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Recent Development Results in Russia of Megawatt Power Gyrotrons for Plasma Fusion Installations

A.G.Litvak[1], G.G.Denisov[1], V.E.Myasnikov[2], E.M.Tai[2],E.V. Sokolov, V.I.Ilin[3].

[1] Institute of Applied Physics Russian Academy of Sciences,
46 Ulyanov Street, Nizhny Novgorod, 603950, Russia
[2] GYCOM Ltd., 46 Ulyanov Street, Nizhny Novgorod, 603155, Russia,
[3] Kurchatov Institute, Kurchatov Square 1, Moscow, 123182, Russia

litvak@appl.sci-nnov.ru ; tel. +7 831 4365810; fax. +7 831 4362061

Introduction

Electron cyclotron systems of fusion installations are based on powerful millimetre wave sources – gyrotrons, which are capable to produce now microwave power up to 1 MW in very long pulses. During last years several new gyrotrons were designed and tested at IAP/GYCOM. Main efforts were spent for development 170GHz/1MW/50%/CW gyrotron for ITER and multi-frequency gyrotrons. Additionally other new gyrotrons were shipped and installed at running plasma installations.

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 lower than without electron energy recovery. The gyrotron is equipped with a CVD diamond output window.

The applied test facility at Kurchatov Institute was upgraded to extend its testing capabilities and to approach them to the ITER specifications. The transmission line includes an evacuated wave guide and an evacuated load. 80kV/50A main power supply of the new test facility will provide gyrotron operation in CW regime at megawatt power. For the new gyrotron version modifications were made in the collector insulator cooling system and they allow the gyrotron to run at ITER nominal parameters. The industrial production prototypes of the ITER gyrotron were tested at power 1.0 MW up to 1000 second pulse duration. For 1 MW power regime the gyrotron efficiency is 53%. The last gyrotron version operates in LHe-free magnet (see Fig.1).

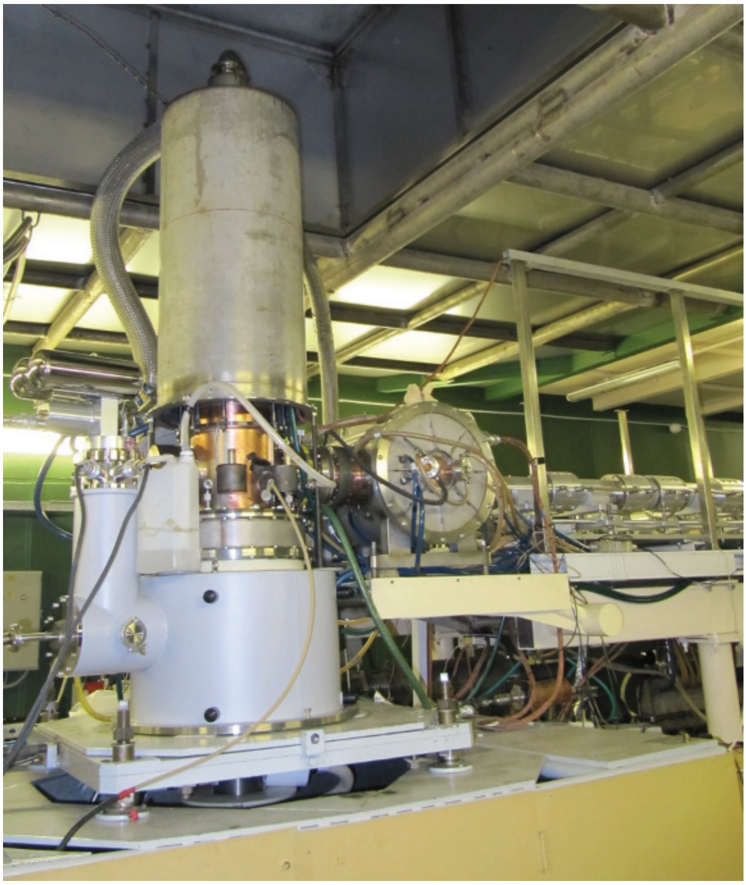

Fig. 1. Gyrotron V-11 at the tests stand in Kurchatov instituite

Full time of operation of V-10 gyrotron with microwaves at megawatt power level now exceeds 30 hours. One more gyrotron prototype (V-11) was fabricated in 2010 and tested in 2011. It is important to note that two last gyrotrons (V-10 and V-11) demonstrate very similar output parameters (see Table 1). The power shown in the Table is measured at MOU output and it is approximately 5% less than gyrotron output power.

