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Optimum Arrangement of Resonator in Micro-bunch Free Electron Laser

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Using a short-bunched beam of electrons from a linear accelator, the output of the micro-bunch FEL has been studied experimentally to clarify the optimum arrangement of an open resonator on the electron orbit. The output depends sharply on the arrangement, and the maximum output is observed when the resonator axis intersects the electron orbit with the angle of 3°.

§ 1. Introduction

Using a short-bunched beam of electrons from a linear accelerator, we have constructed a simple free electron laser (FEL) composed of a resonator and a bending magnet in the millimeter and submillimeter wavelength region [1, 2]. In the resonator, wave packets of coherent synchrotron radiation (CSR) are superposed on the subsequent bunches and are amplified. We call the FEL as micro-bunch FEL, because the electron beam is already bunched to the small size (micro-bunch) of wavelength order [3].

In the previous experiment, the resonator was placed so that its axis touched the electron orbit and the beam passed through mirrors of the resonator [3]. The coherent radiation superposed in the resonator is hence not only CSR but also coherent transition radiation (CTR) generated from the beam passing through the mirrors [4]. Since the radiation pattern of CSR is different with that of CTR, the output of the resonator depends on the arrangement of the resonator on the orbit.

In this report we tried to clarify the optimum arrangement of the resonator to obtain the maximum output by the experiment.

§ 2. Experiment

The schematic layout of the experiment is shown in Fig.1. An electron beam of 150 MeV was bent in the magnetic field applied with the bending magnet BM1 to emit CSR. The orbital radius was 2.44 m and the orbital plane was parallel to the horizontal plane. An open resonator composed of three mirrors

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was placed under the magnetic field of BM1. The output of the resonator was guided to a grating type far-infrared spectrometer. The acceptance angle of the measuring system was ϕ70 mrad, and the radiation was detected with a liquid-helium-cooled Si bolometer.

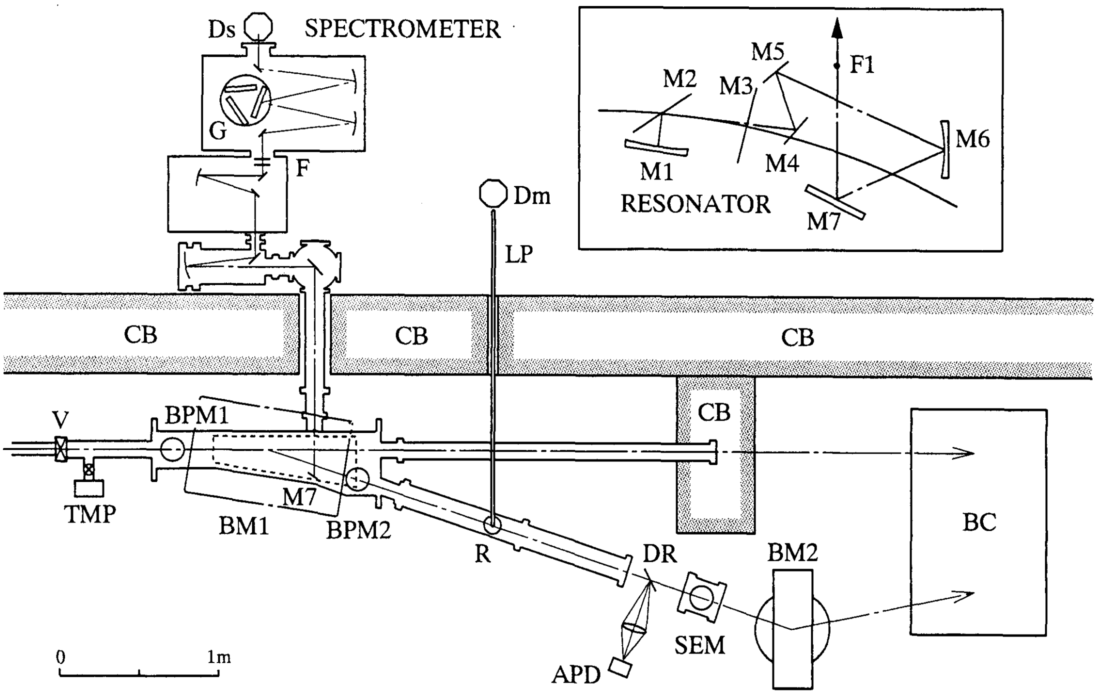

Fig.1. Schematic layout of the experiment. BM1, BM2: bending magnet, V: vacuum valve, BPM1, BPM2: beam position monitor, R: TR radiator, SEM: secondary emission monitor of electron beam, APD: avalanche photo-diode, BC: beam catcher, G: grating, F: filter and polarizer, LP: light pipe, Ds, Dm: detector, CB: concrete block for radiation shield. The inset shows an optical system placed under the magnetic field of BM1.

