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Development in Russia of High Power Gyrotrons for Fusion

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1. Introduction

Electron cyclotron systems of fusion installations are based on powerful millimeter wave sources – gyrotrons, which are capable to produce now microwave power up to 1 MW in very long (hundred seconds) pulses. The paper presents the latest achievements in development at IAP/GYCOM of MW power level gyrotrons for fusion installations. During last years several new gyrotrons were designed and tested at IAP/GYCOM [1-4]. Among them are a new version of 170 GHz gyrotron for ITER and multi-frequency (105-140 GHz) gyrotrons for Asdex-Up. All these gyrotrons are equipped with diamond CVD windows and depressed collectors. The list of gyrotrons developed and tested in last years is shown in Table I.

TABLE I: LIST OF RUSSIAN GYROTRONS DEVELOPED AND TESTED IN 2004-2006

Frequency	**Power**	**Pulse, sec**	**Note**
170 GHz	0.9 MW 1.1 MW* 0.5 MW* 0.35 MW*	20 0.1* 140* 300*	For ITER project *Improved QO converter
170 GHz	1.44 MW**	0.1**	**New design, TE28.12
105/140 GHz	0.8 - 0.9 MW	10	2 tubes delivered to ASDEX-Up
105 -140 GHz* 105-140 GHz**	0.7 – 0.9 MW 1.2 MW	0.1 10^{-4}	* Brewster ceramic window, 11 frequencies, **New QO converter
84 GHz	200 kW 500 kW	1000 - 3900 10	Delivered to LHD
75 GHz	0.8 MW	0.1	Delivered to G Ph I 70% eff. , 98% Gaussian
68 GHz	0.5MW	1	5 tubes , delivered to SWIP

2. 170 GHz gyrotron for ITER

The industrial gyrotron prototype for ITER operates at very high order mode $TE_{25.10}$ which allows efficient cooling of the cavity walls. The calculations show the possibility of 1 MW microwave generation in the cavity in CW regime. Potential depression at the collector provides power load on the collector surface essentially (up to two times) lower than without electron energy recovery. A new efficient mode converter is used in the last gyrotron version. Additional (so called relief) ceramics window is applied in the gyrotron in order to diminish power of stray radiation in the tube. The tests were performed at a specially prepared test stand at Kurchatov Institute. The following gyrotron output parameters were demonstrated so far in many pulses: 0.9MW/20 sec and 0.7MW/ 40sec, 0.5 MW/120 sec, 0.35 MW/300sec. The tests continue.

One of advanced gyrotron concepts that is under development by gyrotron community is a multi-megawatt tube. The most ambitious is Europian team project for 2 MW coaxial gyrotron [ ]. Being limited in funding we selected more conservative way. The very efficient operation of the cavity cooling system demonstrated in our megawatt gyrotrons opens the way to increase the generated power by the gyrotron with traditional cylindrical cavity of slightly increased size. Such kind of project is under IAP/GYCOM development first experiment is carried out with a short-pulse (0.1 sec) mock-up of 170 GHz gyrotron with 1.5 MW output power. The gyrotron operates at $TE_{28.12}$ mode. The main design parameters of the gyrotron are shown in Table II.

TABLE II: MAIN PARAMETERS OF THE GYCOM/IAP 1.5 MW GYROTRON

Cylindrical Cavity Mode	**TE 28.12**
Cavity diameter	41.5 mm
Peak thermal load for ideal copper	< 1.35 kW/cm^2
Beam voltage	100 kV
Beam current	50 A
Pitch-factor	1.2
Efficiency (without DC)	30-33 %

The aims of the experiments are to demonstrate gyrotron operation at the design power and to check an internal quasi-optical converter. The advanced converter produces an output beam with theoretical Gaussian mode content of 98% and diffraction losses as little as 2-3 %. In the first tests of the gyrotron the power 1.44 MW was demonstrated with efficiency of 41%.

