24–84-GHz Gyrotron Systems for Technological Microwave Applications

Yu. Bykov, A. Eremeev, M. Glyavin, V. Kholoptsev, A. Luchinin, I. Plotnikov, G. Denisov, A. Bogdashev, G. Kalynova, V. Semenov, and N. Zharova

Invited Paper

***Abstract*—During the last decade, a line of gyrotrons ranging in frequency from 24 to 84 GHz with the output power from 3 to 35 kW continuous wave, and a series of gyrotron-based systems have been developed by the Institute of Applied Physics, Nizhny Novgorod, Russia, jointly with GYCOM, Ltd., Nizhny Novgorod. Main technical characteristics of the gyrotrons, as well as the architecture of the gyrotron-based millimeter-wave power sources for applications are presented. The purposely developed transmission lines, applicators, and power control make gyrotron systems flexible and easily adaptable tools for research and development. A number of millimeter-wave technologies are extensively studied today using gyrotron systems; ceramics sintering and joining (including nanoceramics), functionally graded coatings, rapid annealing of semiconductors, microwave plasma assisted chemical vapor deposition, multiply charged ion production are among the most advanced development.**

***Index Terms*—Applicator, gyrotron, materials processing, microwave applications, millimeter-wave, power control, transmission line.**

I. Introduction

A GROWING demand of the nuclear fusion community in the millimeter-wave power sources resulted in the development of gyrotrons capable of producing about 1 MW in a practically continuous-wave (CW) regime at frequencies of up to 170 GHz [1]. Electron-cyclotron plasma heating is a unique area of gyrotron application to this date. However, it has become evident during the last decade that many microwave energy applications might greatly benefit from an increase in the frequency of radiation. High-temperature processing of materials, e.g., advanced ceramic sintering, was one of the first fields where the advantages of the millimeter-wave heating as compared with conventionally used power of 2.45 GHz have been demonstrated [2]. The capability of efficient volumetric heating of low-loss ceramic materials and rapid uniform sintering of large size specimens and batches of samples is of great importance for the successful development of processes of industrial interest. Very high uniformity of the millimeter-wave heating is of paramount importance for the annealing of silicon wafers of large diameter ($\geq$300 mm), a necessary step in the manufacturing of ultra large integrated circuits [3]. Significant improvement of performance characteristics of the electron-cyclotron resonance ion sources can be achieved with an increase in the frequency of the applied microwave power [4]. The microwave-assisted chemical vapor deposition of diamond films is another process which gains drastically in the rate of deposition if the plasma is sustained by the millimeter-wave power [5]. The application of the millimeter-wave beams for surface treatment of materials is a promising method which in many cases is competitive with the surface heating by other concentrated energy flows, such as laser, ion, or electron beams, and plasma flow [6].

The awareness of the potential of the millimeter-wave power use in technology initiated in the beginning of 1990s the development of the first gyrotron-based system purposely designed for research in material science [6]. Since then, several types of gyrotron systems of different power, operating at various frequencies, have been developed. A brief description of the key features of these systems is given in this paper, as well as some illustrations of the results obtained with their use.

II. Experimental Facilities

The general concept of the gyrotron system architecture remains invariable despite the differences in the technical specifications of the gyrotrons which are used and the nature of applications (Fig. 1). A gyrotron system is made up as a standard computer-controlled device to which the feedback loop is applied.

The gyrotron systems do not differ from microwave sources of other frequencies in terms of control. However, the difference in the operating frequency results in a drastic dissimilarity of all major components.

The gyrotron systems are designed as an integrated set of the following principal components:

1) a gyrotron, the source of the millimeter-wave power;
2) transmission line for transport of millimeter-wave power to an applicator;
3) an applicator;
4) diagnostic subsystem and PC controller for automatic/manual processing.

The specific design of these components is flexible and depends on a particular application.

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The authors are with the Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia (e-mail: byk@appl.sci-nnov.ru).

