High efficient gyrotron-based systems for technological applications

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Abstract— **High-efficient second harmonic 24 GHz CW gyrotron has been developed and tested at IAP RAS. Record-breaking efficiency of 60% at 6kW output power level has been obtained by magnetic field profile optimization and single-stage energy recovery of the spent electron beam.**

I. Introduction

IN recent years the research in materials processing with the use of millimeter-wave power has been growing extensively. Fabrication of nanostructured ceramics and composites, sintering of fine metal powder compacts and metal/ceramic composites are among the new, most promising but challenging problems of great interest today. The gyrotron complexes[1] created at IAP RAS jointly with GYCOM Ltd. (N.Novgorod, Russia) allow creating materials with new qualities and do not have any analogues with similar functional capabilities. The expansion of these systems to novel technology and industrial applications requires efficiency enhancement. Energy recovery of a spent electron beam is now one of the most effective ways to significantly enhance the gyrotron efficiency[2,3]. Currently, CPD systems are used in all high-power fundamental-harmonic gyrotrons for fusion. The presented results are the first experimental data for the second harmonic gyrotrons. In continuation of the successful development and application of technological gyrotrons, a novel record-breaking high-efficiency gyrotron based on a CPD system has been developed.

II. High efficient second harmonic CPD gyrotron

All gyrotron sources used in materials processing systems operate at the second harmonic of the electron cyclotron resonance to simplify the magnets.

One of the major ways to increase an efficiency of a whole system is performance optimization of the microwave source. The high-efficient second harmonic CPD gyrotron (fig.1) was developed and tested at IAP RAS. High output efficiency has been obtained by magnetic field profile optimization and energy recovery of the spent electron beam..

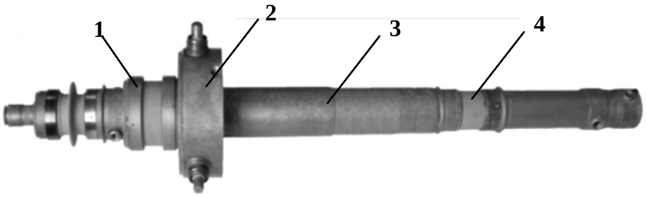

Fig.1. Photo of the CPD technological gyrotron (1 – triode type electron gun, 2 – sputter-ion pump, 3 – cavity region, 4 – collector insulator)

The main gyrotron parameters are given in the Table:

The operating mode	H_{12}
Operating frequency, GHz	24.15
Output power, kW	6.2
Accelerating voltage, kV	17.5
Beam current, A	0.75
Magnetic field, T	0.46
Output efficiency without CPD, %	48
Output efficiency with CPD, %	**60**

The magnetic system consists of the main oil-cooled solenoid and two additional air-cooled coils situated in the electron gun region and in the collector region. The electron gun and the cavity are exactly the same as in the tube without CPD to make sure that the efficiency enhancement is achieved only due to the energy recovery. The high initial efficiency is achieved by a slightly rising of the magnetic field in the cavity region which, according to the theoretical analysis, provides a larger area of the resonance interaction of the microwaves and the electron beam. The collector is electrically insulated from the body with a ceramic insulator. To minimize the losses through the gap in the waveguide, a high-efficiency (with losses less than 0.1%) mode converter is designed using the special method of microwave component synthesis developed at IAP RAS[4,5]. It converts the input H_{12} mode to a mixture of the H_{11} (6.3%) and H_{12} (93.7%) modes with the zero axial current at the wall. The mode converter profile and distribution of azimuth component of H-field at the waveguide wall are presented in fig.2

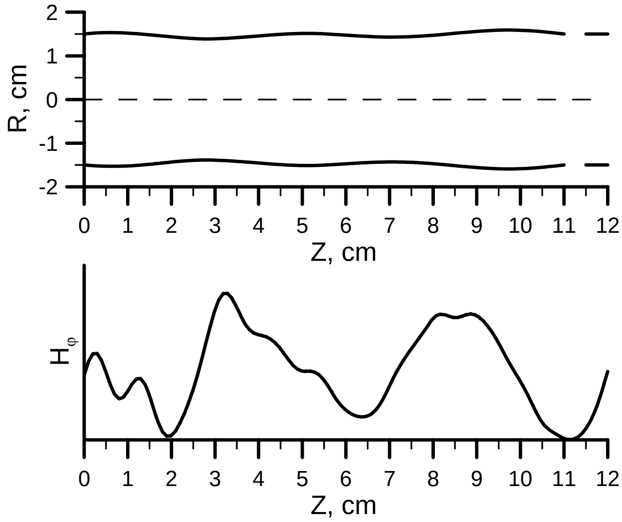

Fig.2. Mode converter profile and distribution of azimuth component of H-field at the waveguide wall.