Table 1. Main parameters of gyrotrons V-10 and V-11

Gyrotron	Beam voltage kV	Beam current A	Retarding voltage kV	Output power* kW	CPD efficiency %	Pulse duration sec
V-10 V-10 V-11	71 71 70	34 34 39.5	30.5 30 30	~750 ~750 ~850	~54 ~54 ~53	1000 600 (serial pulses) 1000
V-10	70	45	31.5	~960	~55	400 (serial pulses)
V-11	70.5	45	31.5	~960	~55	1000

Time traces for the main gyrotron parameters are stable and confirm possibility of the gyrotron operation even in longer pulses. As for a reliability test, 0.8MW/600s shots were repeated with every 50 minutes for 3 days in 12-14 of April 2011. Only 3 pulses of thirty were interrupted by some reasons. Ten pulses were made in presence of IO representatives. Those ten pulses parameters are shown in the Table 2.

Table 2. Serial pulses of V-10 gyrotron.

Ub, kV	Urec, kV	Ib, A	I_m, A	t_req, s	I_g.c	t_ pulse, s	Date	Regime	Pulse stop
70,9	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
70,9	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
70,9	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
71	30	34	82,65	600	1,5	510	13.04.2011	Operating 800kW	Cut-off
71	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
71	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
71	30	34	82,65	600	1,5	600	13.04.2011	Operating 800kW	Regular
70.8	30	34	82,65	600	1,5	600	14.04.2011	Operating 800kW	Regular
70.8	30	34	82,65	600	1,5	600	14.04.2011	Operating 800kW	Regular
70.8	30	34	82,65	600	1.5	600	14.04.2011	Operating 800kW	Regular

It is important to note that even the pulse stopped by cut-off interlock can be restarted in a short time of about several seconds. Main time traces for the serial pulse are shown by fig.2.

Development of a higher power gyrotron in Russia is going on along two directions: power enhancement in well tested gyrotron operating at TE25.10 mode and development of a new gyrotron with a new operating mode – TE28.12.

Detail analysis of the test results showed that a slightly modified ITER gyrotron prototype is capable to operate at power 1.2 MW. First tests of the modified tube are rather encouraging: microwave power 1.2 MW at MOU output was demonstrated in 100 second pulses with efficiency of 53%. Two gyrotron models with TE28.12 operating mode were tested in short-pulse experiment to find out switching-on scenarios and optimal operation parameters. In the tests of an advanced short-pulse (100 μs) gyrotron model continued at IAP and it showed a very robust operation at relatively high electron energies (up to 100 keV in the cavity) necessary to achieve the high goal power 1.5-2 MW.

