# Efficient Low-Voltage Operation of a CW Gyrotron Oscillator at 233 GHz

Melissa K. Hornstein, *Member, IEEE*, Vikram S. Bajaj, Robert G. Griffin, and Richard J. Temkin, *Fellow, IEEE*

***Abstract*—The gyrotron oscillator is a source of high average power millimeter-wave through terahertz radiation. In this paper, we report low beam power and high-efficiency operation of a tunable gyrotron oscillator at 233 GHz. The low-voltage operating mode provides a path to further miniaturization of the gyrotron through reduction in the size of the electron gun, power supply, collector, and cooling system, which will benefit industrial and scientific applications requiring portability. Detailed studies of low-voltage operation in the $TE_{2,3,1}$ mode reveal that the mode can be excited with less than 7 W of beam power at 3.5 kV. During CW operation with 3.5-kV beam voltage and 50-mA beam current, the gyrotron generates 12 W of RF power at 233.2 GHz. The EGUN electron optics code describes the low-voltage operation of the electron gun. Using gun-operating parameters derived from EGUN simulations, we show that a linear theory adequately predicts the low experimental starting currents.**

***Index Terms*—Compact, dynamic nuclear polarization (DNP), gyrotron oscillator, low voltage, nuclear magnetic resonance (NMR), portable, terahertz.**

## I. Introduction

SINCE the power in a gyrotron oscillator increases strongly with beam voltage and current, gyrotrons tend toward operation with high voltage in the tens to hundreds of kilovolts generating tens of kilowatts to one or two megawatts in the microwave to millimeter-wave band. For example, a state-of-the-art commercial CW gyrotron oscillator at 140 GHz, operating at 80 kV and 45 A, has recently achieved a power level of 900 kW for a duration of several minutes [1], [2]. However, many high-frequency applications, such as dynamic nuclear polarization (DNP) [3], require only a modest average RF output power of several watts to several tens of watts. In such cases, it is feasible to generate this amount of power under conditions of low voltage ($<$ 15 kV) and current operation. For instance, using a 140-GHz gyrotron oscillator (14 kV), it has been demonstrated that RF powers as low as 1 W can be sufficient to enhance the nuclear-magnetic-resonance signal using the DNP mechanism [4], [5] and 3–4 W (12 kV) has shown to be sufficient at 250 GHz [6].

In fact, there is no device as well suited to the generation of high average power submillimeter radiation as the gyrotron oscillator. Gyrotrons, whose interaction structures can be several times the operating wavelength, are more robust than conventional vacuum electron devices [such as the klystron, traveling wave tube (TWT), and backward wave oscillator (BWO)], whose circuit dimensions are limited to the order of a wavelength, thus restricting high-power capabilities especially at higher frequencies. In a gyrotron, lowering the voltage at which oscillations occur while maintaining a good efficiency can result in a reduction of the size of the electron gun, power supply, collector, cooling system, and vacuum-pumping system and can further reduce the length and complexity of the microwave-tube processing and conditioning. Lowering the voltage of operation is, therefore, an important step toward miniaturization of the gyrotron.

In this paper, we report a short-wavelength gyrotron operating at a beam voltage as low as 3 kV and producing several watts of output power at 233 GHz. Previously, a gyrotron with a 5–15-kV 2-mA beam has produced 5 W at 9.4 GHz with up to 2% efficiency [7], and a gyrotron with a 20-kV 2–3-mA beam in a 5-T magnet-generated 1 W of power at frequencies up to 140 GHz at an efficiency of up to 2% [8]. The gyrotron reported here differs in several respects from this earlier work. It utilizes a magnetron injection gun, which produces an annular beam. Such a beam has reduced space charge forces and lower velocity spread than a Pierce gun, providing higher electron-beam quality and higher output efficiency. The present gyrotron was also optimized for DNP with the requirements to operate continuously at the second electron–cyclotron harmonic at 460 GHz with 12-kV beam voltage and output powers of between several watts and several tens of watts. A CW power level of over 8 W was observed near 460 GHz [9]. Results reported in this paper are for operation of this gyrotron at the fundamental cyclotron harmonic.

The electromagnetic radiation in a gyrotron oscillator results from the interaction of a mildly relativistic gyrating electron beam and transverse-electric (TE) wave near cutoff in an overmoded cavity resonator situated in a dc magnetic field. The oscillation frequency $\omega$ of a $TE_{m,p,q}$ mode of a cylindrical cavity of effective length $L$ and radius $r_0$ is given by

$$\frac{\omega^2}{c^2} = k^2 = k_\perp^2 + k_z^2 \tag{1}$$

where $k_\perp(=\nu_{\mathrm{mp}}/r_0)$ and $k_z(=q\pi/L \ll k_\perp)$ are the transverse and longitudinal propagation constants, respectively, of

Manuscript received August 15, 2006; revised November 6, 2006. This work was supported by the National Institutes of Health under Grants EB002061, EB002804, EB002026, and EB004866.

M. K. Hornstein was with the Department of Electrical Engineering and Computer Science and the Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139 USA. She is now with the Naval Research Laboratory, Washington, DC 20375 USA.