The electron beam passed through an aluminum foil R after the magnet and was guided to a beam catcher BC through a beam current monitor SEM. The beam position and its cross section were monitored with TV cameras at two points BPM1 and BPM2. The foil R emitted CTR when the beam passed through, and the CTR was guided through a light pipe to another Si bolometer D_m. In the experiment the electron beam fluctuated from time to time with various time scales, and the fluctuation in the resonator output was corrected from the intensity of the observed CTR.

The beam condition was as follows: The energy and its spread were 150 MeV and 2 %, respectively. The duration of a macro-pulse was 1.4μs and its repetition was 16.67 Hz. The average beam current was 1.0 μA. Hence the one macro pulse was composed of about 4000 bunches and an average number of electrons was 9.4×10^7 per bunch. The transverse cross section of the beam was nearly circular and its diameter (FWHM: full width at the half maximum) was about 3 mm.

The open resonator was a semi-confocal type composed of three mirrors as shown in Fig.2. The aluminum evaporated round concave mirror M1 had the focal length of 320 mm with the aperture of ϕ 100 mm, M2 was a 15 μm thick Al-foil plane mirror and M3 was an aluminum evaporated round plane mirror of fused quartz with (ϕ130 $\times$1 mm) in (aperture$\times$thickness). The central part of ϕ25 mm of M3 was a coupling window which was not coated with any materials and transparent, through which the radiation in the resonator was extracted. The resonator length was initially set to 315 mm, the three times inter-bunch distance of the electron beam, and the distance between the mirrors M2 and M3 is 235 mm. The position of the mirror M3 was controlled with a stepping motor to change the length of the resonator.

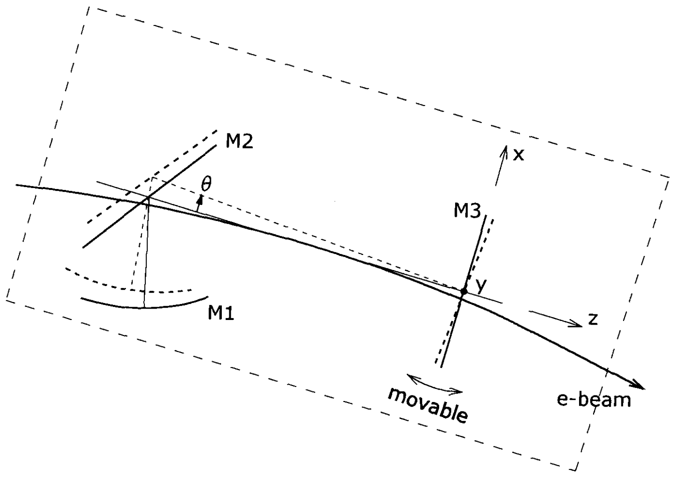

Fig.2. Schematic arrangement of the semi-confocal resonator composed of three mirrors. The plane mirror M3 has a coupling window of ϕ 25 mm in the center. The resonator was controlled to rotate around the y axis with a stepping motor, and θ shows the rotation angle. The rectangle of the broken line shows projection of the iron pole of the bending magnet.

The three mirrors of the resonator were put on an aluminum plate, and the axis of the resonator was initially placed to tangent to the electron orbit at the middle point between the mirrors M2 and M3. The plate was controlled with a stepping motor to rotate around the vertical axis placed at the center of the initial position of M3 (y axis in Fig.2). The rotation angle θ was measured clockwise from the initial resonator axis. The rotation angle was able to be controled from -4.5° to 2.0°, using the apparatus.

At the rotation angle $\theta = 0^\circ$, the resonator axis touches on the ideal electron orbit, and the axis has no intersection point with the orbit for $\theta > 0^\circ$. On the other hand, the axis intersects the orbit at two points for $-0.69^\circ < \theta < 0^\circ$ and intersects at one point for $\theta < -0.69^\circ$.

