Development of 1 MW Output Power Level Gyrotron for ITER ECRH System

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Abstract

The paper presents the approach and results of development of the 170 GHz/1 MW ITER gyrotron in Russia. The main problems of elaborating powerful gyrotrons are discussed. Results of 170 GHz gyrotron tests are analyzed and compared with the theory. ITER related 110 GHz and 140 GHz gyrotrons are also investigated. The possibility to create a 170 GHz/1 MW gyrotron for ITER is proved by calculations and experiments.

1. INTRODUCTION

Gyrotrons are the most advanced powerful sources of millimetre wavelength radiation. They are widely used in electron-cyclotron-wave (ECW) systems of fusion installations. The ITER ECW system requires about 60 gyrotron units operating at the frequency of 170GHz with power 1MW/CW per unit. In the framework of ITER activity the 170GHz/IMW/CW gyrotron is developed at the Institute of Applied Physics in cooperation with the industrial company Gycom Ltd.

Main problems of a elaborating gyrotrons for ITER are associated with attainment of the megawatt RF power level [1,2]. A modern millimetre wave gyrotron consists of an electron gun, which forms an electron beam with helical trajectories of particles (typical gun voltage is 70...90 kV, current 20...40 A, pitch factor l.2...l.4), electron beam tunnel, oversized cavity operating at a high-order mode, quasi-optical mode converter, output window and collector. At the megawatt power level many of the gyrotron subassemblies (cathode, cavity, window, collector) have to operate at thermal loads close to their limits.

Development of the l70 GHz gyrotron is based on the experience of successful elaboration of long-pulse 110 and 140 GHz GYCOM gyrotrons[3-4]. In particular, a 110 GHz high power experimental gyrotron model was tested with a single-stage depressed collector (CPD). At the megawatt power level gyrotron efficiency without CPD is 40% and the enhanced efficiency with single-stage depressed collector is 65%. The industrial version of the 110GHz/1MW gyrotron produces microwaves in pulses up to 2 seconds. 140 GHz industrial gyrotrons [4] with output power about 1 MW in 1.5 s pulses (or 650 kW in 2.5 s, 270 kW in 5 s, 150 kW in 9.3 s) were developed. The gyrotron efficiency is about 40 %. Also an industrial 140 GHz gyrotron with CPD has been tested with a single-stage depressed collector and it showed efficiency over 50% at operating regime 800kW/1sec.

2. 170 GHZ GYROTRON

2.1 Main features of the 170 GHz gyrotron

The magnetron injection gun designed for the 170 GHz gyrotron forms a quasi-laminar electron beam with a high current (80 kV, 40 A), which passes through the tunnel to the cavity without instabilities. This resulted from thorough optimization of the shape of the gun electrodes and technology of the emitter fabrication.

Stable single-mode high-efficient generation in **an oversized cavity** at the megawatt level of output power becomes an extremely complicated problem at high frequencies, especially because this problem has to be solved within a number of limitations. The most difficult one is limitation of the density of Ohmic losses in cavity walls since energy removal in the most efficient cooling systems practically does not exceed 2 - 3 kW/cm^2. The mode TE25.10 was chosen as the operating one. Gyrotron operation at such a high mode in a cavity with novel cooling system provides operation at the megawatt power level.

The converter separating RF radiation and the worked-out electron beam transforms a complicated cavity mode into a paraxial wave beam. The converter includes a specially shaped waveguide cut and several mirrors. The mirrors are profiled to provide: low diffraction losses inside the tube, the optimal RF power distribution over an output window, matching of the output wave beam to the transmission line after the window.

The problem of **the output window** is the main difficulty that hinders creation of 1 MW/CW gyrotrons. Different materials and window designs are under investigation. The most promising approaches for elaboration of a CW window for high-frequency ECW gyrotrons are associated now with new materials having low RF losses and high thermal conductivity such as Au-doped silicon and artificial CVD-diamond.

The collector with dynamic scanning of electron beam by means of additional coils generating magnetic field of the saw-teeth form is used. The collector is compatible with the CPD regime allowing high gyrotron efficiency, over 50%.

2.2. Experimental study of the 170GHz gyrotron

Experiments with the 170 GHz gyrotron are carried out typically along two main lines. New principal solutions in the gyrotron scheme are tested in short pulse prototypes.

Such preliminary short-pulse (50μs) experiments with 170 GHz/1 MW gyrotrons were performed on the automation set-up and dependencies of gyrotron parameters on the beam current, accelerating voltage and magnetic field were analyzed. Results of measurements of the output power P_{out}, and efficiency h depending on the electron beam current I are presented in Fig. 1. The output power level 1 MW was achieved at the $TE_{25.10}$ operating mode in design regime with efficiency of 34%. The maximum output power near 1.3 MW with efficiency 32% was reached.

