Generation of powerful subnanosecond microwave pulses by intense electron bunches moving in a periodic backward wave structure in the superradiative regime

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Experimental results of the observation of coherent stimulated radiation from subnanosecond electron bunches moving through a periodic waveguide and interacting with a backward propagating wave are presented. The subnanosecond microwave pulses in Ka and W bands were generated with repetition frequencies of up to 25 Hz. The mechanism of microwave pulse generation was associated with self-bunching, and the mutual influence of different parts of the electron pulse due to slippage of the wave with respect to the electrons; this can be interpreted as superradiance. The illumination of a panel of neon bulbs resulted in a finely structured pattern corresponding to the excitation of the TM_{01} mode. Observation of rf breakdown of ambient air, as well as direct measurements by hot-carrier germanium detectors, leads to an estimate of the absolute peak power as high as 60 MW for the 300-ps pulses at 38 GHz. These results are compared with numerical simulations. The initial observation of 75-GHz, 10–15-MW radiation pulses with a duration of less than 150 ps is also reported. [S1063-651X(99)00709-6]

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INTRODUCTION

The study of the multifrequency dynamics of backward wave oscillators carried out in Refs. [1,2] showed that when an injected electron current increases the steady state oscillations change to the self-modulation operation regime. It has been noted [1] that high amplitude spikes form in the initial stage of the transient process under such conditions, and that the amplitude of these spikes substantially (2–3 times) exceeds the amplitude of the steady state oscillations. Only recently, however, it was recognized [3] that this spike has a superradiative nature [4–7] because its formation is related to the mutual influence of different parts of the electron beam caused by slippage of the wave with respect to the electrons. Thus, if the electron pulse duration is restricted by the cooperation time T_c, which in the case of a backward propagating wave can be presented as

$$T_c = L\left(\frac{1}{v_z}+\frac{1}{v_g}\right), \tag{1}$$

(where v_z is the electron drift velocity, v_g the electromagnetic wave group velocity, and L the length of the interaction space), it is possible to expect effective generation of high power ultrashort microwave pulses. For an electron pulse duration comparable with the cooperation time, the peak power associated with this spike grows as the square of the electron bunch total charge [3], which indicates that the electrons are radiating coherently.

Taking into account the general interest in superradiance (SR) phenomena in ensembles of classical electrons, which in recent years [4–15] has been considerable, we studied stimulated short pulse coherent emission from intense electron bunches moving through a periodic structure as one manifestation of superradiance. The high-current electron accelerator, based on a RADAN 303 modulator [16] equipped with an adjustable subnanosecond pulse sharpener [17] was used as a driver of intense subnanosecond electron bunches. When such bunches passed through the periodic slow-wave structure and interacted with backward propagating radiation, generation of ultrashort subnanosecond MW level Ka-band microwave pulses based on superradiance have been observed [18]. In these first experiments, however, rather low guide magnetic fields up to 2 T were used. This value of magnetic field was less than the cyclotron resonance value. At the same time it is known [19–26] from previous studies of long (5–30 ns) pulse relativistic backward wave oscillators (BWO's) that as the magnetic field is varied BWO's have two operating ranges separated by the cyclotron absorption region (cyclotron absorption arises when cyclotron resonance conditions are fulfilled for the fundamental harmonic of the wave propagating in the periodic structure). Based on this experience it is reasonable to expect that for the short pulse injection regime for higher guide magnetic fields, the peak power of SR spikes should be several times greater as compared with those attained in the lower magnetic field experiments due to the influence of the magnetic field on the electron emission process and the beam transport [18]. A superconducting magnet was used in a new

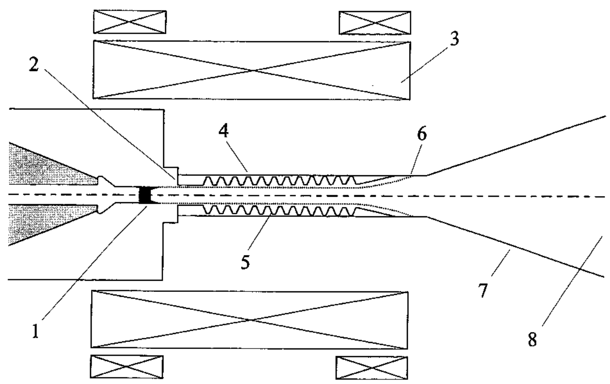

FIG. 1. Experimental configuration of the interaction region (1, cathode; 2, anode; 3, superconducting solenoid; 4, drift chamber; 5, slow-wave structure; 6, electron trajectory; 7, horn; 8, microwave window).