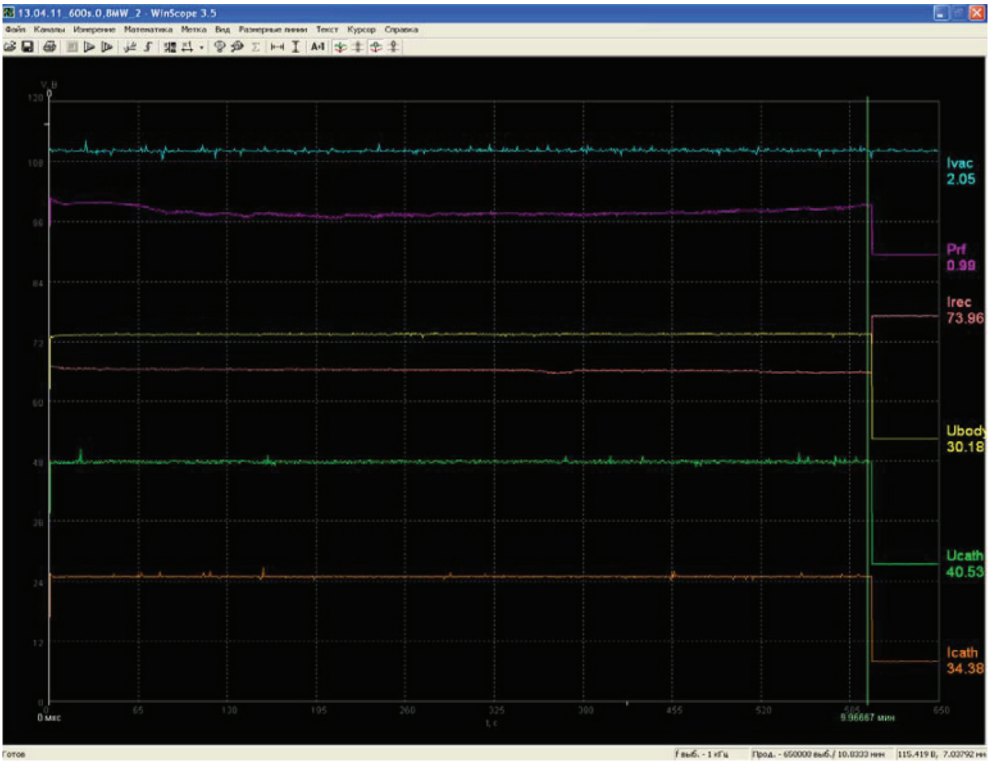

Fig. 2. Time traces for serial V-10 pulse.

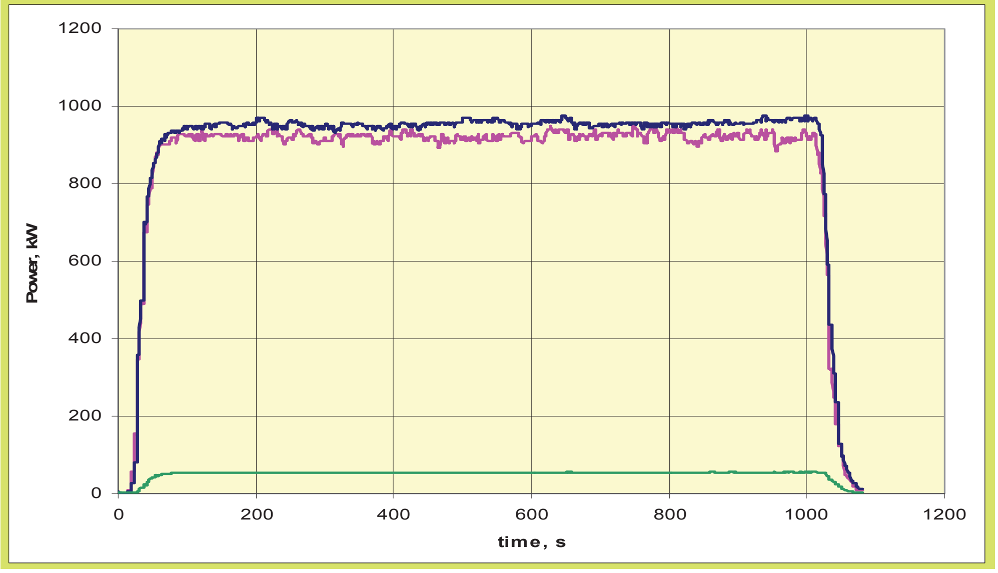

Fig. 3. Power calorimetry in the 1MW/1000s pulse for gyrotron V-11: blue- terminal load, pink- collector, green – cavity.

Multi-frequency gyrotrons

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. Russian team with collaboration with German partners develops a dual- and multi-frequency gyrotrons for 105-140 GHz frequency range. There are also other requests for multi-frequency gyrotrons.

