Experimental Observation of Cyclotron Superradiance under Group Synchronism Conditions

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Intense microwave pulses (several hundreds of kilowatts) of ultrashort duration (less than 0.5 ns) were obtained from an ensemble of electrons rotating in a uniform magnetic field. The comparison with theoretical simulations proves that this emission can be interpreted as cyclotron superradiance. The maximum radiation power was achieved under group synchronism conditions, when the electron bunch translational velocity coincides with the group velocity of the wave propagating in the waveguide. [S0031-9007(97)02760-9]

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Superradiance (SR) in ensembles of classical electron oscillators has recently attracted considerable attention [1–8]. At present, experiments are being carried out with different types of SR (bremsstrahlung, Cherenkov, etc.) [9–11]. In this Letter we report results of the first experimental observation of cyclotron SR and its comparison with theoretical simulations. Cyclotron SR [6–9] involves the process of azimuthal self-bunching and consequent coherent emission in an ensemble of electrons rotating in a uniform magnetic field. This phenomenon can be utilized to generate intense, ultrashort pulses in the millimeter and submillimeter wave range.

It is demonstrated here that conditions of group synchronism when the electron-bunch drift velocity $v_\parallel$ coincides with the e.m. wave group velocity $v_{\rm gr}$ is the most favorable regime for cyclotron type of SR. In fact, this regime includes some of the advantages of gyrotrons [12] as far as in the moving reference frame, electrons as in gyrotrons radiate at quasicutoff frequencies. The regime of group synchronism is realized during waveguide propagation of radiation when dispersion curves of the wave, $k = c^{-1}\sqrt{\omega^2 - \omega_c^2}$, and of the electron flux, $\omega - kv_\parallel = \omega_H$, are tangent [Fig. 1(a)]. In this case the cutoff frequency ω_c and relativistic gyrofrequency $\omega_H = eH_0/\gamma mc$ satisfy $\omega_H = \omega_c \gamma_\parallel^{-1}$, where $\gamma_\parallel = (1 - v_\parallel^2/c^2)^{-1/2}$, $\gamma = (1 - v_\parallel^2/c^2 - v_\perp^2/c^2)^{-1/2}$, and $v_\perp = \beta_\perp c$ is the electron transverse velocity.

It is reasonable to analyze SR under the group synchronism condition in a reference frame K' moving with the electron bunch of length b'. Using Lorentz transformations, we easily find the longitudinal wave number k' and the transverse component of the magnetic field in the K' frame tend to zero. As a result we have an ensemble of rotating electrons, with zero translational velocity, which radiates at a quasicutoff frequency [Fig. 1(b)], i.e., in a gyrotronlike regime.

Assuming that the transverse structure of the radiation $\vec{E}'_\perp(\vec{r}'_\perp)$ is the same as that of the waveguide mode, we present the radiation field as

$$\vec{E}' = \mathrm{Re}[\vec{E}'_\perp(\vec{r}'_\perp) A'(z', t') \exp(i\omega_c t')], \qquad (1)$$

where the evolution of the field distribution axially is described in accordance with the dispersion relation by a parabolic equation

$$i\frac{\partial^2 a'}{\partial Z'^2} + \frac{\partial a'}{\partial \tau'} = 2if(Z')G\langle \beta'_+ \rangle_{\Theta_0}. \qquad (2)$$

The azimuthal self-bunching is caused by the dependence of the gyrofrequency on the electron energy and described by

$$\frac{\partial \beta'_+}{\partial \tau'} + i\beta'_+(|\beta'_+|^2 - \Delta - 1) = ia'. \qquad (3)$$

Assuming in the initial state the electrons are distributed uniformly in cyclotron-rotation phases, aside from small fluctuations ($r \ll 1$), we can write the initial conditions on system (2), (3) as

