Current status and biological research ramifications of photon storage ring as a noble infrared laser source

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Abstract

It has been thought that the small electron storage ring of less than 50 MeV using a normal conducting magnet is useless because its critical wavelength of synchrotron radiation is only 600 nm. A small orbit radius storage ring, however, has the potential to generate micro bunches, leading to sub-pico second pulse UV light and coherent synchrotron radiation in the infra-red region. Moreover, it generates laser light of a few $\mu$m to 100 $\mu$m wavelength range with the aid of a mirror surrounding the electron orbit. This novel laser source is called the photon storage ring (PhSR) under construction. In this paper, a detailed description of the PhSR is given. A way to suppress beam instability of a low energy ring is proposed. Unique application programs for the PhSR are discussed. The usefulness of PhSR in studying living phenomena is pointed out. Continuous large output of PhSR can excite selective reactions of proteins, DNA, water in a living cell, which can open up a new research field and provide new means for cancer treatment. We propose 'a gentle communication with living cells through far infrared signal.' PhSR will make this possible. © 1997 Elsevier Science B.V.

Keywords: Photon storage ring; Compact electron storage ring; Far infrared laser; Coherent synchrotron radiation; Sub-picosecond pulse; Medical and biological applications
1. Introduction

It has been thought that the small electron storage ring of less than 50 MeV using a normal conducting magnet is meaningless, because the critical wavelength of synchrotron radiation is only 600 nm. It is, however, pointed out that a compact storage ring features a short bunch length of sub-pico seconds [1]. We would like to stress that this is one of the ways to generate femtosecond light pulses in the UV light range. Short bunches are useful in generating coherent synchrotron radiation in the far-infrared region. Moreover it may generate laser light of a few μm to 100 μm wavelength range when a mirror is placed around the electron orbit. This novel laser source is called the photon storage ring (PhSR), proposed by Yamada in 1989 [2]. In this study, under the contract with PRESTO Research and Development Corporation of Japan, the lasing mechanism of PhSR was established, and the smallest electron storage ring for PhSR was designed to maximize laser output. A way to avoid beam instability associated with low electron energy and large beam current was found experimentally. A feasibility study for constructing the smallest possible ring was carried out. We have so far succeeded in fabricating ring components such as a 1 m out diameter cylindrical normal conducting magnet, a small accelerator column, and a perturbator magnet for resonance beam injection.

In this paper first we summarize the characteristics, problems, and potentials of free-electron lasers in order to specify the future direction of free-electron laser development, and to clarify what the PhSR is Section 3 devoted to a detailed description of PhSR. The features of a compact electron storage ring used for PhSR are discussed in section 4. In section 5 the way to suppress the beam instability at a large electron beam current is discussed. Unique application programs for PhSR are proposed in section 6. It is pointed out that the PhSR is useful in studying living phenomena.

2. Historical overview of free-electron laser

There has been about a quarter century of history in the development of free electron laser (FEL) since the first lasing was obtained at Stanford University in 1977 [3]. Today stable lasing has been achieved in the infrared range of few μm ~ 1000 μm wavelength. Programs for its use have started at several institutes such as Stanford University [4], California University at Santa Barbara [5], Vanderbilt University (Nashville) [6], and the FOM Institute (Belgium) [7]. Even though the wavelength in practical use is long, the pulse length is only a few ps, thus peak power reaches MW at a few μJ energy per pulse. In the interaction between short pulse laser light and some material, multi-photon absorption is remarkable and the abrasion occurs at any wavelength. In medical treatment, it is used as a laser knife, and it cuts bones instantly without pain. Its cut edge is sharp unlike a thermonic cut.

FEL development in Japan started in the late 80s with the outflow of information after the SDI project had come to end in the U.S.A. and some development
programs have started in the 90s [8]. An s-band linac plan at the Free Electron Laser Institute (FELI) [9] and a super conducting linac plan at the Japan Atomic Energy Research Institute (Tokai) [10] were among them. At FELI they have recently succeeded in a lasing of 0.63 μm wavelength.

At the time the development started, people were expecting X-rays to be generated. However, it turns out that X-rays may not be generated within this century because of the electron beam quality and the X-ray mirror’s reflectivity. Recently, the U.S.A.’s National Research Council submitted a report on the future of FEL development and its use [11]. In the report, they state that X-rays-FEL will be difficult to achieve for some years and they are negative to make new facility for users. In contrast for FEL to the far infrared region, since the technology is well developed and no other light sources are available in this wavelength region, the new research field has become fruitful. They encourage new facilities and suggesting the facility smaller.

There are about forty FELs in the world, and the five facilities previously mentioned are in use. Most of the facilities are under construction, and their purpose is R & D. We have sixteen of them in Japan. Japan’s FEL facilities are shown in Table 1. The use of coherent SR light is active in Japan, so it is included in the table. Table 1 shows necessary information for users, such as tunable wavelength range, pulse length, repetition frequency, pulse power, average power, and present status. Data includes both planned and experimentally obtained parameters. Those indicated as ‘const.’ are under construction and are basically planned parameters. Those indicated as ‘ready’ refer to facilities ready for use. Readers would be surprised at the fact that the average power is small. While conventional small lasers can easily achieve 100 W output, FEL can get light output of a few watts from electrons accelerated to 100 MeV by using a large accelerator. It is, of course, a matter of repetition frequency; however, it is also true that FEL’s total output efficiency is low. After use in a linac-type FEL, electron beams are just thrown away. It is possible to collect accelerated electron energy, but this is practiced only with the Van de Graaff Type FEL at Santa Barbara.

