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Introduction to Free Electron Laser on Electron/Positron Storage Rings

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Abstract

Free electron lasers (FELs) have been developed as new radiation (including microwave region) sources for various fields. Here we are going to briefly introduce current research activities and developments on storage ring based free electron laser (SRFEL) where the gain is relatively low and target wavelength is rather short. Peculiarity of SRFEL 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 FEL oscillation was first demonstrated 20 years ago [1]. 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 [2]. The very small storage ring, ACO, was constructed as a collider more than 30 years ago. The FEL experiment was done after the ACO finished its initial role for the particle physics. 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 [3]. 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 SRFEL, present and past

On a post machine of the ACO, the Super-ACO, the first lasing was obtained 1989 [4], and the activity of the FEL experiment has been continued. The Super-ACO FEL is probably in the most advanced stage for the study of SRFEL dynamics and also for user program. In Japan, the first lasing was achieved on the TERAS ring, ETL, Tsukuba, in 1991 [5], which was followed by another lasing on the UVSOR ring, Okazaki, in 1992 [6]. In 1993, a lasing was obtained on the first dedicated storage ring, NIJI-IV, Tsukuba [7]. In 1996, the latest lasing news was coming from Duke University, Durham, where a new dedicated storage ring was constructed by J.M.J Madey and his group [8]. The Duke storage ring was designed with consideration of optimization to the SRFEL. Another dedicated ring, DELTA, is under commissioning at Dortmund, Germany [9].

Table 1 is a glance of the SRFEL facilities. Only facilities who have installed at least optical cavities are listed. One can immediately notice that the average output power is rather low. Although there are many differences in characteristics among the SRFELs, such as pulse structure and repetition rate, the low output power generally results from relatively low gain and then low transmission rate of cavity mirrors because higher beam energy is required to obtain the short wavelength FEL, meanwhile the gain drops quickly with increasing the beam energy.

In order to secure enough gain even with the high energy beam, very long undulator is necessary. Consequently the dedicated storage rings like the

Table 1 List of SRFEL Facilities and Typical Parameters of FEL

Ring	Location	Activity Period	Beam Energy (MeV)	Spectral Range (nm)	Output Power (mW)	Beam Current (mA)	Typical Gain (%)
ACO*	Orsay (France)	1978 - 1987	240	650 - 460	3	150	0.2
VEPP3*	Novosibirsk(Russia)	1978 - 1994	350	690 - 240	< 3	20	10
SuperACO	Orsay (France)	1988 -	600 & 800	690 - 345	~ 100	30	2
TERAS*	Tsukuba (Japan)	1988 - 1992	230	598	2.5	4	0.5
UVSOR	Okazaki (Japan)	1988 -	500 & 600	550 - 239	~ 3	20	1
NIJI-IV	Tsukuba (Japan)	1990 -	240	600 - 349	low	10	> 5
Duke	Durham (USA)	1989 -	500	413 - 345	~ 10	10	> 10
DELTA	Dortmund (Germany)	1989 -	< 1000	-	-	-	-

* Storage ring itself or FEL project was already shut down.

Duke ring and the DELTA, which equip long straight section of more than 10 m, will play important roles for future progress of the SRFEL.

3 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

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

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 $K_{x,y} = 0.934\, B_{x,y}[T]\, \lambda_u[cm]$, 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 energy gain or loss of electrons is governed by a following formula:

$$\Delta\gamma = \left(\lambda_u \gamma / 4 \pi c\right) \Delta \dot{\varphi}. \qquad (2)$$

The phase of electron with respect to a potential of the optical wave, φ, should satisfy the pendulum equation,

$$\ddot{\varphi} = -\sin\varphi \times e^2 E\, B / \left(m c \gamma\right)^2, \qquad (3)$$

where e and m are the charge and the mass of the electron, respectively, and E is the amplitude of the electric field of the optical wave. In a case of which the electron energy satisfies eq. (1) but individual phase of electrons with respect to the electric field of the optical wave is random, there is totally no energy exchange between the optical wave and the electron bunch. If the electron energy is slightly deviated from the resonance condition, there is energy gain or loss. By evaluating the pendulum equation for the energy exchange depending on the phase, one obtains the small signal gain curve is proportional to the derivative of the spontaneous spectrum, which is namely Madey's theorem [10].

