Feasibility Study of Generation and Observation of Far Infrared Coherent Synchrotron Radiation at UVSOR

Y.Takashima, M.Katoh[A], M.Hosaka[A], A.Mochihashi[A] and S.Kimura[A]

Graduate School of Engineering, Nagoya University, Chikusa-ku Nagoya 464-8603 Japan

A)UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan

We have been considering a method for the generation of far infrared coherent synchrotron radiation from UVSOR storage ring.

Far infrared coherent radiations can be emitted when the electron bunches have density modulations [1]. In order to obtain intense far infrared synchrotron radiations, we have been studying the feasibility to generate coherent radiations by using the bunch slicing technique [3,4,5].

The bunch slice can be achieved by using a laser pulse passing together with an electron bunch through in an undulator [5]. We tune the undulator to the wavelength of the laser, so that the energy of electrons overlapped with the laser are modulated by the interaction with the laser field. If the energy modulation is several times lager than the r.m.s. energy spread of the electron beam, the modulated electrons are separated spatially and a dip is made in the bunch when the electrons pass through a dispersive section. The modulated electron bunch with a dip can emit coherent radiations of which wavelength is in the same order of the size of the dip.

Experimental Equipment

We will use the existing BL5U undulator as an energy modulator in which circulating electrons interact with the laser pulses.

A mode-locked Ti-sapphire laser and an ultrafasst regenerative amplifier is used to make femtosecond laser pulses which should have enough power to make sufficient energy modulation in order to make a dip [5,6].

Intensity of Coherent Radiation

The ratio of the coherent to incoherent radiation intensity is expressed by the following equations [1,2],

$$\frac{P(\omega)_{coherent}}{P(\omega)_{incoherent}} \cong N \cdot f(\omega),$$

where ω is the frequency and N is the number of electrons within a bunch. $P(\omega)_{\text{incoherent}}$ and $P(\omega)_{\text{coherent}}$ are the power of incoherent and coherent radiations, respectively, emitted from a electron bunch. Because of the large number of N ($\sim 10^{10}$), coherent radiations can dominate over the incoherent radiations.

The beam tracking simulations has confirmed that a dip can be made in the bunch at the exit of BM6 [6]. The electrons of the width of 1 ps in a bunch were modulated their energy up to 0.8 % in the existing BL5U undulator (modulator) and then traveled to the BM6. The ratio of the coherent to incoherent radiation intensity generated from the bunch is abut 2 $\times 10^5$ at the wavenumber of 20 cm-1 (wavelength is 0.5 mm) when the beam current is 18mA/bunch (N is 2×10^{10}).

In order to observe the infrared radiation, we plan to use the InSb semiconductor bolometer at BL6. The detector can be used to detect the radiation of wavenumber from 5 to 50 cm^{-1}; in the region the coherent radiations are expected to be yielded much more than incoherent radiations [6].

Summary

We have been planning to generate and observe far infrared coherent synchrotron radiation using the bunch slicing technique at UVSOR. A commercial short pulse laser can be used to slice electron bunches and make dips which are indispensable to generate the coherent radiations. The averaged intensity of the far infrared coherent radiation is about ten times larger than the incoherent radiation if we use the laser of 5 kHz repetition rate and make one dip in each bunch. We can observe the coherent radiation at BL6 using the InSb bolometer.

For further studying, we should consider methods to improve the intensity of the radiation, for example, how to make dips periodically in a bunch.

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BL5U

The First FEL Lasing on the UVSOR-II Storage Ring

M. Hosaka, M. Katoh, A. Mochihashi, J. Yamazaki, K. Hayashi, Y. Takashima*
UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585 Japan
**Depertment of Materials Processing Engineering, Graduate School of Engineering, Nagoya University, Chikusa-ku, Nagoya 464-8603 Japan*

The upgradation of the UVSOR storage ring was successfully done in Spring 2003 and the emittance of the electron beam has been reduced by factor 6 comparing the previous value [1]. The improved performance of the UVSOR-II electron beam is of great advantage for the free electron laser experiment and we expect lasing in much shorter wavelength.

