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The First Decade of the Gyrotronics

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Abstract Our review (Nusinovich et al. *Journal of Infrared*, *Millimeter*, *and Terahertz Waves*, 35, 325, 2014) proved to be of interest for gyrotron researchers, gyrotron users, and specialists in neighboring fields of physics but underwent a fair criticism for a number of historical omissions. So my co-authors G. S. Nusinovich and M. K. A. Thumm advised me to supplement our paper (Nusinovich et al. *Journal of Infrared*, *Millimeter*, *and Terahertz Waves*, 35, 325, 2014) with the following memoir.

Keywords Cyclotron resonance · Maser · Gyrotron

Addendum to the paper
G. S. Nusinovich, M. K. A. Thumm, M. I. Petelin:
"Gyrotron at 50: Historical Overview",
Journal of Infrared, *Millimeter*, *and Terahertz Waves*, 35, 325-381 (2014) [1]

1 Classification of Cyclotron Resonance Masers

In the 1920s, A. Zacek [2] and H. Yagi [3] independently discovered that some "magnetrons" generated a coherent microwave radiation when a tank circuit eigen-frequency turned equal to the cyclotron frequency of electrons moving in crossed magneto-electric static fields. Those first cyclotron resonance masers (CRMs) operated due to interception of "wrong-phase" electrons by the walls of the RF interaction space.

In subsequent CRMs [1, 4, 5], the prevalence of stimulated radiation over absorption was provided with some alternative effects:

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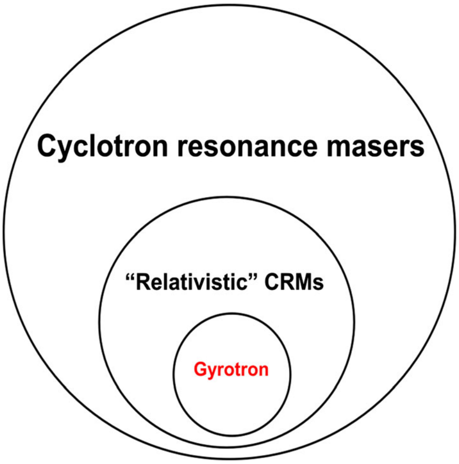
Fig. 1 Sources of coherent cyclotron radiation—classification diagram



- RF field inhomogeneities,
- inhomogeneities of magnetostatic fields,
- dependences of the electron oscillation frequency on the electron energy,
- parametric RF pumping,

The whole CRM family is placed in the large circle of the diagram shown in Fig. 1.

In the 1950s, the CRM family was adhered with fast-wave devices [6–8] (A. Karp named them "simpletrons") whose operation had no adequate explanation, because nobody expected relativistic effects at ~10-kV operating voltages. That opinion was corrected by J. Schneider [9], V. V. Zheleznyakov [10], and A. V. Gaponov [11]. From the quantum viewpoint [9], the relativistic electron mass-on-energy dependence makes Landau levels of the electron gyration energy non-equidistant. So, if the life-time of electrons within the RF interaction space is long enough, the sub-band of stimulated radiation becomes separated from the absorption one. From the classical viewpoint [10, 11], if an electromagnetic wave modulates a helical electron beam near the cyclotron resonance, the relativistic perturbation of the electron gyration frequency causes the azimuthal inertial bunching of electrons (Fig. 3 in [1]), resulting in a distributed (TWT-like) wave amplification.

The theory [9–11] explained operations of the previous fast-wave "simpletrons" [6–8] and stimulated further experiments performed by teams of J. Hirshfield [12–14], I. Bott [15–18], A. V. Gaponov [19–22], and B. Kulke [23][1]). All such relativistic-effect-dominated CRMs are included in the medium circle of the diagram shown in Fig. 1.

A typical scheme of early "relativistic" CRMs (corresponding to Fig. 1 in [18] and Fig. 7 in [23]) is shown in Fig. 2:

- a gun emitting a rectilinear electron beam is placed in the stray magnetic field of a solenoid,
- the beam enters a section with a periodic static resonant magnetic field where a part of the electron energy is transformed into gyration,

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[1] In [23], we found the first international reference to our earlier CRM papers.