3. Dual- and multi-frequency gyrotrons

A gyrotron capable to operate at several frequencies is very attractive for plasma experiments. The use of step-tunable gyrotrons can greatly enhance flexibility and performance of ECRH/ECCD systems due to larger accessible radial range, possible replacement of steerable antennas, higher CD efficiency for NTM stabilization. Even two-frequency gyrotrons can bring real improvements of the system. Russian team with collaboration with German partners develops a dual- and multi-frequency gyrotrons for 105-140 GHz frequency range [5].

The main problems in development of multi-frequency gyrotrons are to provide:

- efficient gyrotron operation at different modes,
- efficient conversion of different modes into a Gaussian beam,

- broadband or tuneable window.

The multi-frequency gyrotron under development is based on a diode type of electron gun. This resulted in the change of optimal electron beam radius (approximately as $f^{1/3}$, f is gyrotron frequency) and consequently in the necessity of an additional collector coil correcting position of the beam on the collector surface. Two window concepts are in consideration: Brewster window and two-disc adjustable window. Both concepts imply the use of CVD diamond discs. The Brewster window is very attractive because of very wide instant frequency band, however the converter design in this case is more complicated.

Dual-frequency gyrotron has a cavity in which $TE_{22.8}$ and $TE_{17.6}$ modes correspond to 140GHz and 105GHz operation, output window based on diamond disk transparent for both frequencies at its 1.8-mm thickness and collector with additional coil sweeping electron beam over its surface. In the two tested dual-frequency gyrotrons, power in the output Gaussian beam exceeding 0.9MW at 140GHz (total radiated power over 1MW) and 0.7MW at 105GHz (radiated power of 0.8MW) was attained at specified 10-s pulse duration. Stray radiation, which was measured for both operating frequencies as 12-15% of generated power, is not dangerous at 10-s pulses from the viewpoint of any gyrotron part overheating but represents the essential loss of power. A new internal mode converter consisting of a synthesized dimpled-wall waveguide launcher and four shaped mirrors recently has been developed for the dual frequency gyrotron and it reduces the power fraction carried away by stray radiation to about 3%.

A possible scheme of an adjustable two-disc window for a multi-frequency gyrotron is shown by FIG. 1.

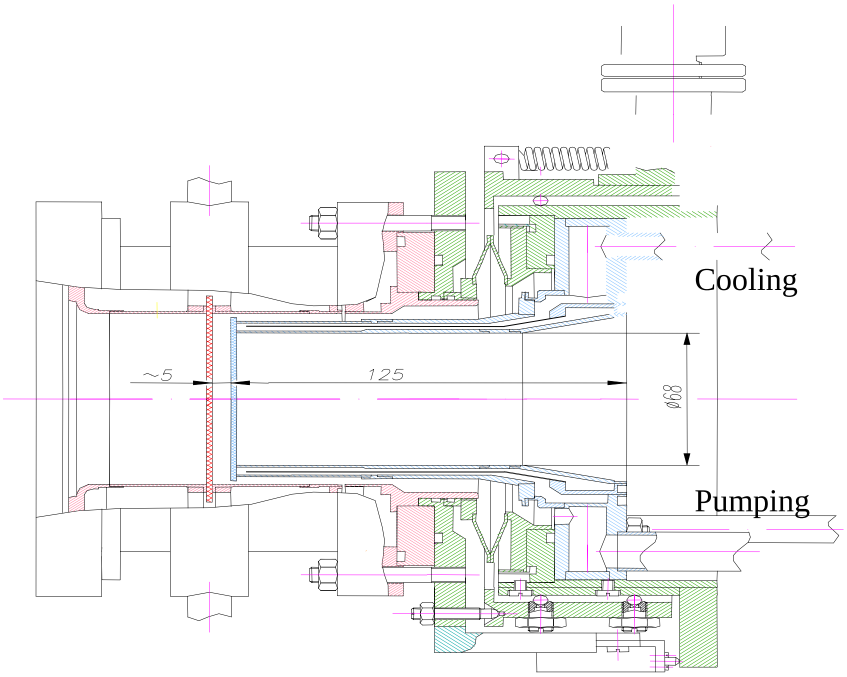

FIG. 1. Double-disc window for a multi-frequency gyrotron. The window consists of a single-disc window, a carrier unit with a flexible copper cuff for adjusting of the second disc, tunable unit with the second disc.

