

Development of the Prototype of High Power Sub-THz Gyrotron for Advanced Fusion Power Plant (DEMO)

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Next stage of the development of controlled nuclear fusion systems after the ITER project in accordance with the European Fusion Roadmap [1] is a demonstrational reactor DEMO, which should be the first thermonuclear reactor generating electrical energy. The parameters of the gyrotrons in the electron cyclotron heating system of the plasma of this reactor are not yet definitively specified, but frequencies of about 230-250 GHz and power up to 2 MW are discussed with an efficiency of more than 60% (full efficiency with energy recovery).

At present, most of the participants of the ITER project, which are involved in creating electron-cyclotron plasma heating systems, have already begun developing prototypes of radiation sources that meet the requirements of the DEMO project [2]. In the Institute of Applied Physics and Gycom Ltd. for these purposes, a prototype gyrotron with a frequency of 250 GHz and a radiation power of up to 200 kW in continuous mode was designed and tested (see fig. 1), intended for use in advanced fusion installations.



Fig. 1. Photo of the gyrotron in the cryomagnet.

The main factor limiting the output power in gyrotrons for plasma heating is the limitation of thermal loads on the cavity. Therefore, to increase the output power, it is necessary to increase the dimensions of the interaction space and use high-order modes. However, for the prototype gyrotron with an operating frequency of 250 GHz, the maximum size of the resonator and the electron-optical system was limited by the magnetic system. To generate the cyclotron frequency at the first harmonic, a magnetic field of more than 9.5 T is required, which is available in the cryomagnet at the IAP RAS, which has a warm bore of 100 mm in diameter. The warm bore diameter determined the dimensions of the electronic optics and

cavity taking into account the technical requirements for cooling systems.

As a result, to ensure stable generation at the selected frequency, the TE_{19,8} mode was selected as the working mode with a cavity radius of 9.34 mm.

Investigation of the coupling factors of the electron beam with the modes of the cylindrical cavity made it possible to determine the optimum radius of the electron beam in the cavity, which simultaneously provides both a large coupling coefficient with the working mode and the smallest coupling with parasitic modes. Due to the close coupling factors of the working mode TE_{19,8} and the parasitic modes TE_{18,8} and TE_{20,8}, the optimal radius of the electron beam is $R_{beam} = 3.93$ mm, which differs slightly from the radius of maximum coupling coefficient with the working mode $R_{opt} = 3.85$ mm.

To ensure the effective interaction of the electron beam with the high-frequency field, the cavity length was optimized. The choice of length is determined by the compromise between the increase in the efficiency of the interaction of electrons with the RF field and the limitation of ohmic losses in the walls of the cavity (see Fig. 2). As a result of modeling, the length of the homogeneous section was chosen to be $L = 10$ mm.

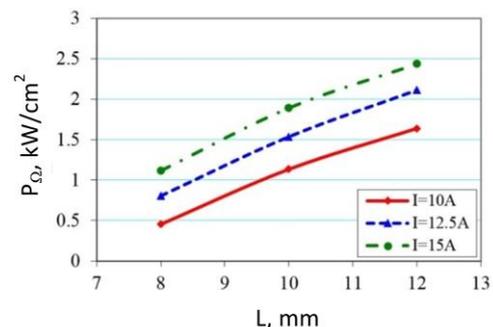
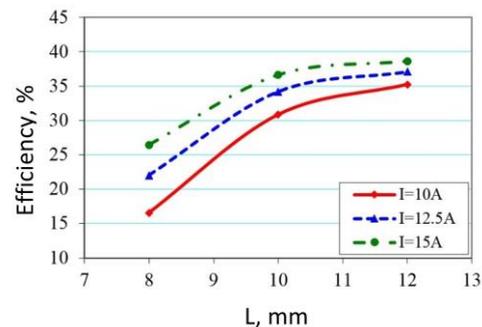


Fig. 2. Dependence of the efficiency and the density of ohmic losses on the length of a homogeneous part of the cavity

The calculated parameters of the developed gyrotron are given in the following table.

Main parameters of the gyrotron

Operating frequency, GHz	250
Operating mode	TE _{19,8}
Cyclotron harmonic	1
Accelerating voltage U_0	55 kV
Depressed collector potential	30 kV
Magnetic field in the cavity	9.6-9.7 T
Beam current (nominal in CW mode)	12 A
Beam current (pulsed mode)	20 A
Cavity radius	9.34 mm
Cavity length (homogeneous part)	10 mm
Beam radius inside cavity	3.93 mm
Pitch factor, not less than	1.1

The tube is equipped with an internal quasi-optical wave beam converter which provides a transformation of the operating mode into a Gaussian TEM₀₀ beam and couples it radially to the vacuum window. The converter consists of a shaped waveguide, a quadratic mirror, four flat mirrors, and a synthesized mirror, which allows directing the wave beam in the output window.