The FEL experiment using UVSOR-II was begun in October 2003. Before the lasing experiment we determined a beam trajectory for the FEL experiment by measuring spontaneous radiation spectra from the helical optical klystron (HOK) [2]. On December 1st the first lasing was achieved after an adjustment of the optical cavity. The lasing wavelength was visible region around 420 nm. Looking at an extracted FEL power, we made more accurate adjustment of the cavity mirror. In the experiment, multi-layers of Ta_2O_5/SiO_2 was employed for the cavity mirrors. The round-trip reflectivity of the cavity mirror was evaluated by a ring-down method and the deduced value was 99.25 %. Reducing an electron beam current, a threshold beam current was measured and the obtained value was 16 mA/2-bunch. Thus the FEL gain is estimated to be 0.75 % at the electron beam current of 16 mA/2-bunch. This value is compared with calculated FEL gain in Fig. 1. As seen in the figure, although the measured gain was higher than previous value of the UVSOR-I, it is smaller than the calculated one of the UVSOR-II. This indicates that the optimization of the FEL system has not been done satisfactory.

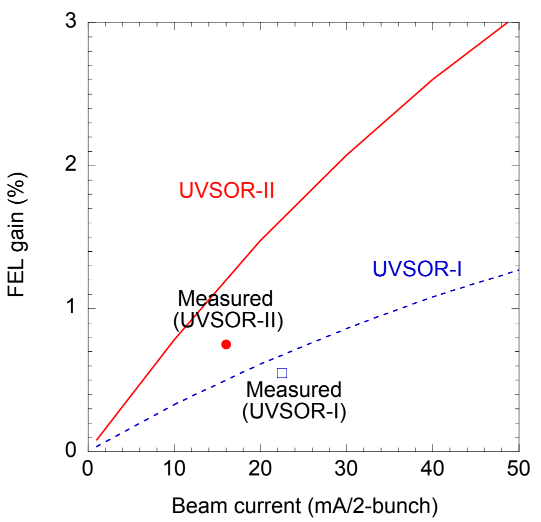

Fig. 1: FEL gain as a function of the beam current. Measured gains for the UVSOR-I and UVSOR-II are compared with calculated ones.

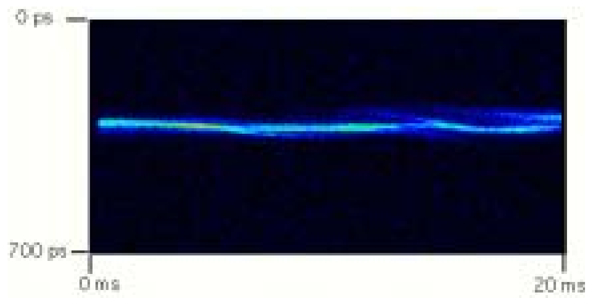

Figure 2: Temporal profile of the FEL at the beam current of 68 mA measured using a dual sweep streak camera.

We suppose that the adjustment of the overlap between the laser and the electron beam whose size is reduced in the upgradation of the storage ring is not sufficient. We are going to employ correction magnets equipped inside HOK to maximize the overlap.

In order to investigate characteristics of the lasing, we measured a temporal profile of the FEL using a dual-sweep streak camera. Figure 2 shows one of obtained profiles. The shortest temporal width was 5 ps, but the stable lasing did not last more than 10 msec. This is because the electron beam was suffered by the transverse/longitudinal instability during the measurement. The source of the instability is supposed to the interaction with the RF cavity system (main cavity and 3rd harmonic cavity). We are going to optimize the operating point of the storage ring to suppress the instability.

In summary, we have successfully obtained the FEL lasing with UVSOR-II, however its performance is not satisfactory. More studies are needed for lasing in shorter wavelength.

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ACCELERATOR AND BEAM PHYSICS

Improvement Plan of RF Cavity in UVSOR-II Electron Storage Ring

A. Mochihashi, M. Katoh, M. Hosaka, K. Hayashi, J. Yamazaki, *Y. Takashima

UVSOR, Institute for Molecular Science, Okazaki 444-8585 Japan

**Graduate School of Engineering, Nagoya University, Chikusa-ku Nagoya 464-8603 Japan*

The improvement of the UVSOR electron storage ring[1] has been finished successfully, and a transverse emittance of the electron beam has been decreased from 165nm-rad to 27nm-rad. Users runs have been performed since September 2003 with high brilliance beam optics, and since then high brilliance SR beams have been supplied routinely for users. Because of the decrease in the transverse emittance, however, Touschek effect becomes prominent and a condition for a beam lifetime becomes severe; before the improvement (ε=165nm-rad) the beam lifetime was about 1700mA·Hour at the multibunch operation, and after the improvement the beam lifetime decreases to 1000mA·Hour in the low-emittance operation (ε=60nm-rad in the achromatic optics). To increase the beam lifetime and make full use of the improved SR beams, we have planned to improve the main RF cavity of the UVSOR-II electron storage ring.

