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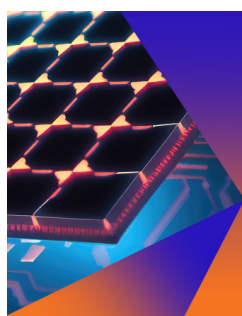


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A 670 GHz gyrotron with record power and efficiency

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A 670 GHz gyrotron with record power and efficiency has been developed in joint experiments of the Institute of Applied Physics, Russian Academy of Sciences (Nizhny Novgorod, Russia), and the University of Maryland (USA) teams. The magnetic field of 27–28 T required for operation at the 670 GHz at the fundamental cyclotron resonance is produced by a pulsed solenoid. The pulse duration of the magnetic field is several milliseconds. A gyrotron is driven by a 70 kV, 15 A electron beam, so the beam power is on the order of 1 MW in 10–20 ms pulses. The ratio of the orbital to axial electron velocity components is in the range of 1.2–1.3. The gyrotron is designed to operate in the TE_{31,8}-mode. Operation in a so high-order mode results in relatively low ohmic losses (less than 10% of the radiated power). Achieved power of the outgoing radiation (210 kW) and corresponding efficiency (about 20%) represent record numbers for high-power sources of sub-THz radiation. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4757290>]

There is a wide range of physical/technical and biological/medical applications for high-power sources of coherent THz radiation.^{1–4} Activity in these areas is hindered by the lack of high-power and efficient sub-THz and THz sources. In part, this situation can be explained by the fact that physical principles of electronic devices which work well at longer wavelengths, as well as those of photonic devices which work well at higher frequencies, become inefficient just in this “terahertz gap.” Low efficiency is often a consequence of high ohmic losses of radiated power in the circuit walls. (The state-of-the-art in the development of vacuum electron-beam driven THz sources was recently overviewed in Ref. 5.)

One of the most promising high-power, highly efficient, and relatively compact (in comparison with free-electron lasers) sources at frequencies below about 0.3 THz is a fast-wave device named the gyrotron,⁶ whose continuous-wave power in the frequency range of 0.1–0.2 THz has been shown to reach the megawatt level.^{7,8} However, since gyrotron operation is based on the cyclotron resonance interaction between fast electromagnetic waves and electrons gyrating in external magnetic fields,^{6,9} the operation at a desired frequency requires a corresponding magnetic field. For example, to operate at frequencies about 1 THz frequency at the fundamental cyclotron resonance between electrons and an electromagnetic wave, it is necessary to have magnetic fields in the range of 40 T. At higher cyclotron harmonics, the required magnetic field decreases inversely proportional to the cyclotron harmonic number. However, the choice of operating modes (and therefore, the achievable power level) in the case of harmonic operation is limited by possible competition of the desired mode with parasitic modes which can be excited at the fundamental resonance.

Since magnetic fields achievable with not too expensive cryomagnets are limited to 15–20 T, it is attractive (at least, for some applications in mind) to use gyrotrons with pulsed solenoids. The first successful attempt to develop gyrotrons with pulsed solenoids resulted in achieving 100 kW power

level with 8.2% efficiency in 80 ms single pulses.¹⁰ A few years ago, some improvements in fabrication of pulsed magnets used for this purpose enabled researchers, first, to demonstrate 1.5 kW level at 1 THz frequency¹¹ and then, to increase the frequency up to 1.3 THz simultaneously with increasing the power up to 5 kW.¹²

Recently, a new application of powerful sources of sub-THz radiation proposed in Ref. 13 stimulated a new direction in the development of high-power sub-THz gyrotrons. In brief, this application is aimed at remote detection of concealed radioactive materials with the use of high-power sub-THz radiation. As is known, even shielded radioactive materials may emit gamma rays through the walls of any container, and these gamma rays cause ionization of air molecules. It is also known that high-power electromagnetic radiation being focused in a spot of the wavelength scale can exceed the breakdown threshold. Therefore, when there are some seed free electrons in such a breakdown-prone volume, the breakdown may take place there. An ambient electron density is usually estimated to be at the level of 1 electron per cubic cm,¹⁴ although there are some reservations about these numbers.¹⁵ When the wavelength is short enough and the wave power is high enough, one can realize conditions for a low breakdown rate in the absence of radioactive materials low, but high breakdown rate in their presence. Corresponding conditions were analyzed elsewhere.^{16–18} In particular, it was shown that an attractive option would be a 670 GHz gyrotron delivering the power above 200 kW in 10–20 ms long pulses. The choice of the frequency was determined by two factors. First, at this frequency there is an atmospheric “window” with relatively low propagation losses of 50 dB/km, i.e., wave attenuation is less than 3 dB at distances of 20–40 m. Second, this frequency is close to the electron-molecule collision frequency at 1 atm., i.e., it corresponds to the bottom of the Paschen curve. The present paper describes some results of the development of such gyrotron.