The development of FEL is now in a new phase. The principle of the lasing mechanism is well understood, and it has come to the phase to develop particular FELs according to its application purposes. The special features of FEL are laser wavelength tunability and high peak power; however, in comparison with conventional lasers, its propagation cannot be promoted as long as linac of over 100 MeV is required. In the future, (1) it is obvious that the reduction of both the electron energy and the size of device must be an important subject. (2) Study of a new method that can increase the duty cycle and the average output power is another important subject. For the terminology of EEL high-output power, we refer to peak value in general; repetition is usually about 100 Hz, thus the average power is a few watts at most. Using super conducting linac is one way to increase the duty cycle but then device enlargement can not be avoided. (3) It is obvious that we should aim at femtosecond pulse as the electron source was improved. Obtainable pulse length range is presently longer than picosecond. We will find many applications
Table 1
List of FEL facilities in Japan

<table>
<thead>
<tr>
<th>FEL facility/ location</th>
<th>Wavelength (μm)</th>
<th>Micropulse</th>
<th>Macropulse</th>
<th>Peak power (J)</th>
<th>Average power (W)</th>
<th>Accelerator</th>
<th>Status User prog.</th>
<th>Comments applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max</td>
<td>Duration (ps)</td>
<td>Rate (MHz)</td>
<td>Duration (μs)</td>
<td>Rate (Hz)</td>
<td>rf-linac/ 150 MeV SC linac/ 15 MeV induction linac rf-linac x-band linac synchrotron synchrotron/ 500 MeV linac/ 70 MeV Marx generator</td>
<td>ready</td>
</tr>
<tr>
<td>TOhoku/Sendai</td>
<td>150</td>
<td>4000</td>
<td>5</td>
<td>2856</td>
<td>3</td>
<td>300</td>
<td>100 μW/ 1%bw</td>
<td></td>
</tr>
<tr>
<td>JAERI: SCARET/Tokai</td>
<td>20</td>
<td>80</td>
<td>4000</td>
<td>10</td>
<td>1000</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>JAERI: LAX-1/Tokai</td>
<td>30 GHz</td>
<td>300 GHz</td>
<td>0.16</td>
<td>1</td>
<td>1GW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UT-FEL/Tokai</td>
<td>43</td>
<td>9.4 GHz</td>
<td>8</td>
<td>476</td>
<td>5</td>
<td>50</td>
<td>82 W</td>
<td></td>
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<tr>
<td>KEK: Accel/Tsukuba</td>
<td>0.177</td>
<td>160</td>
<td>1.6</td>
<td>CW</td>
<td>3</td>
<td></td>
<td></td>
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<td>KEK: PF/Tsukuba</td>
<td>0.48</td>
<td>161</td>
<td>CW</td>
<td>100 MW</td>
<td>R &amp; D</td>
<td></td>
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<tr>
<td>ETL: NIUI/4/Tsukuba</td>
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<td>3.5</td>
<td>2856</td>
<td>20</td>
<td>12</td>
<td>30 MW</td>
<td></td>
<td></td>
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<tr>
<td>NIHON Univ./ Tokyo</td>
<td>7500</td>
<td>27000</td>
<td>1</td>
<td>single</td>
<td>1 MW</td>
<td></td>
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<td>ISAS/Fuchinobe</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>R &amp; D</td>
<td>power transport</td>
</tr>
<tr>
<td>Facility</td>
<td>Coating Rate (μm/year)</td>
<td>Lattice Constant (Å)</td>
<td>Lattice Height (Å)</td>
<td>Beam Power (W)</td>
<td>Beam Current (mA)</td>
<td>Beam Energy (MeV)</td>
<td>Status</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>UVSOR/Okazaki</td>
<td>0.29</td>
<td>0.52</td>
<td>&lt;10</td>
<td>90</td>
<td>40</td>
<td>3 mW</td>
<td>synchrotron/500MeV</td>
<td></td>
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<tr>
<td>PhSR/Kusatsu</td>
<td>3</td>
<td>1000</td>
<td>1</td>
<td>2450</td>
<td>CW</td>
<td>1000 W</td>
<td>const.</td>
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</tr>
<tr>
<td>ILT/Suita</td>
<td>2730</td>
<td>2</td>
<td>90</td>
<td>2</td>
<td>10</td>
<td>16 W</td>
<td>R &amp; D</td>
<td></td>
</tr>
<tr>
<td>ISIR (Osaka Univ.)/Suita</td>
<td>32</td>
<td>40</td>
<td>30</td>
<td>1300</td>
<td>1.8</td>
<td>120</td>
<td>rf-linac/7MeV</td>
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</tr>
<tr>
<td>FELI/Hirakata</td>
<td>0.6</td>
<td>20</td>
<td>10</td>
<td>22.3</td>
<td>24</td>
<td>10</td>
<td>rf-linac/19MeV</td>
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</tr>
<tr>
<td>FELI/Hirakata</td>
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<td>20</td>
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<td>22.3</td>
<td>24</td>
<td>10</td>
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<tr>
<td>Mitsubishi Electric</td>
<td>37</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R &amp; D</td>
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<tr>
<td>Sumitomo Electric/Harima</td>
<td>2.8</td>
<td>2856</td>
<td>10</td>
<td>20</td>
<td></td>
<td></td>
<td>ready</td>
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<tr>
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<td>2856</td>
<td>10</td>
<td>20</td>
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<td></td>
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<td></td>
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</table>
when we succeed in generating femtosecond pulse as discussed in section 6. To pursue these subjects, many FEL configurations other than the combination of linac and undulator have been suggested according to type of accelerators and light generating methods. Studies of new compact FELs that do not use an undulator, such as Smith Purcell type [12], Cherenkov radiation type [13], the photon storage ring type [1], and coherent SR type [14,15] are under development.

