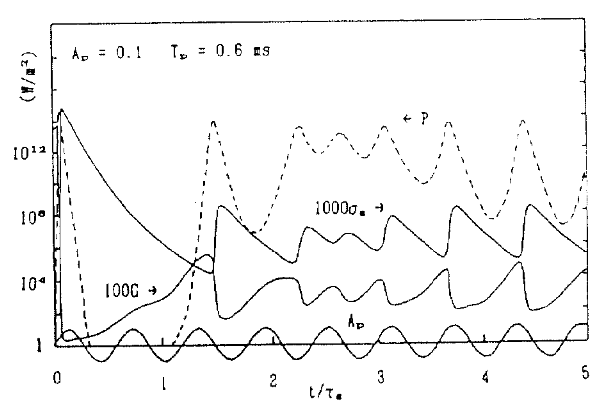

Fig.3 Simulation of FEL power equation with a sinusoidal perturbation in the gain.

3.2 Negative feedback of the radiation power

Without the gain reduction, the radiation power oscillates periodically as shown in Fig.1. The resonant frequency is approximately given by

$$\Omega = 2\pi/T_p \simeq (\delta/\tau_\epsilon T_0)^{1/2} \qquad (14)$$

If the gain is perturbed sinusoidally at this frequency,

$$G_{eff} = G(1 + A_p \sin(2\pi n T_O/T_p)) \qquad (15)$$

the radiation power fluctuates substantially even with A_p=0.1 as shown in Fig.3. The oscillation period of the power is rather at random, which is close to the experimental obserbation of the power. Similar fluctuation is obtained by introducing a perturbation in the energy spread. The fluctuation can not be suppressed by the gain reduction as shown in Fig.4. For this purpose it is effective to introduce a negative feedback of the radiation power in the gain control as shown in Fig.5. Experimentally the feedback can be made by the modulation of the closed orbit distortion of the electron beam or by that of the acceleration frequency.

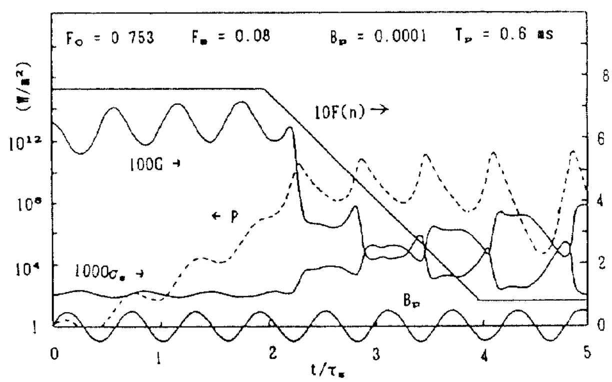

Fig.4 Simulation with a slow rise of the gain in the presence of the sinusoidal perturbation.

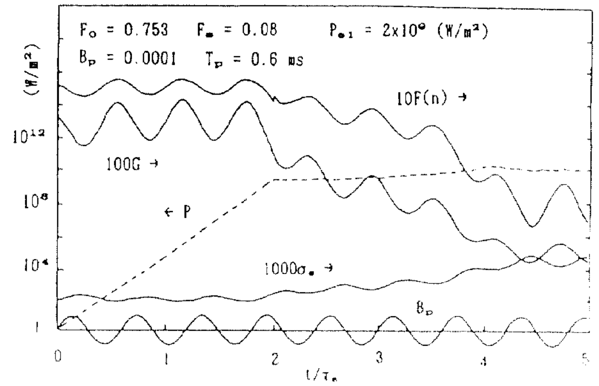

Fig.5 Simulation with a slow rise of the gain and a negative feedback of the radiation power in the presence of the sinusoidal perturbation.

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