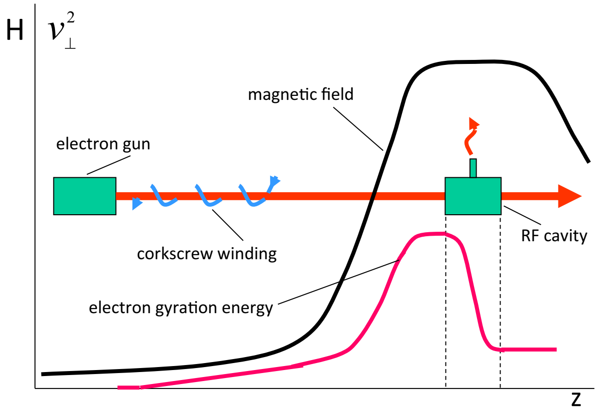

Fig. 2 A scheme of "relativistic" CRM based on I. Bott's technique [18]

- during the further electron motion toward the solenoid center, the energy of electron gyration grows in accordance with the adiabatic invariant $p_\perp^2/B = const$ [23, 24] (here $p_\perp$ is the electron transverse momentum, B is the magnetic field),
- within the homogeneous region of the solenoidal magnetic field, the electron beam may interact with a set of electromagnetic waves under the resonance condition

$$\omega - k_{II} v_{II} \approx s\Omega \tag{1}$$

where ω is the wave frequency, k_{II} and v_{II} are the wave propagator and the electron velocity component longitudinal relative to the static magnetic field $\overrightarrow{B}$, Ω is the "relativistic" electron cyclotron frequency, and s is the cyclotron resonance harmonic number ($s = 1, 2 \ldots$).

In the early 1960s, the elegant Bott's electron gun [15–18] was not known in the Soviet Union. A. L. Goldenberg and I were proposed to realize a configuration similar to that shown in Fig. 2, but instead of the Bott's "corkscrew" we were advised to use an RF pumping resonator. However, the RF pumping was resolutely rejected by A. L. Goldenberg and, instead, I proposed to put a simple conical cathode into the stray magnetic field of a solenoid (Fig. 3). Just at the emission from the cathode surface, both translational and gyration velocities of any electron would turn non-zero. Subsequently, as the electron would move toward the solenoid, the electron gyration energy would grow in accordance with the adiabatic invariant [24] and the whole electron beam would undergo compression. To check the idea, V. A. Flyagin asked his technicians to make a model where a point-like emitter from an old kinescope was inserted into a conical tin cathode surface. And we saw the electron beam trajectory shining in an optimized residual gas—the trajectory was in accordance with the adiabatic theory [24].

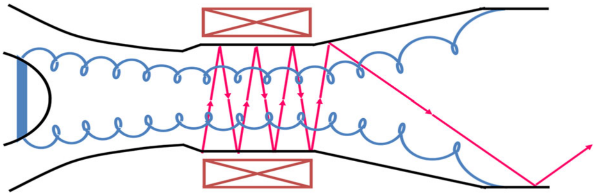

Fig. 3 The simplest scheme of the gyrotron

Fig. 4 The "cold" model of the first gyrotron RF structure—the RF cavity is in the background and the "diffraction-output" waveguide is in the foreground

However, there was no hope that electrons emitted from a sufficiently broad cathode surface could have a tolerable velocity dispersion. A salvatory idea came from a theory of kinetic wave instabilities in magnetized non-Maxwellian plasmas [25]:

- if the static space-charge field of the electron beam in the RF interaction space is not very large, the electrons starting from the equi-potential cathode and arriving to the equi-potential RF interaction space might have a large spread in their axial and orbital velocities, but would have a small spread in total energies and, hence, in gyration frequencies Ω;
- accordingly, if the monochromatic RF field were composed of waves propagating quasi-perpendicular to the static magnetic field (as shown in Fig. 3 $k_{II} < < \omega / c$, c being the velocity of light), the disturbance of the cyclotron resonance condition (1) by the scatter of longitudinal electron velocities v_{II} might be negligibly small—the Doppler broadening of the cyclotron resonance band would be minimized [1].

Our first CRM oscillator of the Fig. 3 type had the electrodynamic structure of rectangular cross-section (Fig. 4) where only the lowest TE_{10} mode could propagate at the operating frequency. That quasi-optical resonator with the diffraction output of RF power was designed by using the theory of L. A. Weinstein [26].

