# HIGH POWER GYROTRONS. DEVELOPMENT AND APPLICATIONS.

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*Abstract*- **We present a brief description of first steps in gyrotron development, analysis of current status of megawatt gyrotron creation for nuclear fusion program and survey of gyrotron applications: for basic researches of quasi-optical millimeter wave beam interaction with matter (including free localized gaseous discharge in focused mm wave beams, mm waves phase conjugation, electromagnetically induced transparency) for electron cyclotron plasma heating and current drive in magnetic fusion devices, dense plasma sources development for nuclear physics and plasma chemistry, new technologies of industrial material processing.**

Gyrotron oscillators have proven to be the most powerful sources of coherent wave radiation in the millimeter wavelength range. Cyclotron resonance maser (CRM) mechanism was discovered 50 years ago independently by several authors [1]. Later experimental manifestation of this effect was made [2]. However only Andrei Gaponov had recognized how promising is this idea for millimeter wave band. He and his students have started the wide theoretical and experimental studies of CRM effect. The gyrotron version of CRM became the most fruitful and the prospective because gyrotron is less sensitive to the thermal velocity spread of the electron beam. At the end of 1960-s the first experimental gyrotrons capable to generate significant power (tens of kW) in millimeter waveband were built by Gaponov's team [3]. The task to demonstrate this power in a real experiment appeared to be urgent. There was proposed on the basis of a theory of a new nonlinear effect of self-focusing em waves in plasma [4] to arrange first experimental observation of this effect. Successful experiment was completed [5] with the use of specially designed and manufactured gyrotron (wavelength 5mm, 12 kW, 0.4 msec pulse duration), that was later described in [6]. After presentation of this experiment Victor Golant and Vladimir Alikaev proposed to use gyrotrons for electron-cyclotron heating of plasma (ECH) in tokamaks FT-1 at Ioffe Institute and TH-3 at Kurchatov Institute.

Initially the ECH experiments were based on a scheme of linear transformation of extraordinary wave launched from an inner side of torus-region of high magnetic field [7]. The ECH activity was additionally stimulated when the possibility was shown to use for ECH an ordinary wave at the fundamental electron cyclotron frequency that can be launched from the external side low magnetic field of torus [8].

The first industrial gyrotron aimed for ECH experiments was built in USSR by industrial company "Salut" about 35 years ago. In the late 1970s several famous industrial companies in USA, Europe and Japan joined the gyrotron development. Unfortunately the progress in the field and the rate of gyrotron practicing were rather slow that strongly reduced the initial level of interest to gyrotron business. Only four companies have survived in this field.

During last 15 years the situation became more optimistic. The plasma physics community has already taken advantage of gyrotron applications in magnetic fusion devices and in development of different kind of dense plasma sources. Two very advanced types of radars were built in Russia and USA basing on gyroamplifiers. Many other prospective gyrotron applications are under development but only a few of them already came out from the lab.

In my talk I'll limit myself by the survey of the current status of development gyrotrons with a megawatt power level that are first of all interesting for magnetic fusion experimental program. Additionally I'll consider a physical basis of some of the most advanced gyrotron applications. The choice of examples is predetermined to some extent by personal bias of the author.

## 1. Gyrotrons with a megawatt power level

Modern advanced gyrotrons are capable now to generate megawatt RF power level in a long pulse or cw regime in a frequency range (30 – 200) GHz. Megawatt gyrotron consist of a magnetron injection gun forming an electron beam with helical trajectories of particles (typical gun voltage 70 – 100 kV, current 30 – 50 A, pitch factor 1.2 – 1.4), electron beam tunnel, oversized cavity operating at high order mode, efficient quasi-optical mode converter, output window and collector. At the megawatt power level most of gyrotron subassemblies have to operate at thermal loads close to their limits. Such regimes of operation are secured by the following principal steps in gyrotron development [see, for example [10, 11].

- efficient and stable operation was demonstrated at very high order volume cavity modes ( for example, $TE_{25.10}$ or $TE_{31.12}$), that allows to solve the problem of thermal cavity loading;
- recuperation of the remaining after generation energy of electron beam at the collector with a voltage depression;

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- design of the advanced built-in mode converter providing a strongly reduced level of stray radiation ( up to 2-3 percents of the generated power level) ;

- use of output barrier window made from artificial CVD diamond disc.

