Guest Editorial

I. INTRODUCTION

CYCLOTRON resonance masers (CRM's) have been known for about four decades. The first papers describing the mechanism of the cyclotron maser instability were published in the late 1950's by Twiss [1], Schneider [2], and Gaponov with Zheleznyakov [3], [4]. The first experiments were also reported in 1959 by Pantell [5], [6] and Gaponov [7] and a little later by Bott [8], [9] and Hirshfield with Wachtell [10]. (A more complete historical survey can be found in [11] and [12].) It is remarkable that in parallel with the vacuum version of CRM's, solid-state CRM's were also suggested by Lax [13]. The latter devices look very attractive, at least because the effective mass of electrons in solids may be one or two orders of magnitude smaller than that of free electrons, thus for generating the electromagnetic waves at a given frequency much lower magnetic fields are necessary.

The most advanced and explored versions of CRM's, the gyrodevices [14], have manifested themselves as the best sources of millimeter- and submillimeter-wave radiation in terms of efficiency, peak microwave power, and energy per pulse in pulsed operation, as well as average power in continuous wave (CW) operation. At present, gyrotron oscillators operating in the millimeter wavelength region produce 1 MW level microwave power in pulses with duration up to 10 s. The gyrotron power per pulse demonstrated by the Russian consortium GYCOM can be characterized at 110 GHz as 0.83 MW/2 s and 0.37 MW/5 s, at 140 GHz as 1 MW/1 s and 0.65 MW/2 s, and at 170 GHz as 1MW/1 s, 0.5 MW/5 s, and 0.27 MW/10 s [15]–[17]. During the last several years the gyrotron activity at CPI (formerly, Varian) was mainly focused on the development of 110 GHz gyrotrons for plasma experiments at General Atomic. As is known, the most critical element for operation at high levels of microwave energy per pulse is the output window. In 110 GHz CPI gyrotrons with sapphire output windows, the operating parameters were 1 MW/0.6 s, 0.53 MW/2 s, and 0.35 MW/10 s. Recently, the sapphire window was replaced by a diamond window and a new tube demonstrated operation at 0.6 MW level in 1.5 s pulses [18]–[20]. In the CW regime, the power of gyrotrons developed at CPI/Varian scales with the wavelength from 1 MW level at centimeters to several hundred kW at long millimeters and down to 100 kW level at short millimeters [18]–[20]. Certainly, the data mentioned above (as well as those which will be mentioned below) are given just for illustrative purposes. A much more detailed description of gyrotron development can be found in gyrotron and free electron maser surveys which are periodically updated by Thumm [21].

Among gyroamplifiers, the most advanced in terms of the output power are gyroklystrons and in terms of the bandwidth are gyro-traveling-wave tubes (gyroTWT's). Millimeter-wave gyroamplifiers driven by electron beams of a moderate energy (operating voltage below 100 kV) are mainly developed at two frequency bands which correspond to atmospheric windows for propagation of millimeter waves, i.e., in the Ka band (or, more exactly, at 34–35 GHz) and W band (i.e., at 93–95 GHz). The maximum power in the Ka band was demonstrated in Russian experiments with two-cavity gyroklystrons in which the pulsed power reached 750 kW level while the gain was relatively low (20 dB) and the bandwidth was about 0.6% [22]. Much higher gain was demonstrated in recent NRL experiments with four-cavity gyroklystrons: the gain achieved was about 53 dB while the power exceeded 200 kW, efficiency exceeded 30%, and the bandwidth was larger than 0.8% [23]. In Russian experiments with W-band pulsed gyroklystrons the output power exceeded 100 kW [24] and in NRL experiments the bandwidth approached 1% [25]. Also in Russian W-band CW gyroklystrons, 2.5 kW power in the 0.3% bandwidth was demonstrated [22]. Recently, collaborative efforts of NRL, CPI, and Litton resulted in the development of a W-band gyroklystron delivering 10.1 kW average power with 11% duty cycle and 33% efficiency [26]. In experiments with Ka-band gyroTWT's done at NRL, the bandwidth over 20% was demonstrated with 30 dB gain at about 8 kW level of output power [27]. The maximum gain (70 dB) was obtained in experiments with Ka-band gyroTWT's carried out at the National Tsing Hua University, Taiwan. These results are presented in our issue below by Chu and his colleagues.