3. Principle for the photon storage ring laser

3.1. Outline of the PhSR

The idea of photon storage ring (PhSR) was originated by author in 1989 [2]. The PhSR is based on an exact circular electron storage ring and a concentric barrel-shaped optical resonator surrounding the electron orbit (see Fig. 1). This instrument may be categorized as a compact free-electron laser, but an undulator is not used at all. Stimulated emissions occur due to interactions between electrons in the circular orbit, and the synchrotron radiation accumulated in the optical cavity when the phase velocity of the radiation in the electron velocity direction and the electron velocity are matched. Transverse electric mode, TE(pj1), is selected to be built in the circular resonator [16]. A large gain is demonstrated by an analytical formula as well as simulations [17]; this gain is common to a circular FEL such as a magnetron [19]. The minimum obtainable wavelength is determined by the quality of the electron beam. The use of relativistic electrons may lead to an oscillation in a wavelength range of a few microns [1]. One other advantage of PhSR is that coherent synchrotron radiation is generated in this small storage ring [20]. The estimated bunch length is of the order of 0.1 mm, which leads to coherent radiation of a 10-micron wavelength. Therefore the lasing starts with this coherent radiation in the PhSR, while it starts with the noise signal in a conventional FEL.

3.2. Lasing conditions

An essential mechanism involved in a free-electron laser (FEL) is a periodic interaction between relativistic electrons and coherent radiation, which leads to the modulation of the electron density at the spacing of its wavelength. For this purpose, coherent radiation must have an electric field component toward the electron velocity. To accomplish this, coherent radiation and electrons are forced to merge at some angle. An undulator is a device that wiggles electrons and causes the electron trajectory and the radiation path to cross. We believe that, as long as the radiation path and the electron trajectory merge at some angle, it is not necessary for the electrons to be wiggled, but the radiation might be 'wiggled.' Of course an electromagnetic wave cannot be wiggled, but it can be reflected so as to merge with electrons at an angle. The PhSR is a device that employs such a concept [2].
Fig. 1. Cross sectional view of the photon storage ring made of one-piece normal conducting magnet having an 0.15 m radius exact circular electron orbit. A cylindrical mirror is placed around the electron orbit to accumulate synchrotron radiations and to generate stimulated emissions.

When coherent synchrotron radiation is generated in the PhSR, the radiation should propagate along the off-tangential line indicated as path a in Fig. 2 to prepare for acceleration of electrons. Once the interaction occurs at point A in the mode of accelerating (decelerating) electrons, the interaction should occur again at point B in the same phase for a successive coherent generation. For this mechanism, the phase of the coherent radiation must be shifted by 180° as the beam progresses from point A to B. The resonant wavelength, $\lambda_R$, is then given by the equation

$$\lambda_R = 2 \rho (\alpha / \beta_0 - \sin \alpha), \quad (3.1)$$

where $\rho$ is the electron orbit radius, $\alpha$ indicates the deflection angle of the radiation from the tangential line as indicated in Fig. 2, and $\beta_0$ is the electron orbital velocity relative to the speed of light. This condition is essentially the same as that for an undulator based FEL. The PhSR corresponds to an undulator with an effectively infinite number of periods. In comparing the resonance condition of
the undulator; \( \lambda_R = \lambda_w/(2\gamma^2)(1 + K^2/2) \), with Eq. (3.1) one can see that the K-value of the PhSR is equal to \( \beta_\theta (\sin \alpha)/\alpha \). The wavelength is, however, not uniquely determined by this equation, since the photon path can be selected arbitrarily. If the angle \( \alpha \) is appropriately selected, any wavelength satisfies the above condition. For this reason the wavelength must be selected by another mechanism.

The wavelength is actually determined by the mirror radius relative to the electron orbit radius. The light pulses confined in the mirror cavity propagate along the single photon path finally leading to the exit opening, and form a pulse train with an exact time period. The Fourier transform of this pulse train corresponds to the frequency of the light wave. This time period can be set to any small value by adjusting the mirror radius or the electron orbit radius precisely. This condition is

\[
\lambda = 2(\theta + n\pi/h)\rho/\beta_\theta - (2\rho \cos \alpha \tan \theta + \mu \lambda),
\]
where \( \mu \) is the amount of phase that is shifted by the reflection, \( n \) indicates the \( n \)th electron bunch that merges with the light pulse, and \( h \) is the harmonic number. The mirror radius is given as \( R_m = \rho \cos \alpha/\cos \theta \). The \( n = 0 \) case is the case in which the interaction of the radiation occurs always with the same electron bunch, which is called the whispering gallery mode.

It is easily shown that the phase between the light pulse and the electron is almost independent of \( \alpha \) when \( \alpha \) is smaller than \( \theta \), because the change of \( \theta \) by the deflection angle \( \alpha \) to the tangential line is

\[
\theta = \theta_0 + \frac{1}{\tan \theta_0} \left( \frac{\alpha^2}{2} - \frac{\alpha^4}{24} + \cdots \right) 
\]

(3.3)

\[
\cos \alpha \tan \theta = \tan \theta_0 + \frac{1}{\tan \theta_0} \left( \frac{\alpha^2}{2} - \frac{\alpha^4}{6} + \cdots \right) 
\]

(3.3')

where \( \theta_0 \) is the value of \( \theta \) when \( \alpha = 0 \). Substituting Eq. (3.3) and (3.3') into (3.2), one can see that Eq. (3.2) is independent of \( \alpha \). Consequently, the wavelength shift is negligibly small for small values of \( \alpha \). In fact \( \alpha \) is as small as \( 1/\gamma \), where \( \gamma \) is the relativistic factor. We can conclude that if the electron orbit is an exact circle, there are no factors that make the interference effect deteriorate in the PhSR. Radiation emitted at any angle interferes coherently at the same wavelength.

