Invited Paper

Design and experimental study of a high power 140 GHz, $TE_{22.6}$ mode gyrotron for EAST

Bentian Liu [*], JinjunFeng, Zhiliang Li, Yang Zhang, Efeng Wang, and BoyangTian
National Key Laboratory of science and technology on Vacuum Electronics,
Beijing Vacuum Electronics Research Institute, Beijing, China.
[*] Email: liubentian@hotmail.com

(Received 22 December 2016)

Abstract: The parameters of a 140*GHz* $TE_{22.6}$- mode gyrotron are presented in the article. A single-anode magnetron injection gun (MIG) and the cylindrical resonant cavity operating in the $TE_{22.6}$- mode are designed for the 140*GHz* gyrotron with output power at axial direction. The theoretical efficiency of the gyrotron with operating voltage 80*kV*, electron current 40*A* is about 42%. The gyrotron has been fabricated and tested. In short pulse operation (~70 microseconds) an output power of ~150*kW* with frequency of 140.36*GHz* is obtained in operating voltage 70*kV*, electron beam 20*A*.

Keywords: Gyrotron, High power, ECRH, EAST, Nuclear Fusion, ITER.

doi: 10.11906/TST.131-140.2016.12.13

I. Introduction

Energy for next generations is a crucial issue due to limited availability of fossil fuels. Fusion energy comes up as a potential and clean energy source for next decades. Fusion reactions require plasma at very high temperatures of $\sim 1\times 10^{9}$ ℃. To achieve such a high temperature, different plasma heating systems are used simultaneously. Electron Cyclotron Resonance Heating (ECRH) is one of the effective heating methods, which requires high frequency (28-170*GHz*), high power continuous wave (CW) RF-sources [1]. Gyro-oscillators (gyrotrons) have been proven to be highly efficient sources of coherent mm-wave radiation with long-pulse capabilities. Among the advantages of gyrotrons are that they use moderate voltages ($\lesssim 100kV$) and that they may be placed well away from the torus. With quasi-optical techniques or with a waveguide system, the generated RF power can be transmitted over tens of meters and launched to the plasma with a relativity simple antenna system.

The gyrotrons have been used successfully for ECRH and Electron Cyclotron Current Drive (ECCD) experiments [2]. For the Wendelstein 7-X stellator at Greifswald [3], ECRH is planned as the main heating system. A 10*MW* system, making use of 1-*MW CW* gyrotron at 140*GHz*, is under development.

EAST which is the abbreviation for Experimental, Advanced, Superconducting and Tokamak, denotes a medium size tokamak facility with a major radius of 1.85 *m* and a minor radius of 0.45 *m* at Institute of Plasma Physics, Chinese Academy of Sciences in China.For the EAST,the 140 *GHz*/4 *MW* ECRH project is under development [4, 5].

The $TE_{22.6}$- mode gyrotron operated at Forschungszentrum Karlsruhe at a frequency of 140*GHz* has been investigated. With a collector depression voltage of 35 *kV* for energy recovery, efficiencies of 60% at 1.6*MW* were obtained [6]. And the demonstration of the 140 *GHz* $TE_{28.8}$- mode gyrotron developed for the Wendelstein 7-X ECRH system by a European team was successful. Output powers up to 1.15*MW* for short pulses and 1*MW* for 10*s* pulses were achieved. At the 640*kW* power level, pulse lengths up to 140*s* were demonstrated [7]. A 140*GHz* 1*MW* $TE_{28.7}$- mode gyrotron for the Wendelstein 7-X stellarator has been developed at CPI. Peak output powers up to 930 *kW* at 34% efficiency have been demonstrated at 5*ms* pulse lengths. At 25*A* beam current and 500 *kW* output power, pulse lengths up to 700*s* in duration were achieved [8].A 3*cm* gyrotron and a second harmonic 8*mm* gyrotron had been fabricated at BVERI in 1981 and had been successfully applied to the HT-6M Tokomak in the Institute of Plasma Physics Chinese Academy of Sciences. Among which the second harmonic 8*mm* gyrotron produced the peak power of 40*kW* and pules length of 5*ms*.

After the ITER plan is implemented since 2007, the theoretical and experimental researches on high-power gyrotron are developed in BVERI [9, 10] to meet the urgently need of the high-power millimeter-wave source used in the EAST and HL-2M Tokomak.

