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Ginzburg, N S and Sergeev, A S and Zotova, I V and Novozhilova, Y V and Peskov, N Y and Konoplev, I V and Phelps, A D R and Cross, A W and Cooke, S J and Aitken, P and Shpak, V G and Yalandin, M I and Shunailov, C A and Ulmaskulov, M P (1997) *Experimental observation of superradiance in millimeter-wave band*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 393 (1-3). pp. 352-355. ISSN 0168-9002

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Experimental observation of superradiance in millimeter-wave band

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Abstract

The first experimental results of the observation of superradiance from a single subnanosecond electron bunch are presented. Superradiance was associated with different varieties of stimulated emission (bremstrahlung, cyclotron, Cherenkov, etc). Unique megawatt power level microwave pulses of short duration (0.3–0.5 ns) have been obtained.

1. Introduction

In recent years much attention has been given to theoretical considerations of superradiance (SR) from space-localized non-equilibrium ensembles of electrons [1–12]. This phenomena includes features of present in both stimulated (selfbunching and coherence) as well as spontaneous processes (absence of threshold). It is reasonable to consider SR in a specific situation when the electron pulse duration essentially exceeds the operating wavelength (otherwise effective traditional spontaneous emission) while at the same time is less or comparable with the interaction length (in contrast with traditional mechanisms of stimulated emission of quasi-continuous electron beams which are used extensively in microwave electronics – FEL, TWT, BWO, CRM, etc). Coherent emission from the entire electron pulse can only occur when a selfbunching mechanism typical for stimulated emission develops. Another natural condition of coherent emission is the mutual influence of different fractions of the electron beam pulse. In the absence of external feedback such influences can be caused by slippage of the wave with respect to the electrons due to a difference between the electron drift velocity and electromagnetic wave group velocity.

2. Superradiance and mechanisms of stimulated emissions

Superradiance can be related with different mechanisms of stimulated emission: bremstrahlung, cyclotron, Cherenkov, etc. In this report we present results of the experimental observation of different types of SR from isolated electron bunch in the K_a frequency band. The SR pulses have been observed from a bunch of electrons moving along helical as well as rectilinear trajectories. The first type of trajectory was realized when electrons started to rotate in a uniform magnetic field after passing through a kicker (cyclotron emission) or oscillated in a combined undulator and guiding magnetic field (undulator emission). The corresponding resonance condition can be presented in the form

$$\omega - kv_{\parallel} = \Omega, \quad (1)$$

where Ω is gyrofrequency ω_H for cyclotron SR and $\Omega = 2\pi v_{\parallel}/\lambda_u$ is the bounce frequency for undulator SR, and λ_u is undulator period. It is important to note that the additional condition of group synchronism has been explored. Under such condition the electron bunch longitudinal velocity coincides with the wave group velocity propagating in a regular waveguide. It has been shown theoretically [11] that this regime gives the possibility to increase the growth rate of the SR instability and also, reduce the sensitivity of the interaction to the spread of parameters of the electrons.

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In the case of a bunch of electrons moving along rectilinear trajectories in a guiding magnetic field Cherenkov type SR has been studied for two types of slow-wave structures. The first was a periodically corrugated metallic waveguide where a bunch radiates under synchronism with the slow spatial harmonic of the backward wave

$$\omega = (-k + k_c)v_i, \quad (2)$$

where $k_c = 2\pi/\lambda_c$, λ_c is the corrugation period. The second used a dielectric loaded waveguide where forward wave radiation occurred under synchronism

$$\omega = kv_i. \quad (3)$$

3. Experimental results

A RADAN 303 accelerator with a subnanosecond slicer was used to inject typically 0.3–0.5 ns, 0.2–1 kA, 250 keV, single electron pulses [13,14]. These electron pulses were generated from a magnetically insulated coaxial diode which utilized a cold explosive emission cathode. Typical oscillogram of the electron bunch current are presented in Fig. 1(a). The fast rising e-beam current and accelerating voltage pulses were measured using a Faraday cage strip line current probe and an in line capacitive voltage probe respectively, with both signals recorded using a 7 GHz Tektronix 7250 digitizing oscilloscope. High current electron pulses were transported through the interaction space over a total length of up to 30 cm in a longitudinal guiding magnetic field of up to 2 T. For measurement of the radiation a hot-carrier germanium detector which had a transient characteristic of 200 ps was used.