§ 3. Results and Discussion

3.1 Detuning curve

The detuning curve or the variation of the output intensity with the resonator length was observed at the wavelength λ of 2.6 mm for the various rotation angle θ from -4.5° to 2.0°. The results are shown by the solid curves in Fig.3.

The curve shows periodic structures composed of a main peak and a secondary peak with a period of $\lambda/2$. The main peak was observed at the resonator length $L = 315.2$ mm and the secondary peak was at $L = 315.8$ mm. We assigned the main peak as the TEM_{00} mode originated mainly from CSR and the secondary peak as the TEM_{01} mode generated from CTR, based on the analysis of the detuning curve of

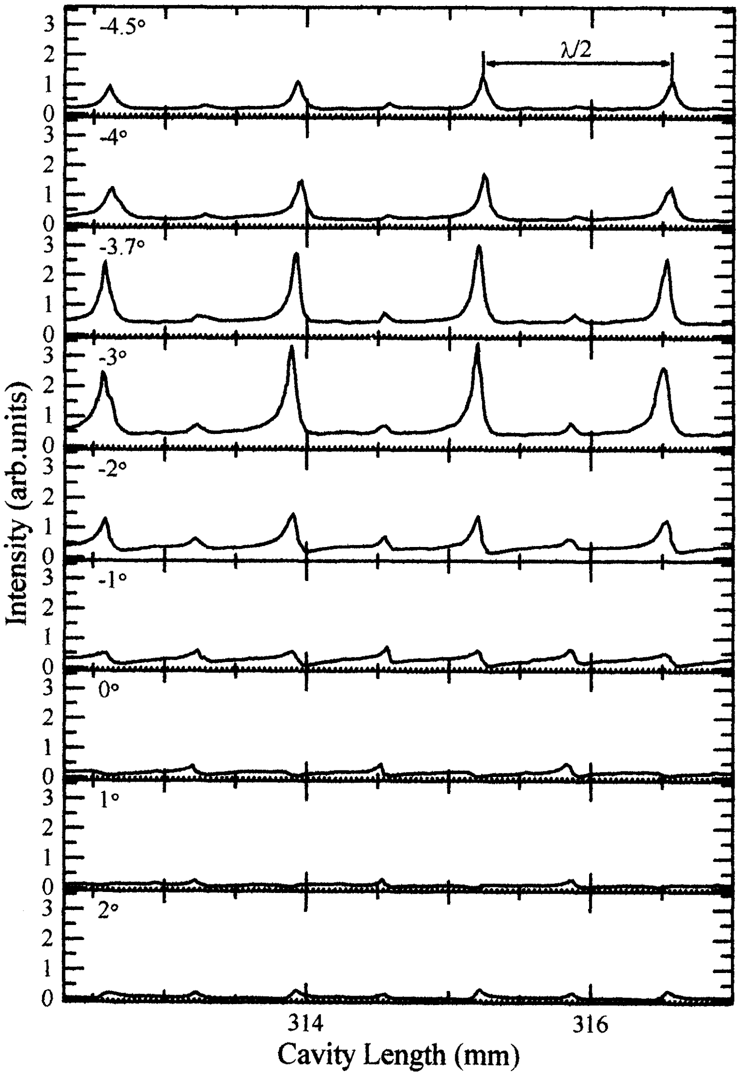

Fig.3. The detuning curve observed at λ of 2.6 mm for various rotation angle θ from $-4.5°$ to $2°$.

the previous experiment [3]. The difference of the resonator length between the main peak and the secondary one corresponds to 83° in phase, which is in agreement with the theoretical phase difference of 90° of the semiconfocal resonator.

The amplitude reflectivity of the resonator per trip around was derived from the bandwidth of the main peak at $\theta = -3.7°$ to be 0.91, which corresponds to the quality factor of the resonator of $Q_{00} \sim 70$ [3]. Since the resolving power of the spectrometer was about 26 at $\lambda = 2.6$ mm, the detuning curve was composed of three higher harmonics of the radio frequency of the liner accelerator.

