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Development in Russia of Megawatt Power Gyrotrons for Fusion

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Abstract. Tests of the ITER gyrotrons were continued after debugging of the test facility in Kurchatov Institute including the evacuated transmission line and power supplies capable to provide gyrotron CW operation. New ITER gyrotron (V-10) with upgraded body insulation, liquid cooling system for DC-break ceramic, improved design of the relief window has been manufactured and is testing now. Max total efficiency near 55% at 1MW level was attained. Maximal pulse duration of 800s at 0.8 MW power was limited at that time by the test stand. At 1MW power level the gyrotron V-10 up to now reached pulse duration of 570 s. Advanced short-pulse (100 ms) gyrotron model operating with $TE_{28.12}$ mode demonstrated a very robust operation at relatively high electron energies (up to 100 keV) necessary to achieve 1.5-2 MW power. Three double frequency gyrotrons have been delivered to Usdex-Upgrade. Development of the multi-frequency gyrotron with a diamond window is in progress.

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. During last years several new gyrotrons were designed and tested at IAP/GYCOM. Main development efforts were spent for development 170GHz/1MW/50%/CW gyrotron for ITER and multi-frequency gyrotrons.

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 gyrotron. The gyrotron is equipped with a CVD diamond output window. The tests were performed mainly at the test stand at Kurchatov Institute. The following gyrotron output parameters (power/pulse duration) were demonstrated so far: 1.02MW/500 sec and 0.8 MW/800 sec. Simultaneously a short pulse gyrotron mock-up with an increased size cavity was tested at power 1.5-2 MW aiming development of ITER gyrotron with the enhanced power.

The applied test facility at Kurchatov Institute was upgraded to extend its testing capabilities and to approach them to the ITER specifications. Switching to an evacuated waveguide assumed for ITER will thoroughly solve a problem of RF arcing. A new transmission line of this kind included an evacuated wave guide and an evacuated load has mounted in a new testing facility. 80kV/50A main power supply of the new test facility will provide gyrotron operation in CW regime at megawatt power. The pulse energies were limited by overheating of the collector insulator. For the new gyrotron version the modifications have been made in the collector insulator cooling system and they will allow the gyrotron to run at ITER nominal parameters. The last gyrotron version operates in LHe-free magnet (fig.1).

(a) (b)

FIG.1. ITER gyrotron prototypes: a- Gyrotron V-9 tested in 2009. GYCOM LHe cryomagnet. Air cooling of DC insulator; b - Gyrotron V-10 tested in 2010. CRYOMAGNETICS LHe –free cryomagnet. Liquid cooling of DC insulator

The industrial production prototype of the ITER gyrotron was tested at power 1.02 MW with pulses up to 570 second pulses, 0.8 MW in 800 second pulses. For 1 MW power regime the gyrotron efficiency is 53-55%. At 1 MW power the pulse length was limited by non-completed gyrotron conditioning. The long-pulse gyrotron tests are now in progress.

Detail test parameters of V-10 gyrotron are presented in Table I.

TABLE I. TEST PARAMETRS OF V-10 GYROTRON

Beam voltage kV	**Beam current A**	**Retarding voltage kV**	**Output power kW**	**Total efficiency (CPD) %**	**Attained pulse length limitation, sec**
71.5	27	30.5	600	~54	800 Set parameter
72	35	30.5	800	~55	800 Set parameter
72	45	30	1000	~53	570 Conditioning

There are two lines in development of gyrotrons with enhanced power: to advance conventional-type gyrotrons with cylindrical cavities and to develop more complicated gyrotrons with coaxial cavities. The main effort in the development of the coaxial tube is carried out by EU team. Many encouraging results have been obtained in short pulse experiments though there are some open questions. IAP/GYCOM studies a possibility to use a higher order mode in a gyrotron conventional cavity (Table II).

TABLE II. MAIN DESIGN PARAMETERS OF GYCOM/IAP 1.5 MW GYROTRON

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

In 2008/2010 two short-pulse (100 μs) gyrotron models operating with TE28.12 mode were tested at IAP. The models showed a very robust operation (microwave power up 2 MW with electronic efficiency of 34 %) at relatively high electron energies necessary to achieve the high goal power (see fig.2).

