CONSIDERATION FOR AN FEL-OPTIMIZED ELECTRON STORAGE RING

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Abstract

Storage ring based free electron laser (SRFEL) has been developped on conventional synchrotron radiation sources. Peculiarity of SRFEL, which is completely different fron linac based FEL, is pointed out by showing some experimental data of the UVSOR-FEL. Future prospect and importance of dedicated storage ring are discussed.

1 INTRODUCTION

The FELs has been proposed as powerful light sources for the wide spectral range with tunability and coherence. Actually a lot of facilities for users are spread over the world with the infrared FELs based on linear accelerators. For the short wavelength FELs, there is, however, an important fact in the progress of the FEL physics and technology. Although electron/positron storage ring has seemed to be a suitable FEL driver for the short wavelength region such as UV, VUV and XUV, the SRFEL has not qualified for expected performances yet.

The first oscillation of the SRFEL in the visible region was performed on the ACO storage ring, Orsay, in 1983 [1]. The success of the ACO was followed by the VEPP3 storage ring, Novosibirsk, in 1988 and the spectral range was extended down to 240 nm [2]. This record of the shortest wavelength had been not broken until 1996. Notwithstanding the long history, the progress of SRFELs seems to be slow, while evolution of the conventional lasers for the wavelength, the power and the pulse width has been very rapid. The matter should be discussed is what difficulties against the development of the SRFEL are.

2 FUNDAMENTALS OF FELS IN LOW GAIN REGIME

Relativistic electrons which have the transverse momentum with respect to propagation axis of the electromagnetic wave are stimulated to emit photons by the electric field of the optical wave (the pendulum force). Generally the transverse momentum of electrons is led by periodic magnetic fields of the wiggler (or undulator). Since the relativistic electron longitudinally moves with the light velocity, there is a phase resonance condition between the electrons and optical wave, which can be easily obtained as

$$\lambda_n = \frac{\lambda_u}{2\,n\,\gamma^2}\left(1 + \frac{K^2}{2}\right), \tag{1}$$

where λ_n, λ_u and γ are the wavelength of the optical wave, the spatial period length of the undulator field and the relative electron energy. For the fundamental wavelength, the harmonic number, n, is 1. Here the deflection parameter, K, is defined as $K^2=K_x^2+K_y^2$ and $K_{x,y}=0.934B_{x,y}[\mathrm{T}]\lambda_u[\mathrm{cm}]$, where K is divided into the horizontal and the vertical component, and B is the peak magnetic field of the wiggler. The resonant condition of eq. (1) is exactly same as the wavelength of the undulator synchrotron radiation. The electron distribution in the phase space inside the optical wave is essential for the FEL gain. However normally the phase space of the electron bunch is much larger than the wavelength of the FEL, therefore in the entrance of the undulator the electron distribution in the phase space of the optical wave packet is almost constant. If the electrons can be condensed into a phase where the electrons are decelerated, the small signal gain would be enhanced.

The optical klystron consists of two undulator sections separated by a large wiggle of magnetic field which produce so-called dispersive section [3]. After passing through the first undulator, a phase advance of energy modulated electrons toward high energy side in the dispersive section is slower while that is fast for the low energy electrons. Consequently at the entrance of the second undulator the electron distribution with respect to the phase of the optical wave is collected and forms "microbunch". In other words, the energy modulation is converted to the density modulation by the dispersive section in the optical klystron.

From an analytical evaluation, the FEL gain with an optical klystron is expressed as

$$g = 1.12 \times 10^{\pm 13}\,\lambda^2\left(N + N_d\right)N^2\,\rho_e\,K^2\left[JJ\right]^2 f_{\mathrm{mod}}\,F_f / \gamma^3, \tag{2}$$

where N the period number of the undulator, N_d the interference order between the two undulators, ρ_e the peak electron density, $[JJ]$ the brightness factor of the radiation expressed by Bessel functions (=1 for the complete circular polarization), and f_{mod} and F_f are the modulation factor and the filling factor coming from the energy spread of the beam and transverse overlapping with the FEL and the electron, respectively.

3 BUNCH-HEATING PHENOMENA

The phase rotation of electrons goes over π, the total energy gain may exceed the loss, which leads the gain saturation. The saturation is expected to be occurred at which the FEL power density is more than ~ 100 W/m^2 for the UVSOR-FEL. This huge power is roughly estimated to be a 200 kW average power in the optical cavity. However an actual saturation of the FEL power comes from a different mechanism on the storage ring.