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, reliable operation of broadband or tuneable window. Considering this three key problems one can say that first two of them are solved. Efficient gyrotron operation at several frequencies was demonstrated in many experiments. New synthesis methods allow design of efficient mode converters for multi-frequency gyrotrons. However realization of a CVD diamond window for a megawatt power level multi-frequency gyrotron met some real difficulties. Several window types have been studied (Table 3).Now a new tunable window concept is under consideration – indicated in the last line of the table.

Table 3. Possible window types for a multi-frequency gyrotron

Window type	+	-
Double- disc	Clear concept	Two discs Narrow band of low reflection => probably disturb gyrotron operation
Brewster, circular	Wide instant band	High field near the disc Require vacuum duct Require thicker disc
Brewster, elliptical	Simple scheme	Probably poor transmission characteristics (?)
Corrugated matched surface	Broad instant band	Expensive fabrication Worse mechanical stability
Travelling wave resonator	**Zero reflection** **Easy tuning**	**Two discs**

The scheme of the *travelling wave window* can be explained by Fig.4. Two windows (shown by violet cuffs) and one or two mirrors form a ring resonator with a travelling wave. The system has zero reflections at the resonant frequency. At non-resonant frequencies some reflection from the cavity occurs, but the reflected wave does not propagate in backward direction and does not disturb the gyrotron operation. Additionally the window unit is transparent for the frequencies where the discs are transparent. The ring cavity mock-up with typical gyrotron wave beam window sizes was tested at low power and found to be an appropriate solution.