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. An invention of the optical klystron by N.A. Vinokurov et. al. was very revolutionary for the SRFELs [11]. The optical klystron consists of two undulator sections separated by a large wiggle of magnetic field which produce so-called dispersive section. 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. Figure 1 shows a spontaneous spectrum from the optical klystron. The Madey's theorem suggests a higher gain due to the steep slope of a jagged-structure of the spectrum that results from interference of two undulator radiations.

The phase space evolution in the optical klystron is shown in Fig. 2, where the undulator field is helical and the electric field of circular polarized optical wave. At the exit of the first undulator, the energy modulation is caused, and then the electron density is modulated by passing through the dispersive section. The microbunched electrons loose their energy in the second undulator. As on can see in the figure at the exit of the optical klystron, total energy gain summing

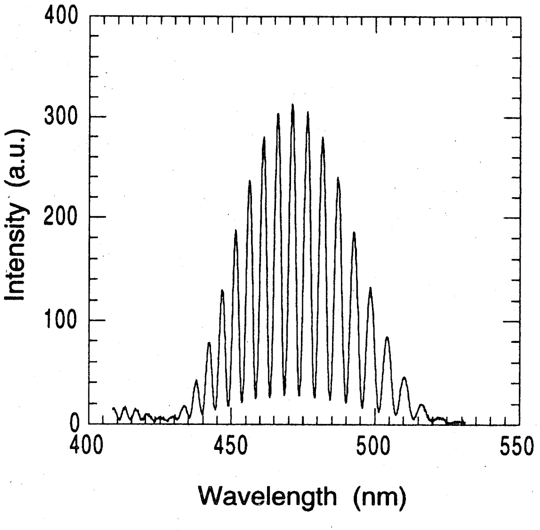

Fig. 1 A spontaneous spectrum from the helical optical klystron on the UVSOR.

