

AMPLIFICATION OF SHORT-PULSE RADIATION FROM THE ELECTRON UNDERGOING HALF-CYCLOTRON ROTATION*

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Abstract

A novel light source which can generate an half-cycle radiation pulse is being developing at Institute of Free Electron Laser, Osaka university.

INTRODUCTION

The number of the optical cycles contained in a radiation pulse is simply determined by the number of the electron wiggles or rotations during which the electron emits the radiation pulse. Electrons passing through a bending magnet emit a radiation pulse whose phase variation is less than unity. The bending magnet radiation, thus, can be used as a broadband continuous-spectrum light source. When such radiation is confined in the optical cavity, the radiation should be amplified via the interaction with the electrons periodically injected by the accelerator. In the bending magnet, however, the interaction length is usually short and the gain, then, should be small. Based on this idea, we are developing a half-cycle light source using the electrons which undergo an half-cycle cyclotron motion in a solenoid field. As described in the following, the pulse length is approximately equal to that of the electron beam. Thus this light source can produce broadband continuous-spectrum radiation in the THz wave range, because the accelerator produces the electron beam with a pulsewidth of a few picoseconds.

THEORETICAL CONSIDERATIONS

The electric field produced by the electron passing through the solenoid field is calculated from the *Liénard-Wiechert* potential and given by

$$\mathbf{E}(\mathbf{x}, t) = \frac{q}{4\pi\epsilon_0} \left[\frac{R(t')}{s(t')^3} (\mathbf{n}(t') - \beta(t')) (1 - \beta(t')^2) + \frac{R(t')^2}{cs(t')^3} \mathbf{n}(t') \times ((\mathbf{n}(t') - \beta(t')) \times \dot{\beta}(t')) \right] \quad (1),$$

where q is the charge of the particle, c the light velocity, ϵ_0 the vacuum dielectric constant, $\dot{\beta}$ is the normalized acceleration vector, \mathbf{R} (R) is the vector (distance) from the

particle to the observation point, \mathbf{n} is a unit vector in the direction of \mathbf{R} , and s is defined as,

$$s(t') = R(t') - \frac{\mathbf{R}(t') \cdot \mathbf{v}(t')}{c} \quad (2).$$

Quantities on right-hand-side in equation (3) are to be evaluated at the retarded time,

$$t' = t - \frac{R(t')}{c} \quad (3).$$

The magnetic field is, then, given by

$$\mathbf{B}(\mathbf{x}, t) = \frac{1}{c} \mathbf{n}(t') \times \mathbf{E}(\mathbf{x}, t) \quad (4),$$

and then the magnitude of the Poynting vector is given by

$$|S(\mathbf{x}, t)| = \epsilon_0 E^2 \quad (5).$$

The calculations are made for a 150MeV electron beam with pulse length of 3ps passing through the 3m-long solenoid magnetic field of 0.7T and the radiation field is shown in figure 1. A uniform electron distribution in a block, $4 \times 4 \times 0.9 \text{ mm}^3$, is assumed. The bunch length of 0.9 mm corresponds to the pulsewidth of 3 ps. The electrons are located at $x_0 = [-2 \text{ mm}, 2 \text{ mm}]$ and $y_0 = [-2 \text{ mm} - r_L, 2 \text{ mm} - r_L]$, so that the centres of the circular electron motion lay in $x_{c0} = y_{c0} = [-2 \text{ mm}, 2 \text{ mm}]$ with the angle of $\theta_{0x} > 0$. Here r_L is the Larmor radius. The initial angle and r_L are 3 mrad and 2.6 mm in figure 1, respectively. The coordinates of the observation points, (x_{ob}, y_{ob}, z_{ob}) , is (0, 0, 5 m), i.e., the centre of the resonator mirror which reflects back the spontaneous emission. The resonant wavelength is to be 65 μm , and corresponding optical period is 217 fs. During passing through the 3 m-long solenoid field, the electron with $\gamma = 300$ executes a half-circulation (166 degree in phase).

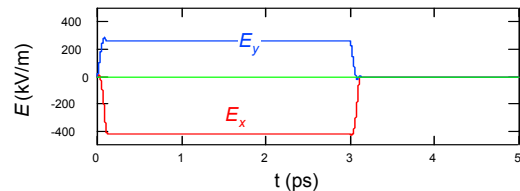


Figure 1. The radiation field at the centre of the resonator mirror produced by a 150MeV electron beam which undergoes a half cyclotron rotation in a 3m-long solenoid field.