The gyrotron fabrication development program in BVERI aims at the design, construction and testing of high power gyrotrons at 140*GHz* with long-pulse or CW operation. The first step towards these goals has been performed with completing the design and fabrication of gyrotron at 140*GHz*. The second step is to test the gyrotron and the next gyrotron with quasi-optical mode converter will be fabricated.

In this paper, the design of a 140*GHz* high-power gyrotron is presented with the operating mode of cylindrical mode$TE_{22.6}$ and single-anode magnetic injection gun. And the performance of the gyrotron is carried out. The high-power 140*GHz* gyrotron under development will be used for EAST and HL-2M.

II. Design of 140 *GHz* gyrotron

The designed gyrotron is expected to achieve more than 500*kW* output power at 140*GHz*. The design parameters are summarized in Table 1.The operating mode of the $TE_{22.6}$ mode at 140*GHz* in conventional cylindrical cavity is adopted. A diode-type MIG and axial output window were used in the gyrotron. A nonlinear up-taper waveguide links the interaction cavity to the larger diameter collector of radius 100*mm*. The output power of the gyrotron is transmitted through axial waveguide system. It operates at an accelerating voltage of around V_b=80*kV* between the cathode and body and a beam current of I_b=40*A*. Between MIG and interaction region, a periodic structure composed of a stack of copper and absorbing ceramic rings with a thickness of 5*mm* has been implemented to suppress spurious oscillations in the beam tunnel. The prototype is shown in figure 1. A uniform magnetic field of 5.56*T* is required at the interaction cavity for better efficiency and power. For 140*GHz* gyrotron, the magnetic field is generated with a 16*cm* diameter warm-bore superconducting magnet.

Tab. 1 Design parameters of the 140 *GHz* gyrotron

Frequency	140 *GHz*
Operating mode	$TE_{22.6}$
Type of the electron gun	Single-anode MIG
Operating voltage	70~80 *kV*
Beam current	35~40 *A*
Velocity ratio	1.3~1.5
Radius of cavity	15.55 *mm*
Length of cavity	16 *mm*
Diffraction Q	1286
Magnetic field	5.56 *T*
material of window	sapphire

Fig. 1 Prototype of the 140*GHz* gyrotron

MIG Design

The single-anode MIG was designed to operate at a nominal accelerating voltage of 80*kV* and a nominal beam current of 40*A*. The average cathode radius is 38.4 *mm* and the average cathode loading is 3.3A/cm^2at 40*A* beam current. The optimized MIG can produce the electron beam with perpendicular velocity spread of 1.9% at the nominal velocity pitch factor of 1.45, and the axial velocity spread of 4.2%. The ratio of the magnetic field at the cathode to the magnetic field in the interaction cavity is 18.5. *A* summary of electron gun design parameters are shown in Table 2.

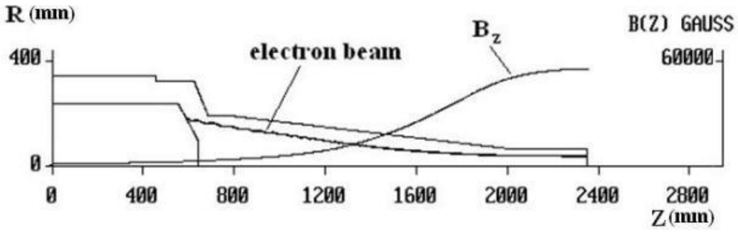

Fig. 2 Schematic configuration of the single-anode MIG and the electron trajectory

Fig. 3 Photograph of the insulation ceramic and cathode of the single-anode MIG

Figure 2 gives electron trajectory and design shape of the MIG, which can produce electron beam with the guiding center of ~8 *mm* corresponding to 0.515 times cavity radius (Rw). The figure 3 shows the photograph of the insulation ceramic and cathode of the MIG.

Tab. 2 Design parameters of the single-anode MIG

Accelerating Voltage	80 *kV*
Beam Current	40 *A*
Cathode Radius	3.54 *cm*
Cathode Half-angle	58°
Average Cathode Loading	$3.3A/cm^2$
Guiding Center Radius,R_e	$0.515*R_w$
Perpendicular Velocity Spread	1.9%
axial velocity spread	4.2%
Average pitch angle α	1.45
Magnetic Field, B_0	5.56 *T*
Magnetic Copression Ratio	18.5

Design of interaction cavity

One major problem of high-power high-frequency gyrotrons is the limitation of the pulse length due to ohmic heating of the cavity. For this reason high-power, high frequency gyrotrons usually operate in high order modes with a cavity with large diameter, and hence large surface area. A disadvantage of such a highly overmoded cavity is mode competition due to higher mode density. Conservative estimates assume that single mode operation in ordinary cylindrical cavities is possible for $D/\lambda \lesssim 15 \sim 20$ (D: diameter of cavity, λ: vacuum wavelength) [11].