Because the FEL photons are produced by the *same* electron bunch turn-by-turn, the beam quality such as the energy spread becomes no longer same as an initial condition. An amplitude of the phase space oscillation increases and then it becomes the large oscillation in synchrotron motion, which is so-called "bunch heating". The gain reduction due to the bunch-heating is much more quicker, and then an average output power of the UVSOR-FEL does not exceed a couple of mW, which correspond to several-ten W in the optical cavity (here the mirror transmission is about 50 ppm).

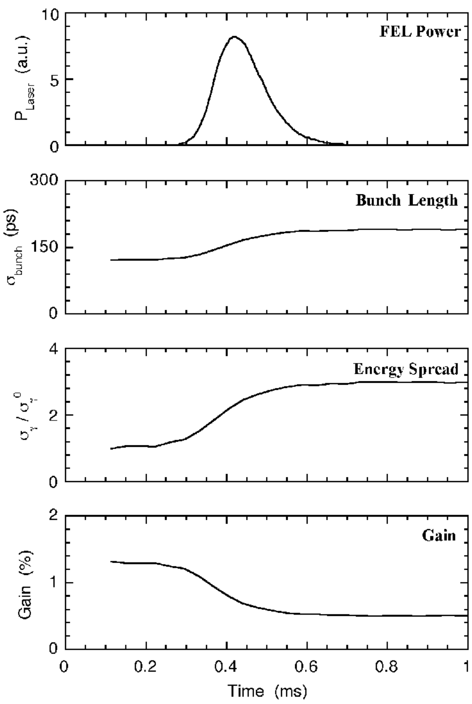

Figure 1: The FEL power and the electron bunch evolutions in a Gain switching lasing. The bunch distribution was observed by a dual-sweep streak camera, and the energy spread was deduced by taking a potential-well distortion into account.

The bunch-heating phenomena was clearly observed by a dual-sweep streak camera on the UVSOR. Figure 1 shows time dependent evolution of longitudinal intensity distributions of the FEL and the electron bunch. The images were taken at the start-up of the lasing. At the high beam current (high gain), the laser light is coming quickly but also quickly disappeared. This is obviously due to the gain reduction induced by the bunch-heating. The bunch length rapidly growth which results from an increase of the energy spread of the beam. After the FEL is killed by the bunch-heating, the gain recovers gradually due to the synchrotron damping and the FEL is back. We should note the saturation mechanism in the FEL oscillation on the storage rings is completely different from that on linac based FELs where fresh beams can be supplied in the lasing process.

On a very stable ring, the FEL intensity and the energy spread of the beam would be in a certain equilibrium state. This scenario for the saturated laser power has been predicted by A. Renieri, which is well-known as "Renieri's limit" [4].

4 GAIN SATURATION AND FEL POWER

From a rise and fall of the FEL macropulse, the gain reduction due to the bunch-heating was re-expressed in terms of the total energy of the produced photons S_{prod} as

$$g = \frac{g_0}{1 + \left(S_{prod}/S_{sat}\right)} \tag{3}$$

where g_0 is the gain with no additional energy spread and S_{sat} is namely the saturation energy. We can notice eq. (3) is analogous to the population inversion in conventional lasers.

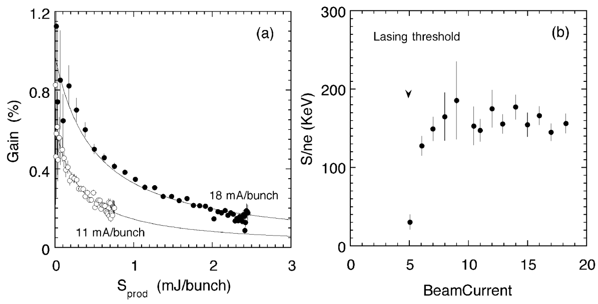

Figure 2: The deduced FEL gain as a function of the total extracted photon energy (a). Saturation energies for one electron at various beam current (b).