### 3.3. Coherent SR generation

Observed coherent SR from a single bunch traveling in a bending magnet [15,26] encourages the proposed lasing scheme of the PhSR. Here the coherent SR denotes radiation emitted from a number of electrons in a bunch all in the same phase. Coherent SR is thought to be dominant in the range of wavelength comparable to or longer than the bunch length. However, the observed much shorter wavelength suggests the importance of electron distribution in the bunch and/or unknown coherent generation mechanism. Including this coherent SR generation, the power, \( P(\lambda) \), from the PhSR has been calculated as

\[
P(\lambda) d\Omega d\lambda = p(\lambda) N_e \{1 + [N_e - 1] F(\lambda) G(\lambda)} d\Omega d\lambda,
\]

(3.4)

where \( p(\lambda) \) is the SR power from one electron, \( N_e \) is the number of electrons in the bunch, and \( F(\lambda) \) is a form factor which is the Fourier transform of the longitudinal electron distribution in the bunch. If Gaussian electron distribution is assumed, \( F \) is given as [21]

\[
F(\lambda) = \exp\left\{-(2\pi \sigma_L/\lambda)^2\right\}
\]

(3.5)

where \( \sigma_L \) is RMS bunch length. The function \( G(\lambda) \) represents the interference of the coherent SR from bunches. This is given for a certain reflection coefficient \( f \) as
Here the phase slippage between different bunches is assumed to be negligibly small. The coherent SR power from the PhSR is proportional to the square of the electron number $N_e$ in the bunch, as well as to the square of the number of bunches, $N_b$, contributed with the help of the optical resonator. Assuming the form factor to be unity and a reflection coefficient of 0.9, the average coherent SR power is estimated to be $400 \text{ W/}[\text{s, mrad, 0.1\% band width}]$ for 100 $\mu\text{m}$ wavelength at 10 A of accumulated current. It is apparent that the yield drops significantly at a wavelength shorter than the bunch length.

When the wavelength is comparable to the bunch length we can extract sufficient coherent power from the PhSR without the lasing process. For generating short wavelengths, electron distribution and the short bunch length seem important.

### 3.4. Gain formalism

The interaction of electron beams and radiation in the exact circular orbit has been studied by analytical methods as well as by simulation [16,17]. Instead of the ray optics described in Section 3.2, we assume that the specific mode $TE(pj,l)$ is generated in the cylindrical mirror cavity. This mode can be expressed by a Bessel function $J_p(x)$ of a very high order of azimuthal mode number, $p$. When the azimuthal phase velocity, $v_\theta(= \omega_p/p)$, is equal to the orbital electron velocity, $v_\theta(= c)$, a resonant interaction is expected. The electric field of the $TE(pj,l)$ mode in a cylindrical cavity is strongest near the electron orbit at $r_m = x(p,1)/k$. The electric field of this mode with a high radial mode number, $j$, diminishes almost exponentially inwards from $r_m$, while it oscillates outward, decreasing as $1/\sqrt{r}$.

The electron-beam energy loss due to electric field $E_\theta$ has been evaluated through the equation of motion,

$$\frac{d\langle \gamma mc^2 \rangle}{dt} = -e\langle \nu_\theta E_\theta + \nu, E_r \rangle = -e\langle \nu_\theta E_\theta \rangle,$$

where $\langle \rangle$ indicates averaging over electron energies. The total electron energy loss $dW/dt$ is obtained by solving the equation of motion using the formula of $TE(pj,l)$ mode. The growth rate, $\Gamma$, is defined as

$$\Gamma = -\frac{dW}{dt}/W_p$$

where $W_p$ is the total radiation power.
The problem was analyzed under the assumption that (1) the radiation filled the resonator mirror uniformly, (2) the electron beam is uniformly distributed at the beginning, (3) the synchrotron oscillation is neglected because the growth rate is faster than that, but (4) the electron beam energy spread and the radial distribution are taken into account. The growth rate in the exponential gain regime is obtained as

$$\Gamma = \frac{(2\pi)^{5/2}}{2\sqrt{e}} \frac{\rho^3 I_0 q \pi}{\lambda e_0 c^3 m (1 - n)} \gamma (\delta \gamma / \gamma)^2 \sigma_I \int_0^{kR} x f_p^2 dx$$

(3.10)

Where $I_0$ is the beam current, $q$ is the charge, $m$ is the electron mass, $n$ is the field index, $\sigma_I$ is the bunch length, and $D$ is the half height of the resonator. The last term is related to the filling factor by the relationship

$$F = \delta z \int_{-\sigma_x}^{\sigma_x} f_p^2 (kr) r dr / D \int_0^{kR} x f_p^2 (kr) dx$$

(3.11)

where $\delta z$ is the vertical beam size of the radiation. To see the start-oscillation condition, we find the dependence of the parameter on the growth rate as

$$\Gamma \propto I_0, \gamma^{-1}, (\delta \gamma / \gamma)^{-2}, (\sigma_x \sigma_y \sigma_z)^{-1}, \lambda^{5/3}, D^{-1}.$$  

(3.12)

To increase the growth rate, we recommend that the beam current should be increased, and the electron beam energy, the bunch length, the orbit radius, the resonator height, and the energy spread should be reduced. The calculated growth rate in the case of 50 MeV electron energy is shown in Table 2.

### 3.4. Micro bunching process

The gain process of free-electron lasers is understood as a micro bunching process of an electron beam. When the complete spacing of micro bunches occurs in the order of the laser wavelength, the laser gain is saturated.

We have, for the first time, pointed out that if the electron bunch length is of the order of the laser wavelength from the beginning, we have to include the beam edge effect and coherent SR in the gain. In our PhSR the bunch size is indeed the order of the laser wavelength.