Besides the development of gyroamplifiers which can be used in radar and communication systems there is also the development of relativistic gyroklystrons for driving the future, TeV-scale linear colliders [28]. These sources operating at voltages of 400–500 kV are under development at the Institute for Plasma Research, University of Maryland. The experiments have been carried out in the X and K bands: at 8.6 GHz the power exceeded 75 MW in about 1.7 μs pulses [29], and at 19.7 GHz the power exceeded 30 MW in pulses of the same duration [30]. Also, gyroklystron designs show the possibility of high-power operation at 34 GHz and 95 GHz. (The latter design is presented in our issue.)

In view of the literature, during the 1980's and the beginning of the 1990's the gyrotron development was well reflected in the Special Issues of the *International Journal of Electronics on Gyrotrons.* (There were seven Special Issues published from 1981 to 1992.) Also, a book on gyrotron oscillators, which was edited by Edgcombe, was published in 1993 [31]. There were also three books of collected papers on gyrotrons published by the Institute of Applied Physics of the Academy of Sciences (Nizhniy Novgorod, Russia) published in, respectively, 1980, 1981, and 1989 in Russian. In recent years, gyrotron development was mainly seen in Special Issues of IEEE TRANSACTIONS ON PLASMA SCIENCE on High-Power

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Participants of the International Workshop "CRM's and gyrotrons" organized by the Israeli Academy of Science in Kibbutz Ma'ale Hachamisha (May 18–21, 1998).

Microwave Generation, which appear every two years. Also, as seen from the list of our references, many gyrotron papers are presented every year at international conferences on infrared and millimeter waves. Most of them are published later in the *International Journal of Infrared and Millimeter Waves* edited by Button.

Reviewing the recent progress in the field, we received the impression that there are some trends to focus the gyrotron research on technological issues. On the one hand, such practical trends should be considered positively since they demonstrate the maturity of gyrotrons. However, on the other hand, these trends may cause some doubts that all principles of CRM's and, in particular, gyrotrons have been exhaustively studied and there is no reason to consider them again. (As an example of possible alternatives, let us just mention the cyclotron autoresonance maser (CARM) [32]–[35] which can be considered as a CRM-version alternative to the gyrotron in the sense that gyrotrons are based on the interaction of gyrating electrons with electromagnetic waves propagating almost perpendicular to the guiding magnetic field while in CARM's the electrons interact with the waves propagating at small angles to this field.) Therefore we decided, first, to organize the International Workshop on CRM's and Gyrotrons, the scope of which would be focused not only on gyrotron development and applications but also include a review of the principles of CRM's, and then, to prepare this Special Issue of IEEE TRANSACTIONS ON PLASMA SCIENCE solely devoted to CRM's and gyrotrons.

Both these initiatives stem from our scientific collaboration under a grant of the USA–Israel Binational Science Foundation. The International Workshop of the Israeli Academy of Sciences and Humanities devoted to CRM's and gyrotrons was held in May 18–21, 1998 in Kibbutz Ma'ale Hachamisha, near Jerusalem. This meeting was attended by 48 researchers from P. R. China, Finland, Germany, India, Israel, Japan, Russia, Taiwan, and the United States. Now our readers can see the Special Issue. This issue includes not only papers based on contributions made during the workshop but also the papers submitted later by those who could not attend the workshop.

Our Special Issue contains eight sections which reflect the main activities in our field. These sections are described below in a successive manner.

II. HISTORY OF CRM's

This section contains two tutorial papers written by the Russian scientists Petelin and Andronov. Petelin (who is one of the inventors of the gyrotron) wrote a paper about the history of cyclotron radiation. Andronov wrote a review paper on solid-state CRM's.

III. GYROTRON OSCILLATORS

This section consists of nine papers on gyrotron oscillators. It starts with a review paper by Nusinovich on the theory of mode interaction in gyrodevices which summarizes the research in this field done during the past 25 years. This review paper is followed by a short paper on multifrequency operation of gyrotrons written by Dumbrajs (Helsinki University of Technology, Finland) in collaboration with his coworkers from FZK, Karlsruhe, Germany, and the Institute of Applied Physics, Nizhniy Novgorod, Russia. The authors discuss and compare different approaches to the analysis of mode interaction in gyrotrons. The third paper reports the experimental results of the studies of a 140 GHz gyrotron with a Brewster window developed at FZK for future experiments on plasma heating and current drive. Note that the level of microwave power radiated by this gyrotron exceeds 1.5 MW in short pulses. The next three papers are devoted to step-tunable, short-wavelength gyrotrons which can be of interest for active plasma diagnostics and electron spin resonance spectroscopy. The first of these three papers is a review paper written by Idehara and his colleages from Fukui University, Japan. This paper reviews the progress in the development of step-tunable, submillimeter-wave gyrotrons in Japan in collaboration with the University of Sydney, Australia. The second paper written by Nusinovich and Read (Physical Sciences Inc., USA) is a theoretical paper in which, first, it is shown how to apply a well-known gyrotron theory to the analysis of step-tunable gyrotrons, and second, the design of such a gyrotron operating at two first cyclotron harmonics in the frequency range of 150–600 GHz is described. The third paper by Pereyaslavets and his colleages from Fukui University presents a study of frequency modulation in a submillimeter-wave gyrotron.