The same $TE_{25.10}$ gyrotron was tested also with a single-stage depressed collector. Fig. 2 shows results of measurements of output power P_{out} and efficiency h in dependence on the retarding collector voltage for the short pulse experimental gyrotron. Output power of 1MW/50 μs is obtained at the beam parameters of (80-40) kV/40 A. The improved efficiency with the use of a single-stage depressed collector is near 60% and in agreement with calculation.

After these tests of the short-pulse prototypes, a long-pulse industrial gyrotron was designed and first experiments were performed.

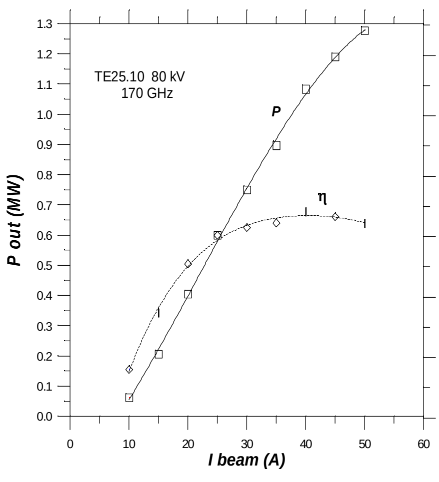


Fig.1 Output power P_{out}, and efficiency h depending on the electron beam current I for short pulse gyrotrons.

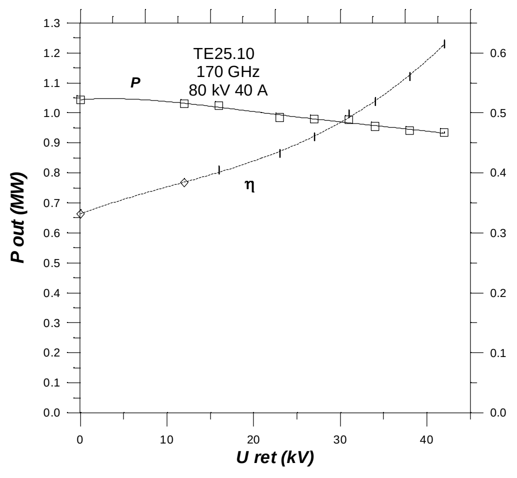


Fig.2 Output power P_{out}, and efficiency h versus retarding collector voltage.

A gyrotron version with a BN window and without a depressed collector showed stable operation with parameters 1MW/1 sec, 0.5MW/5sec, 0.27MW/10sec. In all regimes gyrotron efficiency corresponds to the calculated values.

The gyrotron tests were carried out on a special stand at "Kurchatov Institute". Experimental dependencies of gyrotron output power and efficiency versus beam current are shown in Fig. 3. The maximum output power of 1MW at 1.0 s pulse length was achieved and it was limited by the collector (because no CPD used). Maximal efficiency 34.8 % (Pout = 870kW, U = 76 kV, I = 34 A) is in good agreement with simulating data and results of short-pulse tests.

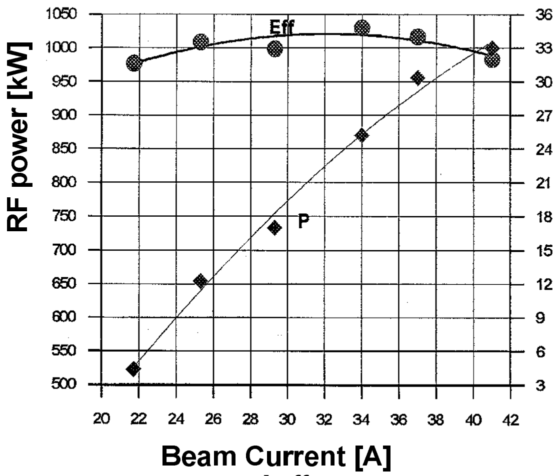


Fig.3 Output power and efficiency versus electron beam current

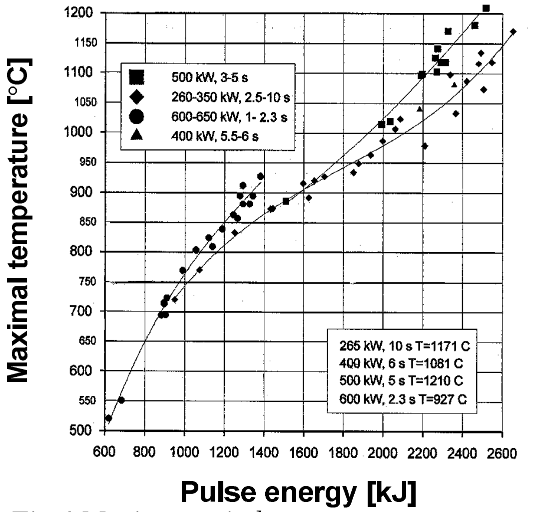


Fig.4 Maximum window temperature versus RF pulse energy.

