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SUBMILLIMETER-WAVE GYROTRONS: THEORY AND EXPERIMENT

V. A., Flyagin, A. G. Luchinin, and G. S. Nusinovich

Institute of Applied Physics, Academy of Sciences of the USSR, Gorky, USSR

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Introduction

Gyrotrons are known to be generators of strong electromagnetic radiation of the millimeter waverange [1,2]. Strong magnetic fields, necessary to fulfill the cyclotron resonance condition $\omega \approx \omega_H$ * in gyrotrons, are usually produced by superconducting solenoids. At present, however, it seems difficult to provide magnetic fields higher than 10-15 T in sufficiently large volumes using such solenoids. This restricts advance of gyrotrons to the submillimeter waverange. In view of this fact, certain perspectives of mastering the submillimeter range may be associated with the use of pulse solenoids [5-7] whose magnetic fields, according to the estimates, can reach 25-30 T in volumes required for gyrotrons.

Pulsed Magnetic Fields

The gyrotron with a pulsed magnetic field (as compared to the one operating in a constant

* Generation at cyclotron frequency harmonics ($\omega \approx n\omega_H$) is also possible [3,4], but we do not discuss this possibility here.

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magnetic field) is characterized by the alternating magnetic field skinning by metal elements of the tube. For example, a 1 mm-thick stainless steel gyrotron body weakens the magnetic field under pulse duration 5 ms by less than 1 %. The skin-effect may also take place on a metal cathode surface, which diminishes the angle between the magnetic field lines and the cathode surface. However, at temperatures common for thermoemissive gyrotron cathodes, the conductivity of the cathode material decreases so that the magnetic field with a pulse duration above 1 ms penetrates into the emitting cathode surface less than $\lesssim$ 1 mm deep practically without changes.

To decrease the volume of the magnetic field, a pulse solenoid fabricated from a copper wire 2.4 mm in diameter was coiled directly onto a thin body of the gyrotron. The solenoid had two sections 5 mm apart, that provided a homogeneous magnetic field with an accuracy 0.1 % at a length 10 mm. The solenoid layers were impregnated with a silicon paste to make the coils monolith, which prolonged their life. The form of the solenoids with a square cross-section was chosen so as to optimize the magnetic field distribution [8]. The axial distribution of the magnetic field was determined by a computer.

The solenoid was fed by a capacitor battery with an operating voltage up to 2 KV and current up to 5 KA. The set up is shown in Fig.1. The pulse duration of the magnetic field was 5 ms. A stabilization assembly provided repetition of the magnetic field amplitude within 0.1 %, which made it possible to sustain a single-pulse gyrotron under optimum efficiency conditions throughout many pulses. When the solenoid was tested, the magnetic field amounted to 24 T. The solenoid was cooled by a liquid nitrogen. This decreased the ohmic heating of the coil and provided thermostatic control of the system. When tested, the solenoid withstood several thousand pulses without deterioration of its characteristics.

Theory of Submillimeter-Wave Gyrotrons

As the operating wavelength of the gyrotron shortens, the beam current density in the elementary interaction cell decreases and, simultaneously, RF power ohmic losses in the resonator walls increase. The gyrotron theory which takes into account both the factors was developed in [9]. In principle, however, these factors do not "enter the game" simultaneously. Analysis of the available electron-optical and electrodynamic gyrotron systems shows that in the wavelength range 0.6-0.8 mm a gyrotron may be constructed in which the beam current density can provide microwave generation with maximum efficiency. At the same time, the ohmic Q-factor of the $TE_{m,p}$ mode in this range $Q_{ohm}=(R/d)\cdot(1-m^2/\nu^2)$ (R is the resonator radius, d is the depth of the skin-layer, ν is the p-th root of the equation $J'_m(\nu)=0$) becomes comparable to the diffraction Q of the open gyrotron resonator $Q_{dif}\sim(L/\lambda)^2$ (here L is the resonator length, λ is the wavelength). For this reason the output gyrotron efficiency

$$\eta_{out}=\left(1-\frac{Q}{Q_{ohm}}\right)\eta_{el} \tag{1}$$

may be essentially lower than the electron efficiency

$$\eta_{el}=\frac{\beta^2_{\perp 0}}{2(1-\gamma_0^{-1})}\eta_{\perp}. \tag{2}$$

In (1)-(2) $Q=Q_{dif}\cdot Q_{ohm}/(Q_{dif}+Q_{ohm})$ is the total resonator Q-factor, $\gamma_0=(1-\beta_0^2)^{-1/2}$ is the Lorentz factor of the electron beam, $\beta_{\perp 0}=U_{\perp 0}/C$ ($\beta^2_{\perp 0}/2(1-\gamma_0^{-1})$ defines the relation between the initial gyration energy and the total kinetic energy of electrons), the orbital efficiency $\eta_{\perp}$ characterizes the bunching of particles. Construction of a nonlinear gyrotron theory which takes into account ohmic losses of microwave power in the resonator is based on the integration of equations of motion of electrons in the external magnetic field and the RF field of the resonator, determination of the orbital efficiency that depends on the normalized cyclotron resonance mismatch, the normalized length of the interaction space and the RF field amplitude (the amplitude of stationary oscillations is defined by the beam current and the resonator Q), and on computation by (1) of the gyrotron parameters corresponding to the maximum output efficiency. The results obtained are given in [10, 11].