The gain formalism to take into account this small bunch size is given as follows. For simplicity we start with Maday's theorem. According to this theory, gain is proportional to the derivative of spontaneous SR power with respect to electron energy $\gamma$. In our case we suggest that instead of spontaneous SR power, we should use the coherent SR power given by Eq. (3.1). The modified gain formalism is given as,

$$\text{gain} = \frac{8\pi^2 I/e dP}{m \omega^2 A dy},$$

(3.13)
where $I$ is the current, $\omega$ the angular frequency of the laser, and $A$ the cross section of the optical pulse. Substituting Eq. (3.1) into Eq. (3.13), we obtain the gain,

$$\text{gain} = -\frac{8\pi^2 I/e}{m\omega^2 A} p(\lambda)N e \left[ \frac{\partial F(\lambda)}{\partial \gamma} G(\lambda) + F(\lambda) \frac{\partial G(\lambda)}{\partial \gamma} \right]$$

$$= -\frac{8\pi^2 I/e}{m\omega^2 A} p(\lambda) \phi(\lambda)$$

where,

$$\phi(\lambda) \equiv N e G(\lambda) \frac{1}{\gamma} \left( \frac{2\pi}{\lambda} \right)^2 \sigma_L^2 F(\lambda)$$

The function $\phi(\lambda)$ is the enhancement factor which is related to bunch form factor $F$ and bunch length $\sigma_L$. Since $G$ is independent of $\gamma$, that disappears in Eq. (3.15). Giving the bunch length to be 0.1 mm, we obtain $\phi(\lambda) = 125$ for the wavelength $\lambda = 0.1$ mm. This value decreases exponentially by $\lambda^2$, and thus drops to 1 at 0.01 mm.

4. Optimized design of the photon storage ring

4.1. Short bunch length

The first exact circular electron storage ring has already been successfully completed, which uses a super conducting magnet [22,23]. This ring was developed as a soft X-ray source for industrial uses such as X-ray lithography. This simple ring is advanced in many regards. We found, for instance, that the beam is very quiet, and the beam position never fluctuates. This results from the simplest magnet configuration based on a weak focusing principle. These features are extremely useful for lasing PhSR.

More attention should be drawn to the fact that the compact storage ring generates short bunches. As is well known, the bunch length of the exact circular ring is given as [24]

$$\sigma_L = c \sigma_r = c (\alpha / \Omega_s)(\sigma_E/E_0),$$

$$(\sigma_E/E_0)^2 = C_q \gamma^2 / (J_E \rho_0),$$

where, $c$ is the velocity of light, $\alpha$ is the momentum compaction factor, $\Omega_s$ is the synchrotron oscillation frequency, $\sigma_E$ is the electron energy distribution, which is determined by $\gamma$, the electron energy in rest mass units, and $\rho_0$, is the central orbit radius. As seen in these equations, bunch size decreases as electron energy is
reduced. Since the synchrotron oscillation frequency is given as

\[ \Omega_*^2 = 2\pi \alpha h(U_0 E_0) f_r^2 \sqrt{q^2 - 1}, \]  

(4.3)
bunch length is shorter for higher accelerating voltage and frequency, \( f_r \), and higher harmonics, \( h \). It is obvious that one way to produce short bunches is to make a low energy compact ring. The smallest size of the ring might be limited by machinery problems. In this regard an exact circular ring may be the smallest ring, since this has no straight sections, and the rf cavity is placed between magnet poles. On the other hand, in order to minimize intrabeam scattering, and to increase the radiation damping rate, we must use the highest possible electron energy. The optimum value will be 50-MeV when a normal conducting magnet is used. The machine parameters of a 50-MeV ring are listed in Table 3. It is seen that the bunch length changes as the betatron tune is changed. To get a shorter bunch size, a smaller field index, \( n \), should be selected. In the table we include natural values at low beam current and corrected values for intrabeam scattering at 1 A beam current. According to these calculations we are encouraged in generating short bunches and coherent synchrotron radiation from this compact ring.

The machine parameters of the electron storage ring are determined as follows. The laser growth rate of the PhSR is inversely proportional to electron energy, \( \gamma \), and energy spread, \( (\delta \gamma / \gamma)^2 \). In the case of the weak focusing exact circular ring, the energy spread is proportional to \( \gamma^2 / \rho \), where \( \rho \) is the central orbit radius. Consequently the growth rate is inversely proportional to \( \gamma^3 \), which suggests that a lower electron energy gives a higher growth rate in principle. In a low energy ring, however, the emittance grows due to the intrabeam scattering, and the damping rate decreases. When we want to construct the ring with a normal conducting magnet, we find that the emittance becomes smallest at 50 MeV under 1 T magnetic field. We are concerned that in this case the Touschek lifetime becomes the smallest value, around 60 s, but this value is large enough for the lasing as well as for the injection of the beam. Another concern is the practical problems of ring construction. The 150 mm electron orbit radius for the 50 MeV ring is almost the smallest size possible for installation of the acceleration cavity and the perturbator for resonance injection, which is discussed in the next section.