The next paper, by Huang and his coworkers from the University of Electronic Science and Technology of China, Chengdu, P.R. China, describes a study of a 35-GHz gyrotron designed for operation at the third cyclotron harmonic. To ensure a stable, selective operation at the third harmonic, the authors consider a step-profile cavity in the first part of which the cut-off frequency of the $TE_{6,1}$ mode is the same as the cut-off frequency of the $TE_{6,2}$ mode in the second part. In such a case, these two partial modes of two sections of one cavity become strongly coupled, thus forming a normal $TE_{6,1}/TE_{6,2}$ mode occupying the whole volume of the cavity, in contrast to other modes whose fields are localized either in the first or in the second part of it. Note that such a concept was already successfully tested in a number of experiments carried out at the fundamental, second and third cyclotron harmonics.

The next paper describes the work done at the Technical University of Hamburg-Harburg, Germany, where a new formalism based on the frequency- and time-domain modal analysis is suggested for accurate description of fields excited in gyrotron cavities. The section ends with a paper written by Barroso *et al*. from INPE, Brasil. The authors present results of particle-in-cell simulations done for a 32 GHz, $TE_{0,2,1}$ mode gyrotron operating at the fundamental cyclotron resonance.

IV. GYRO AMPLIFIERS

This section consists of six papers. The first is an invited paper on gyro-traveling-wave tubes (gyroTWT's) written by Chu and his colleagues from the National Tsing Hua University, Hsinchu, Taiwan, and some United States companies. The authors of this paper describe the theory of gyroTWT's and present the results of an experiment with a Ka band (34 GHz) gyroTWT in which a 100-kW level of output power was realized with 26.5% efficiency and 70 dB gain. The bandwidth in the large-signal regime of operation was 8.6%.

The next paper represents some results of the active development of wide-band, millimeter-wave gyroamplifiers at NRL. The paper is devoted to a W-band (94 GHz) gyrotwystron with three prebunching cavities and an output waveguide. In this experiment, 50 kW peak output power was realized with 17.5% efficiency and 30 dB gain in a 1% bandwidth. The gain-bandwidth product demonstrated in this tube is much larger than in previous W-band amplifiers.

The third paper describes not an amplifier, but a phase-locked gyrotron oscillator experiment done at the University of Maryland. (The paper is placed in this section because the phase control of the output radiation can be realized in phase-locked oscillators in the same way as in amplifiers.) The paper describes an experiment with an inverted gyrotwystron, the device which consists of an input waveguide and an output cavity separated by drift section. In the present device, the input waveguide operates at the fundamental cyclotron resonance (the signal frequency is in the range of 17 GHz) while the output cavity operates at the second harmonic in Ka band. The maximum output power, 180 kW, is realized with 32% efficiency and 35 dB locking gain; the corresponding bandwidth is 1.3 MHz. A much larger bandwidth, 8 MHz, was realized at the 120 kW power level.

The last three papers contain some theoretical and design issues. The first of them reviews the progress in the theory of stagger-tuned gyroklystrons and gyrotwystrons done in recent years at the University of Maryland in collaboration with the Vacuum Electronic Branch of NRL. The second paper, which should be considered as the companion to the first one, describes the nonlinear theory of gyrotwystrons with a multistage stagger-tuned prebunching section. The last paper in this section describes the design of a 95 GHz relativistic gyroklystron done at the University of Maryland. As it mentioned previously, nowadays there is a strong interest in high-power, millimeter-wave drivers for future linear colliders. Therefore this paper, presenting a design which predicts a 7.5 MW output power with more than 50 dB gain and 33.6% efficiency, demonstrates an interesting and very encouraging result.

