# Frequency-Quadrupling Gyrotrons

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Abstract— **In this paper an overview of theoretical studies of frequency-quadrupling gyrotrons (FQGs) will be given. This concept allows one to overcome the use of superconducting solenoids in gyrotrons operating at short wavelengths as well as to master the range of THz frequencies with available superconducting magnets.**

## I. Introduction

Gyrotron operation at cyclotron harmonics is very attractive because it offers reduction of magnetic fields required for generating electromagnetic radiation at a given frequency inversely proportional to the harmonic number $s$. In addition to reducing the magnetic field, there is also desire to operate at relatively low voltages and deliver high frequency radiation at upper millimeter waves and in the THz region. Since the intensity of cyclotron radiation at harmonics decreases with the harmonic number increase as $\beta_{\perp}^{2s}$, the gyrotron design for high harmonic operation faces certain difficulties, and the device efficiency decreases with the frequency and harmonic number. One of the concepts alleviating these tendencies is the concept of a frequency-quadrupling gyrotron (FQG) proposed by H. Guo. Such a device shown schematically in Fig. 1 is a three-cavity gyrotron in which the first, second and last cavities separated by drift regions operate at the fundamental, second and fourth harmonics, respectively, i.e. in this device successive frequency doubling takes place from one stage to another. In the present paper, an overview of theoretical studies of such gyrotrons [1-5] will be given and new results will be presented.

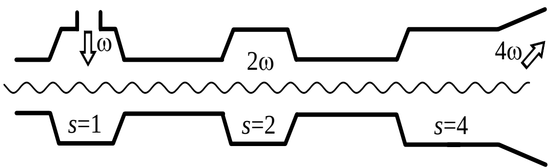


Fig. 1. Schematic of a frequency-quadrupling gyrotron

## II. Results

Theoretical analysis of this concept was started in Ref. 1 from studying the operation of the output cavity excited by a prebunched beam. It was assumed that the prebunching section can be described by a point-gap model (short cavities separated by long drift section). Then, the optimal values of bunching parameters were found which provide the maximum of the fourth harmonic in the electron current density at the entrance to the output cavity, and the optimal parameters of the output cavity were determined for one specific value of its normalized length. In Ref. 2, this approach was used for a further analysis. First, similar calculations of the efficiency were performed for several values of the normalized length of the output cavity and it was shown that the orbital efficiency can be as high as 72%. These results are illustrated by Fig. 2 reproduced from Ref. 2. Then, the limitations on the achievable efficiency at short wavelengths were analyzed; these limitations are determined by two factors – ohmic losses of microwave power in cavity walls and low density of the beam current per a wavelength squared. The concept was pursued further in Ref. 3. There, the design study of an FQG operating in a sequence of modes $TE_{1,2}$-$TE_{2,2}$-$TE_{4,2}$ and driven

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by a 60 kV, 3A electron beam was done for two frequency ranges: W-band and 0.5 THz frequency.

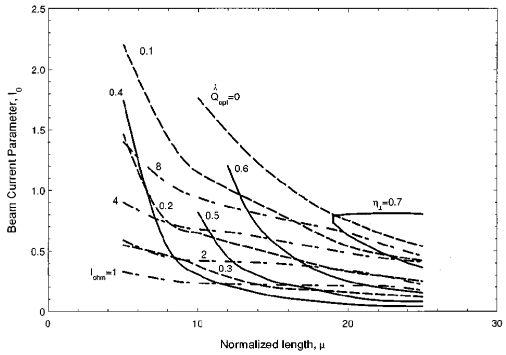


Fig. 2. Contours of equal efficiency (solid), ratio of diffractive to ohmic Q-factors (dashed) and beam current parameter proportional to ohmic Q (long-short dashed) in the plane of beam current parameter versus normalized cavity length.

It was shown that in the W-band FQG the total efficiency (i.e. the one calculated with the account for ohmic losses) can be close to 18% (in the presence of reasonable velocity spread) with the ohmic loss density allowing for CW operation at the 30 kW output level. A similar device with less than 1A beam current designed for the 0.5 THz frequency can operate in the CW regime with the 1 kW output power and the efficiency above 2%. Ref. 4 is focused on the analysis of stability of operation of output cavities in such devices in the presence of competing modes resonant with an electron beam at lower cyclotron harmonics. It was found that by the proper choice of the output cavity length the effect of parasitic backward-wave excitation at the fundamental can be significantly weakened. Finally, in Ref. 5, the electron interaction with cavity fields in FQGs and some possibilities to utilize the energy recuperation there were studied with the use of the Hamiltonian formalism. Some results of this study are illustrated by Fig. 3 which shows electron distribution in energies at the last cavity output in the case of small (a) and large (b) amplitudes of the resonator field. In Fig. 3, electron distribution is shown for the electron fraction with the largest initial orbital velocity, because electrons of this fraction have the lowest axial velocity and, hence, can easily be stopped and reflected back in the region of their deceleration between the last cavity and the depressed collector. The use of single-stage depressed collectors allows one to increase the wall-plug efficiency up to 40% from the 12% electronic efficiency and up to 32% from 19.4% in the cases (a) and (b), respectively.

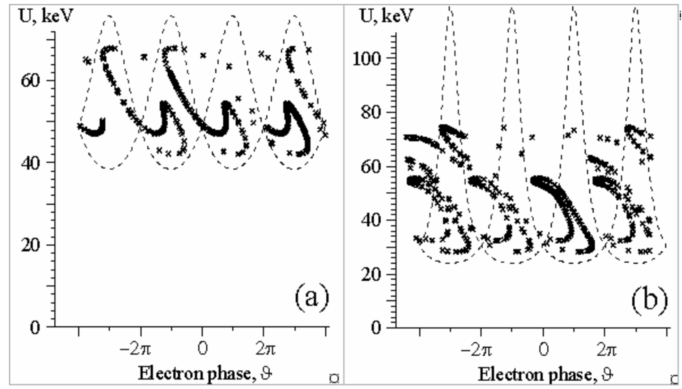


Fig. 3. Electron distribution at the exit for small (a) and large (b) RF amplitudes. Dashed lines show separatrices outlining the area of buckets where electrons can be trapped by the RF field.

These theoretical studies had been followed by a more realistic design of a W-band, frequency-quadrupling gyrotron done with the use of the code MAGY [6]. The design efforts had demonstrated that the device operation is much more sensitive to the beam voltage than to the current. In line with Introduction, the device operation at high harmonics strongly depends on electron orbital velocities which are determined by the voltage, while, in accordance with Fig. 2, even at currents five times smaller than the optimal one the orbital efficiency decreases from 72% to more than 50% only.

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