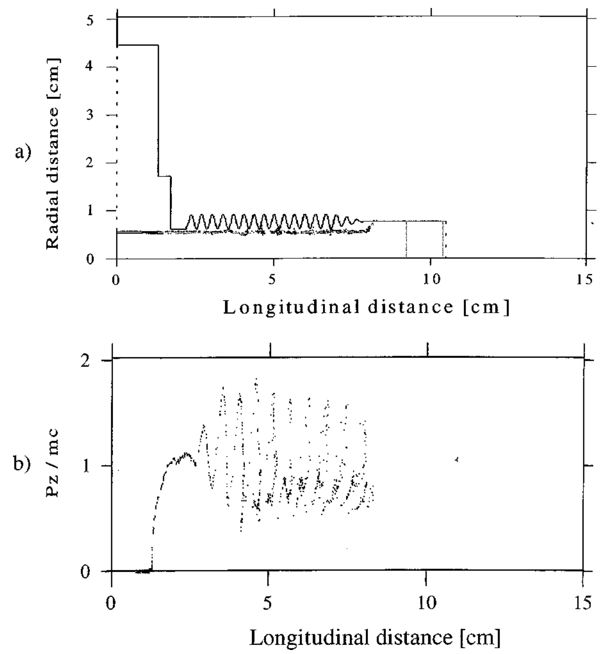

FIG. 2. (a) Geometry of interaction region and positions of electrons at time $t=1$ ns, (b) Phase plane at the same moment.

series of experiments to generate a longitudinal magnetic field with strengths of up to 8.5 T. Using a dc solenoid also permits us to operate in the burst-repetitive mode (25 Hz) to actually create a source of powerful 60-MW, subnanosecond, 300-ps, Ka-band radiation. In recent experiments generation of 150-ps W-band pulses with peak power levels not less than 10–15 MW have been observed as well.

In this paper, results of an experimental investigation of superradiance of intense subnanosecond electron bunches moving through a periodic waveguide structure and interacting with a backward propagating wave are presented. These results are compared with results of the numerical simulation of superradiation based on the particle-in-cell (PIC) code KARAT.

EXPERIMENTAL SETUP

A compact pulsed accelerator based on the RADAN 303 modulator equipped with a subnanosecond pulse sharpener was used to inject typically 0.5–1.2-ns, 1–2-kA, 200–250-keV electron bunches [16,17] into the interaction region. These electron bunches were generated from a magnetically insulated coaxial diode, which utilized a cold, explosive emission cathode (Fig. 1). The cathode unit provided the possibility of a smooth, precise adjustment of the accelerating gap to vary the electron current. The fast rising electron-beam current and accelerating voltage pulses were measured using a Faraday cage strip line current probe and an inline capacitive voltage probe, respectively, with both signals recorded using a 7-GHz Tektronix 7250 transient digitizing oscilloscope. High current electron pulses were transported through the interaction space in the form of corrugated waveguide of total length 3–10 cm, in a longitudinal guiding magnetic field of up to 8.5 T created by a superconducting magnet. The period of corrugation of the Ka-band slow-wave structure was approximately 3.5 mm, the corrugation depth was 0.75 mm, and had a mean radius of 3.75 mm. The W-band structure dimensions were half those of the Ka-band structure. The mean electron bunch diameters were 5.5 mm (Ka band) and 2.5 mm (W-band). For measurement of the Ka (26.5–40 GHz) and W (75–110 GHz) band radiation, a hot-carrier germanium detector which had a transient response as fast as 150 ps was used. In the Ka band the power-to-voltage dependence of the detector was calibrated using 100-ns magnetron pulses. The electron beam current and accelerating voltage probes possessed 200- and 150-ps transient characteristics, respectively.

SIMULATION OF SUPERRADIATIVE EMISSION FROM AN ELECTRON BUNCH MOVING IN A PERIODIC STRUCTURE

Simulation of the radiation from subnanosecond electron bunches passing through periodic waveguide structures was carried out using the PIC code KARAT. Figure 2(a) shows the system geometry (all sizes are in centimeters) and electron bunch 1 ns after a 240-kV driving voltage pulse was imposed on the coaxial line. In the presented simulations the strength of the guide magnetic field was 5 T. The self-consistent current pulse through the cross section at $z=2.5$ cm is plotted in Fig. 3. A pulse duration of about 0.8 ns and a peak current of $\sim$1.3 kA was close to the experimental measurements of the current pulse. In Fig. 2(a) we see modulation of the bunch density. The phase plane (p_z, z) [Fig. 2(b)] shows a strong modulation of the longitudinal momentum developing by this time. The dependence of rf output power on time is presented in Fig. 4(a). The microwave pulse duration is about 300 ps. The peak power reached 75 MW (after averaging over the high frequency, it should be half of the peak magnitude presented in Fig. 4), and the electronic efficiency was about 7%. The spectrum of radiation [see Fig. 5(a)] with a central frequency of about 38 GHz agrees with the experimental data and the frequency which can be found from the resonance conditions. The distribution over the radius of the radial component of the electric field at the output cross section $z=9$ cm is presented in Fig. 5(b), and corresponds to the excitation of the TM_{01} mode.

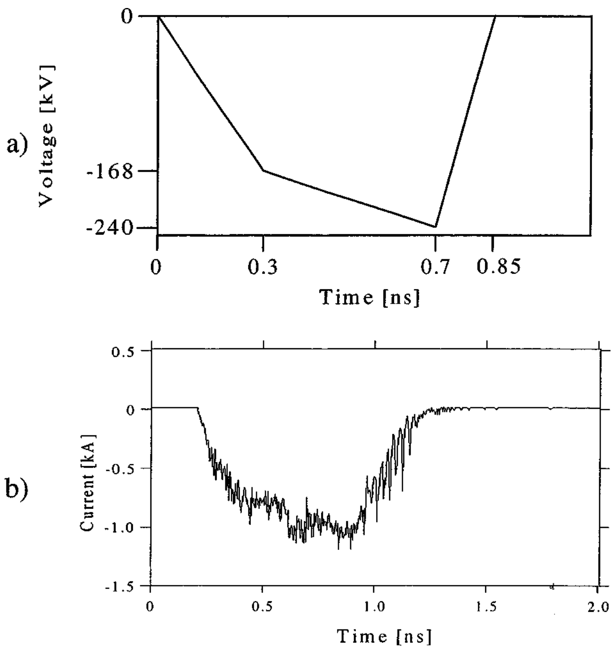

FIG. 3. (a) Accelerating voltage and (b) current pulse profiles.

