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Design study of a free-electron laser on a storage ring at Tohoku University

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A free-electron laser (FEL) based on the proposed Tohoku Light Source storage ring is discussed. In the first stage the FEL is made to operate in the visible region with a relative low beam energy to avoid the complication of mirrors. Then, with a higher beam energy, the FEL can produce radiation of wavelengths in the UV or VUV region. Some simulation results of the storage-ring FEL with wavelengths of ~200 nm are presented.

Keywords: storage rings; free-electron lasers.

1. Introduction

The Tohoku Light Source (TLS) has been proposed for synchrotron radiation applications in many fields (Sato, 1996; Katoh *et al.*, 1996). It is a 1.5 GeV storage ring with a circumference of 187 m. One of the two 15 m-long straight sections is available for insertion devices and for free-electron laser (FEL) experiments. The status of the TLS project is ‘waiting for approval’ and there is a high possibility of starting this project soon after another project, a stretcher–booster ring, is completed (Oyamada, 1993, 1995).

The layout of the TLS storage ring is shown in Fig. 1. It is a racetrack-type ring with a double-bend achromat lattice. The lengths of the dispersive-free straight sections are 15 m, which are reserved for advanced light sources. The main parameters of the TLS storage ring (Katoh *et al.*, 1996) are summarized in Table 1.

The FEL set-up based on the ring is also shown in Fig. 1. The TLS has a wide energy range and low emittance which make the machine a promising driver for an FEL operating in the UV and VUV spectral range or below. In order to compensate for the low gain of FELs, an optical klystron should be used for the facility. Two mirrors, M1 and M2, are set in the two sides of the straight section composing a symmetric near-concentric resonator. It is reasonable in the first stage to make the FEL operate in the visible region with a relatively low beam energy to avoid the complication of mirrors. Then, with a higher beam energy, the FEL can produce radiation of wavelengths in the UV or VUV region. In this report we will discuss an FEL based on the ring. Some simulation results of the storage-ring free-electron laser (SRFEL) are presented.

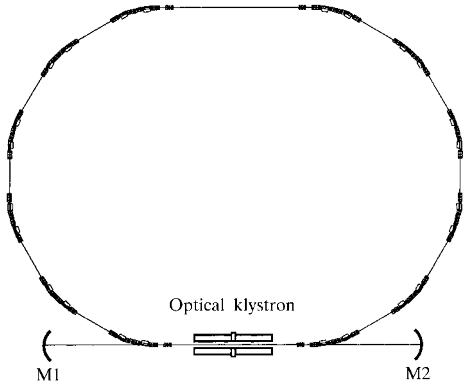

Figure 1
Layout of the TLS storage ring.

Table 1
Main parameters of the TLS storage ring.

Circumference	187 m
Lattice	DBA × 12
Length of straight section	5 m × 10, 15 m × 2
RF frequency	500 MHz
RF voltage	1 MV
Harmonic number	312
Betatron tunes	12.20, 3.15
Natural chromaticities	−46.8, −14.2
Momentum compactor	0.00145
Synchrotron tune	0.0067
Emittance	7.3 nm rad at 1.5 GeV
Momentum spread	6.6×10^{-4}
Natural bunch length	4.3 mm

2. FEL design consideration

The TLS storage ring is designed as a low-emittance storage ring at a beam energy of 1.5 GeV. Its emittance and relative energy spread are estimated as 7.3 nm rad and 6.6×10^{-4}, respectively. As an FEL driver, it is necessary to operate the storage ring at a relatively low energy of about 0.8–1.2 GeV for the sake of reducing the effect of intrabeam scattering. The wavelength of an SRFEL is described by the resonant condition given by

$$\lambda = (\lambda_u/2\gamma^2)(1 + K^2), \tag{1}$$

where λ_u is the undulator period and γ is the electron energy factor. The undulator parameter, $K = 0.934B_u[\mathrm{T}]\lambda_u[\mathrm{cm}]$, describes the characteristic of an undulator, where B_u is the root-mean-square magnetic field of an undulator. Fig. 2 shows the dependence of the FEL wavelength tuning range of the fundamental harmonic on the beam energies and undulator parameters, where we assumed the undulator period λ_u = 12 cm. As shown in the figure, the FEL can operate in the visible region at a low beam energy of 800 MeV and in the XUV region at an energy of ~1.2 GeV.