For a given frequency Fre and mode (TE$_{m,p}$), the corresponding cavity diameter can be calculated to be $D/\mathrm{mm} = 95.427 * \frac{\chi'_{mp}}{2*\mathtt{Fre/GHz}}$, ($\chi'_{mp}$ is the n^{th} zero of J'_m, and J'_m =derivative of the Bessel function of order m). For the TE$_{22,6}$ mode at $140GHz$, one obtains $\mathrm{D} = 31.1mm$ or $D/\lambda = 14.5$ which is the value for single mode operation.

The strength of the interaction is characterized by $J^2_{m\pm1}\left(\chi'_{mp}\, R_e/R_w\right)$, where "+"is for counter-rotating modes,"-"is for co-rotating modes with respect to the rotation of the electrons in the magnetic field, and is the beam radius. The eigenvalues of the operating mode TE$_{22.6}$ and its neighboring modes are listed in Table 3. The potential competing modes are those whose eigenvalues approaches that of main mode. From this table, we see that probable competing modes are TE$_{18.7}$, TE$_{19.7}$, TE$_{21.6}$, TE$_{24.5}$ and TE$_{25.5}$.In figure 4, the coupling coefficient (CoCo)

$$\mathrm{CoCo} = J^2_{m\pm1}\left(\chi'_{mp}\frac{R_e}{R_w}\right)/\left[\pi\left(\chi'^2_{mp} - m^2\right)J^2_m\left(\chi'_{mp}\right)\right]$$

is shown for theTE$_{22,6}$- mode and five of the most dangerous competitors above.

Tab. 3 Mode eigenvalues for operating mode and others

TE$_{mp}$	p=5	6	7
m=18	37. 1605	40. 707	44. 1783
19	38. 375	41. 9445	45. 4356
20	39. 5846	43. 1766	46. 6871
21	40. 7889	44. 4028	47. 9331
22	41. 9877	45. 6243	49. 1733
23	43. 1827	46. 8408	50. 4088
24	44. 3727	48. 0528	51. 6393
25	45. 5593	49. 2603	52. 8653
26	46. 7418	50. 4633	54. 0868

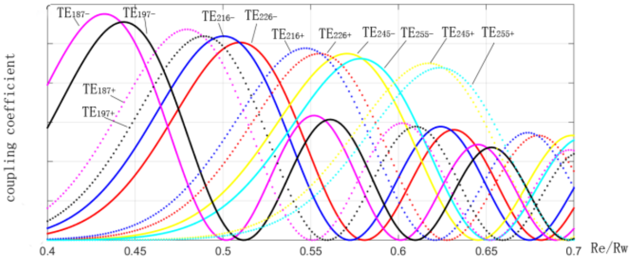

Fig. 4 Coupling coefficient (CoCo) for operating mode and potential competing modes together with beam position (linear scale, arbitrary units).

The electron beam should be placed on the first maximum of theTE$_{22,6}$- order to ensure efficient interaction and to prevent electrons from interacting with modes which are more concentrated at the wall of the cavity. Within the thickness of the beam ($\approx \lambda/8 \approx 0.267\ mm$ distribution of guiding center radii) it is a considerable overlap with neighboring modes, especially with the$TE_{19.7+}$ mode and $TE_{21.6-}$.The frequency deviation of the $TE_{21.6-}$ mode is -3.7 GHz, so competition with this mode in certain parameter regions can be avoided by adjusting magnetic field. For competing mode $TE_{19.7+}$, the beam position of 0.515*Rw is away from the maximum position of the beam-wave interaction so this mode is difficult to be excited. It is Note that this mode is counter-rotating, whereas the design mode is co-rotating.