The aim of the plan is to increase the beam lifetime by increasing in accelerating voltage and easing the Touschek effect. Figure 1 shows change in the Touschek lifetime on the accelerating cavity voltage (V_c) at the achromatic low emittance beam optics (ε=60nm-rad). At the present cavity voltage (V_c=55 kV) the $I\cdot\tau_{Touschek}$ product becomes 1650mA·H in the x-y coupling of 3%; on the other hand, the $I\cdot\tau_{Touschek}$ product is estimated to be 5200 mA·H at the cavity voltage of 150 kV, as seen in the figure. Figure 2 shows calculated value of change in transmitter power on the cavity voltage. In the calculation, the shunt impedance (R_s) of the RF cavity is assumed to be R_s=2.2MΩ, that is one of appropriate values from the calculation with Poisson/Superfish[2] for typical re-entrant RF cavity whose resonant frequency is around 90 MHz. As seen in the figure, the transmitter power to generate the cavity voltage of 150 kV is estimated to be less than 20 kW, that is the maximum power of the transmitter that is in operation in the UVSOR now. From the estimation, the target values of the accelerating voltage and the $I\cdot\tau_{Touschek}$ product have been settled to be above 150kV and 5000 mA·H, that is comparable to the designed parameter of MAX-III[3].

To realize those target values, it is necessary to renew the RF cavity because the shunt impedance of the present RF cavity has only 0.5MΩ. On the other hand, the transmitter that is in use now can be applied to the new RF cavity because it is estimated the transmitter has enough output power to realize the target value of the cavity voltage. Table 1 shows the basic specification of the new RF cavity. As seen in the table, the basic parameters of the RF system such as the RF frequency will not be changed even in the new cavity. The new cavity would be build with pure oxigen-free-copper chamber to stabilize temperature of the cavity easily. The target value of the shunt impedance is 2.2MΩ to realize enough cavity voltage. The cavity will be built in 2004 and installed in S2 section (B1~B2) in the spring of 2005. After the installation and tuning of the new cavity, the present cavity will be removed from the ring.

Table 1. Basic specifications of present/planned cavity.

	Present	Planned
Frequency	90.1 MHz	90.1 MHz
Cavity voltage	55 kV	150 kV
Shunt impedance	0.5 MΩ	2.2 MΩ
Material	SUS + Cu	Cu (OFHC)
Cells	Re-entrant×1	Re-entrant×1
Coupler	Air-cooled	Water-cooled
Tuner	Plunger×1	Plunger×2

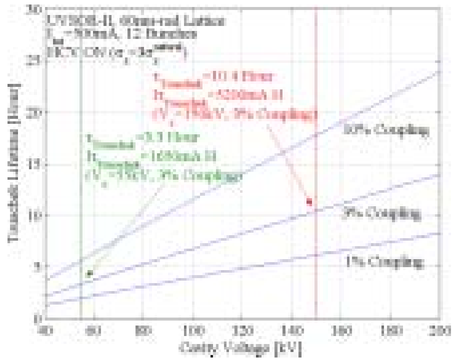

Fig. 1. Dependence of the calculated Touschek lifetime on the cavity voltage.

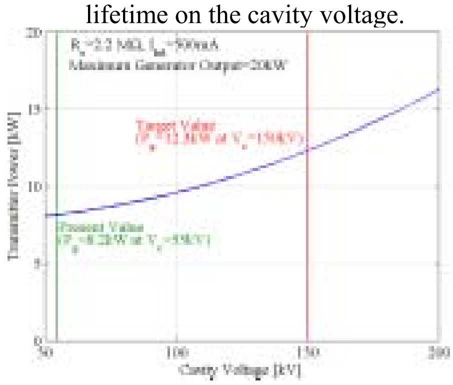

Fig. 2. Transmitter power for the cavity voltage.

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Estimation of the Impedance of UVSOR-II Electron Storage Ring

A. Mochihashi, M. Hosaka, M. Katoh, K. Hayashi, J. Yamazaki, *Y. Takashima
UVSOR, Institute for Molecular Science, Okazaki 444-8585 Japan
**Graduate School of Engineering, Nagoya University, Chikusa-ku Nagoya 464-8603 Japan*

In the improvement of the UVSOR electron storage ring[1], almost all of beam ducts, especially the beam ducts for straight sections, have been replaced, and moreover, two in-vacuum undulators[2] have been installed in the straight sections. We have measured effective impedance of the UVSOR-II electron storage ring by measuring threshold beam current of longitudinal microwave instability. Another values associated with the effective impedance have been estimated, too.