V. NOVEL CONCEPTS

The first paper in this section describes the CRM-array concept developed at Tel Aviv University both in experiments and theory. Like in other multibeam microwave tubes, the different beamlets propagate through parallel channels, thus the restrictions on the total beam current caused by space charge effects are lowered. In addition, the present paper studies new schemes of CRM arrays in two-dimensional and three-dimensional periodic waveguides. It proposes a novel CRM-array antenna, in which the radiation phases in the array elements are controlled electronically, thus allowing spatial steering of the radiation lobe.

The second paper is devoted to large-orbit gyrotrons (LOG's). This concept, which is based on the interaction between an azimuthally rotating wave of a cylindrical waveguide and an azimuthally rotating electron beam whose axis of rotation coincides with the waveguide axis, has been known for years: according to [36], the first experiment with LOG was done by Jory 30 years ago. The advantages of this concept are associated with the superior selective properties of LOG's in which axially encircling electrons can resonantly interact only with electromagnetic waves whose azimuthal index is equal to the resonant cyclotron harmonic number. The main obstacle in realizing a highly efficient operation of LOG's is usually the relatively poor quality of electron beams. In this paper, the authors from the Institute of Applied Physics, Russian Academy of Sciences report the results of a study of LOG's in which a new system of formation of axis encircling electron beams was used. In the experiments described, radiation at the first five cyclotron harmonics was observed at about 1 MW power level.

The next paper is written by a team of researchers from the University of Stratchlyde, Glasgow, U.K., and several Russian institutes. This paper describes the results of theoretical and experimental studies of the effect of cyclotron superradiance. Recall that the effect of superradiance was first discussed by Dicke [37] who considered a two-level quantum system in which an initial spontaneous emission leads to the emission of coherent radiation due to mutual effects between molecules through a commonly radiating electromagnetic field. The present paper describes the theory of this phenomenon in a beam of electrons gyrating in the external homogeneous magnetic field and the experiment in which 200 kW, 35 GHz pulses with a very short (0.4 nsec) pulse duration were observed.

VI. ELECTRON BEAMS AND COLLECTORS

This section starts with two Russian papers, the first of which describes an idea on how to remove electrons that become trapped in the region between the electron gun and the interaction circuit due to the mirroring effect of the increasing external magnetic field in this region. The idea is based on the fact that the drift component of adiabatic motion of electrons moving in crossed static electric and magnetic fields is irreciprocal. Therefore, when the electric field has an azimuthal component, the radial drift of reflected electrons will forward them to the walls while electrons moving toward the interaction region will continue their motion. The authors suggest a certain configuration for realizing this idea and evaluate the region of operating parameters for their scheme. The second paper reports the results of a detailed study of the effects of inhomogeneity of temperature limited emission from gyrotron cathodes on such parameters of electron beams as energy and velocity spread. This kind of information is very important for correct design of gyrotron oscillators and amplifiers because the calculated parameters of electron beams do not always agree well enough with available experimental data.

The next paper, from FZK, Karlsruhe, Germany, describes an experiment with a coaxial cavity gyrotron with depressed collector. In principle, a scheme of a coaxial gyrotron is more complicated since it usually implies the use of an inverse electron gun in which an anode is placed inside the cathode ring. Such an anode is then extended into a resonator as an inner coaxial insert for providing eliminating mode selection and the voltage depression effect. When such an insert is supported from the collector side it may complicate the use of depressed collectors. However, in the experiment described, this insert was not supported from the collector side. Also the built-in quasi-optical mode converter was used for transforming the outgoing radiation from the operating $TE_{31,17}$ mode into a Gaussian wave beam. The use of a single-stage depressed collector allowed an increase in the efficiency from 27% to 41% at the 1.3 MW level of microwave power radiated at 165 GHz.

The last two papers in this section represent the joint activity of the Institute for Plasma Research at the University of Maryland in collaboration with two small industrial companies (Calabazas Creek Research, CA and Diversified Technologies, MA) on the development of multistage depressed collectors for gyrodevices. The first of these two papers describes the trajectory analysis of primary and secondary electrons in two-stage depressed collectors while the second paper is devoted to the system consideration, which means the basic mechanical design including the thermal performance.