The potential drop in the resonator associated with the space charge effect of the electron beam, approximately given by $\Delta\Phi_w = -60\Omega I_b \ln(R_w/R_e)/\beta_z$ is in the range of 4-5.6kV at $V_b = 80$ kV, $\alpha = 1.45$, and $I_b = 40\text{A}$. The limiting current [12], which may be calculated by $I_{lim} = 511\text{kV}\,\gamma_0\left[1-(1-\beta_{z0}^2)^{1/3}\right]^{3/2}/[60\Omega\ln(R_w/R_e)]$ is about 68A**,** which is well above the desired beam current. However, taking velocity spread into account may reduce this value [13].

A weakly tapered conventional cavity resonator is selected as the interaction cavity of 140*GHz* gyrotron. The model is illustrated in figure 5. The main body of the resonator consists of three sections — a uniform section (region B) located between points z_2 and z_3, a conical section (region A) connected to the left, and a horn section (region C) connected to the right.

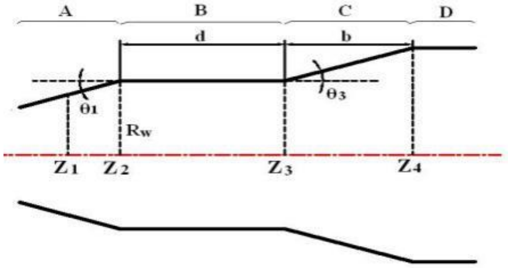

Fig. 5 Model of the interaction cavity resonator

The resonant frequency, diffraction Q and the RF field profile have been optimized to improve the efficiency and solve the problem of mode competition. The obtained parameters are shown in table 4.

Tab. 4 Designed parameters of interaction cavity

Operating mode	$TE_{22.6}$
Input radius	14.3 *mm*
Mid-section radius	15.55 *mm*
output radius	16.8 *mm*
Length of input section	14 *mm*
Length of mid-section	16 *mm*
Length of output section	25.7 *mm*
Angle between input and mid-section	5 °
Angle between output and mid-section	3 °
Diffraction Quality-factor Q_D	1286

The simulation result is given in figure 6. The operating parameters are the beam voltage of 80kV, beam current of 40*A* and velocity ratio of 1.45. The predicted efficiency is about 42% corresponding to saturated peak power 1.3*MW* while the velocity spread of electron beam is not considered.

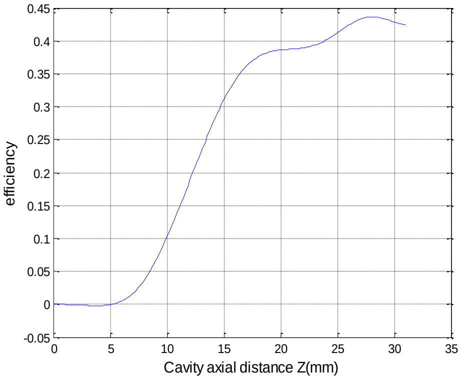

Fig.6 Theoretical efficiency of the140*GHz* gyrotron

Output window design

To define the appropriate concepts for the development of ~1 *MW*, CW mm-wave windows one has to compare the thermophysical, mechanical, and dielectrical parameters of possible window materials related to the load-failure resistance and the power-transmission capacity at different temperatures [14]. The features of beryllia, boron nitride, silicon nitride, sapphire, Au-doped silicon, SiC, and chemical vapor deposition (CVD) diamond are given in [1]. Currently, CVD diamond is attractive due to its good mechanical properties and is the only material for simple, edge-cooled (water) single-disk 1-2*MW*, CW gyrotron windows [15].

For the first-step of the gyrotron devices, an edge-cooled single-disk sapphire window is used for the present design. The thickness for the window disk is

$$d = \frac{n}{2}\frac{c}{f\sqrt{\varepsilon_r}} \; (\mathrm{n} = 1, 2, 3, \dots)$$

Where d is the disk thickness, f the frequency, c the speed of light, and the relative dielectric constant of the material. For the frequency 140*GHz*, disk thickness of the window with diameter 10*cm* is 1.39*mm* $(n = 4)$ to ensure minimal reflections and seal-strength. Figure 7 shows the VSWR of window and supports the successful operation at 140*GHz* for the present design. Figure 8 gives the edge-cooled single-disk window.