It is also interesting to follow the electromagnetic energy fluxes inside the interaction space, which are presented in Fig. 4(b) for the cross section at $z=2.5$ cm. The first pedestal on this diagram is associated with the static electric and magnetic field of the electron bunch. The next negative pulse is just the real microwave backward propagating pulse of superradiation. This pulse is reflected from the cutoff region at the left side (inlet) of the interaction space, and then passes through the same cross-section as the forward propagating electromagnetic energy flux. From the delay in the pulse propagation through the cross sections $z=2.5$ and 9 cm, it is possible to estimate the electromagnetic wave group velocity

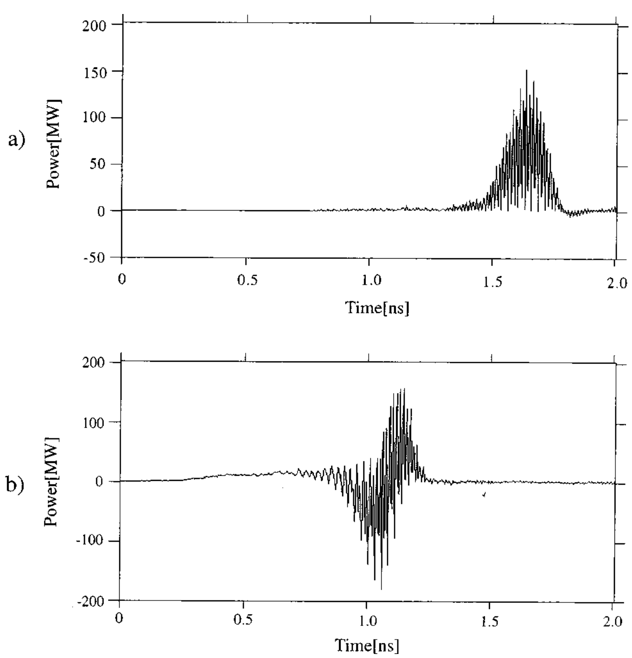

FIG. 4. Poynting vector integrated over the transverse cross section as a function of time at (a) $z=9$ cm and (b) $z=2.5$ cm.

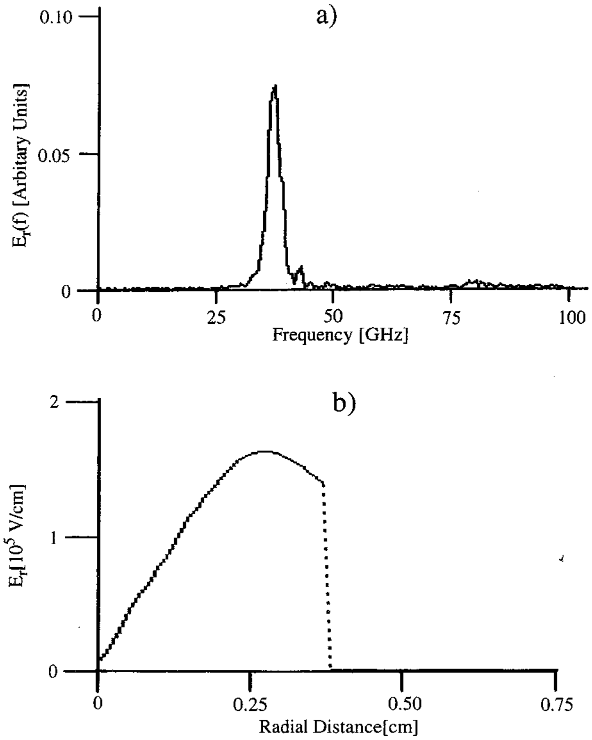

FIG. 5. (a) Frequency spectrum of output signal. (b) The distribution over the radius of the radial component of the electric field at the output cross section.

inside the corrugated waveguide as $0.3c$. The electron drift velocity was about $0.7c$. According to Eq. (1) this gives as an estimate of the co-operation time $T_c=0.8$ ns.

The dependence of peak power on the voltage pulse duration is shown in Fig. 6. Because the electron peak current was practically constant and the electron pulse duration corresponded to the voltage pulse duration, this diagram actually represents the dependence of peak power on the total charge in the bunch. Obviously this dependence is rather close to a square law when the pulse duration is close to the correlation time $T_c=0.8$ ns. Note that for small pulse durations the given interaction length of 6 cm is not sufficient for formation of SR spikes. For long electron pulses, saturation of the growth of the peak power is obviously related to the fact that the pulse becomes too long to provide coherent radiation emission from the entire pulse length. Actually, subsequent microwave spikes are emitted when the pulse duration is increased (Fig. 7).