VII. COMPONENTS AND DIAGNOSTICS

This short section, consisting of three papers, starts with a paper from Massachusetts Institute of Technology, Cambridge, MA, on the design of the internal mode converter, or, more specifically, on the phase retrieval algorithm which reconstructs the field on the mode converter reflector from intensity measurements done outside of the tube. Based on this algorithm, a design was done for a 110 GHz, 1 MW gyrotron operating in the $TE_{22,6}$ mode. The high-power test measurements confirmed the initial cold test measurements and demonstrated the applicability of this method to various applications of high-power microwave radiation. The second paper describes the development of an advanced input coupler for the coaxial X-band gyroklystron which is currently under development at the Institute for Plasma Research, University of Maryland for driving future linear colliders. The last paper in this section describes the development of a waterload capable of dissipating up to 2 MW CW power from short-millimeter-wave gyrotrons with the Gaussian shape of outgoing radiation.

VIII. APPLICATIONS

This short section begins with a review paper on gyrotron application for electron cyclotron resonance heating and current drive (ECRH and ECCD) in stellarators. This paper, written by Erckmann and his co-workers from the Max-Planck-Institute for Plasma Physics, Garching, Germany, FZK, Karlsruhe, Germany, and Stuttgart University, Germany, is mainly focused on experiments done at the stellarators Wendelstein 7-A and 7-AS in Garching; however, it also covers many issues important for various ECRH and ECCD experiments. The second paper, from FZK and the University of Karlsruhe, describes the sintering of advanced ceramics by using 10 kW, 30 GHz, CW gyrotron radiation. Similar experiments in which microwave and millimeter wave radiation is used for material processing are currently going on in many laboratories throughout the world and there is no doubt that further studies should be done in this field. The last paper in this section presents a nonlinear model for microwave heating of temperature dependent dielectric media. The two time-scale model couples thermal and electromagnetic processes using a fast algorithm. The simulations show various effects of heat diffusion in different materials.

IX. Free Electron Lasers and Other Microwave Sources

In the last section we included several papers on free electron lasers and other microwave devices which are not directly related to CRM's and gyrotrons, but which can be treated as their close "relatives." The first two papers describe the work on FEL's done by another group from Tel Aviv University, representatives of which participated in the workshop. The first paper describes nonstationary processes and the oscillation buildup in the FEL oscillator driven by an electron beam produced by an electrostatic accelerator. The second paper describes the traveling-wave prebunching which can be used for preparation of density modulated electron beams suitable for use in various schemes of free-electron maser amplifiers. This paper is focused on the application of such a scheme to a free-electron maser experiment which is currently going on at Tel Aviv University. The next paper discusses the issues of the efficiency and power enhancement of a wave scattered by a relativistic electron beam which propagates in a reversed tapered guiding magnetic field. Finally, the last paper in this section represents the results of PIC simulations done for a new version of a low frequency microwave source based on the known concept of a conventional monotron.

X. Conclusion

As follows from this brief overview, this Special Issue represents an international activity in the field of CRM's and gyrotrons which is going on in at least ten countries, representatives of which wrote the papers for this issue. This work is sponsored by various agencies. (For instance, the United States activity is represented by 12 papers and this work is sponsored by the Office of Fusion Technology and the Division of High Energy Physics of the U.S. Department of Energy, the Office of Naval Research, and the DoD Multidisciplinary University Research Initiative (MURI) Program on High-Power Microwaves. Note that the United States activity in this field will also soon be reflected in the Special Issue of the Proceedings of the IEEE called "New Vistas for Vacuum Electronics," which will appear in May 1999.)

Before closing our brief introduction, let us mention that among the major trends in the nearest future for the development of gyrotrons and CRM's one can foresee the following:

- generation of long pulses of millimeter-wave radiation with microwave energy per pulse at the 10 MJ level;
- mastering of the submillimeter and far-infrared wavelength regions;
- development of high average power, large-bandwidth gyroamplifiers for radar and communication systems; and
- wide use of compact gyrotron based microwave systems for industrial applications.

XI. Acknowledgement

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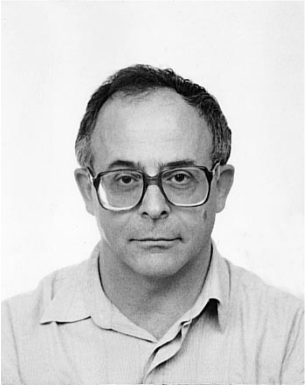

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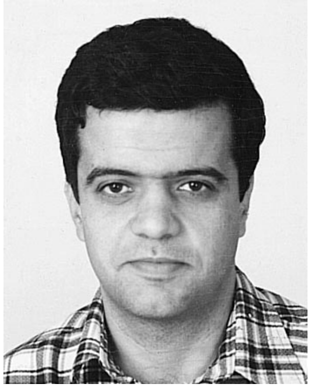

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