Invited Paper

The gyrotron: physical genealogy

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(Received March 12, 2015)

Abstract: This paper is a modification of a review talk delivered by the author at the THz Symposium-2015, Soochow. Elementary fundamentals of the gyrotron – a version of classical electron masers - are summarized.

Keywords: Gyrotron, Cyclotron resonance masers, Mode selection, Quasi-Gaussian beam

doi: 10.11906 /TST.157-169.2015.12.15

1. Introduction

The 50-years history of the gyrotron has been described in a recent broad review [1]. So, the present deductive paper is addressed mostly to newcomers in the field, and, accordingly, below only some key papers will be cited individually.

2. The primary problem of electron cyclotron resonance masers

Any body oscillating in an infinite homogeneous medium is known to radiate waves. So, it was not surprising when just at the next year after the electron discovery by Thomson (1897) Lienar claimed a quite evident effect: any electron gyrating in the homogeneous static magnetic field should radiate electromagnetic waves [2].

However, any DC gun delivers only a stationary electron flow that (even being of any curve configuration) can produce only a static electromagnetic field. We may irradiate this flow with an electromagnetic wave – hoping that the wave would be amplified, but, instead, the electron flow (even energy-inverted) may absorb the wave energy. It depends.

For the cyclotron resonance case, the above “paradox” may be illustrated with a simple model shown in Fig. 1:

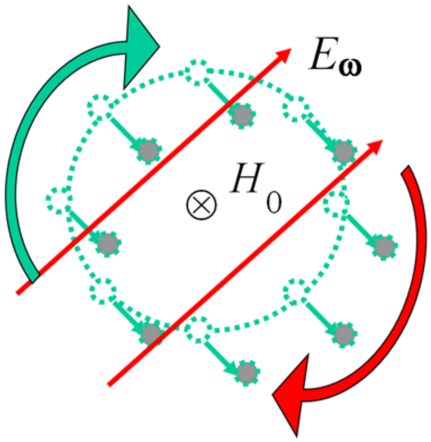

Fig. 1 Cyclotron resonance of non-relativistic electrons: evolution of a primarily stationary electron ring under action of a co-rotating homogeneous electric field.

Take a stationary ring of electrons gyrating in a homogeneous magnetic field, expose the ring to a resonant RF electromagnetic field, Notations in this paper are the same as in [1].

$$\omega \approx \Omega \quad (1)$$

Assume electrons being non-relativistic

$$v << c \quad (2)$$

And accordingly, the electron gyration radius being small compared with the free-space wavelength

$$r << \lambda \quad (3)$$

So, the RF field in the interaction region may be assumed homogeneous. Under the above assumptions, the electron motion is described with differential equations with constant coefficients. As a result, the RF field gives a common perturbation to all particles: in the Fig. 1 the electron ring is shifted as a whole. For some electrons their gyration radius has been reduced and for other electrons it has been enlarged; but as the electron energy is proportional to the electron radius squared, the average electron energy has grown – the RF energy has been absorbed by electrons.

This RF absorption effect stems from the quantum approach as well [2] : under the above assumptions, the electron is equivalent to the linear oscillator which energy spectrum is equidistant; and as the "external" force is assumed homogeneous, the probability of stimulated radiation is less than the probability of absorption.

3. "Non-relativistic" cyclotron resonance masers

To provide a prevalence of the stimulated radiation over the absorption, any of the above limitations may be abandoned. Even if the motion of electrons is still described with non-relativistic equations, there are some options:

1) *The RF field is of a strong transverse inhomogeneity at the electron gyration orbit* [3, 4, 2] : the stationary ring of non-relativistic electrons is unstable relative to a slow azimuthal wave (Fig. 2).