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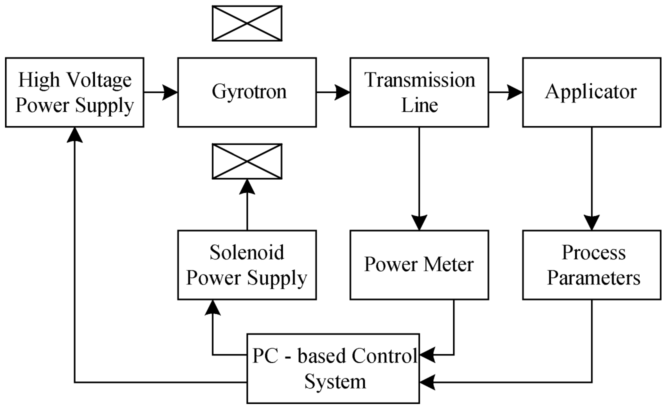

Fig. 1. Block diagram of the gyrotron system.

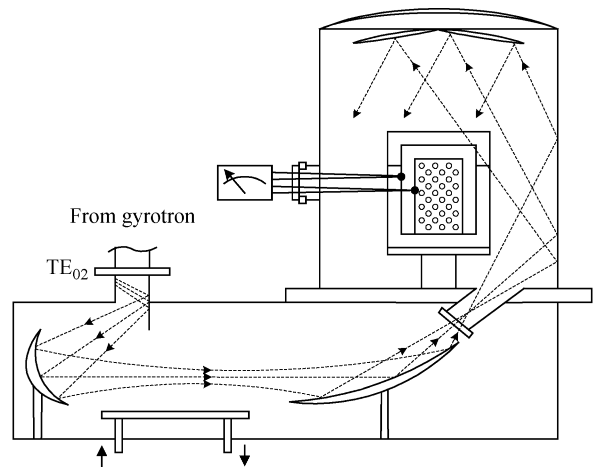

Fig. 2. Schematic diagram of the transmission line of the 30 GHz 15 kW gyrotron system for high temperature processing of materials.

TABLE I
TECHNICAL SPECIFICATIONS OF THE CW GYROTRONS

Frequency, GHz	RF Power, kW	Output Mode	Solenoid
24	0.1 – 3	TE_{11}	water-cooled
24	30	TE_{32}	water-cooled
28	10	TE_{02}	water-cooled
28 [a]	10	TE_{02}	permanent magnet
28 [b]	200	TE_{02}	water-cooled
30	15	TE_{02}	oil-cooled
37.5	15	Gaussian	liquid He cooled
84	35	Gaussian	liquid He cooled

[a] produced by Mitsubishi Elect. Corp. (Japan),
[b] produced by CPI Corp. (USA)

A. Gyrotron and Magnet System

Physical principles that differ a gyrotron from other sources of microwave power and make gyrotrons capable of producing power of about 1 MW in CW at frequencies above 150 GHz are well known. Here, we focus on those features only which conceptually govern the design of the gyrotron-based systems for technological applications.

Table I lists the technical specifications for some of the CW gyrotrons with the output power of several kilowatts in CW operation, which are produced jointly by the Institute of Applied Physics (IAP) and Gycom. Some of these gyrotrons are already used as key components of the technological systems that have been installed at the research centers in Germany, the U.S., China, Japan, and France. It should be emphasized that the listed tubes are only examples of the gyrotrons produced to this date, and gyrotrons with technical specifications that meet a particular user's requirements, in terms of microwave power and frequency, can be designed. Gyrotrons produced by Communications and Power Industries (CPI) Corporation, Palo Alto, CA and Mitsubishi Electric, Japan are also included in Table I to make the picture of the available millimeter-wave sources more complete.

The output power of gyrotrons can be smoothly regulated from about 5% to 100% of the full power by variation of the electron beam voltage. All CW gyrotrons can operate in pulse regime with the same or slightly higher output power. Typical operating voltage of these gyrotrons is in the range of 15–30 kV, and the electron beam current is 1–2.5 A. An efficiency of the standard gyrotrons operating in frequency range of 20–80 GHz is about 0.3–0.4, and about 0.60–0.65 in the gyrotrons with a depressed collector [7].

In gyrotrons, high output power is traded off by the necessity to use the static magnetic field, which increases with an increase in the frequency of microwaves. This means that each gyrotron oscillator comes with its own magnet system. At frequencies of up to 40 GHz, solenoids cooled by water or oil are typically used, if the gyrotron operates at the fundamental or second harmonic of the electron cyclotron resonance. The operation at the second harmonic of the electron cyclotron resonance allows not only significant reduction of the energy consumption by the electromagnet, but also, what is probably more important, the power supply and cooling system for the solenoid become much less operationally strained, compared to gyrotrons operating at the fundamental ECR frequency. At higher frequencies the use of "warm" electromagnets becomes impractical and cryogenically cooled solenoids are exploited.