The field index of the ring must be selected to be near the integer, \( 2/3 \), \( 1/2 \), or \( 1/3 \) resonance values for the resonance injection method. Since field index affects laser gain, we have studied the \( n \)-value dependence of the beam parameters and the laser growth rates for a 100 \( \mu \)m wavelength as shown in Table 3. Both natural values and corrected values for the intrabeam scattering are listed. It is clear from the table that the smaller index gives higher gain. The use of the integer resonance (the case of \( n = 0.01 \)) might be recommended. The problem of the integer injection is, however, that since the damping speed is slower (8.3 s), the injection efficiency might be smaller. A damping speed of 85 ms in the case of \( n = 0.5 \) is fast enough. We have chosen a \( 2/3 \) resonance injection.
4.2. Resonance injection scheme

One of the problems of storage ring driven FEL is an emittance growth due to lasing, and, since an electron beam is utilized repeatedly in the PhSR, the same problem may occur. One might think that in the PhSR the maximum obtainable power is limited by Renieri's law [26]. These problems may, however, be avoided by the unique beam injection mechanism. The injection of electrons is usually carried out in a manner that distorts the electron orbit, and then the beam trajectory in the undulator is also displaced. Therefore, with conventional storage ring driven FEL, the FEL oscillation can not be continued during injection. With the resonance injection scheme, however, specific radial betatron oscillation is resonantly invoked only in the limited area of ±5 to ±60 mm for 0.1 μs duration to expand the acceptance of the beam [25]. The perturbator that excites this resonance generates a non-linear magnetic field that has no gradient in the central orbit region over 10 mm in the radial direction. Therefore the beam in the central orbit is undisturbed by this injection. In this scheme the beam is injected many times to produce a large accumulated current. More than 60% injection yield has been demonstrated [23]. This scheme is extremely useful for the PhSR for two reasons: First, the beam in the central orbit is unperturbed by the injection, so that injection can be continued during FEL oscillation. In this sense the PhSR is classified as a linac driven FEL. Second, this type of machine has a very large dynamic aperture. This is useful in capturing the beam during the very large betatron motion invoked by lasing. The electrons in the region outside the central orbit make no contribution to lasing but also do nothing harmful because their phase velocity is totally different from that of the optical pulse. They are simply kept for circulating until being damped and contribute to lasing again.

4.3. Optical resonator

We use TE(pj1) mode with large azimuthal, p, and radial, j, mode numbers, and axial mode number of one as the operating mode. The whispering gallery mode, which has fundamental mode numbers, (p,1,1), is inadequate for PhSR, because the optical cavity has to be set too close to the electron orbit within one millimeter, and also the power loss due to the ohmic loss becomes too large. The radial mode number dependence of the power loss is shown in Fig. 3, together with the integrated power in the resonator. We can find that the filling factor decreases as the radial mode number increases, but the power loss is reduced more dramatically than the decrease of filling factor.

In order to increase the filling factor, the resonator is made in a barrel shape. The optimized curvature of the barrel shape has been obtained by the Gelerkin technique incorporating the quasi-optics approximation [27]. For 31 μm wavelength we have selected the mirror width, D = 20 mm, the curvature in axial direction, $R_0 = 207$ mm, and the mirror radius, $R = 217.0$ mm. The mirror has a $2 \times 10 \, \text{mm}^2$ slit on the surface for injecting beams as well as extracting laser radiation. Mode mixing due to this slit has been analyzed.
We are now fabricating the mirror, of which is made of SiC ceramics. This material was selected because of rigidity and good heat conductivity. Mirror curvature will be made within 0.1 μm tolerance.

5. Suppression of beam instability by introducing gas in the electron orbit [29]

Laser growth rate of the PhSR increases as the beam current increases, as discussed in section 4.4. Lasing of 30 μm wavelength requires about a 100 mA beam current, and for 10 μm wavelength, nearly 3 A, to overcome the power loss (0.045 for 10 μm wavelength) in the optical resonator. A large beam current is the
essential requirement for the lasing at a shorter wavelength. But the problem is that the electron beam becomes unstable and the beam size grows because of the wake field of beam that appears on the beam duct. This is more significant when electron energy is lower since radiation damping power is smaller for lower electron energy.

Introducing gas into the beam duct is a proposed method of accumulating large beam current without increasing beam size and bunch length. We have, for the first time, demonstrated bunch shortening by using the existing compact ring, AURORA, in 150 MeV operation under $5 \times 10^{-7}$ Torr hydrogen gas pressure. Hydrogen was selected to avoid activation due to $(\gamma, n)$ nuclear reactions. In Fig. 4 the current dependence of the bunch size is shown [28,29]. Usually bunch size grows as beam current increases caused by electron-electron Coulomb interactions as indicated by open circles, but in the case that hydrogen gas was loaded, the bunch size was kept constant as shown by solid squares. We also found in this experiment beam lifetime became longer at high beam current under gas pressure. This result must be the opposite to the high vacuum case, although we couldn’t take the data because we couldn’t accumulate beam more than 600 mA under high vacuum. Usually a storage ring is kept in vacuum pressure as low as possible to avoid the gas scatterings that leads to short lifetime. In our case, however, the lifetime is short anyway because electron energy is low. All the phenomenon we found in this experiment were helpful for operating a low energy ring. We were able to accumulate as much as a 1.3 A beam current, and beam was quite stable.
Our explanation for these results is the following: We think that the forced radiation damping occurred due to bremsstrahlung and ionization losses in the collision of beam and gas. Also strong beam focusing occurred due to the ion trap, which shifts the betatron tune.