In parallel to a double-disc development a Brewster-angle window is under study. Such a window is very attractive since it has very wide instant frequency band.

To analyze the gyrotron behavior with a Brewster window a special short pulse gyrotron was fabricated and tested. The gyrotron was optimized to operate at TE22.10 mode at 140 GHz frequency. The cryomagnet and the design of an electron gun allow gyrotron operation in the frequency range 100-145 GHz.

A circular BN ceramic disc with 120 mm diameter was used for the window (FIG. 2). To provide the required oblique wave beam incidence a couple of mirrors near the disc are applied. The operating modes have different caustic radii and hence that results in slightly different angles of wave beam direction in the horizontal plane. Therefore a polarizer mirror changing polarization from the horizontal to the vertical one is implemented. The use of the latter mirror allows one to provide nearly the same angle of incidence of the wave beam on the window for all frequencies. Note that the BN ceramics has rather close refractive index 2.16 to the index of CVD diamond material (2.38) used for advanced barrier windows and the test results definitely can be used for design of long pulse tubes.

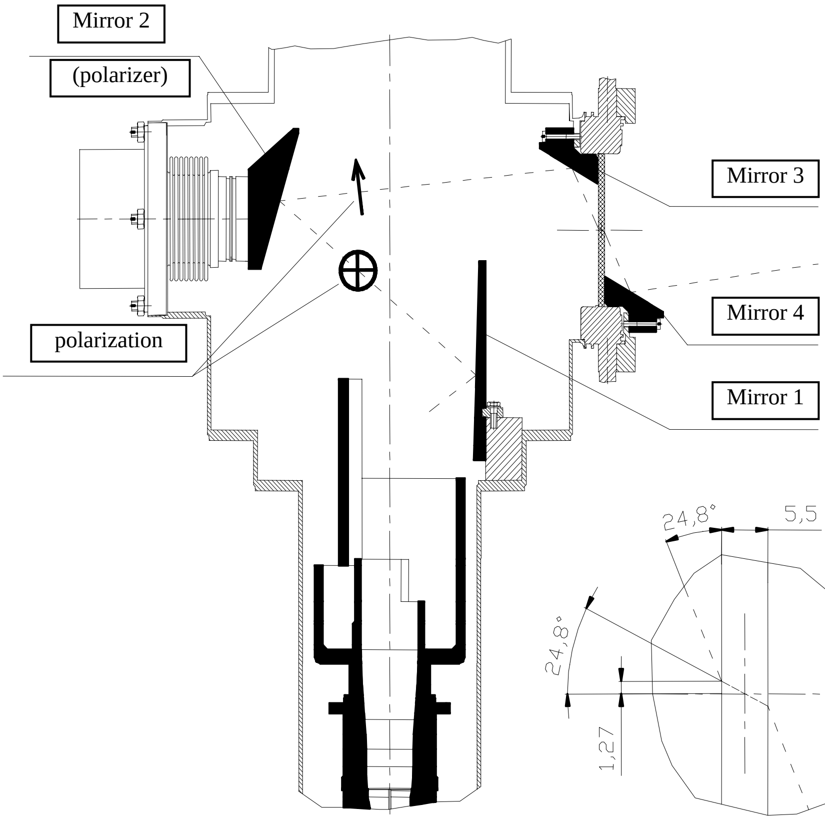

FIG. 2. Schematic of the gyrotron output unit. Dashed line shows the trajectory of the output wave beam from the cavity (at the bottom) through the window (right side).