The whole configuration of that RF oscillator (Fig. 6 in [1]) was named by its makers as "molotok" (English "hammer"). Switched on by I. M. Orlova in September 1964, the "molotok" delivered 6 W at the frequency of 10 GHz. That seemed to be negligibly small compared with 500 W CW at the 34 GHz frequency delivered by the I. I. Antakov's "relativistic" trochotron [21] situated in the same experimental laboratory. Nevertheless, we dared to tell about the "molotok" at the All-Union Electronics Conference—1964 in Moscow. There, surprisingly and fortunately, L. A. Weinstein admitted a good future for descendants of our puny creature and stimulated our hopes. In 1965, after our "discovery" of J. Schneider's paper [9], we wrote [20] that our "molotok" was a "cyclotron resonance maser."

In 1966, when lucky grandchildren of the "molotok" radiated kilowatts and we hoped to reach megawatts by operating at high-order modes (see a relevant section below), V. T. Ovcharov ("Titan," Moscow) advised us to provide the novel version of CRMs with a specific name; and the brand "gyrotron" suggested by A. L. Goldenberg (though previously applied to non-electron devices) was unanimously adopted. This sub-group of the "relativistic" CRMs (illustrated with Fig. 3 above and Fig. 1 in [1]) is situated in the small "gyrotron" circle of the above Fig. 1 diagram.

2 Primary Linear and Non-linear Theories of the Gyroton

The miserable 6-W/10-GHz "molotok" [20] was designed by using a primitive linear theory, in which a two-dimensional open mirror resonator described by L. A. Weinstein [26] was "filled" with stationary magnetized plasma composed of identical helical electron beams [27]. At that time, we hoped [20] that efficiencies of further CRMs of this kind might reach 19%; that strange number was borrowed from V. K. Yulpatov's theory of the "relativistic" BWO-trochotron presented at the All-Union Electronics Conference—1960 in Kharkov.

Immediately after publication of the paper [20], the team led by G. N. Rapoport [28, 29] provided us with encouraging results of their non-linear theory: numerical simulations of CRMs driven by helical electron beams predicted orbital efficiencies up to 31%! Subsequently, during several months, the non-linear theory [28, 29] from Kiev was used by us to design further experimental CRMs.

However, the theoretical model [28, 29] had a couple of minor drawbacks:

1. the transverse distribution of the RF field (corresponding to Fig. 5 of [1]) had zeros where electrons did not interact with the RF field,
2. the Π-approximation of the longitudinal structure of the RF field seemed to be not quite realistic and not quite favorable for an efficient interaction with electrons.

Instead, according to the elementary linear theory [22], in the axis-symmetric gyrotron (Fig. 3) the electron beam gyrotropy cancels the degeneracy of cavity eigen-modes. Consequently, the operating mode becomes rotating (Fig. 5) and, so, all electrons of a thin tubular beam become equally coupled to the RF field. In addition, in the quasi-optical cavity shown in Fig. 3, the natural axial structure of the operating mode is Gaussian-like [26, 30] that is more favorable for compact bunching of electrons than the Π-approximation assumed in [28, 29]. When the gyro-averaged

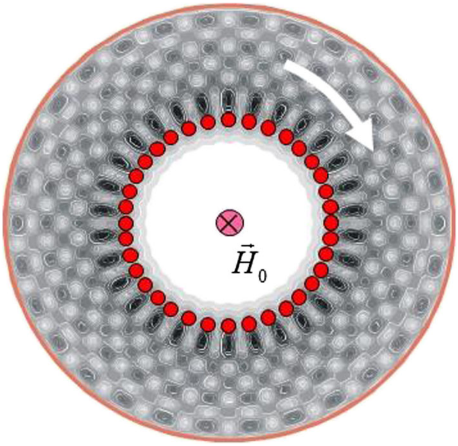

Fig. 5 The transverse cross-section of an axis-symmetric RF interaction space—an annular beam of gyrating electrons excites a rotating TE_{mp} mode

(V. K. Yulpatov 1960) “relativistic”-electron equations were adjusted to design axis-symmetric gyrotrons, the experimental efficiencies exceeded 30% in 1966 (our reports at the All-Union Electronics Conference in Saratov) and approached 50% in 1977.