B. Transmission Line (TL)

Microwaves leave a gyrotron via a waveguide, which is oversized as compared to the wavelength of radiation. Various TLs can be designed for the transport of microwaves from the gyrotron to an applicator. The design of these TL depends mostly on what one would like to have at the input of the applicator in terms of the electromagnetic field pattern and polarization. At frequencies above 20 GHz, a TL can be built either as an oversized waveguide, a set of quasi-optical mirrors, or can be of a mixed type.

The schematics of the transmission line of the 30 GHz 15 kW gyrotron system for high-temperature processing of materials is given in Fig. 2. The output millimeter-wave power is transported from the gyrotron to the furnace through a three-mirror quasi-optical TL. At the gyrotron output a convertor transforms the operating mode of gyrotron TE_{02} into a proper mixture of modes TE_{02}, TE_{13}, and TE_{22} which forms a paraxial wave beam transported by means of metal reflectors. The beam transmitted through the line has negligibly small side lobes, and the efficiency of power transport in the system exceeds 90%. All components of the TL are enclosed in a leakage-proof metal case.

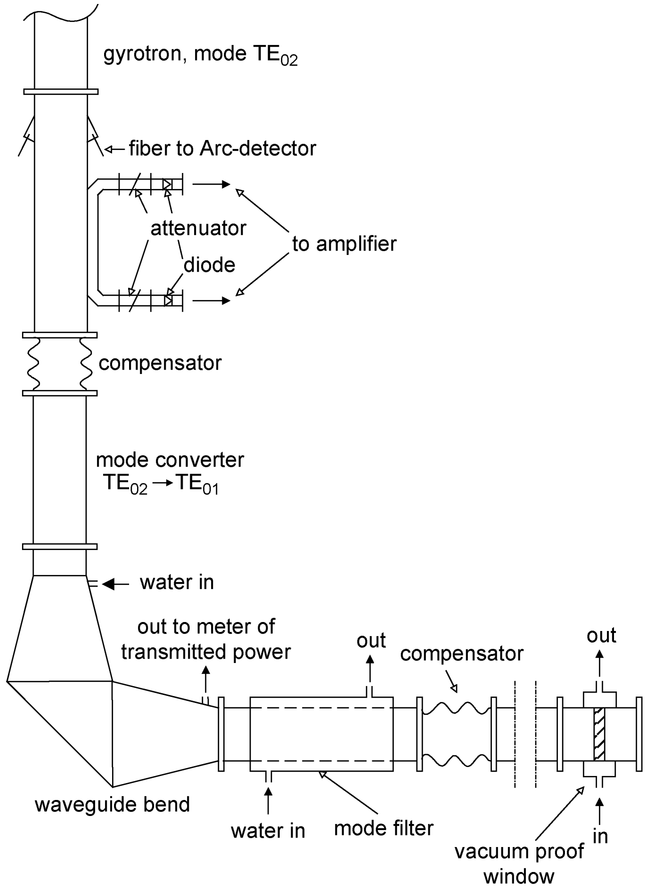

Fig. 3. Schematic diagram of the transmission line of the 28-GHz 10-kW CW gyrotron system for electron cyclotron resonance ion source.

A schematic drawing of the waveguide TL of the 28-GHz gyrotron system designed for powering the electron cyclotron resonance ion source is shown in Fig. 3. The structure of this TL is based on waveguide components. However, it should be realized that at a high frequency, the TL is composed of multimode components. Therefore, the design and principle of operation of these components usually differ greatly from those used at lower frequencies.

The transmission line includes the following components:

1) a bi-directional coupler;
2) a 90° quasi-optical mirror bend. This section can be also used for measuring the absolute value of microwave power produced by gyrotron. For this purpose, the bend is cooled with water and furnished with a set of temperature sensors;
3) a mode convertor, which transforms the operating mode of the gyrotron, TE_{02}, into the TE_{01} mode;
4) a mode filter, which serves to protect a gyrotron against the microwave power reflected back from the ion source. Operation of the filter is based on selective absorption of power of nonsymmetrical modes;
5) a launcher, which produces the required electromagnetic field pattern at the input of the ion source;
6) additionally, the line is equipped with an arc detector, which serves to shut off the power if, by some reason, arcing occurs in the transmission line.