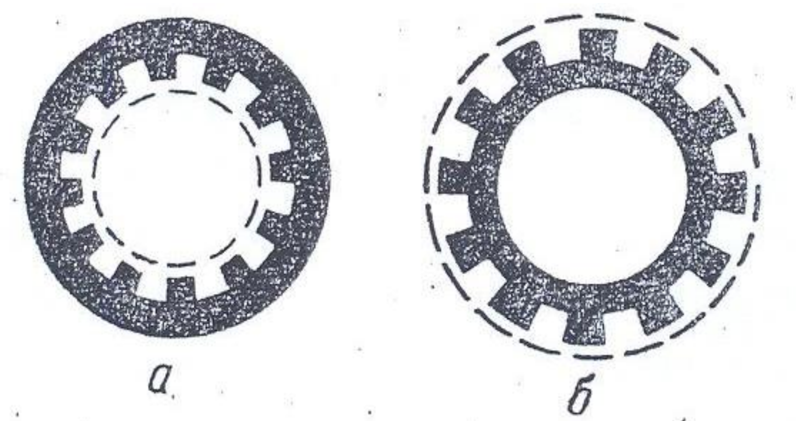

Fig. 2 The peniotron: anomalous Doppler cyclotron resonant interaction between an electron ring and a slow eigen-wave of azimuthally-periodic structure.

2) *The RF field is strong inhomogenous in the static magnetic field direction* [5, 2]. In this case, from the quantum viewpoint, the cyclotron-resonance wave amplification is provided with the electron momentum recoil. The effect, in its pure form, may be realized, for instance, at injection of a helical electron beam into a slow-wave structure (Fig. 3).

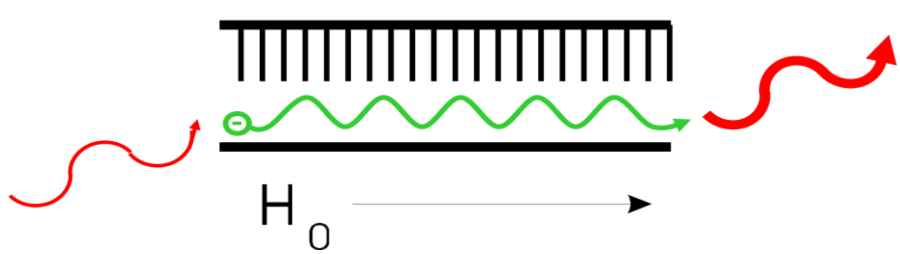

Fig. 3 Cyclotron resonance interaction of a helical electron beam with a slow electromagnetic wave.

3) *The static magnetic field is transverse non-uniform* [6, 2] (Fig. 4). In such a field, electrons move along quasi-trochoidal trajectories with electron gyration frequency, gyration amplitude and the translational velocity being inter-related. Accordingly, the electromagnetic wave cyclotron resonant to the electron flow stimulates a klystron-type bunching of electrons and, finally, is amplified.

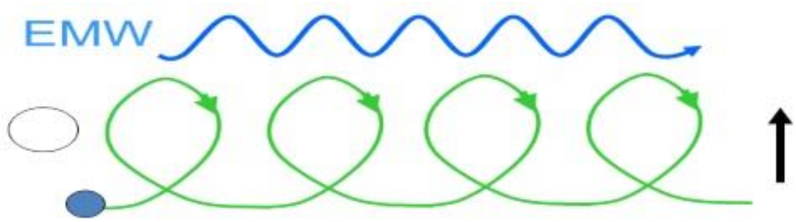

Fig. 4 Amplification of an electromagnetic wave by a trochoidal electron beam guided with a transverse non-uniform static magnetic field.

4) *The static magnetic field is longitudinally non-uniform* [7, 2]. A simple model of such an amplifier is the magnicon (Fig. 5): a thin electron beam is deflected within an input RF section, the deflection grows in the drift region, then electrons enter a solenoid where, at the cyclotron frequency, radiate their energy into an output resonant cavity.

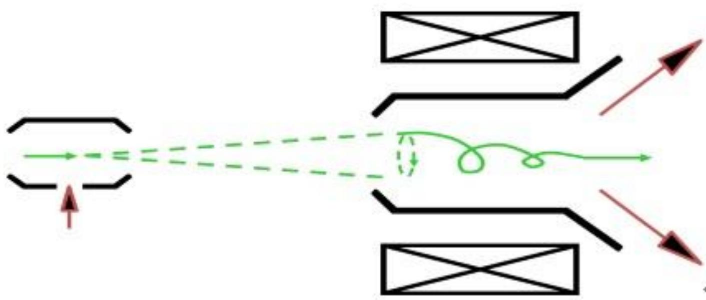

Fig. 5 The magnicon: a klystron-type RF amplifier with cyclotron radiation of electrons in an output cavity.