Subsequently, the non-linear theory of gyrotrons was further upgraded by the theoretical teams in Kiev [31–33], Minsk [34–36], and Gorky [37–40]:

- in addition to free running gyrotron oscillators (gyro-monotrons and gyro-backward-wave oscillators), gyro-amplifiers—gyro-klystrons, gyro-TWTs, and gyro-twystrons (Table 1 in [1])—were described by relevant non-linear theories,
- the quasi-static (non-resonant) component of the RF field produced by the modulated electron flow was taken into account [36],
- longitudinal profiles of the electrodynamic structures and of the static magnetic fields were optimized so that theoretical orbital efficiencies approached 90% [32–35].

However, even presently, electronic efficiencies of practical high-power gyrotrons rarely exceed 50%—because the electron guns produce intense beams with relatively broad spreads in the electron pitch-factors (ratios of the electron orbital-to-axial velocities). To increase the wall-plug efficiencies of high-power gyrotrons, depressed collectors seemed attractive from the very beginning [40], but the recuperation was realized successfully—with up to 60% efficiencies—only in the 1990s [41, 42].

3 Mode Selection

The gyrotron research started soon after the advent of lasers; so the methods developed for designing the laser structures were immediately applied to the gyrotronics. Our Gorky team was generously consulted by V. I. Talanov (Appendix to [43]), L. A. Weinstein [44], and B. Z. Katzenelenbaum [45]. Those wise “diffractioners” advised us to start any quasi-optical design with building a ray “skeleton” and finalize the design by covering the “skeleton” with a “diffusion meat”.

Electrodynamic Selection In resonators shown in Figs. 3, 4 and 5, eigen-modes composed of rays propagating quasi-perpendicular to the metallic walls have diffractive Q factors [26, 44]

$$Q_q \sim \frac{\omega_{c-o} L \big/ v_{gr,q}}{1-|R_q|} \tag{2}$$

where L is the resonator length, ω_{c-o} is the relevant cut-off frequency of the quasi-cylindrical structure, $v_{gr,q}$ is the wave group velocity in the axial direction, R_q is the coefficient of wave reflection from the resonator output, and q is the number of longitudinal variations of the RF field. The longitudinal wave propagator k_{II} is proportional to q; so enlargement of q is followed with reduction of the Brillouin angle between any elementary wave beam and the cavity axis; consequently, the group velocity $v_{gr,q} = c^2 k_{II}/\omega$ turns proportional to q. The denominator in (1) is also proportional to q, because enlargement of the group velocity $v_{gr,q}$ reduces the wave reflection $|R_q|$ from the resonator output. Due to the combination of above effects, the Q factors (1) turn inversely proportional to q^2 [26]. In addition, the operating "single-humped" ($q = 1$) mode exceeds "multi-humped" ($q > 1$) ones in the above mentioned "Doppler-broadening resistance."

Electronic Selection Designing a Fig. 3 gyrotron, we may take into account only the "single-humped" ($q = 1$) Doppler-resistant modes: their longitudinal wave propagators $k_{II} \approx \pi/L$ are sufficiently small and the cyclotron resonance condition (1) reduces to

$$\omega_0 \approx s\Omega. \tag{3}$$

But if the cavity cross-section is planned to be large enough, the cavity mode eigen-frequencies ω_0 may turn close to each other. Analyzing the mode competition in the axis-symmetric cavity (Figs. 3 and 5), it is convenient to approximate each rotating mode with a trajectory of rays successively reflecting from the cavity wall (Fig. 6) [44]. The ray trajectory at its minimal distance from the cavity axis is tangent to a cylindrical caustic, where—from the viewpoint of geometrical optics—the RF field would be infinite. Accordingly, for selective excitation of a chosen cavity mode, it seems expedient to inject a thin annular electron beam near the mode caustic (Figs. 5 and 6)—where the beam-mode coupling impedance is maximal. This recipe is further specified with the linear theory [22]: the radius R_b of the annular electron beam should be adjusted to maximize $J^2_{m-s}(\omega R_b/c)$ where $J_l(x)$ is the Bessel function and m is the azimuthal index of the operating mode.

Of course, if radii of both the cavity and of the electron beam are planned to be sufficiently large, modes with close eigen-frequencies would have close inner caustics and, so, close start currents. However, even in this case, the gyrotron (Figs. 3 and 5) may be designed—by using the Van-der-Pol-Rabinovich effect of mode competition [46, 47]—so that one of rotating modes would suppress its rivals at the non-linear stage [48].