During the test of the gyrotron 11 modes were easily excited: TE23,10 (143.08 GHz), TE22,10 (140.09 GHz), TE21,10 (137.07 GHz), TE22,9 (132.08 GHz), TE20,10 (134.08 GHz), TE21,9 (129.07 GHz), TE21,9 (129.07 GHz), TE20,9 (126.12 GHz), TE20,8 (118.06

GHz), TE19,8 (115.11 GHz), TE18,8 (112.13 GHz), TE18,7 (104.10 GHz). Gyrotron output power 0.8 MW was limited by the applied power supply. The maximal pulse duration (0.15ms) was defined by overheating of the ceramics window. Change of ceramics disc to the CVD diamond one would allow gyrotron operation in long (or CW) pulses.

4. Some other development results

During last 3-4 years some supplementary interesting experiments and studies were performed which were very important to understand processes in gyrotrons and to enhance gyrotron parameters. There is no possibility to observe all of them and here we just mention very few things.

4.1. High-efficiency gyrotron

A megawatt power gyrotron with a very high efficiency up to 70% was tested. The 75 GHz gyrotron is equipped with a single-stage depressed collector. The tests were performed for electron beam energy 77keV = (52keV + 25keV). Gyrotron power and efficiency on electron current are shown by FIG. 3.

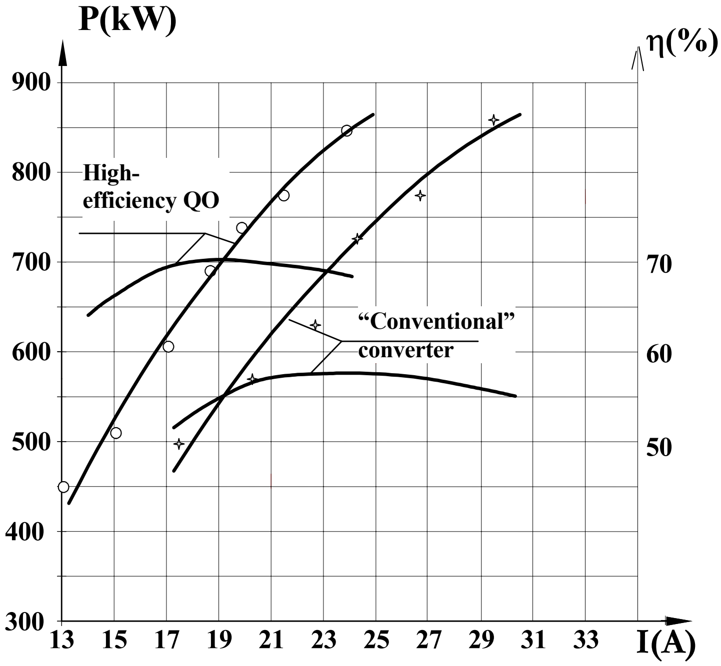

FIG. 3. Power and efficiency of 75GHz gyrotron versus current for the tube equipped with conventional and high efficiency quasi-optical mode converter.

Since the gyrotron efficiency was higher than usual for a megawatt power tube the gyrotron was carefully analyzed. It was found that this high efficiency resulted from two factors: very good electron beam quality at currents around 20 A and very good performance of the mode converter providing near 98% Gaussian mode content in the output beam and only about 1 % diffraction losses inside the tube. It is important to note that the gyrotron was fabricated by the use of industrial technology and tested at pulse duration of 0.1 seconds which defines in general the tube behaviour at longer pulses.

4.2. CVD diamond window growing and brazing

The windows based on a CVD diamond are very expensive but today they are the only option for a megawatt CW window. Calculations show that the windows based on the best discs are capable to transmit even 2-3 MW power. Diamond windows allow edge cooling of discs by water at room temperature. This makes their use much more comfortable as compared with previous window schemes operating at cryogenic temperatures or using some sophisticated coolants. Diamond discs for gyrotron windows must be brazed to metal constructions with a high temperature alloy in order the tube can pass the process of baking out.