The detuning curve shows the following dependence on the rotation angle θ. (1) The peak intensity of the TEM_{00} mode depends sharply on the angle θ. In the region of $\theta > -3°$, the peak intensity sharply decreases as θ increases. The main peak of the TEM_{00} mode seems to disappear around at $\theta \sim 1°$, where the detuning curve shows not a peak but a local dip at the cavity length just corresponding to the peak position of the TEM_{00} mode. The main peak again appears at around $\theta = 2°$. The peak intensity is plotted as a function of θ for $\theta \leq 0°$ in Fig.4 (a). The result shows that the maximum output was observed at $\theta = -3°$. (2) The secondary peak of the TEM_{01} mode also depends on

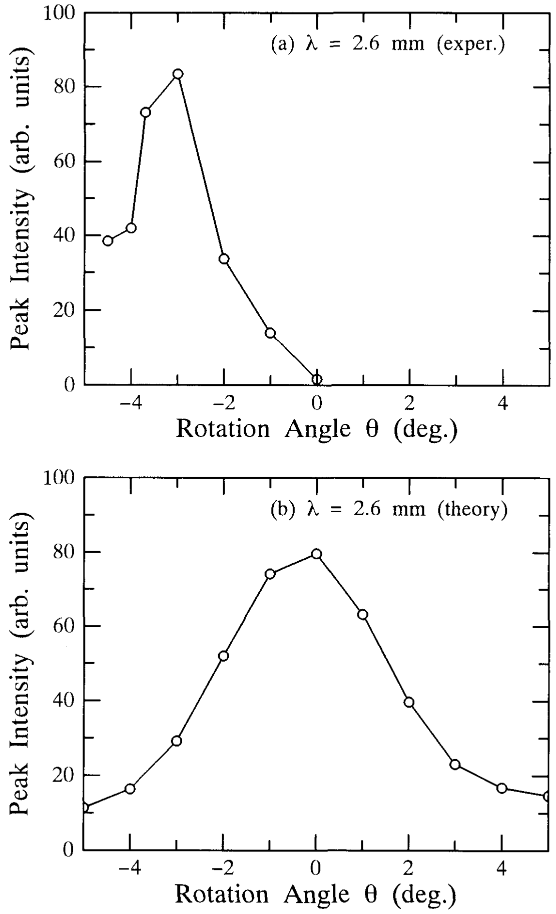

Fig.3. The peak intensity versus rotation angle relation of the TEM_{00} mode at $\lambda = 2.6$ mm obtained from the experiment (a) and from theory (b).

θ. In contrast to the main peak, however, the dependence is mild. The intensity ratio of the main peak to the secondary one hence depends sharply on the rotation angle θ. At around $\theta = 0°$ the intensity of the secondary peak was higher than that of the TEM_{00} peak. (3) The main peak shows asymmetric distribution as a function of the resonator length. In the range of $\theta \leq 0°$, for example, the gradient of the main peak in the short side region of the cavity length is smaller than that of the long cavity side. The asymmetry was due to the interference between the resonator output and the coherent radiation generated downstream of the resonator [3]. At $\theta = 2°$ the asymmetric distribution of the main peak is reversed to that of $\theta \leq 0°$.

To examine influence of the injection point of the electron orbit into the resonator, we controlled the electron beam horizontally with a beam steering magnet placed about 6 m upstream from the resonator. The beam shifted within the range of ±10 mm. During the steering, we fixed the resonator at the rotation angle $\theta = 0°$ and observed the detuning curve. The beam steering changed a little the detuning curve and the peak intensity. We therefore consider the above dependence (1)−(3) was caused mainly from the change of the intersection angle between the resonator axis and the orbit.

The interference in (3) is expressed as [3],

$$I(\lambda, x) = \left| \frac{C_1}{1 - r \exp(i\phi)} + C_2 \exp(i\psi) \right|^2 \qquad (1)$$

$$= \frac{C_1{}^2+C_2{}^2+2C_1C_2\,[\cos\psi - r\cos(\phi+\psi)]}{1+r^2-2\,r\cos\phi}, \tag{2}$$

$$\phi = 4\pi\frac{x}{\lambda} + \Delta\,\phi_{00}, \tag{3}$$

where the first term of Eq. (1) shows the resonator output and the secondary term is the downstream radiation, C_1 and C_2 are coefficients of the amplitude of the radiation ($C_1 > 0$, $C_2 > 0$), r is the amplitude reflectivity of the mode per trip around, x is the length of the resonator, $\Delta\,\phi_{00}$ is the phase of the TEM$_{00}$ mode, and ψ stands for relative phase difference between the output and the downstream radiation. The peak position of the TEM$_{00}$ mode is determined from the resonant condition, $\cos\phi = 0$. The asymmetry of the peak is caused from the angle bracket term of the numerator of Eq. (2), which is written by,

$$\cos\psi - r\cos(\phi+\psi) = (1-r\cos\phi)\cos\psi + r\sin\phi. \tag{4}$$

Since the speed of the electrons of 150 MeV is very near to the light velocity, the phase difference ψ of the radiation field between the output and the downstream radiation is taken as constant for the variation of the resonator in length around the peak. On the other hand, the phase term ϕ changs its sign whether resonator length is shorter than the peak position or not. The last term of Eq. (4) accordingly changs the sign and causes the asymmetry in the intensity distribution of the peak.