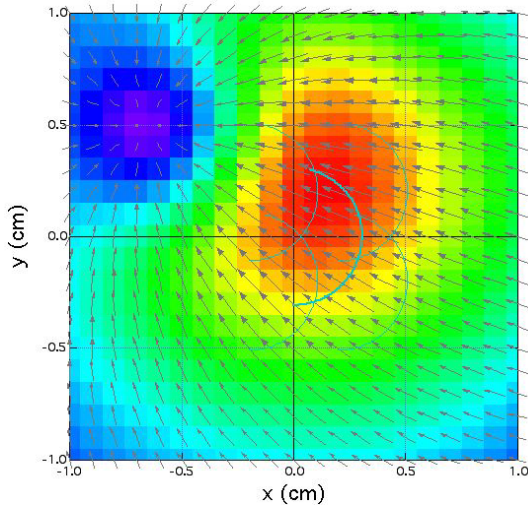


Figure 2 The energy flux distribution and the polarization of the radiation field.

The z -component of the field, E_z , is negligibly small comparing to E_x , E_y . As expected, the phases of the fields, E_x and E_y , do not vary by 2π : the field remains almost constant during its pulswidth. It depends on the observation point that if the field starts from negative or positive value.

The distribution of the energy flux of radiation, $\int dt' |S(x, t')|$, are shown in figure 2 for the same condition used in figure 1. Typical electron trajectories, for the centre and edge of the electron beam, are projected on the figure as the arcs. The energy flux has a peak at

(0.15 cm, 0.2 cm) and falls to 10 % of the peak at a distance of 1.6 cm from the origin, i.e., the axis of the cyclotron motion and the resonator. The radiation should be confined in a radius of 2 cm on the mirror. The contours tend to be displaced from the axis toward first quadrant in the graph. This is because the electrons undergo the half-circulation mainly in the region $x > 0$, and rise from fourth quadrant to first quadrant as they are passing through the solenoid field. This tendency becomes more remarkable as larger the initial electron angle is.

Note that the product of the electron velocity and the electric field, $\mathbf{v}_\perp \cdot \mathbf{E}_\perp$, is positive in the most of the part, especially in the region where the radiation field is intense. Thus it is possible to amplify the radiation via the successive interaction with the electron beam if the radiation can be confined in the resonator.

Figure 3 shows the distribution of energy flux for the initial angle of 1, 3, 5 and 10 mrad at $z_{ob}=5$ and 10 m. The electron trajectories are set so that the guiding centre of the electron beam may be located at the centre of the resonator axis in all cases. All the distributions are normalized by their peaks. The variation of the peak intensity is shown in figure 4.

It is clear that the increase in the initial angle enlarges the cross-section of the radiation field. The position of the peak flux also deviates remarkably with the large initial angle. In detail, the position of the peak is almost the same in the cases of 1mrad and 3 mrad injection, while it deviates at larger initial angles. That is, the radiation propagates unparallel to the axis of the optical cavity when initial angle is large.