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The operation of a CPD gyrotron requires two high-voltage power supplies (HVPS). The main HVPS is connected between the ground and cathode. Its current was equal to the beam current and its voltage was less by the value U_D than the voltage in the scheme without the energy recovery. The second, low-power (due to close to zero current of reflected electrons) HVPS has the voltage U_D. This HVPS is also capable of modulating the output power up to frequencies of several kHz, typically[6]. Thus, the CPD collector system allows us to increase the output efficiency, to reduce the energy consumption and the dimensions of the main power supply, to simplify the protection system, and to increase the possibilities of controlling the gyrotron oscillation regime by using a low-power HVPS. At the same time, the CPD collector system reduces the thermal load on the collector sufficiently, thus making it possible to simplify the cooling system.

During the test experiments the decelerating voltage is formed by a variable resistor, which connects the collector with the ground (the experimental scheme is similar to that in[7]). The gyrotron body is grounded. The output power is measured using a dummy load, which is also insulated by a teflon spacer between the collector and the dummy load. This fact slightly reduces the measured value of the output power and results in a microwave leak through this space.

The experimental data of the gyrotron output power (triangles) and efficiency (circles) versus the relation of the collector decelerating voltage U_D to the electron beam voltage U_0 are shown in the Fig.3.

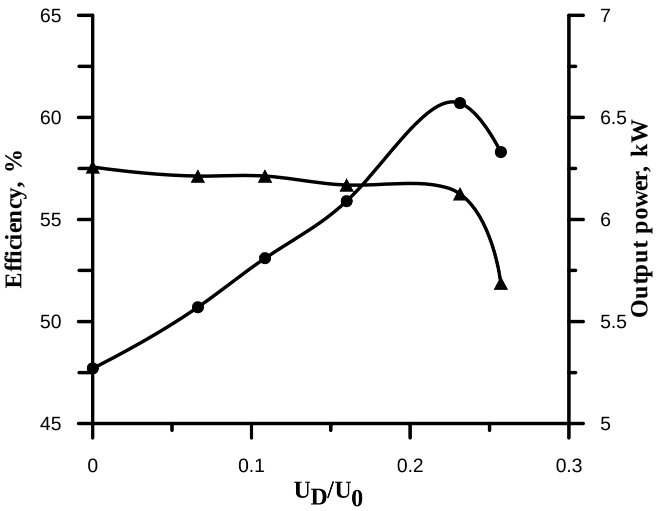

Fig.3. The gyrotron output power (triangles) and efficiency (circles) versus the relation of the collector decelerating voltage U_D to the electron beam voltage U_0

With an increase in the CPD potential, the total gyrotron efficiency first increases till the decelerating voltage becomes close to the minimal returning potential. The subsequent collector voltage increase results in the reflection of electrons and the efficiency decreases. The minimal returning potential value (according to the experimental data) was about 0.2 of the electron beam accelerating voltage and agreed with the calculated value.

The experimental tube was developed based on the serial technological gyrotron and cavity dimensions and electron gun are the same with the gyrotron without CPD. The increase of the cavity length forms a more adiabatic profile of the microwave field and, hence, due to adiabatic reasons, the minimal electron beam energy can also increase. Thus, the optimal cavity length necessary for the highest total efficiency should be increased for the CPD operation. The dependence of the output efficiency on the cavity length was simulated numerically. As follows from calculations, the fixed-value increase of the cavity length results in a small increase in the minimal electron beam energy due to the adiabatic effect. A more important result is that while the microwave field amplitude decreases, the electron efficiency also decreases slightly, but the minimal energy becomes significantly higher. Thus, the cavity extension may result in further increase of the gyrotron efficiency with energy recovery (for a present electron beam parameters up to 65-70% in calculations).

III. CONCLUSION

The possibility of the significant output efficiency enhancement due to energy recovery for the gyrotrons operating at cyclotron harmonics was demonstrated. The second-harmonic 24 GHz gyrotron for technology application with output efficiency of 60% was developed and tested at IAP RAS. The record efficiency was obtained by optimizing the profile of the magnetic field and using the energy recovery for the spent electron beam.

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