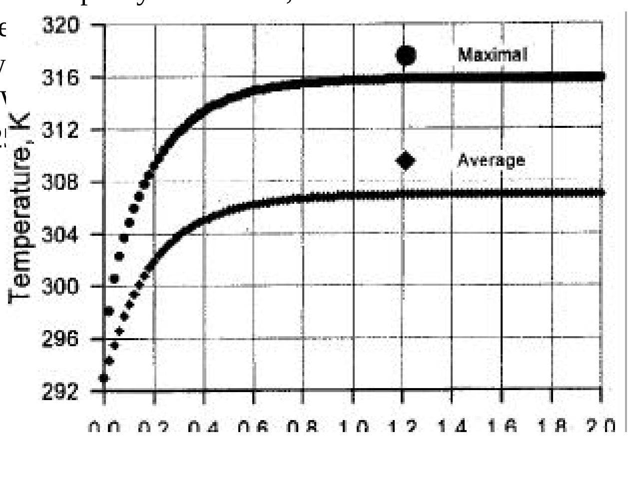
Maximal energy in microwave pulses (2.5 MJ) was limited by the BN window. During tests the temperature distribution over window surface was measured by means of an infrared camera with computer data processing. Maximal temperature on the window surface versus pulse output energy is shown in Fig. 4. RF pulse energy of 2.5 MJ (500 kW/ 5 s 270 kW/ 10 s etc.) corresponds to the window temperature around 1200°C.

The tests also confirmed reliable operation of gyrotron cooling systems (for cavity, collector, mirrors, body…).

3. WINDOW DEVELOPMENT

Recent investigations revealed very attractive features of using CVD diamonds for window development. In last years rather big (up to 120mm diameter, 2mm thickness) diamond disks with low-loss tangent were demonstrated. Windows based on such disks may have water edge cooling and very high transmission capability (up to 2MW/CW). Developing this very promising idea of a diamond window the following steps were made in Russia:

- measurements of loss tangent and thermal conductivity for several diamond disks in the temperature range of 20…450°C for various frequencies (Fig.5). In particular, properties of disks produced in Russia were measured. The Russian disks have diameter up to 70 mm and thickness up 1.5 mm;
- thorough study was performed for diamond window transmission capacity and stresses in it. The calculations show reliable transmission capacity over 1MW;
- a high power test was performed. In the passed through a model of a diamond w such as thermal conductivity (2000 $(2.4\times10^{-4} \pm10\%)$ and time constant (0.2 lower power measurement results.



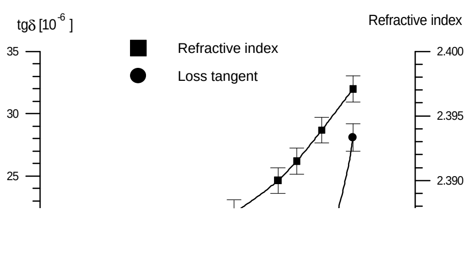


Fig.5 Measured characteristics of Russian CVD diamond disk. Diameter 66mm, thickness 1.11mm, growth rate 0.0025 mm/h.

Fig.6 High power test of the diamond window. Window temperature.

These studies show that there are no doubts in feasibility of diamond window.

4. CONCLUSION

The possibility of development of the 170 GHz /1MW/CW gyrotron has been proved in recent theoretical and experimental studies. Principal steps have been made in solving the most acute gyrotron problems such as: stable and efficient gyrotron operation at a very high operating mode; gyrotron efficiency enhancement by means of a depressed collector; output window development. Stable operation of the gyrotron with $TE_{25.10}$ was demonstrated. The output power of 1 MW with efficiency of 32 % (without CPD) at pulse length of 1.0 s was reached. The maximum pulse energy about of 2.5 MJ was limited by temporary used single-disc NB window. Experimental and industrial prototypes of the 170GHz/1MW/CW gyrotron operate at design parameters. These points make a reliable basis for elaboration of a tube operating in the full-scale regime. An advanced 170GHz gyrotron with a new diamond window, one-stage depressed collector and CW cooling of all elements is planned to be tested in December 1998. It is expected to reach 1MW/10-20 s with efficiency over 50%.

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