The effect of bremsstrahlung and ionization on the damping time might be understood as follows. The damping rate, \( \alpha_e \), is related not only to synchrotron radiation loss but also to bremsstrahlung and ionization losses, \( U_t \), as given by the formula:

\[
\alpha_e = \frac{1}{2T_0} \left[ \frac{dU_t}{d\varepsilon} \right].
\]  

(6.1)

The total radiation loss \( U_t \) is a function of orbit length \( L_\varepsilon \):

\[
U_t n_i (E_0 + \varepsilon) \sigma_{in} L_\varepsilon = n_i (E_0 + \varepsilon) \sigma_{in} L_0 \left( \frac{\alpha \varepsilon}{E_0} + 1 \right)
= n_i \left( E_0 + \alpha \varepsilon + \frac{\varepsilon^2}{E_0} + \varepsilon \right) \sigma_{in} L_0
\]

(6.2)

where \( n_i \) is the ion density, \( E_0 \) and \( \varepsilon \) are the central electron energy and the electron energy deviation from the central value, respectively, \( \sigma_{in} \) is the inelastic scattering cross section, \( \alpha \) is the momentum compaction, and \( L_\varepsilon \) and \( L_0 \) are the orbital length for any electron energy and for the central electron energy, respectively. Substituting Eq. (6.2) into (6.1), we obtain

\[
\alpha_e = \frac{1}{2T_0} n_i \sigma_{in} L_0 \left[ \alpha + 1 + 2 \frac{\alpha}{E_0} \varepsilon \right].
\]  

(6.3)

We see here that the bremsstrahlung and ionization loss always cause a damping effect when the momentum compaction value \( \alpha \) is positive. We expect damping speed of a few ms even if the \( n \)-value of 0.01 is assumed.

The bunch shortening can be explored by the increased synchrotron oscillation due to bremsstrahlung according to Eq. (4.3). \( U_t \) is used instead of \( U_0 \) again in this formula. It should also be mentioned that the emittance growth due to gas scattering is insignificant at this gas pressure.

Trapped ions are also functioning to focus electron beam, and to neutralize electron charges. All of these helps stabilize the beam. The maximum obtainable beam current can be explained as the Alfvén-Lawson limit.

6. Medical and biological applications of the PhSR

The most attractive features of the PhSR are the large average power and the short pulse width compared with other FELs as seen in Table 1. The peak power is
lower than other FELs, and the tunable laser wavelength is longer than a micrometer. We, however, think that the applications of far infrared rays ranging from a few µm to 100 µm and short time phenomena in the range of pico to sub-pico seconds are rather interesting. It is evident that all wavelengths are produced by synchrotrons and lasers, but so far we have not obtained such a bright source in the far-infrared region. We believe that this is an exciting opportunity to study living phenomena in which the energy and information exchanges happen between biological molecules, and between biological molecules and water by far infrared rays.

Table 3 shows the time evolution involved in molecular and biological dynamics and the speed of electronic transfer and energy transfer [31]. The relaxation time of molecular vibration is 0.1 ~ 10 ps, the cycle of molecular vibration is 10 ~ 100 fs, the revolution time of a molecule is 1p ~ 100 ns, the ionizing time by light and protein's internal motion is over ps, and the relaxation time of formation by photo-synthesis is 3.5 ps. Therefore, PhSR makes it possible, for instance, to observe every moment of the photo-synthesis mechanism, the sensing process of eye, and the protein’s dynamics. As high speed ‘non-radiative’ transitions are said to exist in complicated living bodies, the organic functions of cells formed with numerous proteins result from small changes in the specific state of proteins. These are called non-radiative but this means that transition energy is extremely small. Therefore, living phenomena can hopefully be investigated by using coherent infrared and far infrared rays to observe the influence of transitions among the different states of organic materials. The important thing is to examine how the living cell functions or behaves when a small transition in a specific element is caused directly to organic materials without breaking down the living phenomenon by short wavelength rays. We can analyze and find the structures of these states by Raman spectroscopy using short wavelengths, but we can not see the dynamics of the living organic materials in this way. We say that ‘we try gentle communications between human and living organic elements.’

D. Fayer’s group at Stanford have turned their attention to the measurement of relaxation time by using a linac type FEL [31]. They focused on CO’s vibration in myoglobin and are observing how relaxation time changes according to temperature or how it is different according to various hem-CO conditions. We are able to see further more the macroscopic signatures of the living phenomena by PhSR, because this source is bright enough to excite mass of molecules consisting a living element. This means that we might be able to control the functions of organic materials in this way.

There have been many arguments, with superstition and science mixed, on the effect of far infrared rays on the human body. For medical use, it is difficult to come to a distinct conclusion since it differs individually and people’s mind reflects on it. However, examples using red lasers such as the cure of atopy skin disease, change in the growth of damaged bone tissue, and the relaxation of pain have been reported [32]. From experience, red lasers works better than blue, and a CW laser seems better than a pulse laser. This research has been conducted only by using easily available laser; dependence on variable wavelengths has not yet been
Table 2
Machine parameter of 50 MeV ring under following conditions: RF-voltage = 120 keV, coupling constant = 0.1, harmonics = 8. The growth rate is calculated for 100 μm wavelength. Correction for intrabeam scattering (IBS) is calculated at 1 A beam current.