In 1967, the theoretical and experimental studies of the gyrotron were awarded with a State Prize of the USSR, and the Soviet Ministry of Electronics started funding the program "O-Mega" aimed at developing high-order-mode gyrotrons with ~1-MW output pulse powers. However, in 1970, a 10 GHz/TE$_{5.2}$ gyrotron (named "Oryasina," i.e., English "beanpole") produced only 400 kW, reported by us at the international conference—1972 in Moscow. The

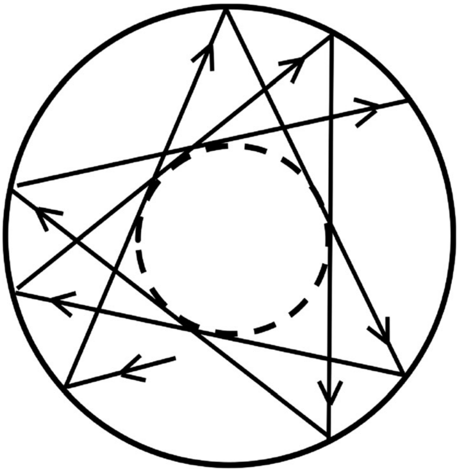

Fig. 6 Ray approximation of a high-order mode rotating in an axis-symmetric cavity (the *dashed circle* is the mode's caustic)

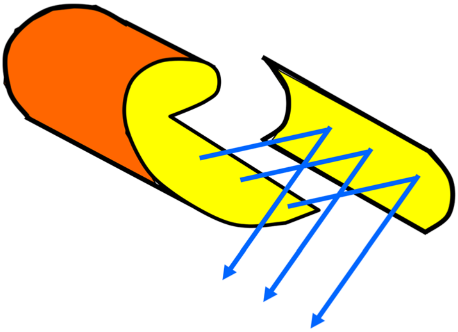

Fig. 7 Conversion of a high-order waveguide mode to a flow of parallel rays

longed-for 1 MW was reached by us—a 42 GHz/$\mathrm{TE}_{15.1}$ pulsed gyrotron operated in a cryomagnet—only at the very end of 1973.

4 Mode Conversion

In 1968, B. Z. Katzenelenbaum invited me to give a talk about the gyrotron at his seminar in Moscow. After my talk, he asked me, "Misha, presently your gyrotrons are heating calorimeters. But how might your further gyrotrons be matched to more complicated loads?" I answered, "B. Z., using your nice theory [45], we have developed a mode converter based on selective wave scattering within a helically corrugated waveguide [49].[2] However, for higher-order-mode gyrotrons such converters would be regrettably long." Immediately after the seminar, my friend N. A. Mayer acquainted me with L. I. Pangonis (a student of B. Z. Katzenelenbaum), assuming that fresh results of L. I. Pangonis might be helpful for us. And indeed, L. I. kindly explained me the performance of his asymmetrical waveguide cut that radiated a relatively high-order waveguide mode into a limited solid angle [51–53]. Right the next day, upon my return to Gorky, I asked I. M. Orlova to upgrade the Pangonis's radiator [51–53] with an additional quasi-parabolic mirror—to convert the primary radiated wave flow into a system of parallel rays [54], see Fig. 7 below and Fig. 9 in [1]. If the upstream waveguide wall in the Fig. 7 configuration is properly pre-shaped [55], the high-order mode may be converted into a Gaussian wave beam with over 95% efficiency [56].

5 Summary

Among classical-electron sources of coherent microwave radiation, the gyrotron has reached the highest handicap parameter Pf^2 (P being the CW RF power and f being the radiation frequency). Compared with other CRMs, the gyrotron is advantageous due to its robust composition (Figs. 3 and 7):

- the magnetron-type electron gun with adiabatic compression of the beam from the cathode to the resonator,

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[2] In 1971, such a converter was inserted into a gyrotron which was used for self-focusing of a wave beam within a plasma [50].

- combination of quasi-optical and electronic methods to provide selective Doppler-effect-resistant operation at a single high-order mode,
- the diffraction conversion of the operating mode into a quasi-Gaussian wave beam.

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