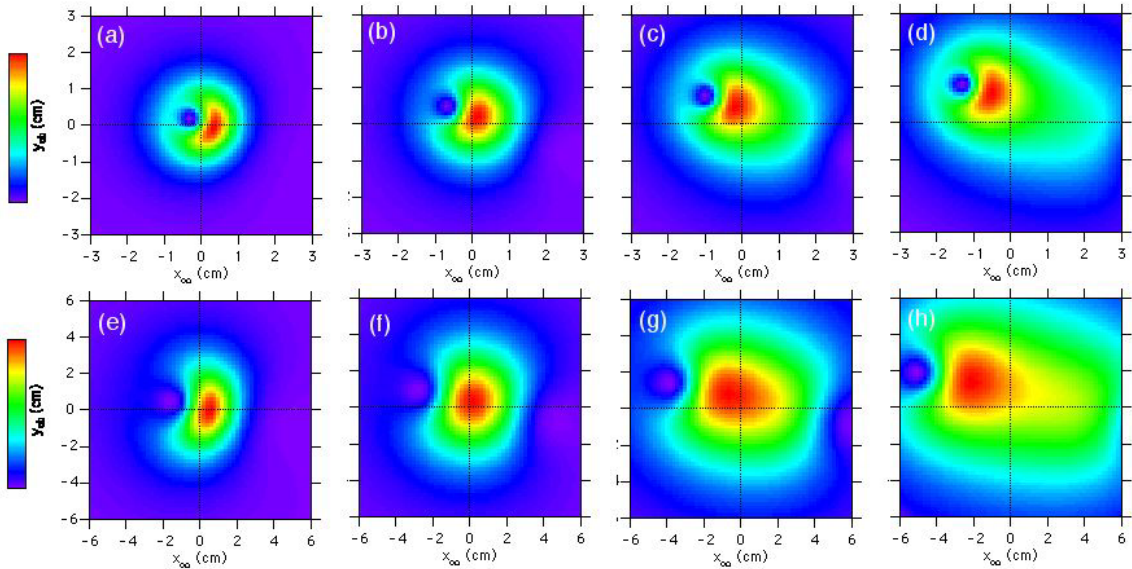


Figure 3 Dependence of the field distribution on the initial angle. (a)-(d) and (e)-(h) show the distribution at the $z_{ob}=5$ and 10m, respectively. The initial angle is 1mrad for (a) and (e), 3mrad for (b) and (f), 5mrad for (c) and (g), 10 mrad for (d) and (h). All distributions are normalized by their peak.

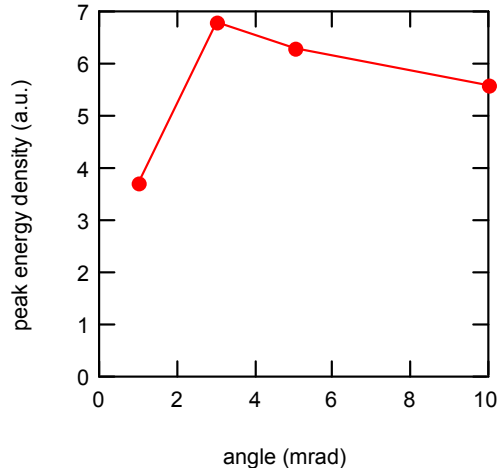


Figure 4. Dependence of the peak flux on the initial angle.

As shown in figure 4, the peak intensity rapidly increases when the initial angle is increased and then slowly decreases above 3mrad. Total energy of the radiation increases monotonically with the angle, because the cross section increases with the angle, though the angle should be chosen around 3mrad to store the radiation in the cavity.

The divergence angle in the case of 3 mrad initial angle is evaluated to be 4-5 mrad. The radiation field, therefore, can be stored in the optical resonator. Because the radiation field has negative or positive value as shown in figure 1, it can be expected that the field can be added up coherently at each round trips analogously to FEL fed by the coherent synchrotron radiation emitted by electron bunches.[1] Then this radiation source will produce broadband far-infrared radiation. The additional growth process via the interaction between the electron and the radiation, $\mathbf{v}_\perp \cdot \mathbf{E}_\perp$, is now being studied.

EXPERIMENT

The experiments are underway on the 150 MeV beam line, which was used for the demonstration of ultraviolet free-electron laser. A S-band rf-linac produces the electron bunch of 0.25 nC / 3 ps at a repetition rate of 22.3 MHz (1/128 of S-band frequency) for 25 μ s. Thus the macropulse contains 550 electron bunches. The UV undulator was replaced with 3 m-long solenoid coil wound around a drift tube with an inner radius of 8.5 mm.

This solenoid is located between two pairs of bending magnets used to detour the electron beam around the cavity mirrors. The coil is fed by a capacitor bank (0.1 F/ 500 V) and generates a magnetic field of 1.0 T with a current of 1.5 kA. The discharge time constant is 30 ms so that the change in the solenoid field is negligibly small (less than 0.2 %) during the macropulse duration of 25 μ s.