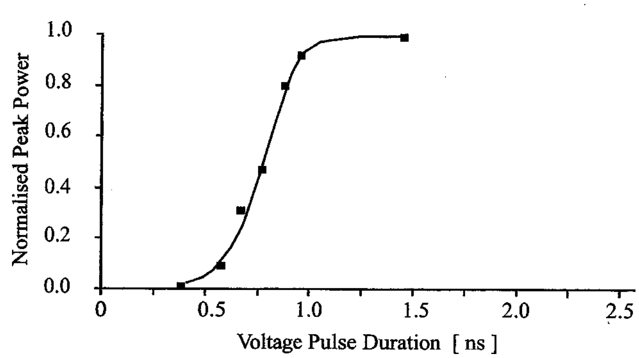

FIG. 6. Dependence of peak power on accelerating pulse duration (simulations).

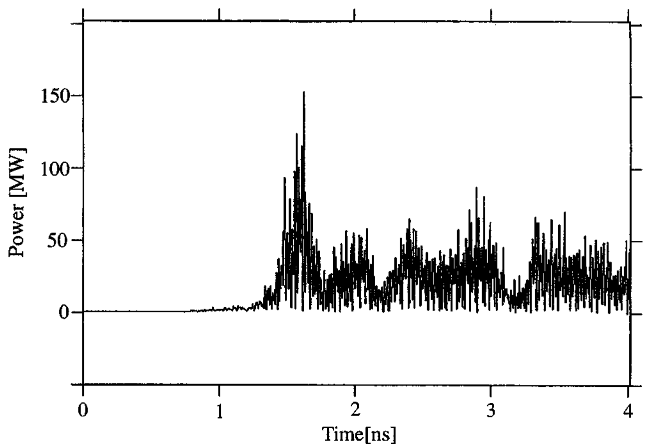

FIG. 7. Poynting vector integrated over the transverse cross section as a function of time for the long 5-ns electron pulse.

EXPERIMENTAL RESULTS

Ka-band experiments

A typical oscilloscope trace of the Ka-band microwave signal from an electron pulse passing through a periodic waveguide of total length 6 cm is presented in Fig. 8. The observed microwave spikes have a duration of about 300 ps and a rise time of 200 ps. It is important to note that for optimal conditions the pulse wave form, as well as the peak power, did not change when the interaction length was increased up to 10 cm. This fact agreed with the result of the simulations, which also indicated that a 6-cm interaction length is sufficient for the formation of a superradiance spike.

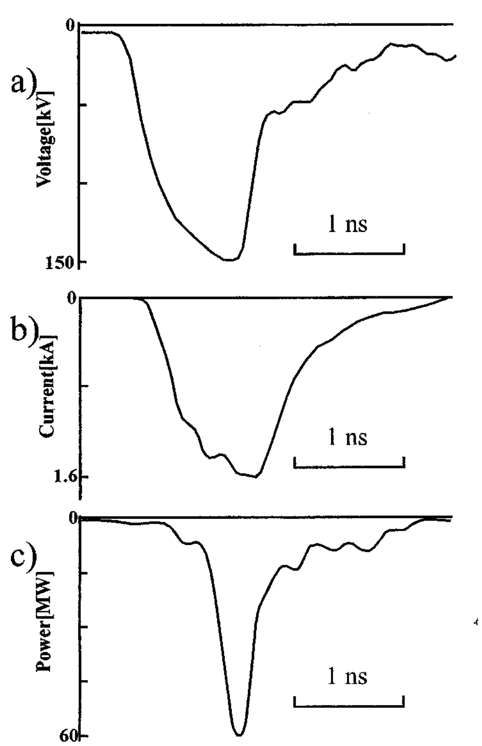

FIG. 8. Typical waveforms of (a) the accelerating voltage and (b) the pulsed electron current. (c) Ka-band superradiative microwave pulse recorded by the germanium detector.

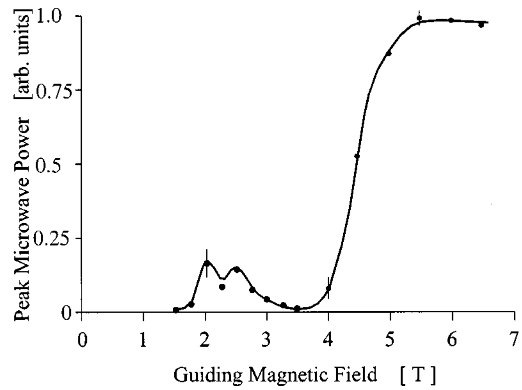

FIG. 9. Peak microwave power as a function of the guide magnetic field.

The dependence of the peak power on the strength of the guide magnetic field is shown in Fig. 9. In this diagram it is clearly seen that there is a region of cyclotron absorption near the resonance magnetic field value of 3.25 T, and then two operating regimes with low (1.5–3 T) and high (>4 T) magnetic fields. The initial experiments on the observation of SR in corrugated waveguides were carried out only in the region of low magnetic fields [18]. Implementing the strong guide magnetic field resulted in a drastic 4–5 times increase of the peak power. Because the experiment uses a field immersed explosive-electron-emission cathode, with electrons being emitted in random directions, increasing the magnetic field reduces the transverse freedom of the electron motion and also improves the uniformity of the emission process itself [27]. The increase in power can be easily explained by a consequent improvement in the quality of the electron beam, and a decrease to 0.4 mm (measured by the beam imprint on dosimetric film) of the transverse width of the hollow electron bunch. As the electron bunch mean transverse diameter was only 0.5 mm less than the smallest diameter of the slow-wave structure, and the effect of the increased magnetic field is to reduce the electron gyroradius, the tendency for the electrons nearest this structure to be intercepted is reduced. Therefore, the increased magnetic field has the effect of improving the electron transport, especially for those electrons whose orbital guiding centers were closest to the slow-wave structure, thereby decreasing the gap between the mean diameter of the electron beam and the corrugations. Note that all the experimental data for the Ka-band pulses discussed below were obtained for a magnetic field of 5 T.