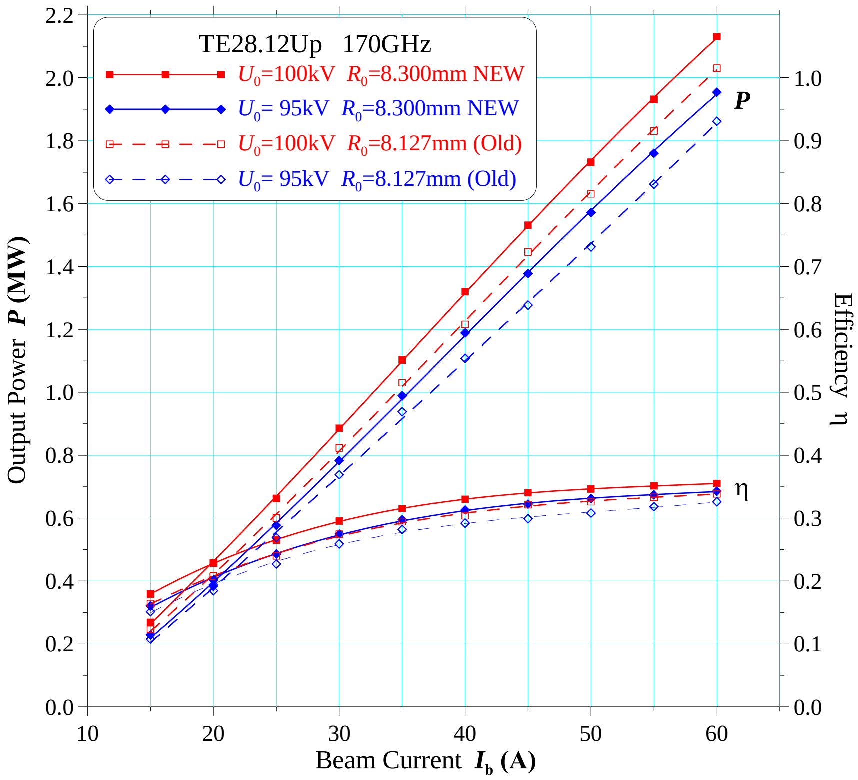

FIG.2. Power and efficiency (without CPD) of two ("old" and "new") high-power gyrotron models. The new model has modifications in the electron gun and in the quasi-optical mode converter.

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. 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. Now three window concepts are under consideration: Brewster-angle window, window with matched surfaces and double-disc resonant window.

A new internal mode converter consisting of a synthesized dimpled-wall waveguide launcher and four shaped mirrors recently has been developed for the gyrotron and it reduces the power fraction carried away by stray radiation (due to diffraction losses on the mirror apertures) to about 3% for all operating modes.

Three two-frequency gyrotrons delivered to ASDEX-Upgrade showed the output microwave power 0.95 MW at 140 GHz and 0.85 MW at 105 GHz in the specified 10 second pulse duration. 100% power modulation was demonstrated by the gyrotron switching “on-off” with up to 1-kHz frequency as well as 50% power modulation by ~10-kV modulation of cathode voltage with up to 20-kHz frequency.

The capability to have a step tuning of gyrotron frequency extends the operating space of the ECRH at ASDEX in terms of both magnetic field and deposition radius. Preliminary test of gyrotron mock-up at short pulse duration proved that it capable to produce desired 1-MW output power at 140GHz and over 800-kW power at few additional points within 105-140GHz frequency range. Basing on these results GYCOM and IAP designed the gyrotron with CPD collector and electron gun which forms electron beam capable to interact efficiently with 4 chosen cavity modes at frequencies of 105GHz (TE17.6), 117GHz (TE18.7), 128GHz (TE21.7) and140GHz (TE22.8). Electron gun of the gyrotron was designed to form 40-45A electron beam at accelerating voltage of 70-75kV.

Several versions of an output window for a multi-frequency gyrotron are in consideration. In the first one, output radiation should pass through single diamond disc at the Brewster angle providing window transparency in the whole frequency range. To provide vertical polarization necessary to put output radiation through diamond single disc window at Brewster angle mode converter includes wide band polarizer. Diamond disc having thickness of 1.96 mm and conventional diameter of 106 mm was brazed into female copper cuffs. To pass radiation through the diamond disc of a window at Brewster angle of 67 degrees it was necessary to place from its both vacuum and atmosphere sides additional mirrors which direct radiation in a proper way.

At 100-ms pulse duration output power of 1MW for 140GHz and over 800kW for 105GHz, 117GHz and 128GHz frequencies was measured as it was requested. Under pulse extension frequent arcs in vicinity of external window surface took place which finally caused failure of the diamond disc. These arcs could be initiated by output radiation fractions reflected from edges and supporting structures of additional mirrors placed too close to diamond disc surface. Because of this failure the work with the multi-frequency gyrotron of the mentioned design was stopped.

An idea to groove diamond disc surface to provide its transparency in a wide frequency range has arisen recently. In a success it can be considered as an option of multi-frequency gyrotron window as well as its double-disc version. Conventional diamond disc of 1.84-mm thickness is matched at 140GHz and is transparent also at 105GHz. It was used to change the gyrotron design to provide two-frequency gyrotron operation. Additional mirrors and polarizer were canceled and radiation was directed perpendicularly to disc surface. All another units were the same.

4. Summary

Tests of the ITER gyrotrons were continued after debugging of the test facility in Kurchatov Institute including the evacuated transmission line and power supplies capable to provide gyrotron CW operation.

V-9 prototype of ITER gyrotron with air cooling of DC-break ceramic reached maximal pulse duration of 785s at 0.6 MW power and of 200s at 1MW. Pulse extension was limited by overheating and arcing of DC-break ceramic.

New ITER gyrotron (V-10) with upgraded body insulation, liquid cooling system for DC-break ceramic, improved design of the relief window has been manufactured and is testing now. Max total efficiency near 55% at 1MW level was attained. Maximal pulse duration of 800s at 0.8 MW power was limited at that time by the test stand. At 1MW power level the gyrotron V-10 up to now reached pulse duration of 570 s.

Advanced short-pulse (100 ms) gyrotron model operating with $TE_{28.12}$ mode demonstrated a very robust operation at relatively high electron energies (up to 100 keV) necessary to achieve 1.5-2 MW power

Three double frequency gyrotrons have been delivered to Usdex-Upgrade. Development of the multi-frequency gyrotron with a diamond window is in progress.

5. References

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