To avoid significant ohmic losses of the radiated power in the circuit walls, it was decided to operate in a high-order $TE_{31,8}$ -mode whose ability to operate stably at a megawatt level was recently demonstrated in a 170 GHz gyrotron developed for plasma experiments in ITER.⁷ Design of a 670 THz gyrotron operating in this mode¹⁹ showed that the ohmic Q factor of a copper cavity can be as high as 30 000, while the cavity diffractive Q responsible for the outgoing sub-THz radiation does not exceed 3000. So the ohmic losses should be less than 10% of the radiated power, while in devices such as, for example, extended interaction klystron even in the W-band (95 GHz) ohmic losses are at a 1/3 level of the power radiated by an electron beam.⁵ Design of a gyrotron cavity was performed with the use of code MAGY²⁰ under the assumption that oscillations can be excited by a 70 kV, 15 A electron beam with the orbital-to-axial velocity ratio of 1.2–1.3. The cavity radius was chosen equal to 4.54 mm, which corresponds to operation in the $TE_{31,8}$ -mode at the 670 GHz frequency. The electron beam radius was taken equal to 2.3 mm, which corresponds to the maximum beam coupling to this mode co-rotating with electrons gyrating in the external magnetic field. The cavity profile was found to yield 35% interaction efficiency even in the presence of electron velocity spread.¹⁹ The cavity profile and the efficiency as the function of the external magnetic field are shown in Figures 1(a) and 1(b), respectively.

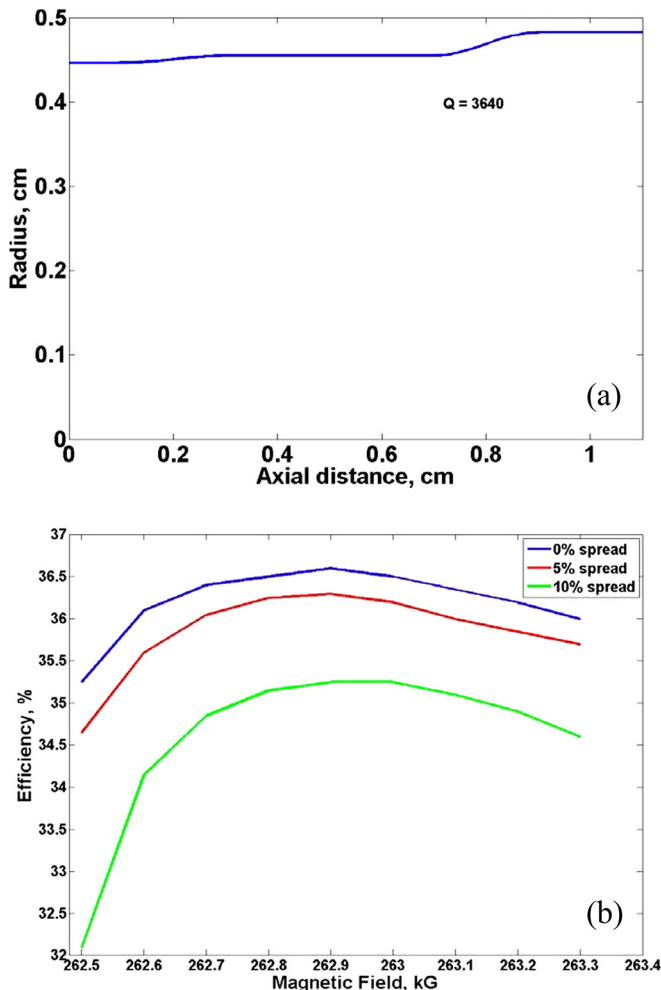


FIG. 1. Cavity profile (a) and the efficiency as the function of the magnetic field (b).

tively. (The length of a constant radius straight section is equal to 10 wavelengths. The efficiency shown in Fig. 1 corresponds to the mean value of the velocity ratio equal to 1.3.) Correspondingly, the output efficiency accounting for ohmic losses can exceed 30% which is comparable with the efficiency of high-power 100–200 GHz range gyrotrons operating without depressed collectors. It should be noted that similar results can be also achieved in a gyrotron operating in the $TE_{25,10}$ -mode, as shown in the design study described in Ref. 21.

As is seen in Fig. 1(b), to run a 670 GHz gyrotron at the fundamental cyclotron resonance one should have the magnetic field about 27 T. Such field can be produced by a pulse solenoid similar to those used in previous experiments.^{10,11} To provide penetration of a variable magnetic field inside a gyrotron, the duration of the magnetic pulse was programmed to be about 2 ms and the gyrotron body was made of a 1 mm thick stainless steel. Two versions of gyrotron cavities were fabricated and tested: one from bronze and another from a stainless steel with inner coating by a 10 μ m thick layer of copper (at this frequency, the skin depth in copper is less than 1 μ m).