Frequency measurements at Ka band have been made using a set of cutoff waveguide filters, and showed that the main peak has a central frequency of approximately 38 GHz. The relative radiation spectrum bandwidth found from these measurements was about 5%. The radiation had a polarization corresponding to the TM_{01} mode. The measured radiation pattern also corresponded with good accuracy to the excitation of the TM_{01} mode (Fig. 10). This measurement allowed the absolute peak power to be estimated by integrating the signal from the detector over its radial position. The peak power estimated by this method was about 60 MW. A rather high level of radiation power was also indicated by the illumination of a neon bulb panel when the radiation signal irradiated the panel at a distance of 30 cm from the output

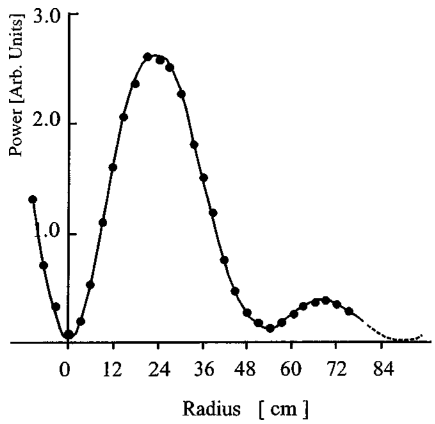

FIG. 10. Radiation pattern measured by the germanium detector.

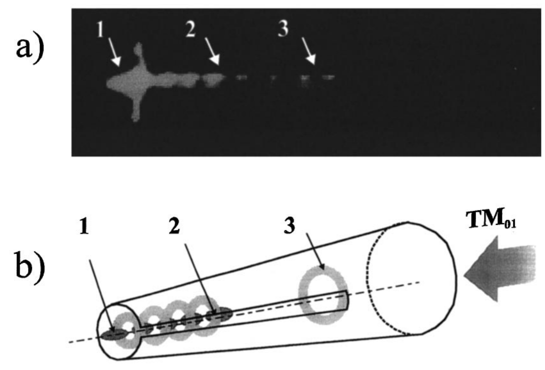

FIG. 12. Breakdown of ambient air caused by a subnanosecond microwave pulse inside the conical horn. (a) Photography. (b) Geometry of the horn and scheme of the breakdown.

horn (Fig. 11). Thus the operating mode, the microwave pulse width, and the spectrum, as well as the absolute power found from experiments, are in good agreement with the results of simulations.

Additional evidence of the high peak power was obtained from the observation of rf breakdown of ambient air for subnanosecond pulses in the focus of a parabolic reflector as well as inside a receiving concentrating conical horn with minimum output diameter 12 mm [Fig. 12(a)]. It is reasonable to try to determine the real peak microwave power based on the previous experimental observation of breakdown initiated by both 2–4-ns, high-power Ka-band microwave sources [28,29] as well as subnanosecond, high voltage modulator produced unipolar (without microwave carrier) voltage pulses [30]. A summary of these experimental data is presented in Fig. 13. It follows from the diagram that for a microwave pulse duration of 300 ps, the air breakdown strength is about 130 kV/cm. The utmost, limiting plasma spot observed during the breakdown processes in the field of the standing wave was located in a horn cross section having a diameter of 13.5 mm [point 2, Fig. 12(b)]. The separate plasma spot was excited in a horn region of 15–16-mm diameter [point 3, Fig. 12(b)]. Based on the above data, and applying the standard method of calculation for the fields inside a circular waveguide, it is easy to see that a radial electric field of 130 kV/cm at a cross section with a diameter of 15 mm corresponds to an input power of ~60 MW. So the estimation of the peak output power from observations of breakdown are in good agreement with the results of measurements of the power by the germanium detector.

Simple calculations show that the energy of an electromagnetic pulse with peak power of 60 MW and a half-amplitude pulsewidth duration of 300 ps is about 2×10^{-2} J which corresponds to a 5% efficiency of energy transforma-

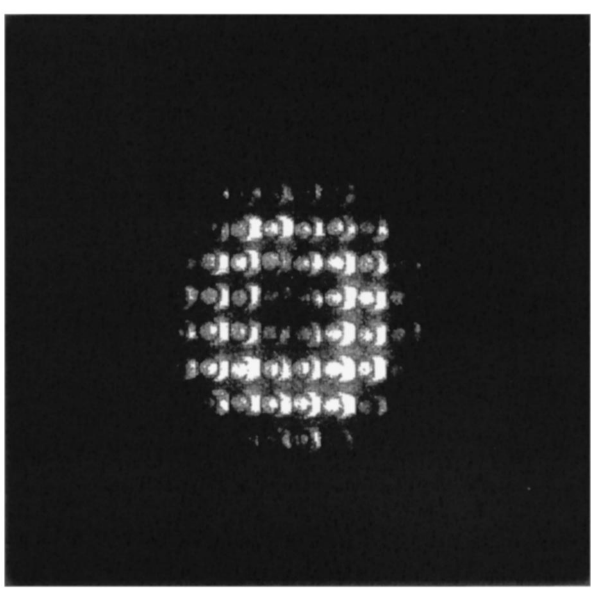

FIG. 11. Luminescence of the matrix gas-discharge panel irradiated by superradiation pulse. Light corresponds to the radiation pattern of the TM_{01} mode.