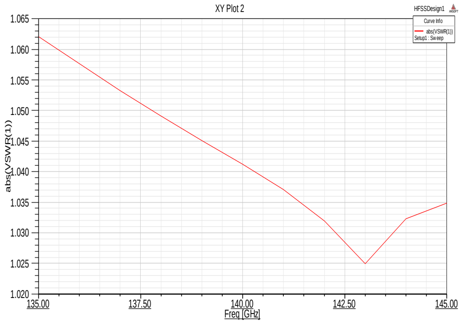

Fig.7.Calculated VSWR of the RF window

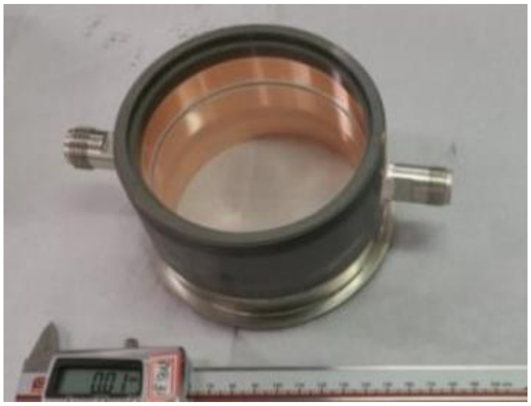

Fig. 8 The edge-cooled single-disk sapphire window

III. Experimental results

The gyrotron is powered by a modulator which provides a pulse of 0–90*kV* with a pulse length of 50*us*-5*ms* and a variable repetition rate of 10–1000*Hz*. The superconducting magnet system provides the axial magnetic field of 5.8 Tesla. Output power is measured by a calibrated calorimeter. Frequency of the output signal is also detected by a spectrum analyzer. The operating mode can be identified by measuring the frequency of the output signal.

The experiments on the 140*GHz* $TE_{22.6}$- mode gyrotron have been performed in pulsed operation with pulse length 50*us* and repetition rate 10*Hz.*The output power of ~150 *kW* is achieved with voltage of 70*kV* and current of 20*A*. The measuring frequency of output signal is 140.36*GHz* which corresponds to the $TE_{22.6}$ mode in cylindrical cavity with diameter of 31.1*mm*. The tested frequency is shown in the figure 9 and the waveforms shown in figure 10.

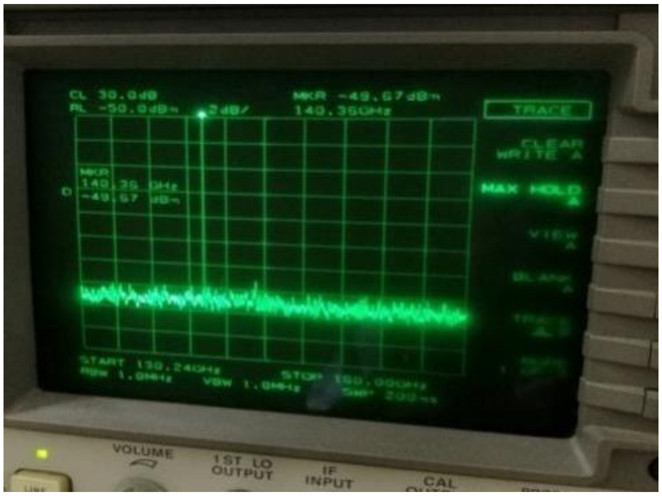

Fig. 9 The tested frequency of output signal

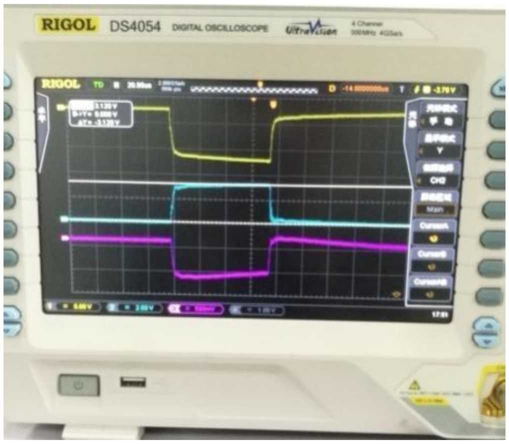

Fig. 10 The measured waveforms of the gyrotron
(upper line: operating voltge, middle line: beam current; lower line: output signal)

The tested output power of the gyrotron is lower than the theoretical results, firstly, the guiding center of the electron beam is consistent with the theoretical value because the magnetic field in region of the MIG is stronger than the designed value; secondly, beam velocity ratio α is lower than the theoretical value because the operating voltage and beam current do not reach the designed values. And thirdly, the beam is intercepted by the straight section connecting the interaction cavity and the collector section, which leads to the worse vacuum condition in the gyrotron; hence the increase of velocity spread of the electron beam decreases the efficiency of the gyrotron.