An efficiency of the millimeter-wave power transport through the entire TL is over 0.97.

C. Applicator

One of the promising areas of millimeter-wave industrial applications is high temperature processing of materials, such as sintering and joining of advanced ceramics, annealing of semiconductors, etc. Most of the gyrotrons systems designed to this date are furnished with a microwave furnace, which comprises an untuned cavity resonator, vacuum-proof in the wide pressure range ($10^{-4} - 2$ bars). High uniformity of the microwave energy distribution in the furnace is an essential prerequisite for the processing of large size specimens and for reproducible heating of many specimens processed simultaneously in one batch. The approaches to attaining a distribution of high spatial uniformity are different for the multimode applicators fed with the millimeter-wave $(L \gg \lambda)$ and microwave $(L \geq \lambda)$ radiation (where L is the size of applicator and λ is the wavelength of radiation). The millimeter-wave radiation usually enters the furnace as a wave beam (see, for example, Fig. 2) or through an opening in the multimode waveguide. High uniformity of the microwave energy distribution in the furnace is achieved as the result of superposition of the electromagnetic fields of hundreds simultaneously exited modes. A rigorous calculation of the electromagnetic field in a super-multimode untuned cavity which is highly oversized compared to the radiation wavelength is impractical, and the use of approximate methods for computer simulation of the microwave energy distribution appears to be inevitable. Two approximate methods have been developed independently [8], [9]. Both of them are based on the so called "ray tracing" approach which represents the fed-in radiation as a set of separate ray tubes of given intensity and makes it possible to calculate microwave intensity in an individual spatial cell of a furnace by summarizing intensities of the rays passing through that cell. These methods, consuming rather modest computation time, have proven their high practical value for the improvement of the millimeter-wave energy distribution in oversized applicators.

It should be noted that the use of ray tracing techniques makes it possible not only to calculate the microwave energy distribution within the cavity, but also to accomplish computer simulation of the microwave heating of materials. Such an approach can be especially helpful in the problem of sintering of large-size specimens because it allows to reduce drastically both the experimental efforts and amount of materials needed for trials.

Mode-stirrers similar to those used in the standard 2.45-GHz furnaces are also employed in applicators powered by the millimeter-waves to equalize the energy distribution further by eliminating the standing wave structure.

The 24-GHz 3-kW gyrotron system shown in Fig. 4(a) features an unparalleled capability of both volumetric heating of specimens by the millimeter-wave energy uniformly distributed over the whole volume of the cavity [Fig. 4(b)] and local heating by a focused wave beam [Fig. 4(c)] [10]. This is achieved by the use of two types of mirrors alternatively directing the wave beam entering the applicator to the stirrer or to a specimen.