Oscillograms of microwave SR pulses for different mechanisms of emission are presented in Fig. 1(b)–(e). The typical main pulse duration was 0.3–0.5 ns. The maximum peak power was several hundreds of kilowatts for cyclotron and undulator emission and about 1–2 MW for Cherenkov emission.

Note that the microwave signal in the case of a periodical slow-wave structure (Fig. 1(d)) consisted of several peaks. The first small peak corresponded to the high frequency radiation propagating in the same direction as the electron beam (TWT mechanism), while the second larger peak corresponded to the designed counter-propagating emission mechanism. Subsequent bursts are related with reflection of radiation from the edges of the slow-wave system.

In the case of cyclotron SR (see also [15]) the emission appears as a set of two pulses (Fig. 1(b)) related with more fundamental physics. In fact, under group synchronism condition in the comoving reference frame electrons radiate isotropically at the quasi-cutoff frequencies in both the $\pm z$ directions. But in laboratory frame both components of

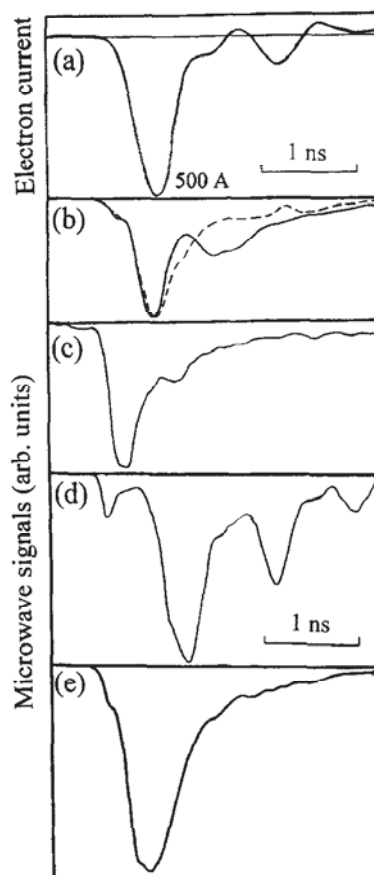


Fig. 1. Oscillograms: (a) electron bunch current, (b)–(e) microwave pulses for different types of superradiance: (b) cyclotron SR, (c) undulator SR, (d) Cherenkov SR in the case of periodical waveguide and (e) Cherenkov SR in the case of dielectric-loaded waveguide. Dashed line in (b) corresponds to signal passing through the cutoff filter.

the radiation propagate towards the bunch at the longitudinal velocity. So, the first pulse is created by photons emitted in the K' frame in the $+z$ direction, while the second one is by photons emitted in the opposite direction. Naturally due to the Doppler effect the frequency in the first pulse exceeds the frequency in the second pulse. For the same reason the peak power of the first pulse is essentially greater than that in the following pulse and the duration of the first pulse is less than the duration of the second pulse. To prove that the frequency in the first pulse exceeds that of the second pulse a set of cut-off waveguides have been used. The dashed line in Fig. 1(b) illustrate the essential suppression of second low frequency pulse by a high pass filter of cut-off frequency 33.3 GHz.

In general, measurements showed a very broad radiation spectrum width which covered the band

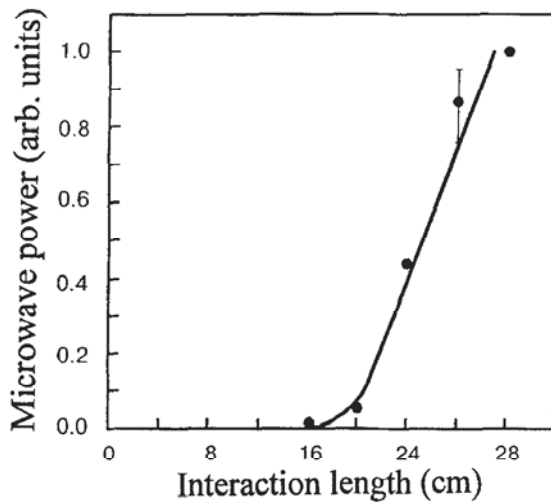


Fig. 2. Dependence of peak microwave power on interaction length, in the case of dielectric-loaded waveguide.