According to the analysis of the gyrotron experiments, the next research on the 140 *GHz* gyrotron is to improve the structure of the straight section of output part and add an adjusting magnetic coil in region of the MIG, so as to enhance the efficiency and the output power of the gyrotron.

IV. Conclusion

The design studies of operation of a 140*GHz* conventional cavity gyrotron have been presented for electron cyclotron heating application for EAST tokamak. The gyrotron with output power in axial coupling adopts a single-anode magnetron injection gun (MIG), the cylindrical resonant cavity and sapphire output window. The theoretical efficiency of the gyrotron with operating Voltage 80*kV*, electron current 40*A* is about 42%. The gyrotron has been fabricated and will been tested. The tested output power is less than the designed goal because of the experimental condition. In the future, the straight section of gyrotron will be modified and the operating condition will be improved so as to enhance the output power of gyrotron, and the 140*GHz* $TE_{22.6}$- mode gyrotron with single depressed collector is being fabricated.

This work is supported by the National Magnetic Confinement Nuclear Fusion Power Special Fund of China (Grant No. 2013GB110003).

REFERENCS

1. M. Thumm. “State-of-the-art of high power gyro-devices and free electron masers, update 2015”. *Kanpur Inst. Technol., Karlsruhe, Germany, KIT Sci. Rep.* 7717 (2015).
2. T. C. Luce. “Application of high-power millimeterwaves in fusion energy research”. *IEEE Trans. Plasma Sci.* 30, 3, 734-754 (2002).
3. G. Dammertz, H. Brauce, V. Erckmann, et. al. “Progress in the 10-MW ECRH system for the stellator W7-X”. *IEEE Trans. Plasma Sci.*, 32, 1, 144-151 (2004).
4. D. J. Wu, X. J. Wang, H. D. Xu, et al. “Polarization and mode control of EAST 140 GHz ECRH&CD system”. *J Fusion Energ.*, 33, 634-639 (2014)
5. X. J. Wang, F. K. Liu, J. F. Shan, et al. “Status of ECRH project on EAST Tokamak”. AIP Conference Proceeding, 1580, 538-540 (2014).
6. Gunter Dammertz, Oliver Braz, et al. “Recent results of the 1-MW 1140-GHz TE22.6-mode gyrotron”. *IEEE Trans. Plasma Sci.*, 27, 2, 330-339 (1999).
7. G. Dammertz, S. Alberti, A. Arnold, et al. “Development of a 140-GHz 1-MW continous wave gyrotron for the W7-X stellarator”. *IEEE Trans. Plasma Sci.*, 30, 808–818 (2002).
8. M. Blank, K. Felch, P. Borchard, et al. “Demonstration of a high-power long-pulse 140-GHz gyroton oscillator”. *IEEE Trans. Plasma Sci.*, 32, 3, 867-876 (2004).
9. Bentian Liu, Zhiliang Li, et al.. “A single-anode MIG for 140-GHz $TE_{22.6}$-mode gyrotron”. 2015 IEEE International Vacuum Electronics Conferenc (IVEC).
10. Bentian Liu, JinjunFeng, et al. “Research of 140 GHz, $TE_{22.6}$ mode gyrotron for EAST”. 2016 IEEE International Vacuum Electronics Conferenc (IVEC).
11. G. Gantenbein, E. Bore, G. Dammertz, et al. “Experimental results and numerical simulations of a high power 140 GHz gyrotron”. *IEEE Trans. Plasma Sci.*, 22, 5, 861-870 (1994).
12. A. K. Ganguly and K. R. Chu. “Limiting currents in gyrotrons”. *Inter.J. of Infrared and Millimeter Waves,* 5, 103-121(1984).
13. Sh. E. Tsimring. “Limiting current of helical electron beams in gyrotrons”. *Inter. J.* of *Infrared and Millimeter Waves,* 14, pp. 817-840 (1993).
14. M. Thumm. “Recent advances in the worldwide fusion gyrotron development”. *IEEE Trans. Plasma Sci.,* 42, 3, 590-599 (2014).
15. O. Braz, A. Kasugai, K. Sakamoto, et al. “High power 170 GHz test of CVD diamond for ECH window”. *Int. J. Infr. Millim. Waves*, 18, 8, 1495–1503 (1997).