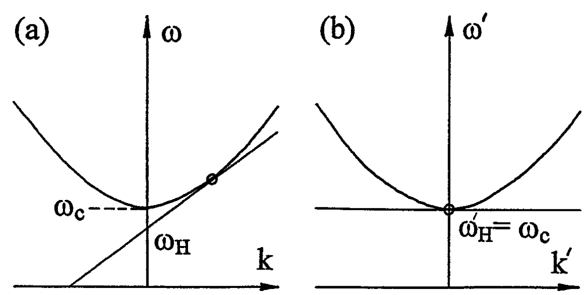

FIG. 1. Dispersion characteristics corresponding to grazing regime in (a) laboratory and (b) moving reference frame.

$$\beta'_{+}|_{\tau'=0} = \exp[i(\Theta_0 + r\cos\Theta_0)],\ \Theta_0 \in [0, 2\pi],$$
$$a|_{\tau'=0} = 0\,.$$

Here $\beta'_{+} = \exp -i\omega_c t'(\beta'_x + i\beta'_y)/\beta'_{\perp 0}$ is the normalized transverse electron velocity; $Z' = z'\beta'_{\perp 0}\omega_c/c$, $\tau' = t'\beta'^2_{\perp 0}\omega_c/2$, $a' = (2eA'/mc\omega_c\beta'^3_{\perp 0})J_{m-1}(R_0\omega_c/c)$, $\Delta = 2(\omega'_H - \omega_c)/\omega_c\beta'^2_{\perp 0}$ is the detuning of the unperturbed gyrofrequency from the cutoff frequency;

$$G = \frac{1}{2\pi}\frac{eI}{mc^3}\frac{1}{\beta^4_{\perp 0}\beta_{\parallel 0}\gamma^3_{\parallel}}\frac{\lambda_c^2}{\pi R^2}\frac{J^2_{m-1}(R_0\omega_c/c)}{J^2_m(\nu_n)(1 - m^2/\nu_n^2)}$$

is a form factor written under the assumption that the electron bunch is hollow with an injection radius R_0; I is the total current in the lab frame; R is the radius of the waveguide; m is the azimuthal index of the operating mode; J_m is a Bessel function; and ν_n is the nth root of the equation $dJ_m/d\nu = 0$. The function $f(Z')$ describes the axial distribution of the electron density. We assume further that $f(Z')$ is a rectangular function of normalized width $B = b'\beta'_{\perp 0}\omega_c/c$.

Based on Eqs. (2) and (3) we simulate cyclotron SR with the normalized parameters $G = 1.5$ and $B = 10$, corresponding to the following experimental values: operating mode TE_{21}, waveguide radius $R = 0.5$ cm, beam injection radius $R_0 = 0.2$ cm, pitch factor $g = \beta_\perp/\beta_\parallel \sim 1$, total current $I = 150A$, pulse length $b = b'/\gamma_\parallel = 7$ cm. In the simulations presented we assume for simplicity that the azimuthal bunching parameter r is constant over the bunch length. The level of initial perturbation $r = 0.001$ was chosen from consideration that the process of SR develops during the bunch transit time through the interaction space of total length $\sim$30 cm. Simulations carried out with $r(Z')$ as a random quantity demonstrated practically similar SR pulse profiles, which can readily be explained by spatial synchronization of radiation from different parts of the bunch. The dependence of the radiation power in the moving frame K' on time, for different values of the detuning parameter, are plotted in Fig. 2. Note that the maximum growth rate corresponds to the grazing condition $\Delta = 0$. However, SR also occurs for both negative and positive Δ. The possibility of radiation under negative Δ is caused by electron frequency detuning; although ω'_H is less than ω_c, the radiation frequency exceeds the cutoff frequency. Such detuning, however, can support radiation only in a limited range and for $\Delta < -1$ the SR instability ceases. At the same time for positive Δ, assuming an ideal bunch instability the radiation persists for any Δ. The growth rate only slightly falls with increasing Δ.