5) *The electron beam is parametrically pumped* [8, 9, 2]: a rectilinear electron beam is cyclotron-resonance modulated in an input section, then pumped by a second harmonic RF field or by a longitudinal-periodic static field at an intermediate section (Fig. 6), and finally, radiates its enhanced oscillatory energy into an output RF section.

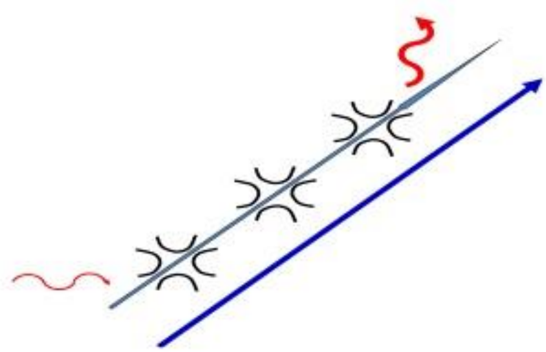

Fig. 6 A "parametric" cyclotron resonance RF amplifier: the "seed" gyration energy of electrons is enlarged in a section with periodic static magnetic field.

6) *The lifetime of electrons depends on their energy*. Let a stationary electron ring be primarily situated near a metallic wall of a resonator (Fig. 7). If the RF field accelerates an electron at its first turn, the electron radius is enlarged and the particle is absorbed by the wall. But if an electron at its first turn is decelerated by the RF field, the electron radius is reduced and the particle continues to give its energy to the RF field during a large amount of gyrations [10, 2]. A similar mechanism for the negative RF conductivity takes place in non-equilibrium plasmas where electrons are colliding with neutral molecules [11, 12, 2].

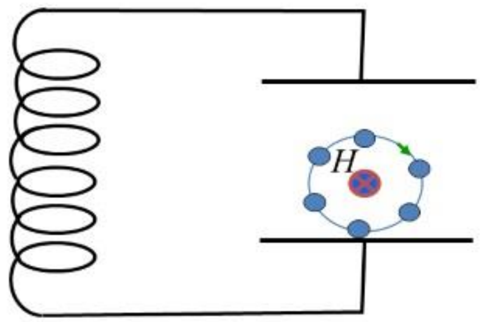

Fig. 7 A cyclotron resonance maser based on extraction of "wrong-phase" electrons by the resonator wall.

4. "Relativistic" cyclotron resonance masers

However, among various cyclotron resonance masers (CRMs), the most robust version proved to be based on the relativistic electron mass-on-energy dependence [13, 14, 5].

From the quantum viewpoint [13, 1], the relativistic effect makes electron eigen-energies non-equidistant (Fig. 8): so the frequencies of absorption and stimulated radiation turn different (Figs. 8, 9).

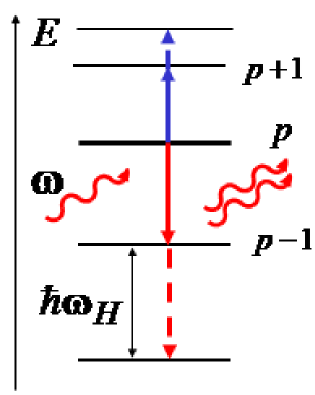

Fig. 8 The energy spectrum (Landau levels) of the relativistic electron in the homogeneous static magnetic field.

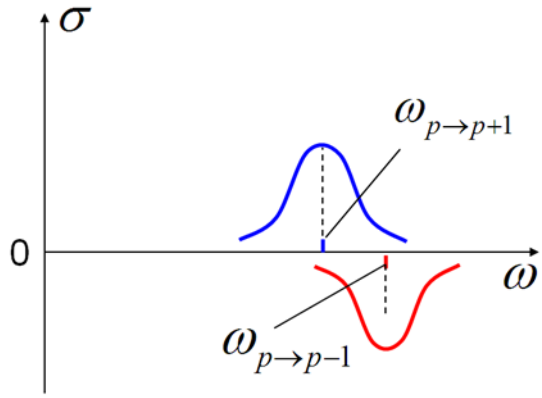

Fig. 9 Partial conductivities of a stationary ensemble of electrons: the upper curve corresponds to the RF absorption at the transition $p \to p+1$, the lower curve corresponds to the stimulated radiation at the transition $p \to p-1$ in Fig. 8.