We have chosen to use an optical klystron in this facility. The optical klystron consists of two undulators and a dispersive section. It can reduce the interaction length of the electron beam and light while maintaining a higher FEL gain. Therefore, it is

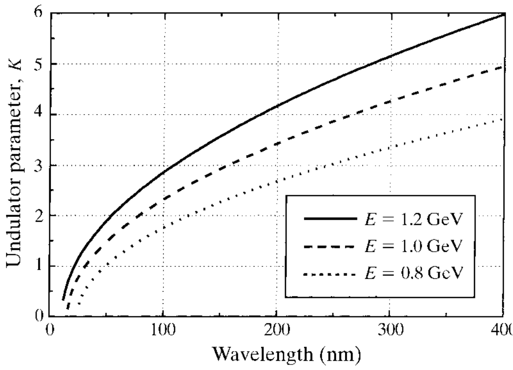

Figure 2
Dependence of the FEL wavelength-tuning range on the beam energy and undulator parameters.

Table 2
Parameters for the TLS FEL.

Electron beam	
Energy	0.8–1.2 GeV
Current	300 mA
Emittance	10 nm rad
Relative energy spread	5×10^{-4}
Optical klystron	
Total length	10.08 m
Undulator length	4.8 m
Period	0.12 m
Undulator parameter	0–6
Dispersive section length	0.48 m
N_d parameter	0–300
Resonator	
Symmetric, near-concentric	
Cavity length	46.75 m
Rayleigh length	~5 m

particularly useful in a storage ring which has short straight sections and high beam quality. The effect of the optical klystron can be described by the effective number of periods, N_d, which is the number of wavelengths of light passing over an electron in the dispersive section,

$$N_d = \frac{1}{2\lambda\gamma^2}\left\{L_d + \frac{e^2}{m^2c^2}\int_0^{L_d}\left[\int_{\infty}^{u} B(z)\,dz\right]^2 du\right\}, \qquad (2)$$

where L_d is the dispersive-section length and $B(z)$ is the field of the dispersive section at the longitudinal coordinate z. We have chosen a dispersive length of 48 cm, and N_d is adjustable in the range 0–300. The undulator period is 12 cm and the undulator parameter can be adjusted in the range 0–6.

As the gain of an SRFEL is low, a resonator is necessary. A Fabry–Perot-type cavity will be used for our FEL oscillator because of its simplicity and easy alignment. The cavity length equates to one-quarter of the circumference of the ring to make the optical pulses in the resonator remain synchronous with beam bunches entering the undulator, where two-bunch operation is assumed for the storage ring. In order to obtain the maximum gain, the resonator is chosen as a symmetric near-concentric resonator. Multilayer dielectric structure reflectors have been used in this facility. For wavelengths greater than ~150 nm, a normal-incidence reflectance in excess of 0.95 is available (Kortright, 1990). The Rayleigh length is about 50% of the interaction length to obtain a relatively high gain and to increase the tolerances on the cavity parameters. The parameters of the SRFEL are shown in Table 2.

3. Simulation results

We modified the simulation code *TDA* to carry out the calculation for the FEL oscillator with an optical klystron. The original version of the code employed non-linear equations of motion for the electrons and paraxial wave equations for the radiation to simulate the FEL amplifiers (Tran & Wurtele, 1989; Tran, 1990). According to the method of decomposition of the electromagnetic fields into the Gauss–Laguerre function, this code was modified to calculate the FEL oscillator with drift space and two reflection mirrors.

In the case of the optical klystron, the energies of electrons in the first undulator are modulated. When the modulated electron beam passes through the dispersive section, the electron energy modulation is converted into a spatial phase modulation. As the magnetic field in the dispersive section satisfies the condition that the first and second integrals over the longitudinal coordinate z vanish, the electron energy, transverse displacements and angular deflection will not change. In the case of a small energy modulation in the first undulator, the difference among the transit times of the electrons with the same position in z but different energies can be described as the difference of the phases,

$$\Delta\psi = 2\pi N_d\{-1 + 2[(\gamma - \gamma_0)/\gamma_0]\}, \qquad (3)$$

where γ and γ_0 are the electron energy and the reference energy, respectively. The parameter N_d represents the effective number of periods in the dispersive section.

We used the parameters given in Table 2 to simulate the performance of the SRFEL with a near-concentric optical cavity and an optical klystron placed at the centre. The initial distribution of electrons in a bunch is assumed to have a Gaussian distribution in space and a random form in energy. In the simulation, an electron beam with an energy of 1.0 GeV, a bunch length of 4.3 mm and a beam peak current of 100 A are assumed. A relative energy spread of 5×10^{-4} and an electron beam emittance of 10 nm rad are chosen. The period and number for each undulator are 12 cm and 40, respectively; therefore, the total length of the optical klystron is 10.08 m. An undulator parameter $K = 3.5$ is used. According to the FEL resonant condition, the radiation wavelength is ~207 nm. As discussed in §2, a cavity length of 46.75 m must be chosen to satisfy the synchronization condition between the light beam and the electron beam.