The first experimental tests of the developed gyrotron were carried out at the IAP RAS on a high-frequency gyrotron setup equipped with a dry cryomagnet Jastec JM10T100 with a warm bore of 100 mm in diameter and a magnetic field of up to 10 T. Due to the limitations of the power sources existing in the IAP RAS, the first experiments were carried out in a pulsed mode. For this tests a removable BN output window with a diameter of 66 mm was manufactured and installed. The thickness of the window was chosen to be about 3.1 mm in order to minimize the reflections at the operating frequency of 250 GHz. The pulse duration in the experiment was 20-40 μ s with a repetition frequency of 10 Hz. The power was measured with a water calorimetric dummy load equipped with thermal sensors in the inlet and outlet nozzles, the calibration was carried out with a heater in the circuit of a calorimeter with a known power of 100 W. The output power of the gyrotron was calculated on the basis of the measurement of the steady-state average power in the pulsed mode, taking into account the duty cycle of 2500.

The frequency of the output radiation was measured using a resonant-cavity wave meter. The registered value of 249.74 GHz has been obtained at the following operating parameters: accelerating (cathode) voltage $U_0 = 55$ kV, beam current $I_b = 12.5$ A, and magnetic field $B = 9.625$ T. These results are in agreement with the simulation data.

Reduction of the thermal load on the resonator during operation in the pulsed mode made it possible to test gyrotron with parameters exceeding the nominal design values. Thus, with an increase in the electron beam current, it was possible to reach a power of 330 kW at a beam current of 20 A and an accelerating voltage of 55 kV. The obtained experimental results are shown in Figures 3 and 4.

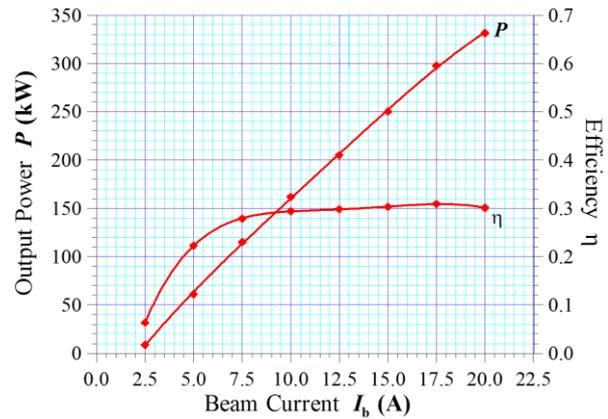


Fig. 3. Dependence of the output power and efficiency on the beam current, $U_0 = 55$ kV.

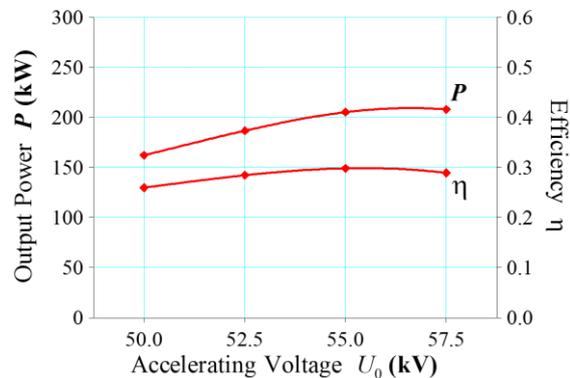


Fig. 4. Dependence of the output power and efficiency on the accelerating voltage, $I_b = 12.5$ A.

Measurements of the transverse distribution of the microwave beam formed by the built-in quasi-optical gyrotron converter were made, and the content of the TEM₀₀ wave (Gaussian beam) was estimated. The measurement was performed according to the thermal imaging technique [3] in several cross sections during the propagation of a wave beam. As the analysis showed, the content of a Gaussian wave beam in the reconstructed wave beam is 98.6%.

Thus, the tested 250-GHz gyrotron showed output parameters close to the calculated ones: the power of 220 kW at a beam current of 12.5 A (corresponds to the beam current in a continuous mode) and 330 kW at a beam current of 20 A. The generation efficiency was about 30% (without energy recovery), the content of the TEM₀₀ wave in the output beam is 98.6%.

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References

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