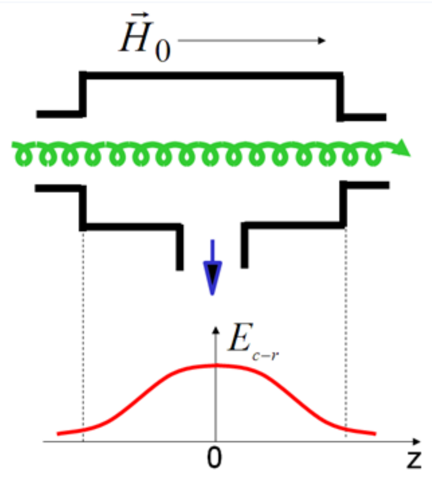

Fig. 10 A helical electron beam radiates a cavity RF mode.

Let a helical electron beam interact with an eigen-mode of an RF cavity (Fig. 10). The beam energy may be efficiently converted to the coherent electromagnetic radiation under the following conditions:

There is an optimal number of electron gyrations within the cavity:

$$N \sim \beta_{\perp}^{-2} \tag{4}$$

There is an optimal positive difference

$$\omega - \Omega \sim \beta_{\perp}^{2}\Omega \tag{5}$$

between the alternating field frequency ω and the electron injection gyro-frequency Ω. Under the conditions (4) and (5), the electron beam conductivity is negative and close to its extreme value (Fig. 9), the bandwidth $\sim\omega/N$ of the RF force frequency spectrum (Fig. 11) is commensurable with the difference between the "cold" Ω_0 and the "hot" (injection) $\Omega=\Omega_0\left(1-\beta^2/2\right)$ electron gyro-frequencies, and the electrons may be driven to the lowest Landau levels at Fig. 8 by the co-rotating RF electric field E_{c-r} of a proper amplitude:

$$eE_{c-r}(2\pi r)N \sim mv_\perp^2/2. \tag{6}$$

From the purely classical viewpoints[1, 5, 14] this process is composed of 3 overlapping stages:

1) The near-resonant co-rotating RF field changes electron energies,

2) The resulting electron energy perturbations being phase-dependent (Fig. 1), the electron gyro-frequencies turn phase-dependent as well, which results in a klystron-type azimuthal bunching of electrons,

3) Under the optimal resonance mismatch (5), the electron bunch turns situated in the decelerating phase of the RF field and finally, the RF field of the proper length (4) and amplitude (6) takes a considerable part of the bunch energy.

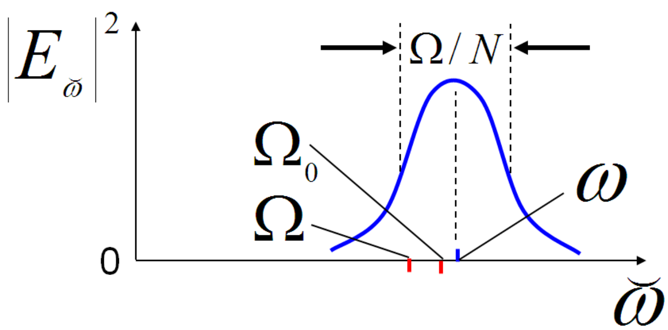

Fig. 11 The spectrum of the co-rotating RF field acting on the electron piercing the Fig. 10 cavity.

During such a process in a Fig. 10 configuration, the motion of a single sub-relativistic electron may be described with an averaged equation (reported by V. Yulpatov at an Electronics Conference in Kharkov, 1960)

$$\frac{dp}{d\varsigma}+ip\left(\Delta+|p|^2-1\right)=f, \tag{7}$$

Where p is a dimensionless gyration electron velocity, f is a dimensionless complex amplitude of the co-rotating electric RF field, ς is a dimensionless longitudinal coordinate, and Δ is a dimensionless cyclotron resonance mismatch (proportional to $\omega-\Omega$). At the entrance of the RF interaction space, different electrons have different initial phases θ_0 relative to the RF field: $p_{in}=e^{i\theta_0}$. Accordingly, at the end of the RF interaction space, the dimensionless electron velocity p_{out} depends on θ_0 and the averaged part of the orbital energy given by electrons to the RF field is

$$\eta_{\perp}=1-\frac{1}{2\pi}\int_0^{2\pi}\left|p_{out}\right|^2 d\theta_0. \tag{8}$$

The relativistic theory [13, 14, 5] explained performances of some previously developed CRMs [15-17] and stimulated further developments of such devices. However, until 1965, powers and efficiencies of helical beam CRMs were much less compared with those delivered by other microwave sources at the same frequencies [1]; those CRMs were susceptible to the electron velocity scatter: in any of such cases, at the interaction between a real electron beam and an electromagnetic wave, the Doppler-shifted cyclotron resonance condition

$$\omega-k_{II}v_{II}=\Omega(\vec{v}) \tag{9}$$

But could not be satisfied for all electrons of the beam; in (9) v_{II} is the electron velocity component parallel to the static magnetic field, and k_{II} is the longitudinal wave number.