However, it is reasonable to expect that this dependence will be much sharper for real bunches with a finite spread of longitudinal velocities. In the moving frame for such a bunch different electrons can drift with respect to each other. The longitudinal mutual displacement will essentially influence the radiation if the displacement exceeds the waveguide wavelength $\lambda' = 2\pi/k'$. In the exact group synchronism regime, when $\Delta = 0$, k' tends to zero [Fig. 1(b)] and λ' to infinity, and longitudinal displacement of the electrons is not important. As we increase Δ and go away from the grazing regime k' increases, λ' falls, and the same displacement can strongly reduce the radiation. Such behavior has been actually observed in the following experiments.

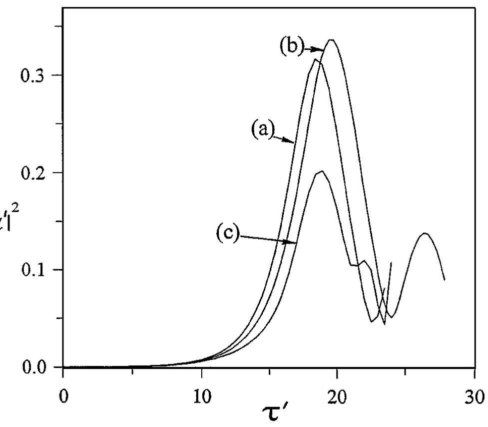

FIG. 2. Time dependence of the square of the amplitude of the electric field of the SR pulses in the moving frame: (a) $\Delta = 0$, (b) $\Delta = -0.4$, (c) $\Delta = 1$.

Results are plotted in Fig. 2 corresponding to the radiation power in the comoving frame K' where the electron bunch radiates isotropically in the $\pm z'$ directions along the waveguide axis. However, in the laboratory frame the situation is totally different and both components will propagate in the same $+z$ direction. To find the radiation which affected the observation point (detector) it is appropriate, using Eqs. (2) and (3), to determine the field on the line $z' + v_\parallel t' =$ const along which the detector is moving in the K' frame. Using such a method the temporal dependencies of the radiation power and instantaneous frequency, $\Omega = \partial(\arg a)/\partial\tau$ in the laboratory frame are presented in Fig. 3(a), for the case $\Delta = 0$. We see that the radiation appears as a set of two pulses. The first pulse is created by photons emitted in the K' frame in the $+z'$ direction, while the second is created by photons emitted in the opposite direction. The detector will overtake the second packet of photons if its velocity, which in the K' frame equals the bunch velocity $v_\parallel$, exceeds v'_{gr} (note that the group velocity of radiation v'_{gr} in the K' frame is extremely low, being proportional to the small detuning of the radiation frequency above cutoff). Naturally, due to the Doppler effect the frequency in the first pulse exceeds the frequency of the second pulse. For the same reason the peak power of the first pulse is essentially greater than that of the following pulse and the duration of the first pulse is less than the duration of the second pulse.

It is also important to remark that for negative Δ, the group velocity v'_{gr} becomes so small that the divergence between photons emitted in the $\pm z'$ direction is negligible and for a given observation distance in the laboratory