Last years significant efforts were done by IAP/GYCOM in order to solve the whole scope of problems associated with the use of CVD diamond windows in gyrotrons: growing of discs (FIG. 4), their cutting and polishing, and then high-temperature brazing and mounting to a tube [6].

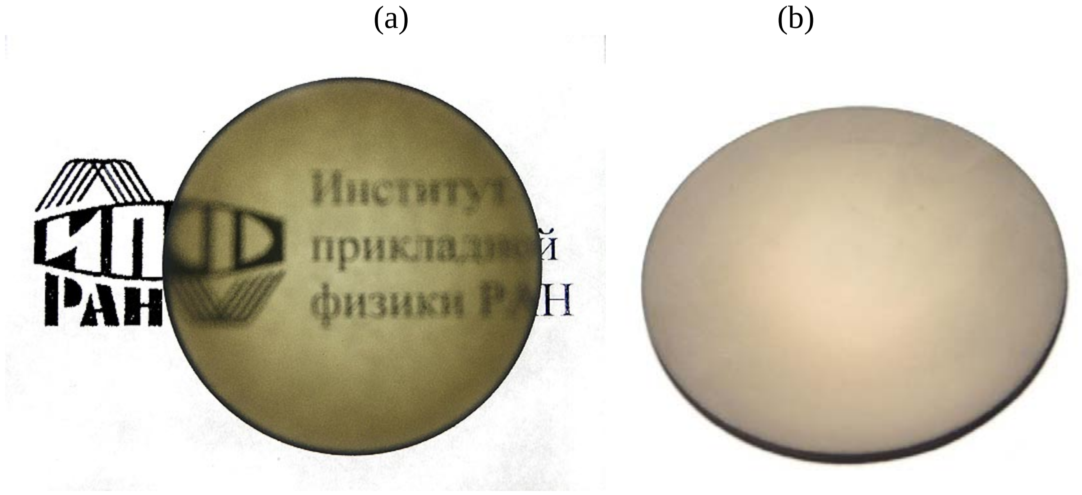

FIG. 4. IAP diamond disk of 75 mm in diameter: a - as grown (1.6 mm thickness at the center),
b – the disc after polishing -1.35 mm thickness.

Two setups for growing diamond discs have been put into operation: the first one bought from Aixtron company, Germany (but without technology) is based on a magnetron and conventional receipts for discs growing, the second one is an experimental gyrotron based setup operating at high frequency 30 GHz and it aims to increase the disc growth rate.

The first discs grown at IAP have acceptable mechanical and electrical parameters (see, for example, FIG. 5). The IAP/GYCOM discs have been successfully brazed at near 800°C temperature to metal constructions and will be tested soon with high-power gyrotrons.