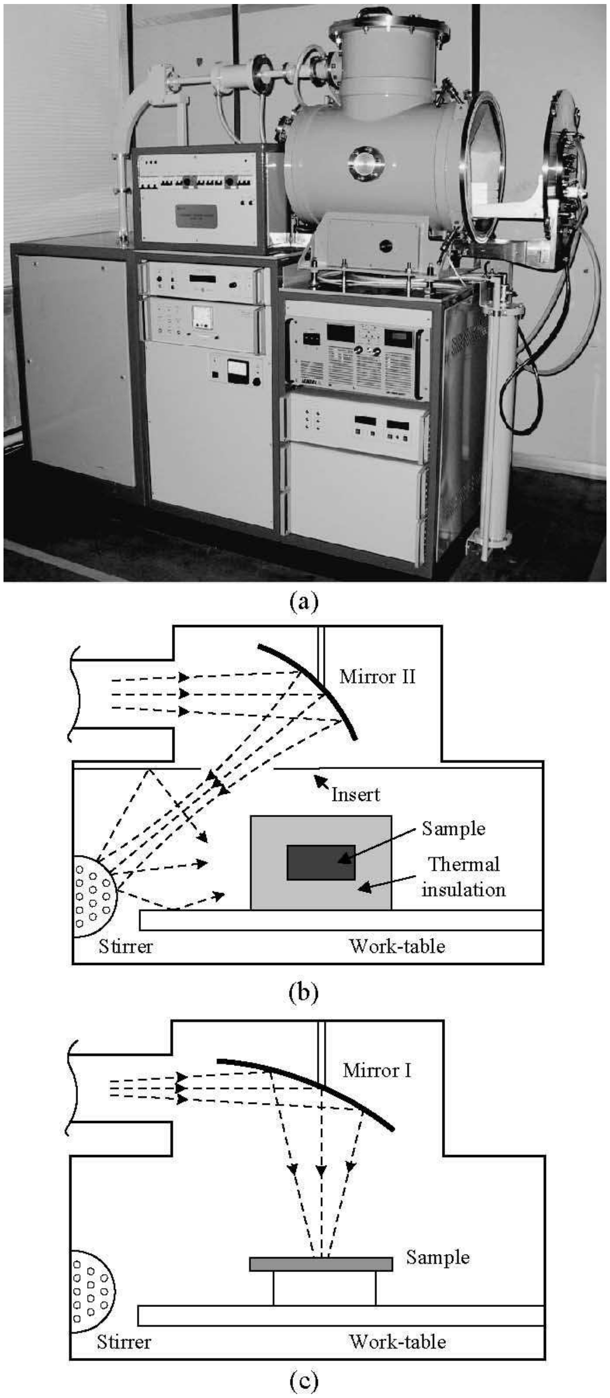

Fig. 4. (a) 24-GHz 3-kW gyrotron system. (b) Schematic of volumetric heating of materials. (c) Schematic of local hearing by the wavebeam.

D. Control System

The gyrotron systems are supplied with a computer control system (CCS), which provides the following:

1) control of the microwave power delivered to the applicator;
2) trouble-free operation.

The trouble-free operation is supported by the operation control subsystem which has the following functions:

1) starting up the microwave source in accordance with a preset algorithm;
2) automatic (full or partial) shutoff of the power supplies in case of a failure in the set of power supplies or in the cooling system, or in emergency.

The operation control subsystem includes a programmable microprocessor controller with auxiliary modules and a set of sensing elements. The data from the operation control subsystem are transmitted from the microprocessor to the computer control enabling the operator to check the current status of different components of the microwave power source.

The microwave power produced by the gyrotron and delivered to the applicator is controlled by the feedback-loop power control subsystem (PCS). The PCS makes it possible to control the microwave power in both manual and automatic modes. In the automatic mode, a code, specially developed using *LabWindows 6.0* package, supports multichannel monitoring of process parameters and the major gyrotron operation parameters: voltage and current of the electron beam, output millimeter-wave power, and dc current in the main magnet. The choice of the controlling (key) parameter is determined by the nature of a specific application. When a fixed power is required, the PCS provides an accuracy of about 1%. In the case of high-temperature processing of materials, the thermocouple and optical pyrometer signals are typically used as the key parameters. The 0.2% accuracy of maintaining the temperature of ceramic samples at the hold-stage of sintering ($T \approx 1600$ °C) is provided when either a thermocouple or the Luxtron Model 10 Optical Fiber Thermometer are used for measurements.

III. Application

The specifics of the interaction of millimeter-waves with materials and the technical features of gyrotron systems determine a distinct class of processes which gain from the increase in the frequency of microwave power. However, even in industrial scale processes, based on the use of microwave power of lower frequencies, the introduction of gyrotron systems can bear a radical technical innovation. Such an innovation can be in the use of gyrotrons operating at frequency as low as, for example, 2.45 GHz but with the output power of an order of 100-kW CW and more, i.e., higher than achievable with any other sources of microwave energy. It should be noted that in the low frequency range ($1 \div 10$) GHz the efficiency of high-power gyrotrons can be at least comparable with that of such microwave sources as magnetron or klystron, widely used by industry. The use of gyro-backward-wave oscillator (BWO), operating efficiently within a broad frequency band, can also open a new possibility for processes strongly susceptible to the temperature runaway instability. The output power of 5 kW with smooth frequency tuning within the range of about 1 GHz has been obtained in the first experiments on a 24-GHz gyro-BWO operating in a CW regime [11].

A significant interest in the research and development of industrial applications using the millimeter-wave energy is proved by a number of gyrotron systems operating today throughout the world. Here, we give a list of only some results of the laboratory studies which have a good potential to be developed to the industrial scale processes.