<table>
<thead>
<tr>
<th>Parameters/n-value</th>
<th>0.01</th>
<th>IBS</th>
<th>0.3</th>
<th>IBS</th>
<th>0.5</th>
<th>IBS</th>
<th>0.7</th>
<th>IBS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural</td>
<td></td>
<td>Natural</td>
<td></td>
<td>Natural</td>
<td></td>
<td>Natural</td>
<td></td>
</tr>
<tr>
<td>Emittance (π mrad)</td>
<td>3.88E-07</td>
<td>8.87E-06</td>
<td>1.45E-08</td>
<td>1.88E-06</td>
<td>1.03E-08</td>
<td>1.40E-06</td>
<td>9.49E-09</td>
<td>8.57E-07</td>
</tr>
<tr>
<td>Energy spread (ΔE/E)</td>
<td>9.05E-05</td>
<td>4.46E-04</td>
<td>9.76E-05</td>
<td>1.11E-03</td>
<td>1.11E-04</td>
<td>1.29E-03</td>
<td>1.92E-04</td>
<td>1.82E-03</td>
</tr>
<tr>
<td>Horiz. damping T (sec)</td>
<td>8.40E + 00</td>
<td>2.00E-01</td>
<td>8.50E-02</td>
<td>3.60E-02</td>
<td>3.60E-02</td>
<td>9.49E-09</td>
<td>0.485</td>
<td></td>
</tr>
<tr>
<td>RMS bunch length (mm)</td>
<td>0.247</td>
<td>1.22</td>
<td>0.317</td>
<td>3.6</td>
<td>0.425</td>
<td>4.9</td>
<td>0.949</td>
<td>9</td>
</tr>
<tr>
<td>Horiz. bunch size (mm)</td>
<td>0.235</td>
<td>1.16</td>
<td>0.051</td>
<td>0.58</td>
<td>0.047</td>
<td>0.545</td>
<td>0.051</td>
<td>0.485</td>
</tr>
<tr>
<td>Vert. bunch size (mm)</td>
<td>0.074</td>
<td>0.365</td>
<td>0.0063</td>
<td>0.055</td>
<td>0.0047</td>
<td>0.055</td>
<td>0.0041</td>
<td>0.039</td>
</tr>
<tr>
<td>Growth rate (1)/turn</td>
<td>14.7</td>
<td>0.266</td>
<td>13.5</td>
<td>0.021</td>
<td>12.2</td>
<td>0.008</td>
<td>1.85</td>
<td>0.0022</td>
</tr>
<tr>
<td>Growth rate (2)/turn</td>
<td>23.5</td>
<td>0.426</td>
<td>22.2</td>
<td>0.034</td>
<td>19.5</td>
<td>0.013</td>
<td>2.96</td>
<td>0.0032</td>
</tr>
<tr>
<td>Power loss/turn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.014</td>
<td></td>
</tr>
</tbody>
</table>

(Note) growth rate (1): cylindrical resonator growth rate (2): barrel shaped resonator.
studied. We could say that there is no risk in these treatments since the wavelength dependence is insignificant. For that reason, it is appropriate to note that red light excites molecular motion indirectly by Raman process, not by direct photo-chemical process. If that is true, it is very important to see the effect on the various above mentioned examples by using PhSR for scanning wavelength of far infrared rays. If a shorter wavelength than far infrared is used, various states will be excited at once by the Raman process, thus making observation of pure effect difficult.

States of biological molecules always interact with water, and we cannot ignore the influence given on living activity by water structure. Water has many absorption lines in the range of sub-millimeter waves. We may excite a specific water structure by irradiating with the specific wavelength light which gives a specific reaction on a living phenomena. To make a specified protein state active, a specific wavelength with extremely narrow band width is necessary. With PhSR, the wavelength can be changed freely so research can be done as desired. And its high output power makes it possible to achieve wavelength resolution of $\Delta \lambda/\lambda = 10^{-7}$. Study on living phenomenon should start with taking detailed data of substance’s absorption and reflection against far infrared rays in this order of resolution.

We are planning to apply our method, ‘gentle communication’, to the treatment of decease. We will be able to use PhSR by tuning it to the distinctive wavelength which is strongly absorbed by arterioscleroses, cancer, and lighiastis. We expect these materials to disintegrate and to solve in a water without pain and side effects. Since PhSR has high average power, such use is excellent. We have a possibility to open up a new medical treatment, which just irradiate with a specific wavelength far infrared ray from outside of a human body, if this wave has a narrow band width and is not absorbed by water and another proteins.

In summarizing we expect new research field in biology and medicine which are directed by the philosophy, ‘gentle communication with a living element.’ In this way we will be able to research the living phenomena in a normal state. and to control externally the function of living cell. The PhSR will make these possible, and will provide ‘gentle’ medical treatment for cancer and other decease.
7. Conclusions

We have discussed the photon storage ring (PhSR) as a novel extremely bright far infrared source. The PhSR is based on the world smallest electron storage ring. We have introduced many new features to the smallest electron storage ring such as generating short bunches in sub-picoseconds, accumulating a large beam current of more than ampere by using the resonance injection method, generating stimulated emission by means of cylindrical mirror surrounding the electron orbit, and stabilizing beam and reducing bunch size by introducing gas into the beam orbit. By all these means the smallest electron storage ring becomes an extremely powerful light source. We have shown the design of the smallest electron storage ring, one meter out diameter exact circular ring made of a normal conducting magnet. The PhSR has the potential to generate kW of CW laser in the range of a few $\mu$m to 100 $\mu$m wavelengths as well as to generate 100 mW/[0.1%band width, mrad^2] UV radiation.

A new light source of a few to 100 $\mu$m wavelength is now available for medical and biological research. The ramification of PhSR are enormous, we believe. The usefulness of far infrared light is not yet established, however, the far infrared rays are deeply related to living phenomenon. The new research direction is a kind of 'a gentle communication with living organism through the far infrared signal.' The PhSR make this possible by its tunable and continuous radiation. The PhSR will provide 'gentle' medical treatment for cancer and other decease. We are now constructing this new light source, and will start with lasing at about 30 $\mu$m in 1997.

Acknowledgements

The author is grateful to Dr. Takayama for collaboration in designing the compact electron storage ring. The author is also grateful to Dr. A.I Kleev and Dr. A.B. Manenkov for collaboration in analyzing the practical mode in the barrel-shaped mirror resonator. Special acknowledgement is given to Mr. Tsutsui for developing the simulation code. The operation crew of AURORA are appreciated for taking data of the exact circular ring. Prof. K. Shimoda and Prof. K. Mima for their stimulating discussions and encouragement in studying the lasing mechanism of the PhSR are appreciated. Finally author acknowledges special thanks to Prof. J. Chikawa and Prof. K. Kora for their help in promoting this research program.

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[29] Yamada et al., to be published.