High-Harmonic Large Orbit Gyrotrons in IAP RAS

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***Abstract*—The results of experiments with THz-range Large-orbit gyrotrons (LOGs), which have been carried out over years in the Institute of Applied Physics, Russia, and the new projects of the LOGs operating at up to 4th cyclotron harmonic are presented.**

I. Introduction

LARGE-orbit gyrotrons (LOGs) have been developing in the IAP during last two decades. As compared to gyrotrons with conventional magnetron-injection guns, LOGs provide better modes selectivity, especially when operating at high cyclotron harmonics. In the IAP, LOGs with the moderately relativistic electron energy of 250 keV operated at the 3rd–5th harmonics at the frequenices up to 130 GHz [1] and 410 GHz [2]. A record frequency of 1 THz has been obtained in the 3rd-harmonic LOG with lower voltage of 80 kV [3]. Since then, a proof-of-principle experiment demonstrating the possibility of significant decreasing of Ohmic losses by the use of specially profiled cavity in 1 THz gyrotron was carried out, and a novel design of a 30 kV LOG aimed to operation at DNP frequencies of 260/390/520 GHz at the 2nd, 3rd and 4th cyclotron harmonics, respectively, began to be realized.

II. A 80-kV 1 THz pulsed gyrotron

A key element of a LOG is the electron gun capable of providing a thin axis-encircling electron beam with sufficient current and pitch-angle and acceptable velocity spread. Such a gun utilizing the cusp of axi-symmetric magnetic field was successfully realized in IAP in 2008 and produced a 80 kV electron beam with a current of up to 0.7 A and a pitch-factor of 1.4 guided by a 14 T magnetic field. Based on this gun, a pulsed LOG capable of operating at up to the 3rd cyclotron harmonic at the frequency of up to 1 THz was successfully demonstrated. Though providing a fairly high electron efficiency and output power of 0.4 kW, this gyrotron had a low output efficiency of about 1%, which was mainly due to very high level of Ohmic losses inside the long (24 wavelengths) operation cavity. To increase the useful diffraction losses of the cavity and preserve the large length of the interaction space necessary for efficient 3rd harmonic excitation, a special axial profile of the cavity wall was proposed and tested in the experiment. It was shown [4], [5] that using a three-section cavity with a relatively large central widening (Fig. 1) allows decrease of the Ohmic losses by several times and thus could help to increase substantially the output gyrotron efficiency.

Naturally, a complicated cavity profile can provoke a spurious excitation of the closed middle section. This was the main reason to decrease the operation frequency down to 740 GHz in the first experiment under the sectioned-cavity gyrotron. In this experiment, we aimed at reproducing the electron beam parameters of the regular-cavity experiment of the 1-THz third-harmonic LOG [3]. This was designed for operation at a relatively low voltage of 80 kV with a pulse duration of 10 μs. However, the electron beam created in the new experiment was slightly different. First of all, the electron current was lower (0.55–0.60 A instead of 0.70 A). Second, the pitch factor was higher (1.55–1.70, depending on the value of the electron current, instead of 1.4).

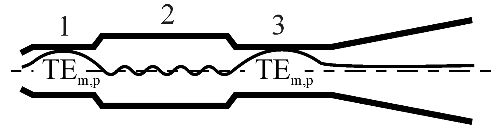

Fig. 1. Three-section gyrotron cavity with central widening.

In this experiment, stable selective excitation at the third cyclotron harmonic was achieved at a magnetic field close to 10.2 T. The output signal at a frequency of 0.74 THz corresponded to the transverse mode $TE_{3,5}$. The detected output power was 100–250 W and it increased with an increase of the value of the electron current (Fig. 2a). The output efficiency amounted to 0.5–0.6%.

At a higher magnetic field (11.3 T), the LOG operation at the second cyclotron harmonic was observed at a frequency of 0.55 THz. This frequency corresponds to the operating transverse mode $TE_{2,4}$. The maximum output power and efficiency exceeded 500 W and 1%, respectively (Fig. 2b). Figure 3 shows oscilloscope traces of the electron voltage, current and output THz power at the third harmonic.

The measured efficiency in the third-harmonic LOG experiment (under 1%) is significantly lower than the expected efficiency (several percent, [5]). The reason is that the profile of the sectioned cavity had been designed for the operation at a frequency of 1 THz ($\lambda = 0.3$ mm), whereas the frequency of the excited mode was lower ($\lambda = 0.4$ mm). Thus, the length of the cavity measured in the wavelength was shortened. According to the analysis of the electron-wave interaction and of the electron-beam formation, the oscillator operated in the close-to-start regime with a relatively low efficiency.