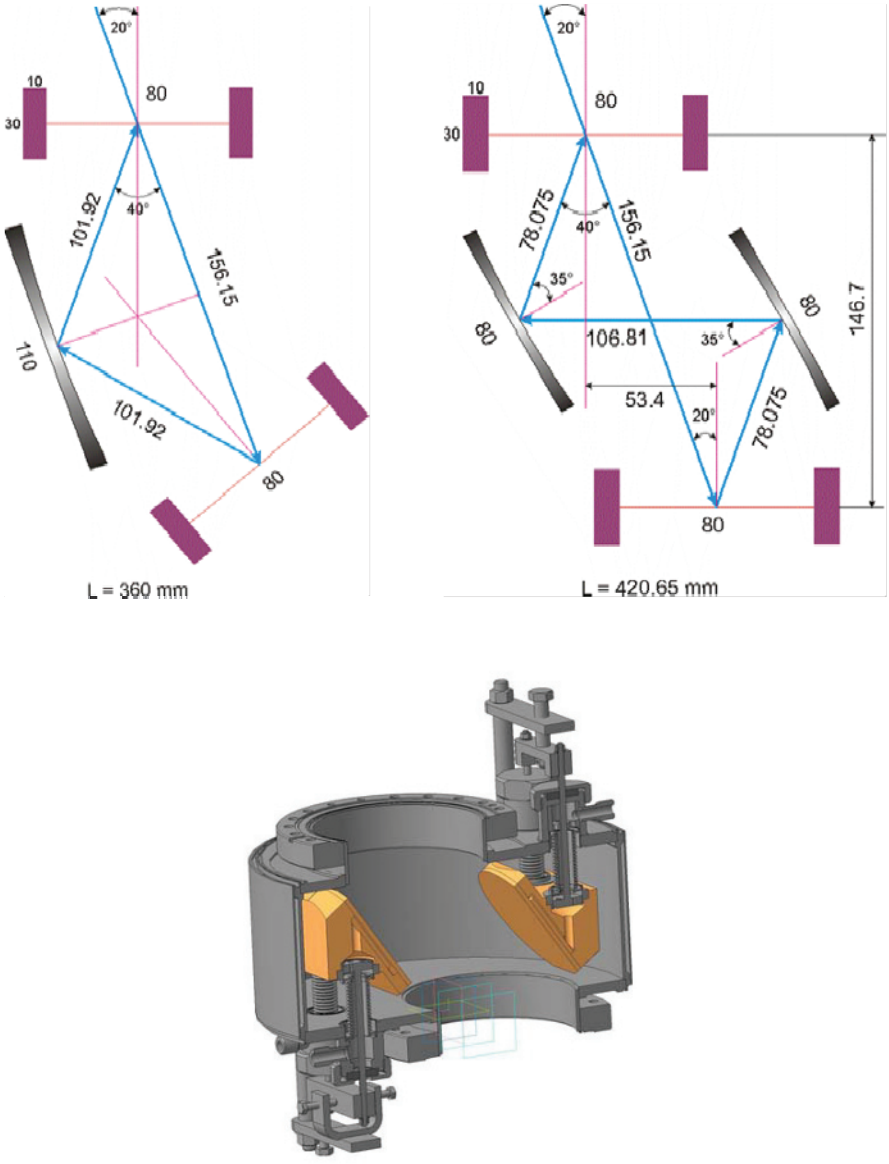

Fig. 4. Possible trajectories for the window ring cavity and 3D drawing for the second option.

The gyrotron with such a window for ASDEX-Upgrade was developed and fabricated in collaboration of IAP/ GYCOM (Russia) and IPP/KIT (Germany). Firstly the gyrotron was baked-out and tested with BN ceramics window in 0.1 second pulses. Operation at for frequencies – 105 GHz, 117 GHz, 127 GHz, 140 GHz was demonstrated. Output wave beam structures were measured (see for example fig.5). After that the ceramics window was replaced by the CVD diamond one. So far the gyrontron was tested with pulses up to 3 seconds.

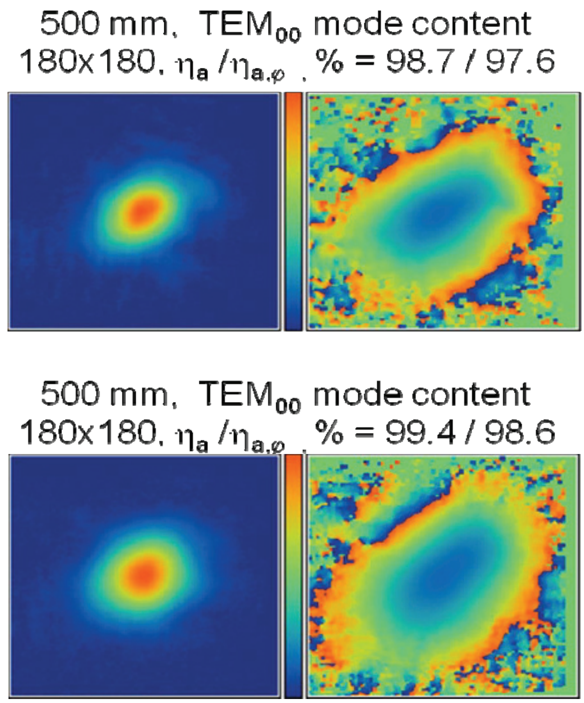

Fig. 5. Field structures for 140 GHz (upper row) and 117 GHz gyrotron operation.

Summary

Regime with 1000-s pulse duration at 1MW output power and efficiency ~53% has been implemented in the ITER gyrotron prototype. Upgrade of few gyrotron units was undertaken to increase its operation reliability. New gyrotron prototype equipped with modernized units will be manufactured in summer and its test will start in autumn 2012. Interfaces between a gyrotron and an equipment which is to be delivered as its integrated package from one side and ITER systems and services from another side are now main subject of discussion with IO team.

Manufacturing and testing of the multi-frequency gyrotron for ASDEX Upgrade with new tunable window is in progress. Short pulse (0.1 sec) tests showed good operation at 4 frequencies. Gaussian mode content in the output wave beam is high. Ceramics window used for the short pulse tests was replaced to the diamond window. In 3 second pulses the gyrotron showed 0.9 MW at 140 GHz and 0.8 MW at 105 GHz. Gyrotron conditioning will be continued in July 2012.

References

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