1) Successful sintering of the near full-density alumina with grain size of 85–90 nm shows that the control of the millimeter-wave heating rate can be the feasible method to produce nanostructural ceramic and composite materials [12].
2) Pure alumina- and silicon nitride-base ceramic specimens with size of 200 mm and about 1-kg weight have been sintered in the furnaces powered by the 28- and 30-GHz gyrotrons [13], [14]. Ceramics of fine and uniform microstructure have been produced in a process time reduced by an order of value as compared with conventional sintering.
3) Pure oxide ceramics can be effectively heated and joined using the millimeter-wave energy [15]; a joint can be used in high-temperature application because it does not contain secondary glassy phases.
4) Greatly increased rate of solid-state diffusion reactions makes it possible to synthesize materials in a record-short time [16] and crystallize the amorphous ferroelectric (Ba, Sr)TiO_3 thin films at the temperature by 250 °C lower than that of conventional annealing [17].
5) The results of the millimeter-wave annealing of silicon wafers shallow doped with low-energy boron satisfied to the 0.13-μm technology node [18].

IV. Conclusion

1) A number of gyrotron systems with microwave power up to several tens of kilowatts CW and frequency ranging from 24 to 84 GHz have been designed and are currently used for research and development in various technological applications.
2) The developed mathematical codes make it possible both to optimize supermultimode applicators for uniform materials heating and to synthesise microwave beams with desirable intensity patterns.
3) The gyrotron systems have proved to be a versatile, flexible, and user-friendly tool for materials science research and pilot tests.

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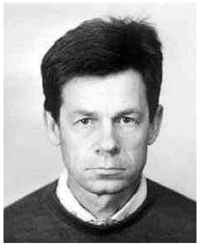
Yu. Bykov, photograph and biography not available at the time of publication.

A. Eremeev, photograph and biography not available at the time of publication.

M. Glyavin was born in 1965. He received the Ph.D. degree in physics from the Institute of Applied Physics, Russian Academy of Sciences, Moscow, Russia, in 1999. His Ph.D. dissertation concerned gyrotron research, in particular, the efficiency of gyrotron operation and energy recovery.

Since 1988, he has been with the Institute of Applied Physics, where he is engaged in the development of high-power gyrotrons for nuclear fusion. From 1999 to 2004, he was a Visiting Scientist at FIR FU, Fukui, Japan. His research interests include the theoretical and experimental research in gyro-devices, including gyrotron application to materials processing. He has more than 100 publications on the theoretical and experimental investigations in high-power vacuum electronics.

V. Kholoptsev, photograph and biography not available at the time of publication.



A. Luchinin received the M.S. degree in radiophysics from Lobachevsky State University, Gorky, U.S.S.R. (now Russia) and the Ph.D. degree in physics from the Institute of Applied Physics, Russian Academy of Sciences, Moscow, U.S.S.R. (now Russia), in 1985. His Ph.D. dissertation concerned the study of powerful gyrotrons at millimeter and submillimeter wavelength.

He is currently a Senior Scientist with the Institute of Applied Physics, where, since 1977, he has been working at the Department of Plasma Physics and High-Power Electronics. His research interests include the development of high efficiency, powerful sources of microwave radiation for nuclear fusion and technological applications. He has published more than 50 papers in these areas.

I. Plotnikov, photograph and biography not available at the time of publication.

G. Denisov was born on April 30, 1956, in Gorky, U.S.S.R. (now Russia). He received the M.S. degree from Gorky State University, in 1978, and the Ph.D. and Professor degrees from the Institute of Applied Physics, Nizhny Novgorod, Russia, in 1985 and 2002, respectively.

He is currently Head of the Gyrotron Division, Institute of Applied Physics. His research interests include relativistic microwave oscillators and amplifiers (e.g., free-electron masers and cyclotron autoresonance masers), transmission lines and antenna systems for high-power microwave radiation, methods for measurement and control of wave beam parameters, powerful microwave sources for ECRH systems in fusion installations (gyrotrons), and technological setups.

Dr. Denisov received the international award from Fusion Power Associates for Excellence in Fusion Engineering in 1996.

A. Bogdashev, photograph and biography not available at the time of publication.

G. Kalynova, photograph and biography not available at the time of publication.

V. Semenov, photograph and biography not available at the time of publication.

N. Zharova, photograph and biography not available at the time of publication.