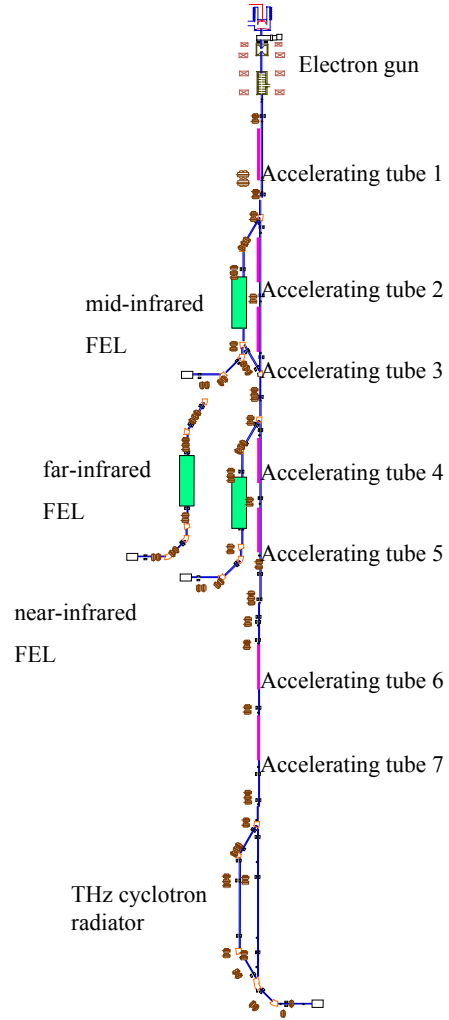


Figure 5. Accelerator system at iFEL and cyclotron radiator.

The incident angle of the bunch is controlled by a set of 'kicker coils' installed at the entrance of the solenoid. The effect of the beam emittance (10 π mm-mrad in normalized emittance) on the beam trajectory is also negligibly small, because the incident angle ranges from 1-5 mrad in the experiment. The optical resonator consists of a pair of the Au-coated concave mirrors spaced 6.72 m apart. At the 22.3 MHz bunch repetition rate, a single radiation pulse is stored in the resonator. Thus the radiation pulse can interact with the electron bunch 550 times during the macropulse.

The intensity of the spontaneous emission was measured for various field strength of the solenoid by removing the downstream cavity mirror. The cyclotron resonance condition,

$$\omega = \omega_{co} / (1 - \beta_z) \quad (6),$$

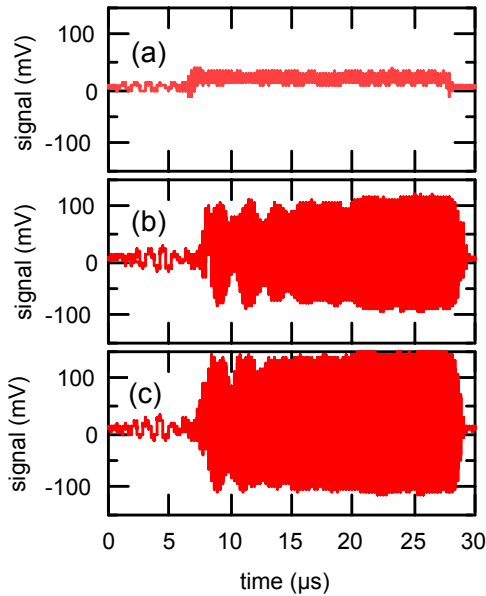


Figure 6. Time trace of the microwave diode response. The solenoid field is 0 T, 0.7 T and 1.0 T for (a)-(c), respectively.

where ω_{co} , γ and β_z are the cyclotron frequency, the electron relativistic factor and the normalized axial velocity, gives a resonant frequency of 4.0 THz for typical experimental condition, an electron energy of 150 MeV, an incident angle of 5 mrad and a solenoid field of

1 T. Under these conditions, the electron undergoes a half-cyclotron rotation while it passes through the solenoid. Figure 6 shows the time traces of the response of the microwave diode with a cutoff frequency of 100 GHz. The signal involves the pulses synchronized to the electron bunches and thus appears as it is hatched in the figure. The radiation signal when the solenoid field was off, in fig. 6 (a), generated at the bending magnets. And the radiation power increased as increasing the magnetic field up to 1 T. The radiation power with the solenoid field of 1 T exceeded that without the solenoid field by a factor 10.

CONCLUSION

A novel radiation source, which can generate a half-cycle radiation, is being developed at iFEL Osaka university. This source is based on the cyclotron radiation from the electron that undergoes a half-cyclotron rotation in the solenoid field. The numerical study revealed that the radiation can be stored with a certain initial pitch angle of electron. Furthermore the polarization of the radiation directs the same direction with electron cyclotron motion. Thus the radiation can be amplified by interacting with successive electron beam. Substantial power of the spontaneous emission was observed experimentally on the 180 MeV electron beam-ling of iFEL accelerator. The lasing experiment is now under way.

REFERENCES

- [1] M. Asakawa, et al., Appl. Phys. Lett. 64 (1994) 1601