Measurement

To measure the threshold current of the microwave instability, we have stored single bunch and observed a modulation factor of the spectrum emitted from the optical klystron. Because the modulation factor depends on the energy spread of the electron beam, the threshold current of the microwave instability can be measured by observing the change in the modulation factor of the undulator radiation from the optical klystron on the beam current. Figure 1 shows change in the energy spread on the beam current by measuring the modulation factor by Hosaka[3] in the beam energy of 600 MeV. As seen in the figure, it is clearly seen that the energy spread drastically increases around the beam current of 70 mA.

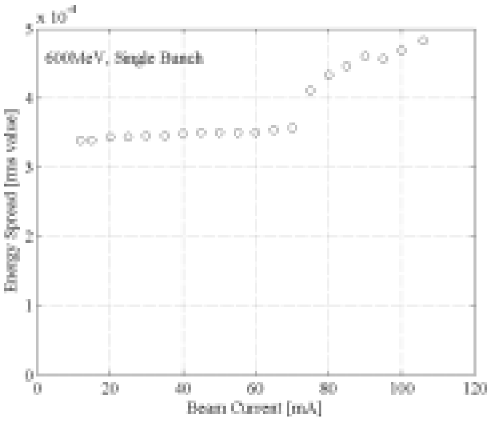

Fig. 1. Measured value of the change in the energy spread on the beam current in UVSOR-II.

Estimation of the Impedance

The threshold current[4] I_{th} of the microwave instability is written as

$$I_{th} = \frac{\sqrt{2\pi}\, k_b \nu_{s0}^2 E}{e\alpha \left|Z/n\right|_{crit}} \left(\frac{\sigma_0}{R}\right)^3 \left(\frac{\sigma_{th}}{\sigma_0}\right)^2, \qquad (1)$$

where k_b is the RF wave number, ν_{s0} is the synchrotron tune, E is the beam energy, e is the electron charge, α is the momentum compaction factor, $\left|Z/n\right|_{crit}$ is the critical impedance[4], R is the average ring radius, and σ_0 and σ_{th} are the natural bunch length and the bunch length at the threshold current, respectively. From the measurement of the bunch length with a streak camera, the ratio σ_{th}/σ_0 is estimated to be 2.12 in case of I_{th}=70mA. From Eq. 1, the critical impedance is estimated to be $\left|Z/n\right|_{crit}$=1.2Ω.

The effective impedance[4] $\left|Z/n\right|_{eff}$ is given by

$$\left|Z/n\right|_{eff} = \left|Z/n\right|_{crit} \left\{\left(\frac{\sigma_{th}}{\sigma_0}\right)^2 - 1\right\} = 4.2\Omega,$$

which is larger than the measured value before the improvement of the UVSOR[5]. The cause of the increase in the effective impedance has not yet become clear; it might be because of the two in-vacuum undulators that have been installed at the improvement.

From the longitudinal effective impedance, the transverse broad band impedance Z_T can be estimated by the approximate relation:

$$Z_T = \frac{2R}{b^2}\left|Z/n\right|_{eff}, \qquad (2)$$

where b is the effective radius of the beam duct. For the beam duct which has an elliptical cross section the effective vertical radius is written as[4]

$$b = \frac{a}{2\left\{2(\xi_1 - \varepsilon_1)\right\}^{1/3}}, \qquad (3)$$

where $2a$ is the horizontal width of the beam duct, and ξ_1 and ε_1 are the Laslett parameters[6], respectively. From Eq. 3, the transverse broad band impedance is estimated to be Z_T=1.8×10^5 Ω/m. From the broad band transverse impedance, the dependence of the vertical tune on the beam current can be given by

$$\frac{d\nu_y}{dI_b} = -\frac{r_0 b c Z_T}{16\pi e f_{rev}^2 \gamma C \omega_\beta}, \qquad (4)$$

where r_0 is the classical electron radius, c is the speed of light, f_{rev} is the revolution frequency of the beam, γ is the Lorentz factor, C is the circumference of the ring and $\omega_\beta/2\pi$ is the vertical betatron oscillation frequency, respectively. From Eq. 4, the change in the vertical tune on the beam current by the transverse broad band impedance is estimated to be -3.3×10^{-5} /mA in UVSOR-II.

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