Experimental Study of the Gyrotron

The gyrotron calculated according to the results of the nonlinear theory [11] was tested at the electron beam voltage up to 70 KV and current up to 20 A. The duration of the microwave and high-voltage pulses was 80 mcs. The magnetic field was tuned from 14 to 22 T. With an increase of the magnetic field the electron pitch-factor $\beta_{\perp 0}/\beta_{\parallel 0}$ decreased, which according to (2) was to reduce the electron efficiency. To compensate this effect, the gyrotron construction provided for axial shift of the cathode. In fact, removal of the cathode from the resonator weakens both the magnetic and the electric fields in the emitter region simultaneously. The reduction of the magnetic field on the cathode increases compression of the electron beam in the adiabatic electron gun of the gyrotron (i.e. the gyration velocity of particles in the resonator), on the contrary, the reduction of the electric field decreases the initial gyration velocity. Both the effects were analyzed in [12]. According to [12],as a rule, the geometry of electron-optical systems in gyrotrons is such that the removal of the cathode from the resonator results in an increase in the electron gyration velocity.

In gyrotron experiments (their results were described in [12-14]*) magnetic field tuning from 14 to 22 T was accompanied by separate excitation of the whispering gallery modes $TE_{m,p,1}$

* [13, 14] give the results of the first experiments.

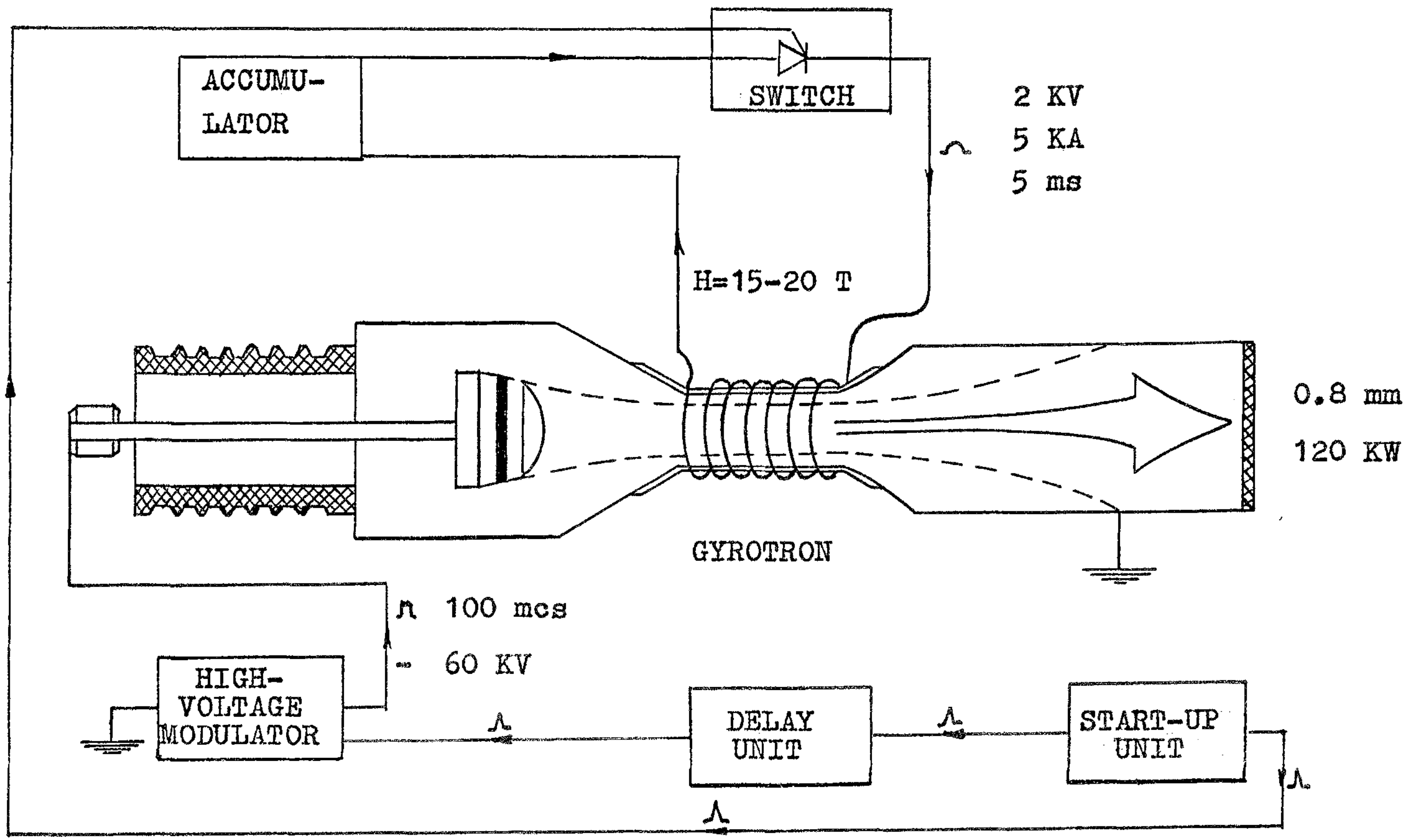

Fig.1. Gyrotron set-up.