As described in Ref. 22, numerical optimization of the shape of electrodes for a cathode of 22 mm radius allowed us to expect that for a beam current of 15 A, the electron optics will yield a beam with the mean value of the orbital-to-axial velocity ratio $\bar{\alpha} = 1.27$ and the spread in orbital velocities (neglecting the effect of the emitter surface roughness) equal to 9%.

The demountable gyrotron tube with a pulse magnet manufactured by GYCOM in accordance with the above design requirements was delivered to the University of Maryland. Experiments with this gyrotron shown in Fig. 2 were started at the University of Maryland and in parallel with its replica at the Russian Institute of Applied Physics.

The solenoid was made of a rectangular copper cable, wired directly on a thin stainless steel gyrotron body. The solenoid was cooled with liquid nitrogen to reduce ohmic heating and has reproducible shot-to-shot operation. The operating magnetic field (coil current) was selected based on the calibration made by Hall-effect device in a low-field CW regime. The voltage and the coil current did not exceed 3.5 kV and 7 kA, respectively; total stored energy was about 20 kJ. The pulse-to-pulse reproducibility of the magnetic field was within 0.05%. Due to the limitation of the pulsed solenoid cooling time, pulse-to-pulse reproducible results were obtained with the repetition rate not exceeding one shot in 3 min.

Experimental results were obtained for 670 GHz operation at the fundamental cyclotron resonance. Detection of microwave power was made by a silicon point contact diode and by a dummy load. In the IAP experiment, the calorimeter described in Ref. 23 was used, which has the sensitivity allowing for detecting the microwave energy in single shots at a 10 mJ level and above. The sensitivity of a calorimeter developed at the University of Maryland was at about 50 mJ level. The magnetic field was varied for maximizing the output power and efficiency. Typical oscilloscope traces of high voltage, beam current, and microwave signal are shown in Figure 3. The bottom figure shows the signal measured by a

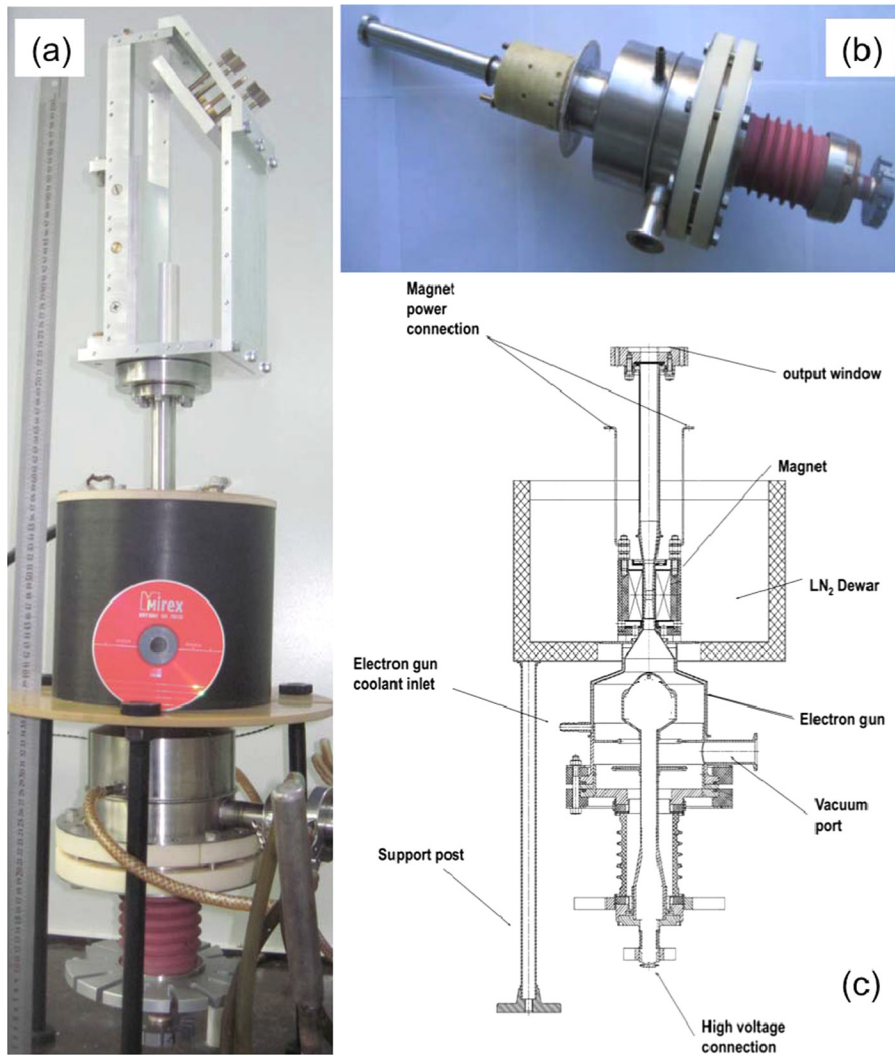


FIG. 2. (a) The 670 GHz gyrotron with the 28 T pulsed solenoid, Vlasov converter, and mirrors. The ruler (1 m) and CD are shown for scale. (b) The gyrotron tube without connections to the liquid nitrogen Dewar. (c) Schematic diagram of the gyrotron.

calibrated calorimeter; the jump in the signal corresponds to 0.56 J of microwave energy.