5. The gyrotron: a robust cyclotron resonance maser

For keeping the whole electron flow within the cyclotron resonance band, all electrons should be provided with a common energy – then all electrons will have a common gyrofrequency Ω, the RF field should be composed of waves propagating perpendicular to the static magnetic field: $k_{II}=0$ – then the Doppler shift $k_{II}v_{II}$ for all electrons will be equal zero. consequently, the resonance condition (9) will be satisfied for all electrons – no particles will be jobless [1]. To provide a common energy for all electrons, let them leave an equi-potential cathode and arrive to an equi-potential RF interaction space. The Doppler shift may be minimized, for instance, by using a quasi-optical resonator with mirrors parallel to the static magnetic field (Fig. 12).

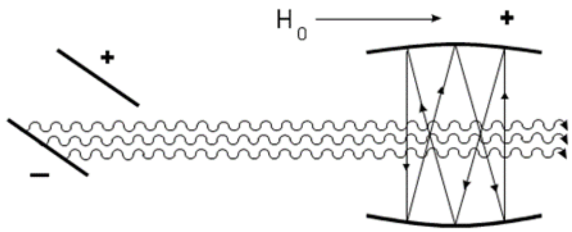

Fig. 12 A configuration to minimize the Doppler broadening of the electron cyclotron resonance line.

Usually solenoids to produce static magnetic fields are axis-symmetric. Accordingly, the simplest gun is axis-symmetric as well (Fig. 13): near the cathode, the electron motion is almost the same as in the kitchen magnetron, but the axial component of the static electric field extracts electrons in the direction of the solenoid; on the way from the cathode to the solenoid, the tubular beam undergoes compression and the electron gyration energy enhances in accordance to the adiabatic invariant.

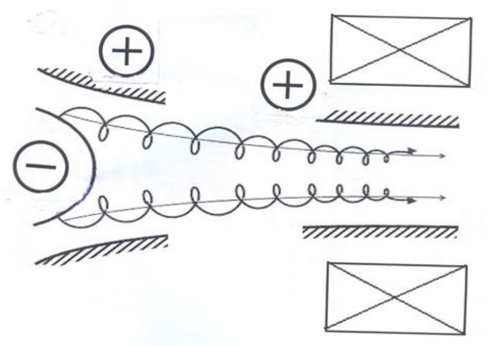

Fig. 13 The magnetron injection gun.

The RF interaction space in most of gyrotrons is axis-symmetric as well and represents a slightly irregular metallic tube (Fig. 14). At the electron gun end of the RF cavity, the operating mode is shut with a below-cut-off neck. At the opposite end, the wave reflection is relatively low and the RF power is radiated in the electron collector direction.

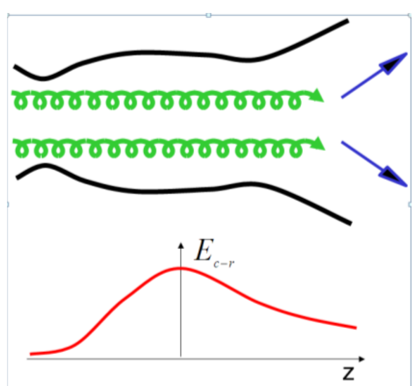

Fig. 14 The cavity of the axis-symmetric gyrotron and the longitudinal structure of the co-rotating RF field.

6. Mode selection in gyrotrons

The very first (reported at a Moscow conference in 1964) gyrotron (Fig. 6 in [1]) – with the magnetron injection gun, the near-cut-off cavity and the diffraction output of RF power – operated at the simplest H_{10} mode of an irregular rectangular cross-section waveguide. After that, to produce higher RF powers, higher-order modes were used.