The list of the most remarkable last time achievements of gyrotron development includes the following results:

- EU team development and industrial production of the series of megawatt cw gyrotrons for stellarator W-7 X( 140 GHz, 0.92 MW, 1800 sec , efficiency 45 % ) [12].

- JAERI development of megawatt gyrotron for ITER (170 GHz, 1.0 MW, 800 sec, efficiency 55%) [13].

- development of the industrial gyrotron prototype for ITER (170 GHz, 1.0 MW/116 sec; 0.83 MW/203 sec; efficiency 53%; pulse duration is limited by the current capability of test stand) [14].

- IAP/Gycom construction of a gyrotron for stellarator L-2 with a record value of efficiency 70% (75GHz, 800 kW, 0.1 sec) [14].

One of the advanced gyrotron concepts that is under development by the gyrotron community is a multi-megawatt tube [14-16]. The most ambitions is the European team project for170 GHz, 2 MW coaxial gyrotron for ITER [15]. We selected a more conservative and a possibly more reliable way based on a very efficient cavity cooling system demonstrated in our megawatt gyrotrons. The new gyrotron mock-up with conventional cylindrical cavity designed for the power level 1.5 MW (operating mode TE 28.12) has demonstrated in the first short pulse (0.1sec) tests 1.44 MW power with efficiency 41% [14].

Another very attractive for plasma experiments project is connected with development of a gyrotron capable to operate at several frequencies. The main problems in the development of such gyrotron are to provide efficient operation at different modes with chosen frequencies, efficient conversion of the different modes into Gaussian beam, design of a broadband or tunable barrier window.

Initially these problems were successfully solved for dual frequency case – for these two frequencies the diamond disc of the barrier window is resonantly transparent. Two gyrotrons with parameters 105 GHz, 0.7MW, and 140 GHz, 0.9 MW, operating at 10 sec pulses were delivered for tokamak Asdex-UP [17].

The tube aimed to operate at 4 frequencies (104.9; 117.4; 127.4; 139.5 GHz) provided with a specially designed internal mode converter and additional polarizer mirror was successfully tested at pulses 100 msec showing design parameters (1.0MW at 140 GHz and 0.8 MW at other frequencies). Now the gyrotron equipped with a diamond Brewster window is under full program of tests for 10 sec pulse operation.

## 2. Nonlinear quasi-optics.

Creation of gyrotrons reveals new possibilities for experimental investigations of quasi-optical mm-wave beams interaction with matter. I'll mention some interesting works in this field:

- First manifestation of the em wave self focusing in plasma [5 ]

- Theoretical and experimental study of a freely-localized gaseous discharge in the focused mm-wave beams [18, 19].

These works have found the new nonlinear branch of low temperature plasma physics having various applications – from new type of technology of diamond films and discs production [20] up to creation artificially ionized layer in upper atmosphere for recovering ozone holes and freon parification [21].

- Effect of the wave phase conjugation of the mm-wave beam based on the nonlinearity connected with the saturation of the molecule rotational transitions in gas [22].

- A classical model of the parametric effect of electromagnetically induced transparency (EIT) within the line of resonance absorption of em wave in the medium [23]. On its basis the EIT effect for em-waves at frequencies of electron-cyclotron resonance in plasma is analyzed. Similar to the analogous quantum scheme the EIT window in plasma is characterized by strong deceleration of EC-wave and excitation of intensive plasma wave capable accelerate ion beams [24].

## 3. Electron cyclotron (EC) plasma heating and current drive in magnetic fusion devices.

The fusion experiment became the primary customer of gyrotron development starting with appearance of first research devices. The main advantages of using EC-waves in magnetic fusion devices were already formulated in [8] (see, also [9]. They include a rather simple design of antenna system to form quasi-optical wave beams, high efficiency of absorption in a wide temperature range, possibility to control local energy deposition, negligible (as a rule) role of nonlinear effects. Later it was shown [25] sufficient efficiency of EC current drive.

Today the majority of tokamaks and stellarators have been equipped with modern gyrotron complexes. The largest of them are the TCV tokamak complex (EPFL, Lausanne) with 9 half-megawatt gyrotrons and the D-IIID complex (General Atomics) comprised by 6 gyrotrons with their power level about 1MW.

The most important results in the area of stable plasma confinement in toroidal setups which have been obtained using mm-waves are results of experiments on neoclassical tearing mode

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stabilization in tokamaks Asdex-UP and D-IIID [26,27], realization of stationary regimes with completely non-inductive current in the TCV tokamak [28] and heating of plasma with above-critical density in the stellarators and tokamaks using excitation of Bernstein waves [29]. A new stage in gyrotron development is connected with the construction of ITER and W-7X where ECH is now considered as a leading method of heating and current drive.