Some typical numerical simulation results are shown in the following. In Fig. 3 the power gains are shown as a function of

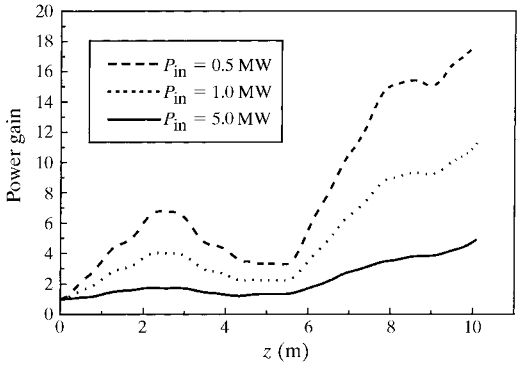

Figure 3
Dependence of the FEL gain corresponding to different input powers on the longitudinal position in the optical klystron.

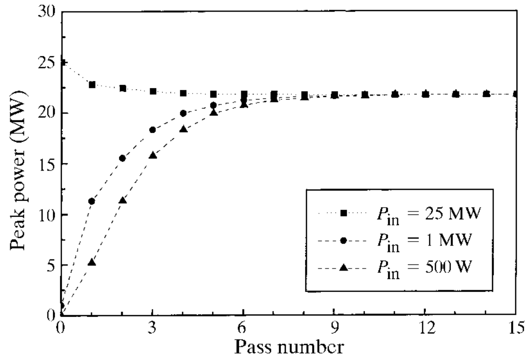

Figure 4
Dependence of the radiation power corresponding to the different input powers on the oscillating numbers of radiation pulses between the reflection mirrors.

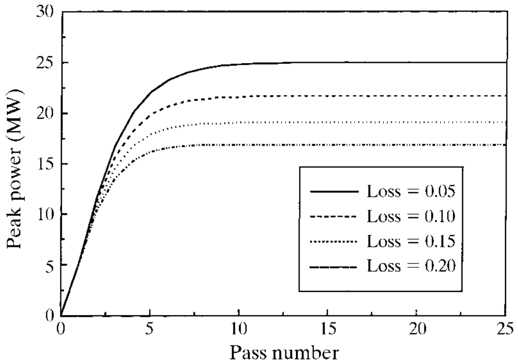

Figure 5
Dependence of the radiation power on the oscillating numbers of radiation pulses between the reflection mirrors. The saturated powers correspond to different round-trip losses in a cavity.

axial position. As shown in the figure, after the energy modulation in the first undulator and the phase change in the distribution section, the radiation power enhances rapidly in the second undulator. The power gains of this single-pass amplifier mode depend on the initial input powers. However, in the case of the oscillator the radiation saturated power is independent of them, as shown in Fig. 4, where we have assumed a total reflectance of the cavity of 0.9. Over about ten round trips in the cavity, the radiation powers reach a saturation value of 22 MW.

Fig. 5 shows the radiation peak power as a function of round-trip number of radiation pulses between the reflection mirrors. The radiation power of the FEL oscillator increases rapidly from the initial energy of 500 W before the pass number of 10. After that, it gradually reaches saturated values corresponding to the different round-trip losses in the cavity. Assuming 10% of the radiation power to be coupled from the hole of one mirror, a laser peak power of several megawatts will be available.

4. Conclusions

The conceptual design and some simulation results of an FEL based on the Tohoku Light Source storage ring are presented. Based on the above discussion, it is possible to operate the FEL in the visible and UV regions. Due to the expected high losses of normal-incidence optical cavities at wavelengths below 100 nm, the FEL should provide much more gain per pass compared with that obtainable in the visible region. To compensate mirror losses, it is necessary to increase the peak currents of the ring and the undulator period number. A low-loss resonator, such as a multi-faceted-mirror ring resonator, should be used for operating the FEL in the XUV region.

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References

Katoh, M., Sato, S., Suzuki, S. & Yamakawa, T. (1996). *The 5th European Particle Accelerator Conference*, Sitges, Spain.

Kortright, J. B. (1990). *Laser Handbook*, Vol. 6, pp. 463–483. Amsterdam: Elsevier Science.

Oyamada, M. (1993). *Proc. 9th Symp. Accel. Sci. Tech.*, pp. 486–488, Tsukuba, Japan.

Oyamada, M. (1995). *Proc. 10th Symp. Accel. Sci. Tech.*, pp. 463–465, Hitachinaka, Japan.

Sato, S. (1996). *Synchrotron Rad. Sci. Tech. Inf.* **6**, 34–40.

Tran, T. M. & Wurtele, J. S. (1989). *Comput. Phys. Commun.* **54**, 263–272.

Tran, T. M. & Wurtele, J. S. (1990). *Phys. Rep.* **195**, 1–21.