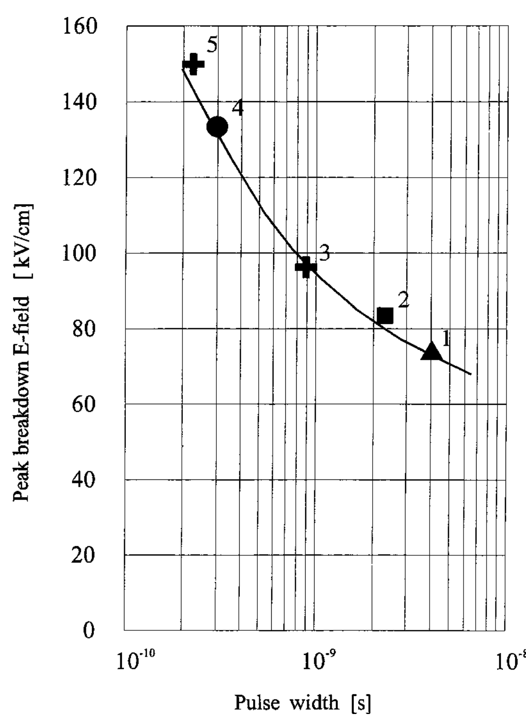

FIG. 13. Summary of previous peak breakdown *E*-field measurements for several microwave and unipolar pulses with different durations. Points 1 and 2 correspond to breakdown induced by microwave pulses, and points 3 and 5 to breakdown induced by unipolar pulses. Point 4 corresponds to the 300-ps duration of the output pulse from the SR experiment, and indicates a field strength of 130 kV/cm.

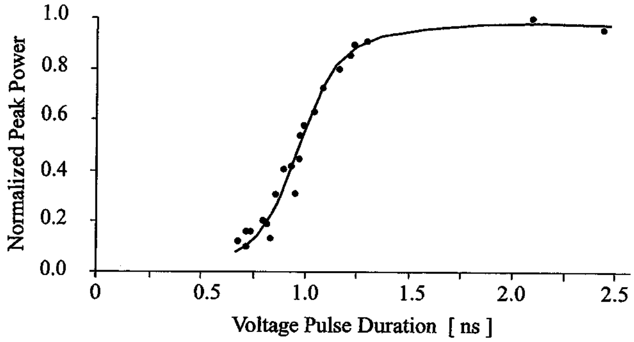

FIG. 14. Dependence of the peak microwave power on the accelerating voltage pulse duration.

tion from the 4×10^{-1} J electron bunch into the microwave pulse. For some applications it is also an important factor that the microwave power rise time was very high, being up to 300 MW/ns.

It is pertinent to note that the generated Ka-band microwave pulses possess high stability and reproducibility. Coupled with the capability of operation of the RADAN 303 modulator in the repetition rate mode and the availability of permanent magnetic fields for the electron bunch transportation, the ability to generate reproducible microwave pulses with a repetition frequency of 25 Hz was demonstrated.

The dependence of peak power on electron pulse duration is presented in Fig. 14. To obtain this dependence, the accelerating pulse duration was varied while keeping the accelerating voltage amplitude constant. Obviously this dependence is rather close to a square law in the region of pulse duration 0.5–1.2 ns. This means that the electrons radiate coherently from the entire volume of the electron pulse. Note that for small pulse durations of less than 0.5 ns, the given interaction length of 6 cm is not sufficient for formation of SR spikes. With an increase of the electron pulse duration above 1.2 ns, saturation of the growth of the peak power is obviously related to the fact that it is impossible to provide coherent emission from the pulse with a duration substantially exceeding the cooperation time, and actually subsequent microwave spikes are emitted. Note that the experimental dependence is rather close to the results of the simulations (see Fig. 7).

By integrating the electron current pulse over time, the total charge of the electron bunch has been found (Fig. 15).

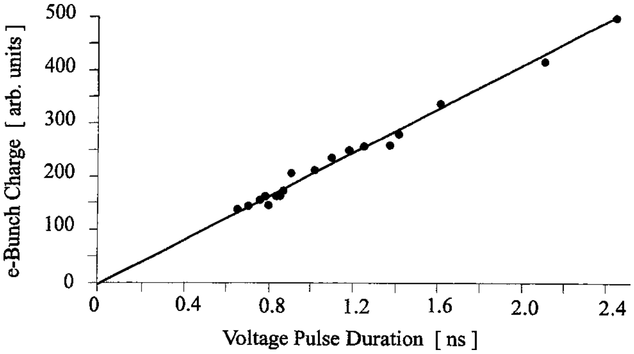

FIG. 15. Dependence of the electron bunch total charge on the accelerating voltage pulse duration.

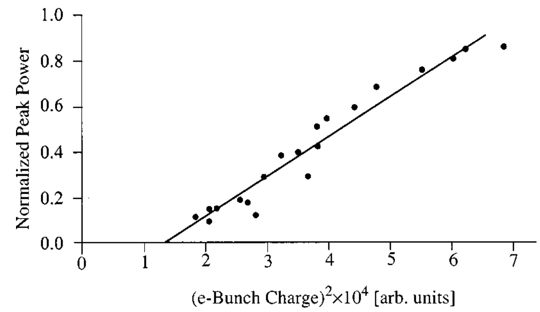

FIG. 16. Dependence of the peak microwave power on the square of the electron bunch total charge.