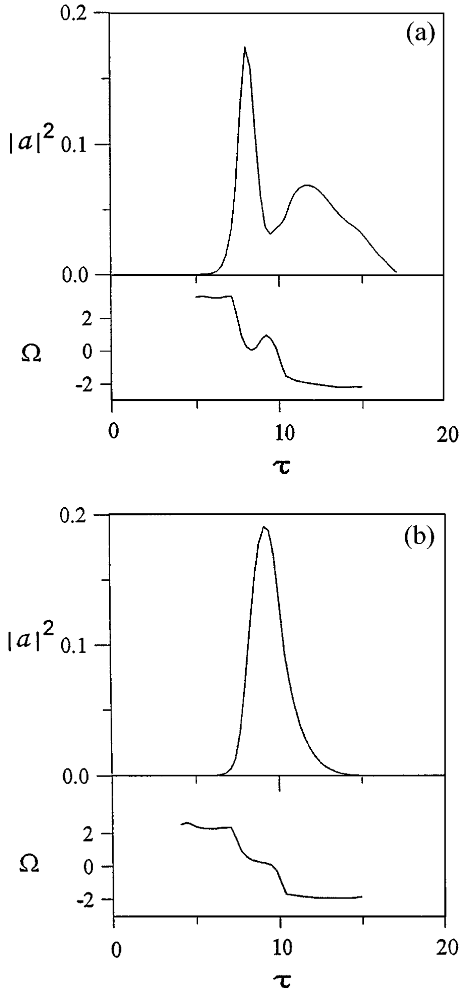

FIG. 3. Time dependence of the square of the amplitude of the electric field and the instantaneous frequency of the SR pulses in the laboratory frame: (a) $\Delta = 0$, (b) $\Delta = -0.4$.

frame the signal received by the detector will look like a monopulse [Fig. 3(b)].

A RADAN 303 accelerator with a subnanosecond slicer was used to inject 0.3–0.5 ns, 0.05–1 kA, 250 keV electron pulses [13]. The electron source was a cold, explosive-emission cathode within a magnetically insulated coaxial diode [Fig. 4]. The fast *e*-beam current and accelerating voltage pulses were measured using a strip line current probe and an in-line capacitive probe, respectively. Typical oscillograms of the electron current are presented in Fig. 5(a). These signals were recorded using a 7 GHz Tektronix 7250 digitizing oscilloscope. High-current electron pulses were transported through the interaction space of total length up to 30 cm in an axial guide magnetic field of up to 2 T. For measurement of the radiation a hot-carrier germanium detector with a transient characteristic of 200 ps was used. To change the electron current a special collimator was used. Transverse momentum, corresponding to a pitch factor g of about unity, was imparted to the electrons by the kicker installed immediately after the collimator.

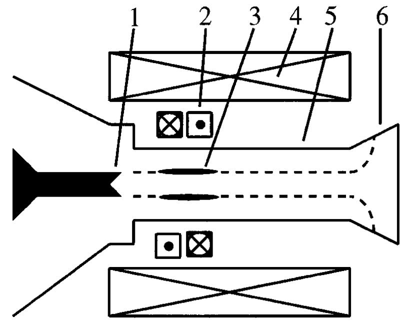

FIG. 4. Experimental apparatus for the investigation of cyclotron superradiance from short electron bunches; (1) knife-edged tubular explosive cold cathode, (2) kicker, (3) electron pulse, (4) guiding solenoid, (5) circular waveguide, (6) microwave horn.

By variation of the strength of the magnetic field microwave, pulses were observed in two separate regions corresponding to the grazing condition with the modes TE_{21} and TE_{01}. For the first region, emission occurred in the magnetic field range between 1.18–1.22 T. The oscillograms presented in Figs. 5(b)–5(e) confirm the

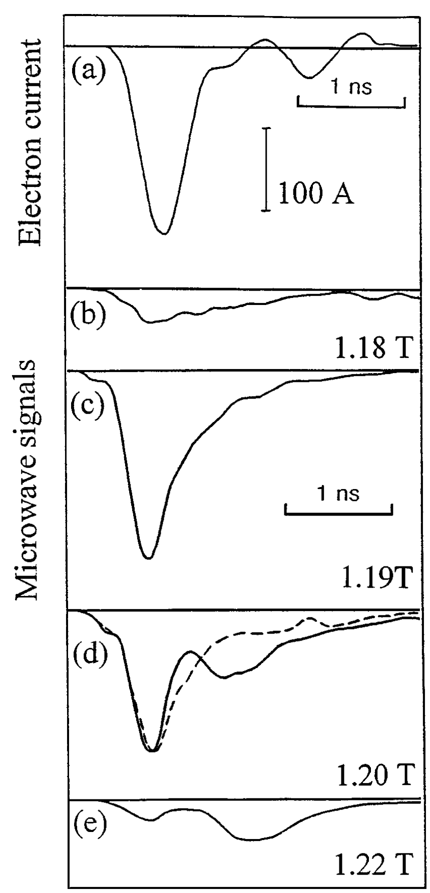

FIG. 5. (a) Oscillograms of electron-bunch current and (b)–(e) microwave signals for different values of magnetic field. Dashed line on the oscillogram (d) corresponds to the signal passed through a filter with cutoff frequency 33.3 GHz.