As mentioned above, in the experiments, two types of cavities had been used: first, the bronze and, then, the stainless steel with a thin internal copper layer coating. The length of a straight section was varied from 4 to 6 mm for both materials. In experiments with the bronze cavity, it was found that the maximum power realized in a 4 mm long cavity is close to 100 kW, while in the case of a 6 mm long cavity the maximum power is about 130 kW. Therefore, after that, a gyrotron with a 6 mm long cavity made of a stainless steel with copper coating allowing for smaller ohmic losses was tested in more detail. The fact that the maximum efficiency was realized in a longer cavity indicates that in this experiment the electron pitch ratio was smaller than its design value of 1.27.

To optimize the orbital-to-axial electron velocity ratio (beam pitch-factor), the position of cathode was slightly changed in the axial direction. These changes had allowed us to reach the maximum radiation power averaged over a single pulse equal to 210 kW. This power level was achieved with a 58 kV, 22 A electron beam and corresponds to 16.5% output efficiency. The maximum output efficiency of 20% was realized at lower currents, viz., in a 57 kV, 16 A operating regime. Taking into account microwave losses in a 2 mm

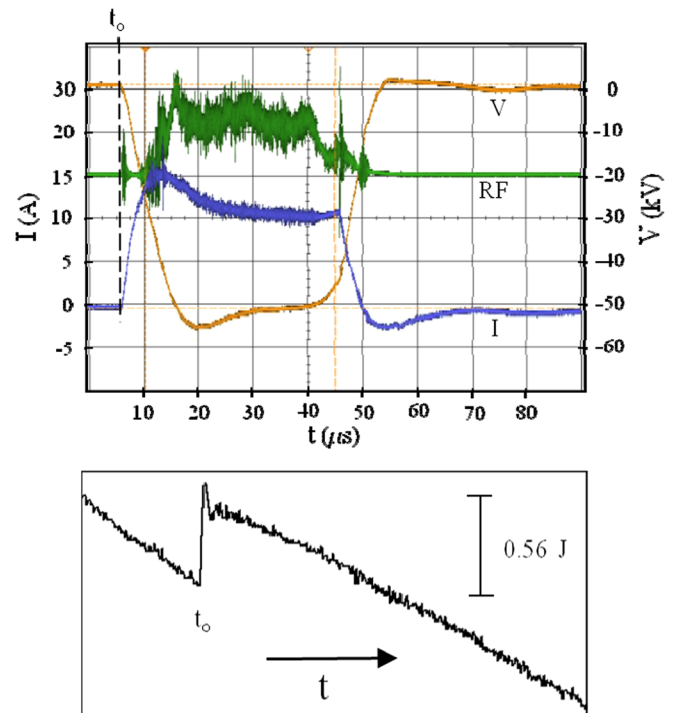


FIG. 3. Top: Oscillograms of the voltage (brown), current (blue), and microwave signals (green). Bottom: Calorimeter response to a 0.56 J single pulse (time frame shown is on the order of 10 s).



FIG. 4. THz breakdown spots on a metallic plate located in a focal plane.

thick teflon window (17%–20%) and about 9%–10% of ohmic losses of the power radiated in the $TE_{31,8}$ -mode, one can conclude that the interaction efficiency in this experiment was at about 30% level that agrees reasonably well with the simulation data.¹⁹

The radiated power was converted with the use of standard quasi-optical methods (see, e.g., Ref. 9) into a Gaussian-like wave beam and focused by a focusing mirror on the metallic plate with some sharp metallic needle-like breakdown initiators. This focusing resulted in THz breakdown events leading to the appearance of micro-plasmoids seen in Figure 4. The fact that there are several micro-plasmoids agrees with observation data reported in Ref. 24 and can be explained by the presence of several metallic micro-needles in a focal spot of gyrotron radiation. The temporal evolution of such micro-plasmoids will be analyzed in the subsequent work.

In summary, it has been experimentally demonstrated that with a gyrotron operating in pulsed magnetic field, coherent 670 GHz radiation with the microwave power of 210 kW, 20% efficiency and the microwave energy of 6.3 J in single shots was obtained.

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