Based on the results presented in Figs. 14 and 15, the dependence of peak power on the square of the total charge is drawn in Fig. 16. This dependence is very close to linear. Some shift of the fitted linear function from the origin can be explained by the fact that at the leading and trailing edges of the accelerating pulse there are low energy electrons. These electrons cannot participate in the resonant interaction with the electromagnetic pulse. With decreasing accelerating pulse duration, the relative number of such electrons increases. That is why the radiation power tends to zero faster than the square of the total charge.

W-band experiments

Alongside the investigation of the generation of subnanosecond microwave pulses at the Ka band, a similar series of experiments were performed for a W-band backward-wave microwave structure (all geometrical sizes of this structure were half the size of those of the Ka-band structure). The PIC code simulations have shown a peak power of up to 30 MW can be attained for a half-amplitude pulsewidth of 100–150 ps at a frequency of 75 GHz. The rise time of the front of the pulse did not exceed 100 ps. In the experiments such pulses were clearly observed (Fig. 17) with the use of the germanium detector which was recalibrated using 3-ns W-band pulses produced by relativistic BWO oscillators [29], and a specially developed calorimeter that is similar to the one described in Ref. [31]. The integral mode pattern scan has shown that the total peak power of the W-band pulses was between 10 and 15 MW when the accelerating voltage at the cathode was as high as 250 kV, the electron-beam current was up to 800 A and the axial B field was 3.5 T. The W-band spikes possessed an extremely sharp leading edge of $<$120 ps, i.e., rising two times faster than the Ka-band pulses. Such a fast front corresponded to the limits of

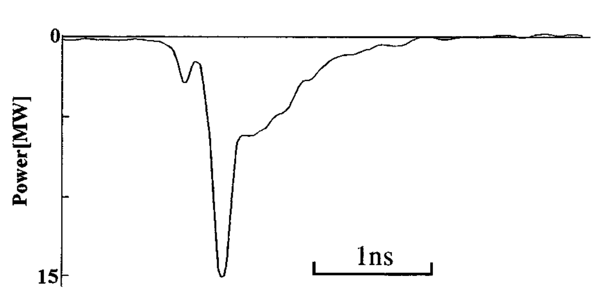

FIG. 17. W-band superradiative microwave pulse (oscilloscope trace).

the transient response of the oscilloscope's cable delay line provided for the measurements (120 ps). Due to these bandwidth limitations of the measuring system, we believe that the peak power was somewhat underestimated. This is also a contributing factor in explaining the discrepancy in the peak power obtained in the simulations (~30 MW) as compared to the value measured experimentally. Air breakdown from W-band pulses has been experimentally observed when the output cross section of the conical horn was reduced to 8 mm. However, cross-checking the peak power using the air breakdown measurements appears to be less accurate for the W-band pulses as compared to the Ka-band pulses because of the instrumental uncertainty in the measurements of the shorter microwave pulse duration as well as the more restricted availability of data on the breakdown strength of air for ~100 ps duration pulses. It is reasonable to conclude, therefore, that the estimate of the experimentally measured peak power in W-band pulses of 10–15 MW represents a lower limit on the actual emitted peak power.

CONCLUSION

In conclusion, we believe that the experiments, carried out together with simulations of the electron bunch–electromagnetic wave interaction, give us reason to affirm that the observed emission can be interpreted as superradiative. The microwave pulses generated by such a mechanism have a unique short duration of 300 ps with a 60-MW peak power level measured in the Ka band. In addition, we have reported preliminary observations of ~150-ps pulse durations with at least a 10-MW peak power level in the W band. The achieved repetition frequency of 25 Hz also supports the conclusion that an interesting source of powerful subnanosecond pulses has been developed. In this context an important factor is that the whole device is in the form of a tabletop system.

Even at the present stage, when sources are still very rapidly developing to the 100-MW level and beyond, it is promising to consider the application of subnanosecond multimegawatt Ka- and W-band pulses in areas such as diagnostics and the study of nonlinear phenomena in plasmas and solids. Another potential area of interest is in radiotechnical applications. It would also be interesting to test the influence of such pulses on biological matter.