To operate efficiently at a high order mode in a broad cross-section axis-symmetric cavity, parasitic modes are excluded by combining the following effects [1]:

1) Modes outside the cyclotron resonance band have no chance to self-excite;

2) Multi-humped longitudinal modes have relatively large group velocities, relatively lower end reflections and, consequently, relatively low Q-factors;

3) if the tubular electron beam is injected into a vicinity of the inner caustic of the rotating operating mode (Fig. 15), the start current for this mode is less than for rival ones,

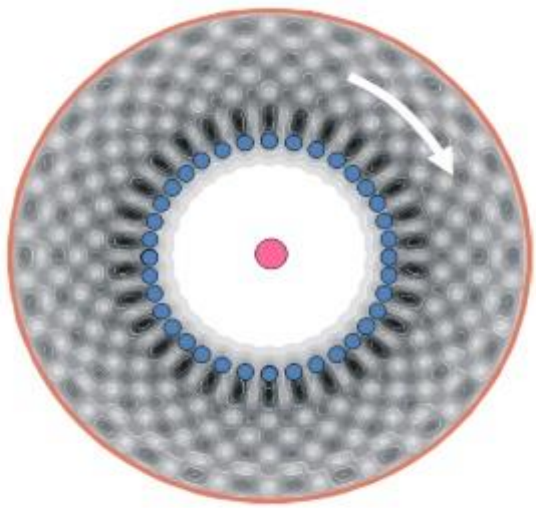

Fig. 15 An optimized transverse configuration of an axis-symmetrical gyrotron (H15.4/110 GHz/1MW pulse/1977).

4) if the operating mode has started, then, under an optimized switching-on scenario, this mode non-linearly suppresses rival ones.

High order modes, not convenient for most of applications, are usually converted to quasi-Gaussian beams [1] (Fig. 16):

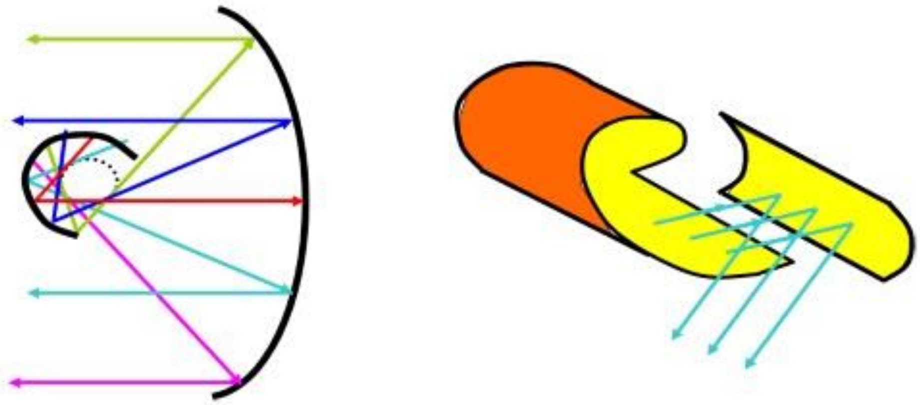

Fig. 16 Conversion of a high order mode to a quasi-Gaussian beam.

- the mode radiated from the cavity is approximated with a system of rays consequently reflected from waveguide walls;

- downstream, an asymmetric cut of the waveguide forwards these rays into a relatively narrow solid angle,

- finally, a matching mirror converts the wave flow to a system of parallel rays.

To minimize the wave beam side lobes, the waveguide surface upstream the asymmetric cut is optimally pre-shaped. The resulting quasi-Gaussian beam is radiated from the gyrotron vacuum volume through a broad flat dielectric window.

7. State of the art and current advances

Presently gyrotrons deliver the highest CW powers at sub-THz frequencies; for instance, at 0.17 *THz*, the power is near 1 *MW* [1]. At 1 *THz*, the pulse power is presently over 1 *kW* [1]. Over 50% efficiencies are obtained in gyrotrons with depressed collectors [1]. In some gyrotrons, the frequency is step-tuned by changing the solenoid magnetic field [1].

For upgraded gyrotrons, new types of cavities – coaxial, multi-mirror and echelette ones – are being developed [1].

Some gyrotrons – gyroTWTs and gyroklystrons – operate as amplifiers [1]. For instance [18], a 35 *GHz* gyroklystron pulse power is 15 *MW*.

Acknowledgement

The author is grateful to Professor Liu Shenggang for numerous discussions and fruitful cooperation.

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