28.5–36.5 GHz. Thus, the relative spectrum width amounted to 20%. Note also that SR was observed in a rather narrow range of detuning of the uniform magnetic fields corresponding to grazing conditions with TE_{21} and TE_{01} modes. It was thus proven that the regime of group synchronism is optimal for cyclotron emission.

In the case of a bunch passing through an undulator SR has also been registered under grazing conditions with the designed TE_{11} mode. Adiabatically tapering of undulator entrance was used to provide excitation of bounce oscillations. The SR was registered for both group I and group II stationary orbits [16]. The first group of orbits corresponds to the so called reverse guide magnetic field regime at a magnetic field strength of 1 T while the second group of orbits was obtained and a direct magnetic field of strength 1.3 T which slightly exceeded the cyclotron resonance value. The maximum peak power was observed for the second case for the amplitude of undulator field 0.2 T. Typical oscillogram for this case is presented in Fig. 1(c).

The important confirmation of the stimulated nature of the observed radiation is the dependence of the peak power on interaction length. Typically dependence is shown in Fig. 2 for the case of Cherenkov SR. This figure clearly demonstrates that the radiation power is very small for short interaction lengths and increases drastically as the interaction length is increased. This means that at the initial stage self-bunching of electrons developed and the radiation power exceeded the threshold of the detector's sensitivity only after formation of the electron bunches. The squared dependence of the power of Cherenkov radiation with respect to the number of

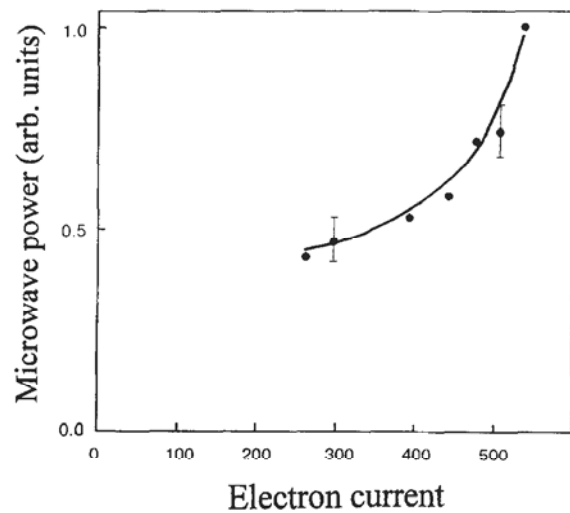


Fig. 3. Dependence of peak microwave power on electron bunch current, in the case of periodic waveguide.

electrons (Fig. 3) also confirms the coherent nature of observed radiation.

4. Conclusions

Summarizing the experimental results presented, we believe that the radiation observed was related with a novel mechanism of stimulated coherent emission of short electron bunches, namely superradiance. We should emphasize here that coherent emission occurs from an isolated subnanosecond electron bunch. Of course, the results discussed here give only a rather general physical picture of superradiance, which needs further investigation, which would specifically concentrate on more accurate measurements and comparison with theoretical simulations. However even at this early stage it must be emphasized that the radiation especially in the case of BWO-like regimes was characterized by a high level of stability and reproducibility from pulse to pulse. The efficiency of energy transformation amounted to 1% for the backward wave mechanism and up to 3% for the forward mechanism. The unique characteristic of microwave pulses such as duration (0.3–0.5 ns) in combination with megawatt power levels is encouraging for future applications in areas such as novel diagnostics and the studying of nonlinear phenomena in plasmas. Another advantage of the RADAN subnanosecond accelerator and consequently any associated experiments is that the whole system is in the form of a table-top system. In addition this accelerator is capable of operation in the repetitive, up to 100 pps regime.

This work was supported by the Russian Fund of Fundamental Research, grant 95-02-04791 and by the United Kingdom DRA and EPSRC.

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