behavior described above. The radiation is a monopulse with duration less than 0.5 ns, when the magnetic field is smaller than the value corresponding to the grazing condition $H \sim 1.2$ T [Figs. 5(b) and 5(c)] and is converted to a double pulse when the magnetic field exceeds this value [Figs. 5(d) and 5(e)]. The fast decline of the microwave signal for smaller magnetic field values, less than 1.18 T, is obviously caused by violation of the synchronism conditions (large negative Δ), while the similar decrease in signal for larger magnetic fields, exceeding 1.22 T (large positive Δ), is related to the mechanism discussed above of increasing sensitivity to the spread of the electron drift velocities.

To prove that for the double pulse regime the frequency in the first pulse exceeds the frequency in the second pulse, a set of cutoff waveguide filters was used. The dashed line on the oscillogram Fig. 5(d) illustrates suppression of the second low frequency pulse for the filter with cutoff 33.3 GHz. In general, measurements carried out showed a very broad radiation spectrum and in this case covered the band 28.6–36.4 GHz. Thus the relative spectrum width amounted to 20%.

Important confirmation of the stimulated nature of the observed emission can be found from the dependencies of the peak power on the emission distance (in fact, on the interaction time). The graphs plotted in Fig. 6 have been obtained by variation of the length of the homogeneous magnetic field for two different values of the electron current. In the initial stages the peak power grows according to an exponential law. The corresponding gain was approximately two times less than the predictions of a computer simulation for an ideal bunch. Such a discrepancy can be easily explained by the electron velocity and energy spread. Note that if the emission was caused only by the initial modulation of the electrons over azimuthal phases (without subsequent self-bunching) near the cutoff regime the power should grow as the square root of the emission distance. For cyclotron SR the simulations also show that, because of the influence of cyclotron absorption, the dependence of peak power on total current (total number of electrons) is more complicated than in the case of SR in a wiggler field [1,2]. As a result, in these experiments, we observed the peak SR power increasing at slightly less than the square of the current.

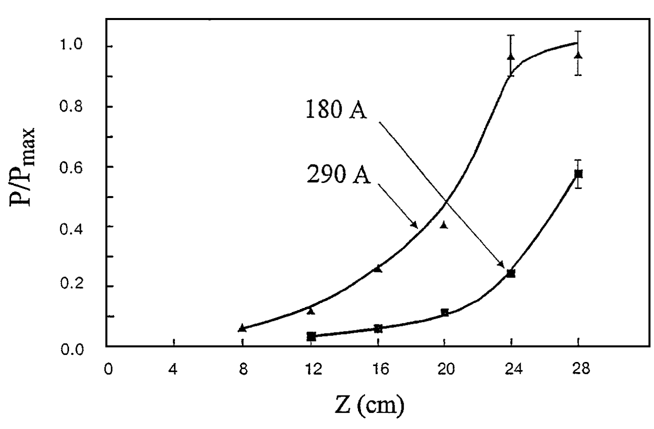

FIG. 6. Peak power of a SR pulse as a function of the interaction distance of the electron bunch, for two different values of the electron current. The magnetic field is 1.2 T.

In the case of 290 A current, saturation of the growth of the peak power was observed. For a smaller current of 180 A saturation for the given maximum length was not achieved. The absolute radiation power was estimated by integrating the detector signal over the radiation pattern. For the TE_{21} mode this power exceeded 200 kW, which corresponded to an efficiency of energy transformation of more than one percent.

In conclusion, a new physical phenomenon has been reported here, which can be theoretically interpreted as cyclotron superradiance. It has also been shown that group synchronism conditions are optimal for experimental observation of cyclotron SR. Based on this phenomenon powerful microwave pulses with ultrashort duration (less than 0.5 ns) were obtained.

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