The main result of the sectioned-cavity third-harmonic LOG experiment is the following: a high-harmonic gyrotron operating in the THz frequency range with an extremely low diffraction Q-factor (and, therefore, a low level of Ohmic losses) was realized. Although the total length of the cavity

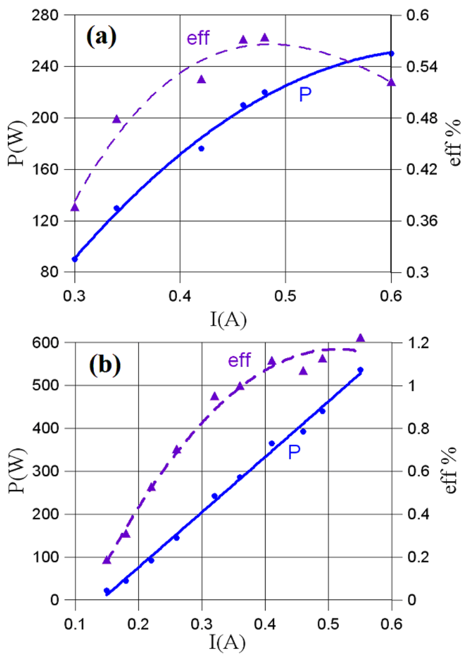

Fig. 2. Measured output THz power and efficiency of the LOG vs the operating current at the third (a) and second (b) cyclotron harmonics.

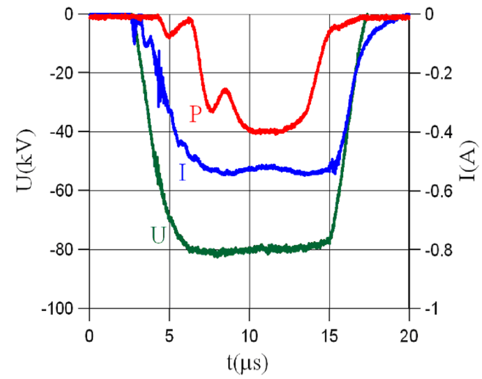

Fig. 3. Oscilloscope traces of the electron voltage (U), current (I) and output THz power (P) of the 3rd harmonic LOG.

was as long as 30 wavelengths, the diffraction Q-factor was about 2,000 only, and the share of the Ohmic losses was about 20–25% of the THz power radiated by the electron beam. To compare, in the regular-cavity THz LOG experiment carried out on this installation [3], the share of the Ohmic losses was as high as 85% of the radiated power.

At the time, an amended cavity which is thoroughly calculated to be free from the selectivity issues is being manufactured. In addition, a possibility of effective using simpler sectioned cavities with a small central widening, which also do not complicate the discrimination of parasitic modes, was theoretically studied [6].

III. A 30-kV CW gyrotron

The main peculiarity of the CW LOG project is ability to use the same electron-optical system for operation at three different frequencies of 260, 390 and 520 GHz. These frequencies are to be achieved when operating at the 2nd, 3rd and 4th cyclotron harmonic, respectively, and the choice is accomplished only by the choice of the cavity. The cusp gun of the setup is integrated with the special cryomagnet and provides a continuous axis-encircling electron beam with the current of up to 0.7 A and a pitch-factor of up to 2 in the magnetic field of 4.9 T. The original electron collector with rotating in time magnetic field provides beam scattering over a large surface ensuring that the average density of deposited power does not exceed 700 W/cm^2.

Calculations show, that while a conventional cylindrical gyrotron cavity should properly operate at the 2nd and 3rd harmonics, selective excitation at the 4th cyclotron harmonic requires special measures to increase the operation efficiency and to prevent the spurious low-harmonic oscillations. A possible solution can be based on using a three-sectioned cavity with modes transformations and short middle transit section optimizing the efficiency [7]. According to simulations, such a cavity will allow achievement of the output power of about hundred watts at the frequency of 520 GHz.

IV. Conclusion

A series of experiments with Large Orbit Gyrotrons has been carried out in the IAP over years. The experience gained during this time allowed creating efficient electron-optical systems capable of providing high-density axial-encircling beams, which were used for selective gyrotron operation at up to 5th cyclotron harmonic and at the frequencies of up to 1 THz. Novel projects include power and efficiency enhancement for the existing pulsed 3rd harmonic 1-THz gyrotron, as well as creating of a new CW 4th harmonic gyrotron for DNP-spectroscopy.

Acknowledgment

The work is supported by the RFBR, grants No. 13-02-01048 and No. 14-02-00594.

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