## 4. Development of high-density plasma sources

In terms of the technology of gaseous microwave discharges, the transition from traditional sources in the S and X bands to frequencies 30 GHz reveals the possibility to generate much denser plasmas in focused beams of mm-waves. Here, of great interest are sources of ion beams (ECRIS), in which EC resonance breakdown and microwave plasma heating are used to create ion beams with high charge states. Such sources serve as injectors in heavy nuclei accelerators, as well as in material surface modification. The experiments at IAP [30] proved demonstratively that the use of mm-waves made it possible to obtain ion beams with a much higher charge and current as compared with the existing sources. Currently several laboratories develop new-generation ECRIS using gyrotrons operating at the frequency of 28 GHz. One should note specially fabrication of such a heavy-ion injector for the Large Hadron Collider (CERN) and for the Beta Beam neutrino project.

One of the projects aimed at application of the high-pressure gas discharge is the research effort made at IAP to use mm-waves in a plasma reactor in order to grow polycrystalline diamond films by the method of deposition from the gaseous phase (CVD technology). Currently microwave plasma reactors that are used to produce optically transparent diamond films, employ microwave sources operating at the frequencies of 0.9 GHz and 2.45 GHz. The use of much higher frequency (30 GHz) and quasi-optical system forming the microwave beams should make it possible to remove limitations for the diamond film diameter, as well as eventually increase their growth rate. At the experimental set up the growth rate 9 micron/hour was demonstrated that is about 5 times greater than in conventional 2.45 GHz reactor [20].

## 5. Microwave processing of materials

Technological use of mm-wave energy has not yet come out of laboratories. However, the number of mm-wave systems designed specifically for such research is increasing in spite of their rather high cost.

Owing to the intermediate position of the mm-wave range on the frequency scale, this radiation can be used either as a quasi-optical wave beam or as a means to fed oversized applications where the microwave energy is spread over a large volume, like a conventional microwave oven. In the first case, intense wave beams can be utilized for surface treatment of materials. In the second, volumetric heating of materials is the primary basis for applications.

The following features of exploiting mm-wave energy are of great importance for technological applications;

- High capability of absorption mm-waves inherent in most non-metallic materials;

- High uniformity of electromagnetic field distribution in the applicator.

Several research centers (FZK, Germany: NIFS and University of Osaka, Japan: General Atomics and NRL, USA: IAP, Russia) are developing now mm-wave material processing technologies.

The list of the processes that are currently under investigation includes sintering of high performance structural electronic ceramics and composites, synthesis of inorganic powder materials, modification of oxide thin films, fabrication of reinforced glass, resin and rubber curing etc.[31,32].

Sintering of advanced ceramic materials is currently the most thoroughly studied high-temperature process employing gyrotron radiation. Of great interest is sintering of nano-structured materials, which is possible due to a very fast heating rate associated with volumetric absorption of mm-waves. Presumably enhanced plasticity of nanoceramics can be used beneficially in joining dissimilar ceramic materials for reduction of residual thermal stresses. This problem is very important for fabrication of functionally graded materials to be used, as thermal barrier coatings.

Another promising application of mm-wave energy is associated with rapid thermal processing of semiconductors. Experimental results on spike annealing of Si wafers in a gyrotron system at the frequency of 30 GHz demonstrate that mm-wave heating may be an alternative RTP technique for processing large-size wafers, which are in demand today for shallow junction formation.

The new example of microwave technology application was demonstrated in [33] where microwaves interaction with powder magnetite material was used for greener steel making. This process possibly could be attractive for iron industry because of essential reduction of carbon dioxide emission.

## 6. Miscellaneous

There is a large set of mm-wave application projects, all of them at the stage of predevelopment now. To list the most interesting ones: the project of transmitting energy by using Ka-band wave beams (which has been discussed for quite a long time),

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studies of generating gyrotron radiation harmonics aiming at creation of sub-mm radiation sources, proposals to use selective heating of molecules to enhance sensitivity of microwave molecular spectroscopy, studies of NMR signal enhancement using electron parametric resonance excitation by mm waves. Wide prospects for realization of such ideas are associated with development of frequency-tunable powerful mm and terahertz-wave sources.

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