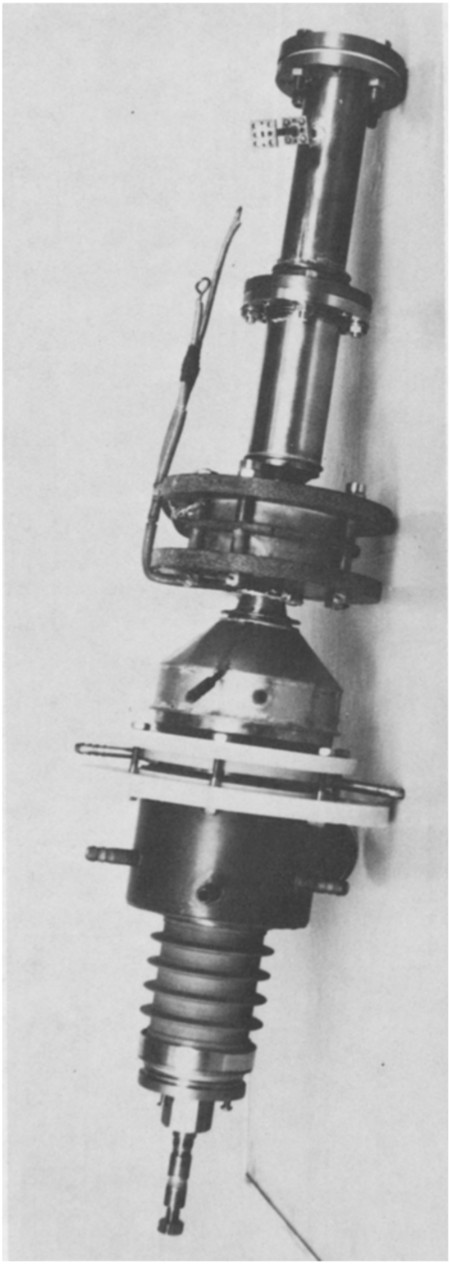

Fig.2. Photo of the gyrotron.

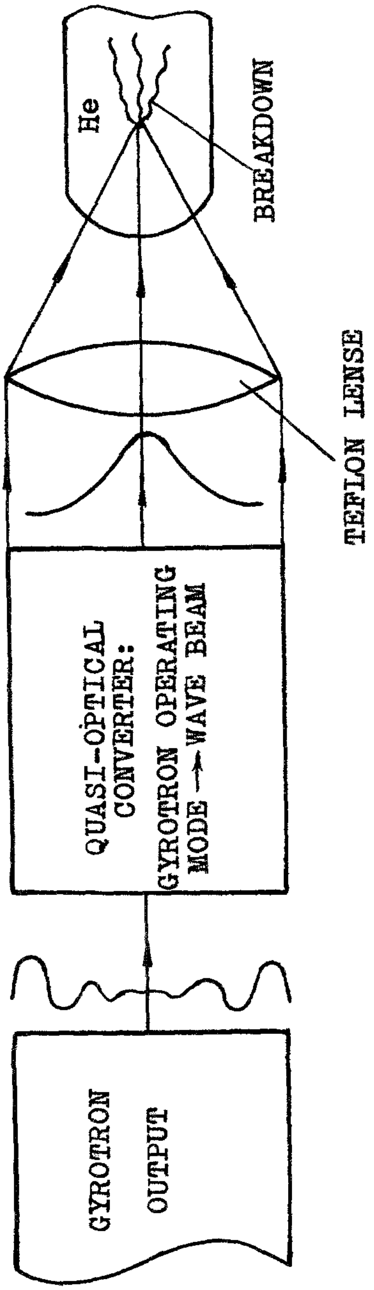

Fig.3. Scheme of the experiment with RF discharge by focused submillimeter-wave radiation.

$(m \gg p)$,whose frequency difference satisfied the condition $|\Delta\omega|/\omega \sim 1/m$. The gyrotron is shown in Figure 2 [12]. The microwave power was measured by a calorimeter. The maximum output power of 120 KW was recorded at the voltage 66 KV and current 12 A, which corresponded to the gyrotron efficiency 15%. The magnetic field at maximum power was about 15 T, the operating wavelength was 0.8 mm. At the wavelength 0.71 mm the output power amounted to 80 KW. With a smaller resonator length (and, respectively, a smaller diffraction Q) at a wavelength 0.6 mm, voltage 70 KV and current 18 A a microwave power of 100 KW with efficiency 8.2% was obtained; at a wavelength 0.54 mm the output power reached 60 KW.

At the gyrotron output a quasi-optical converter was placed which transformed the operating gyrotron mode into the wave beam. The converter efficiency was about 65%. The focusing of the wave beam by a teflon lense (Figure 3) made it possible to observe a high-frequency discharge in a discharge tube filled with the mixture of air and helium under the pressure 0.5Atm.

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