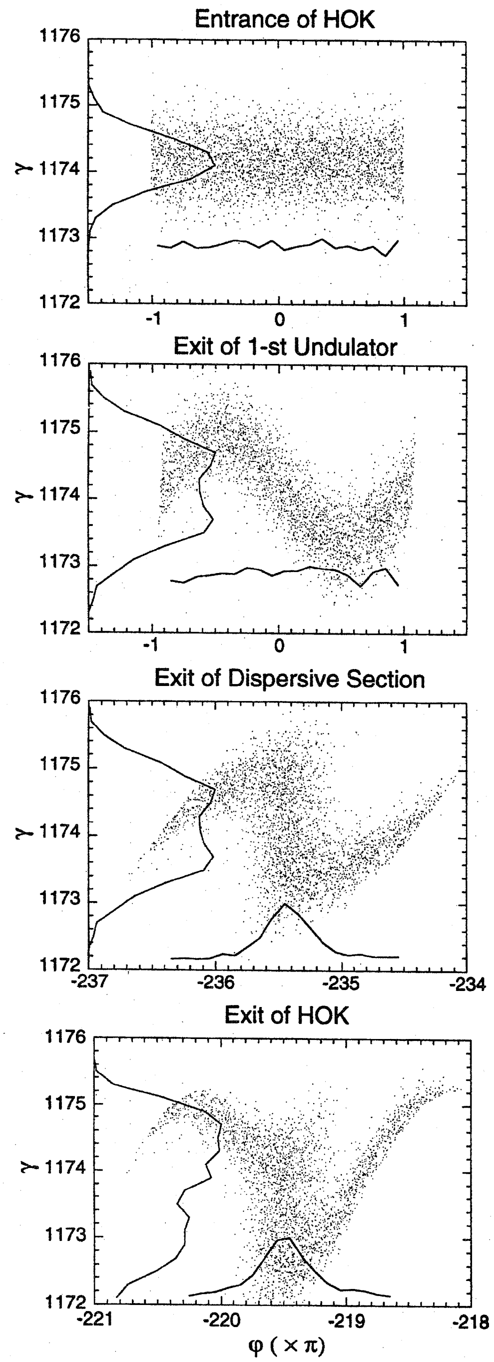

Fig. 2 Phase space evolution of the electrons in the bucket of the optical wave along a helical optical klystron. The initial electron energy of 600 MeV and the energy spread of 3×10^{-4} and a very high power density of the laser is employed to emphasize the motion of the electrons.

over all electrons is negative, which is converted to stimulated photon emission.

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

$$g = 1.12\times 10^{-13}\,\lambda^2(N+N_d)\,N^2\,\rho_e\,K^2[JJ]^2 f_{\mathrm{mod}}\,F_f/\gamma^3\ , \quad (4)$$

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.

4 Bunch-heating and gain saturation

As one presumes from Fig. 2, 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

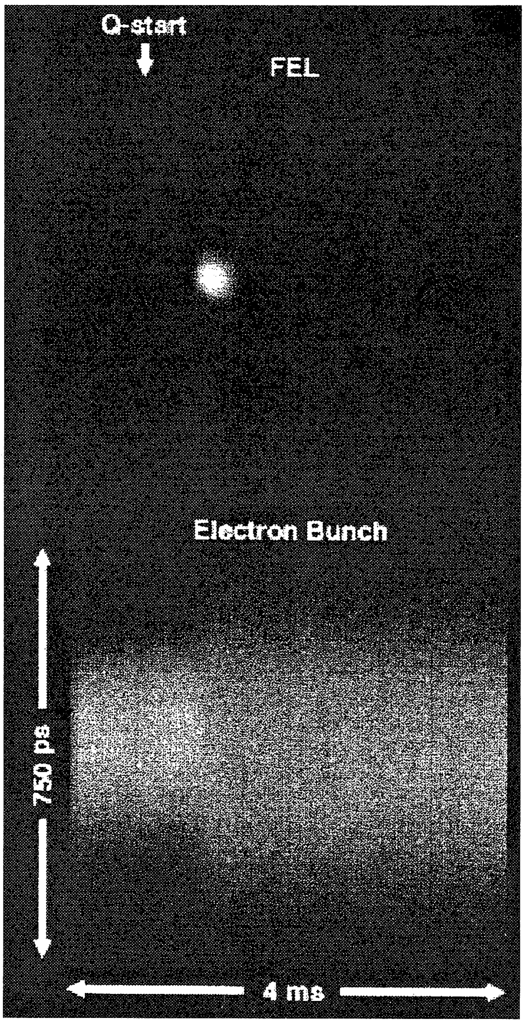

Fig. 3 Start-up of lasing (upper) and the bunch-heating. Q-start means the frequency jump of the RF to synchronize the electron bunch to the optical bunch so that the FEL interaction begins.

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. As shown in Fig. 2, 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 W in the optical cavity (here the mirror transmission is about 50 ppm).

The bunch-heating phenomena was clearly observed by a dual-sweep streak camera on the UVSOR. Figure 3 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" [12].

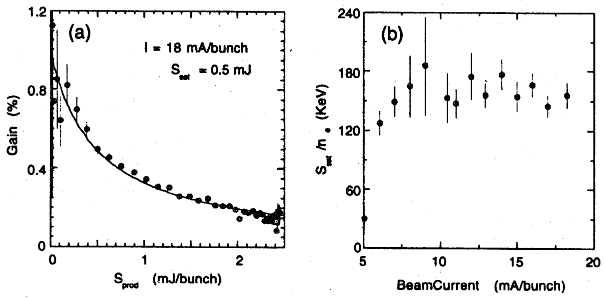

Fig. 4 The deduced FEL gain as a function of the total extracted photon energy (a). Saturation energies for one electron at various beam current (b).