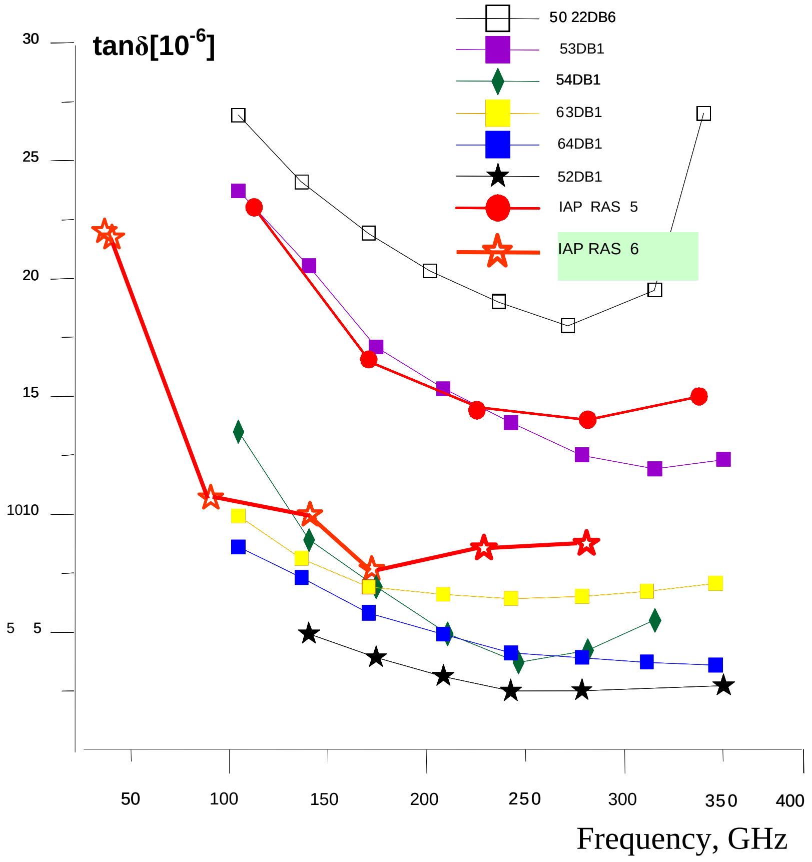

FIG. 5. Loss tangent for some De Beers and IAP/GYCOM CVD diamond discs.

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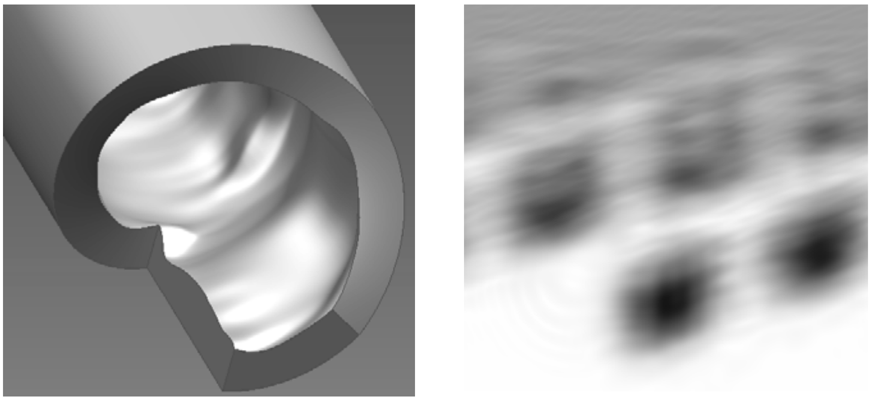
4.3. Advanced methods for calculation of gyrotron microwave systems

Last years a big progress was demonstrated in development of numerical methods for analysis and synthesis of oversized gyrotron systems: cavities, up-tapers and quasi-optical mode converters.

One particular important task is a design of gyrotron mode converter which transforms high-order operating mode into a Gaussian wavebeam with minimal diffraction, polarization and Ohmic losses. For one chosen mode the amount of mentioned losses can be brought down to a very low level about 1%. The analysis and synthesis methods are based on scalar integral equations [7] or system of coupled waves [8].

Advanced methods allow also optimization of the systems for many frequencies simultaneously. For example, optimization of the mode converter for a multi-frequency gyrotron results in low diffraction losses (2-3%) for 10 gyrotron operating modes in the range of 105-140GHz.

The optimized launchers look more sophisticated (see FIG. 6) than the conventional ones and their fabrication requires more efforts, nevertheless no doubts that new advanced tubes will be equipped with such quasi-optical components.



(a) (b)

Fig.6. Exaggerated (surface distortion increased about 10 times) inner surface of the launcher for TE25.10 mode converter (a); b - current distribution on the unrolled wall surface (azimuth coordinate is shown as the horizontal one). It is seen that just before its launch the wave beam has near Gaussian spatial distribution.

5. References

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