Experimental data is well reproduced by the eq. (3) as shown in Fig. 2. It was found out that experimental values of the saturation energy for one electron were almost constant in a wide range of the beam current, which means the output power of the FEL is restricted by the saturation energy. Consequently the average output power P_L is roughly estimated from analytical evaluations [5],

$$P_L \approx 2\,\frac{T}{\alpha}\log\left(\frac{g_0}{\alpha}\right)\frac{S_{sat}}{\tau_s} \tag{4}$$

where T, α and τ_s are the transmission rate of the cavity mirror, the round-trip cavity loss and the synchrotron damping time, respectively. Eq (4) is nothing but Renieri's limit. From an investigation for an original form of Renieri's limit, the saturation energy S_{sat} is found to be proportional to the beam energy and inversely proportional to the period number of the undulator (for the optical klystron, it depends on the field strength of the dispersive section). Consequently the formula can be rewritten as

$$P_L \approx \frac{T}{\alpha} \log\left(\frac{g_0}{\alpha}\right) \frac{f_{\mathrm{mod}}}{\pi\left(N+N_d\right)} P_{SR} \tag{5}$$

where P_{SR} is synchrotron radiation power. Although the performance of the mirror is very important factor for the FEL experiment, here let us assume an ideal mirror $\alpha = 4$ % (2 % loss in each mirror) to estimate the average power. If an identical optical klystron of the UVSOR-FEL is used, we can estimate the intracavity as a function of the beam energy and the bending radius, because the synchrotron radiation power is proportional to the fourth power of the beam energy and is inversely proportional to the bending radius.

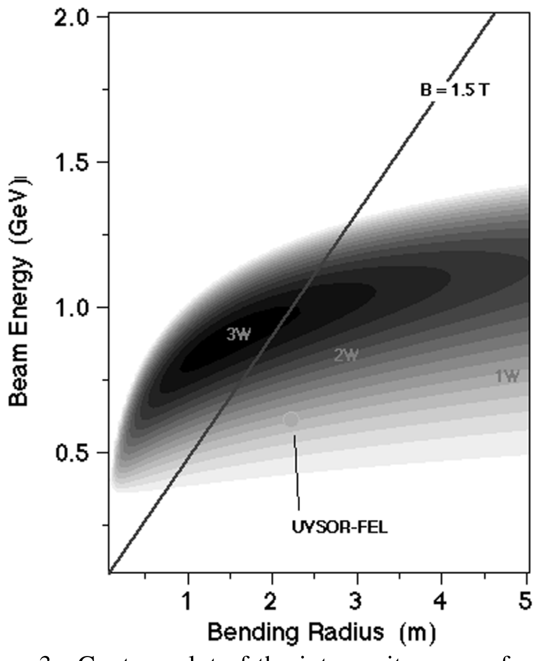

Figure 3: Contour plot of the intracavity power for 200 nm FEL. The cavity loss of 4 % is assumed. The solid line shows the border between field strengths of normal conducting magnets and superconducting magnets.

Since the gain steeply drops as the beam energy increases, the maximum energy for the FEL oscillation is limited. To obtain the highest power of the FEL, a small bending radius is required because the damping time gets faster. The result is strongly depending on the performance of the undulator. However it can be noticed from Fig. 3 that choise of the beam energy including the bending radius is crucial to obtain the highest performance of the FEL. Moreover it is not always correct to use the small bending radius because of other properties of the electron beam such as the emittance. Here the effect of the transverse beam size and the matching with the FEL transverse mode are not included. At lease it can be concluded that the storage ring should be optimized to the FEL oscillation together with the undulator.

5 SUMMARY

The bunch-heating is originating from a stochastic process of the energy modulation by the FEL interaction and the synchrotron oscillation. If the energy damping time is very fast, the gain saturation would be slow. Otherwise the ring with zero momentum compaction is realized, the stochastic heating would be avoided. This was proposed as isochronous storage ring FEL by D.A.G. Deacon [6]. An important point for progress of the SRFEL is the performance of the SRFEL strongly depends on the storage ring, in other words the progress of the SRFEL itself is identical to that of the storage ring.

At the moment, the performance of the SRFEL does not exceed that of the conventional lasers even the Super-ACO FEL where they are now supplying the FEL photons to user experiments. The SRFEL has progressed on the old machines as a parasitic function so far. Although a lot of works concerned in the SRFEL are left on those rings, necessity of dedicated storage ring should be argued to future development.

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