The reverse in the asymmetry shows that the phase difference ψ at $\theta = 2^\circ$ should change the sign from that in the region $\theta \leq 0^\circ$, because the first term of Eq. (4) is symmetric with respect to the change in the resonator length. Since the downstream radiation is insensitive to the rotation of the resonator, the phase difference should be caused from change in the resonator output. The reason of the change is not clear at present. It may be caused from the small variation of the optical pass of the wave packets due to the rotation of the resonator.

The radiation field of the CTR is symmetric with respect to the electron beam (in case of forward CTR) or to its specular reflection (backward CTR). The radiation field of CSR and CTR projected on the *xy* plane of Fig.2 is schematically shown in Fig.5, where the figure (c) shows synthesis of CSR and CTR. When the resonator is rotated around the *y* axis in Fig.2, the electric vector of CTR observed on the resonator axis changes its direction. On the other hand, CSR is hardly influenced from the rotation angle around at $\theta = 0^\circ$. The change of the sign of the phase difference ψ therefore seems to be caused from CTR.

From the theory of SR and TR, we calculated the peak intensity as a function of the rotation angle to simulate our experiment. The result is shown in Fig.4(b): The distribution of the peak intensity is nearly symmetric with respect to $\theta = 0^\circ$ and that the intensity ratio of the maximum peak to the minimum one is about 5.5 for $-4^\circ \leq \theta \leq 4^\circ$. The distribution shows that the maximum output is expected at the angle $\theta \sim 0.3^\circ$. The calculated shift of the maximum intensity toward the negative rotation angle is qualitatively in accordance with the experiment. The simulation, however, fails to reproduce the maximum output at around $\theta = -3^\circ$ and the disappearance of the TEM$_{00}$ mode at around 1°.

The comparison of the experiment with the theory suggests that the TEM$_{00}$ mode originates from

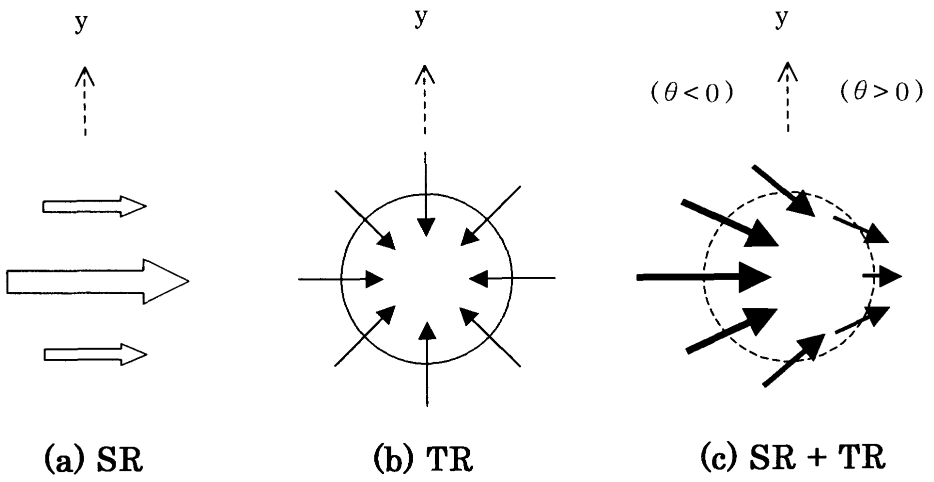

Fig.5. Schematic pattern of the radiation field of (a) SR, (b) TR and (c) synthesis of SR and TR.

not only CSR but from CTR and that the intensity of CTR is not so weak in comparison with that of CSR, even if the resonator length is much shorter than the formation length of TR [4]. Since the radiation field of CTR is axially symmetric and weak around the electron orbit, the relative importance of CTR on the TEM_{00} mode seems to be strange. The reason of the difference between the experiment and theory is not clear at present.

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