ACKNOWLEDGMENTS

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[1] N. S. Ginzburg, S. P. Kuznetsov, and T. M. Fedoseeva, Sov. Radiophys. Electron. **21**, 729 (1979).
[2] Y. Carmel, W. R. Lou, J. Rodgers, H. Guo, W. W. Destler, V. L. Granatstein, B. Levush, T. Antonsen, and A. Bromborsky, Phys. Rev. Lett. **69**, 1652 (1992).
[3] N. S. Ginzburg, Yu. V. Novozhilova, and A. S. Sergeev, Pis'ma Zh. Tekh. Fiz. **22**, 39 (1996) [Sov. Tech. Phys. Lett. **22**, 359 (1996)].
[4] R. H. Bonifacio, C. Maroli, and N. Piovella, Opt. Commun. **68**, 369 (1988).
[5] R. H. Bonifacio, B. W. J. McNeil, and P. Pierini, Phys. Rev. A **40**, 4467 (1989).
[6] R. H. Bonifacio, N. Piovella, and B. W. J. McNeil, Phys. Rev. A **44**, 3441 (1991).
[7] R. H. Bonifacio, L. De Salvo, L. Narducci, and E. D'Angelo, Phys. Rev. A **50**, 1716 (1994).
[8] N. S. Ginzburg, Pis'ma Zh. Eksp. Teor. Fiz. **14**, 440 (1988) [JETP Lett. **48**, 399 (1988)].
[9] N. S. Ginzburg and A. S. Sergeev, Opt. Commun. **91**, 140 (1992).
[10] N. S. Ginzburg and A. S. Sergeev, Pis'ma Zh. Eksp. Teor. Fiz. **60**, 501 (1994) [JETP Lett. **60**, 513 (1994)].
[11] G. R. M. Robb, N. S. Ginzburg, A. D. R. Phelps, and A. S. Sergeev, Phys. Rev. Lett. **77**, 1492 (1996).
[12] V. V. Zheleznyakov, V. V. Kocharovsky, and Vl. V. Kocharovsky, Usp. Fiz. Nauk **159**, 193 (1989) [Sov. Phys. Usp. **32**, 835 (1989)].
[13] N. Piovella, P. Chaix, G. Shvets, and D. A. Jaroszynski, Phys. Rev. E **52**, 5470 (1995).
[14] D. A. Jaroszynski, P. Chaix, N. Piovella, D. Oepts, G. M. H. Knippels, A. F. G. Van Der Meer, and H. H. Weits, Phys. Rev. Lett. **78**, 1699 (1997).
[15] N. S. Ginzburg, I. V. Zotova, A. S. Sergeev, I. V. Konopolev, A. D. R. Phelps, A. W. Cross, S. J. Cooke, V. G. Shpak, M. I. Yalandin, S. A. Shunailov, and M. R. Ulmaskulov, Phys. Rev. Lett. **78**, 2365 (1997).
[16] G. A. Mesyats, V. G. Shpak, S.A. Shunailov, and M. I. Yalandin, in *Proceedings of the 9th IEEE International Pulsed Power Conference, Albuquerque, NM*, edited by K. R. Prestwich and W. L. Baker (IEEE, New York, 1993), pp. 835–838.
[17] G. A. Mesyats, V. G. Shpak, S. A. Shunailov, and M. I. Yalandin, Proc. SPIE **2154**, 262 (1994).
[18] N. S. Ginzburg, A. S. Sergeev, I. V. Zotova, Yu. V. Novozhilova, N. Yu. Peskov, I. V. Konoplev, A. D. R. Phelps, A. W. Cross, S. J. Cooke, P. Aitken, V. G. Shpak, M. I. Yalandin, S. A. Shunailov, and M. R. Ulmaskulov, Nucl. Instrum. Methods Phys. Res. A **393**, 352 (1997).
[19] E. A. Abubakirov, N. S. Ginzburg, N. F. Kovalev, and M. I. Fuchs, Radioteck. Elek. **34**, 1058 (1989) [Sov. J. Commun. Technol. Electron. **34**, 129 (1989)].
[20] A. Vlasov, G. S. Nusinovich, B. Levush, A. Bromborsky, W. R. Lou, and Y. Carmel, Phys. Fluids B **5**, 1625 (1993).
[21] N. F. Kovalev, M. I. Petelin, M. D. Raizer, A. V. Smorgonskii, and L. E. Tsopp, Pis'ma Zh. Eksp. Teor. Fiz. **18**, 81 (1973) [JETP Lett. **18**, 138 (1973)].
[22] Y. Carmel, J. Ivers, R. E. Kribel, and J. A. Nation, Phys. Rev. Lett. **33**, 1278 (1974).
[23] S. M. Miller, T. M. Antonsen, B. Levush, A. Bromborsky, D. K. Abe, and Y. Carmel, Phys. Plasmas **1**, 730 (1994).
[24] B. Levush, T. M. Antonsen, A. Bromborsky, W. R. Lou, and

Y. Carmel, Phys. Fluids B **4**, 2293 (1992).

[25] A. S. Elchaninov, S. D. Korovin, G. A. Mesyats, V. V. Rostov, V. G. Shpak, and M. I. Yalandin (unpublished).

[26] R. A. Kehs, A. Bromborsky, B. G. Ruth, S. E. Graybill, W. W. Destler, Y. C. Carmel, and M. C. Wang, IEEE Trans. Plasma Sci. **PS-13**, 559 (1985).

[27] G. A. Mesyats and D. I. Proskurovsky, *Pulsed Electrical Discharge in Vacuum* (Springer-Verlag, Berlin, 1989).

[28] M. I. Yalandin, G. T. Smirnov, V. G. Shpak, and S. A. Shunailov, *Proceedings of the 9th IEEE International Pulsed Power Conference, Albuquerque, NM* (Ref. [16]), pp. 388–391.

[29] M. I. Yalandin, G. A. Mesyats, V. G. Shpak, G. T. Smirnov, and S. A. Shunailov, Proc. SPIE **1872**, 333 (1993).

[30] M. I. Yalandin, V. G. Shpak, S. A. Shunailov, and M. R. Ulmaskulov, Proc. SPIE **2557**, 289 (1995).

[31] N. M. Bykov, V. P. Gubanov, A. V. Gunin, S. D. Korovin, V. V. Rostov, and M. I. Yalandin, Russ. Inst. Exp. Techn. **6**, 107 (1987).