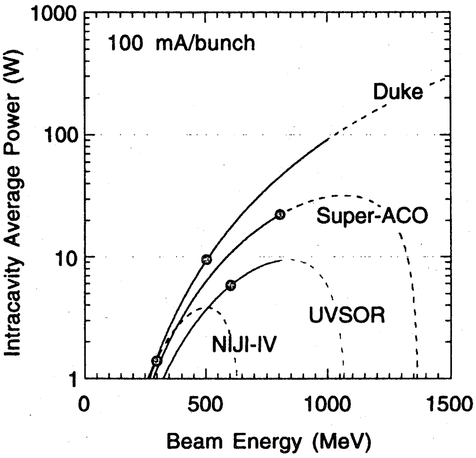

Fig. 5 Expected maximum intracavity average power of UV FEL at the beam current of 100 mA/bunch plotted as a function of the beam energy. Solid lines are available range of the beam energy and circles indicate current operation energies for each facility.

5 How much power can be extracted

From a rise and fall of the FEL macropulse shown in Fig. 3(upper), the gain reduction due to the bunch-heating was re-expressed in terms of the total energy of the produced photons S_{prod} as

$$g = \frac{g_0}{1 + \left(S_{prod}/S_{sat}\right)}, \tag{5}$$

where g_0 is the gain with no additional energy spread and S_{sat} is namely the saturation energy. We can notice eq. (5) is analogous to the population inversion in conventional lasers. Experimental data is well reproduced by the eq. (5) as shown in Fig. 4. 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 [13],

$$P_L \approx 2\frac{T}{\alpha}\log\left(\frac{g_0}{\alpha}\right)\frac{S_{sat}}{\tau_s} \text{ or} \approx 2\frac{T}{\alpha}\log\left(\frac{g_0}{\alpha}\right)\frac{S_{sat}}{n_e}\frac{P_{SR}}{E_{beam}} \tag{6}$$

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. In the second formula, P_{SR} is synchrotron radiation power at a beam energy E_{beam}. Eq (6) is nothing but Renieri's limit. From an investigation for an original form of Renieri's limit, the saturation energy S_{sat}/n_e 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).

Although the performance of the mirror is very important factor for the FEL experiment, here let me assume an ideal mirror $\alpha = 1\%$ to estimate the average power. The gain steeply drops as the beam energy increases (see eq. (4)), then the beam energy limitation can be seen in Fig. 5. However the Duke-FEL has extremely high potential. It is obvious that the very high gain obtained by using a 7 m-long undulator on the Duke ring leads the high saturation power. Since the ratioT/α is expected to be 0.01 using dielectric multilayer mirrors, an average power of 1 W would be extracted from the optical cavity at an 1 GeV operation on the Duke ring.

6 Summary

The expected power shown in Fig. 5 may be widely fluctuated by the absolute value of the gain. At the high beam current like 100 mA/bunch, the beam property becomes an important factor. In the calculation, the gain at 100 mA/bunch has been just extrapolated by optimistic prospects. However, for example, the bunch lengthening reduces the peak current, which appears as ρ_e in eq. (4), and a single bunch instability, i.e., microwave instability, increases the energy spread and also reduces the gain. These phenomena are surely kinds of the ring characteristics, but have not been included in the estimation in Fig. 5. On the DELTA ring, they have improved the shape of the vacuum chamber to reduce a broad band impedance to avoid the bunch lengthening and make a threshold current for microwave instability very high. That is one of approaches from the accelerator physics.

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 [14]. 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. For instance, stochastic cooling of the beam recently becomes subject to be frequently discussed. Same issues such as forced damping will be included in the future development of the SRFEL.

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. However both dedicated rings of the Duke and the DELTA have just opened the door for new generation of the SRFEL. 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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