V. S. Bajaj and R. G. Griffin are with the Department of Chemistry and Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

R. J. Temkin is with the Department of Physics and the Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

Digital Object Identifier 10.1109/TPS.2006.889295

the $TE_{m,p,q}$ wave, $c$ is the velocity of light, $\nu_{\mathrm{mp}}$ is the $p$th root of $J'_m(x)$, and $m$, $p$, and $q$ are the azimuthal, radial, and axial mode numbers, respectively. The resonance condition for the excitation of the cyclotron-resonance maser instability is satisfied when $\omega$ and $k_z$ in (1) satisfy the beam-mode dispersion relation

$$\omega - k_z \beta_{z0} c \approx n\omega_{c0} \tag{2}$$

where $\omega_{c0}(= eB_0/\gamma m_e)$ is the relativistic cyclotron frequency, $\gamma = (1 - \beta_z^2 - \beta_\perp^2)^{-1/2}$ is the relativistic mass factor, $m_e$ and $e$ are the electron rest mass and charge, $\beta_\perp$ and $\beta_z$ are the transverse and longitudinal velocities, respectively, of the electrons normalized to the velocity of light, $n$ is the cyclotron harmonic number, $B_0$ is the magnitude of the static axial magnetic field, and the subscript "0" denotes that the value is taken at the start of the interaction region.

## II. Low-Voltage Experiment

In this paper, the axis of the gyrotron lies along the vertical bore of a 9.2-T superconducting magnet, while the microwave power is extracted via a quasi-optical mode converter (optimized for $TE_{0,6}$ waveguide mode radiation) through an auxiliary horizontal room-temperature bore, which intersects with the main bore above the main coil of the superconducting magnet. The gyrotron is shown schematically in [9] and [10]. The high-voltage power supply used in this paper is 3-kW limited with maximum output voltage of 25 kV and maximum output current of 192 mA.

The experiment employs a low-voltage diode-type electron gun, which was analyzed using the EGUN electron optics and gun-design program [11]. The results of this study over a range of 5–15 kV and 7.8–9.2 T were reported in [10]. For operating parameters corresponding to excitation of fundamental modes, EGUN simulations predict large variations in the velocity-spread and velocity-pitch ratio with changes in the beam voltage and the magnetic field.

A parametric study of the gyrotron modes involves independent variation of the electron-beam voltage and current, main magnetic field, and the gun magnetic field. Fig. 1 is a plot of the mode-excitation regime that was generated during microsecond-pulse low-duty operation charting the regions of mode excitation in the parameter space of interest. For a fixed magnetic field, the excitation region is narrow in voltage-space for the second-harmonic modes and has, therefore, been represented as a line. In Fig. 1, three main parameters have been varied—the main magnetic field, the beam voltage, and the cathode magnetic field for a fixed beam current of 100 mA—to determine the operational limits of each mode. The electron-beam voltage was varied up to 15 kV, the main magnetic field was independently varied up to 8.5 T, and the cathode magnetic field was varied by 30%. All measurements were taken at the end of a 2-m-long copper waveguide of 2.54-cm inner diameter that couples directly to the output window.

In the region of interest, there are two second-harmonic modes, the $TE_{2,6}$ at 456 GHz and the $TE_{0,6}$ at 459 GHz, and one fundamental mode, the $TE_{2,3}$ at 233 GHz. The studies of the $TE_{2,3}$ fundamental harmonic mode reveal that the mode

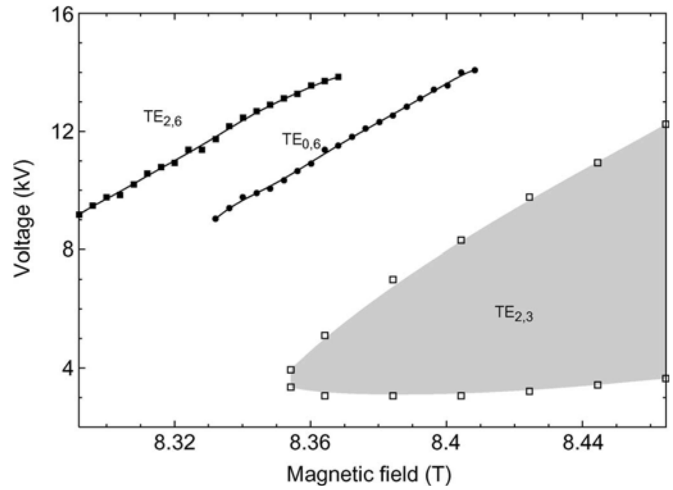


Fig. 1. Mode excitation regions for two second-harmonic modes ($TE_{2,6}$ and $TE_{0,6}$) and nearby fundamental harmonic mode ($TE_{2,3}$) over beam voltage, cavity, and, implicitly, cathode magnetic fields.

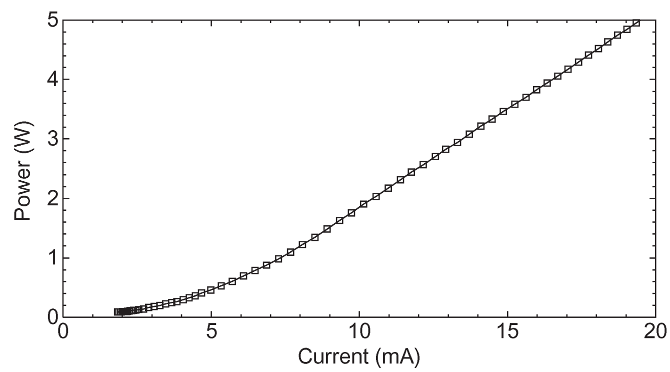


Fig. 2. CW output power in the $TE_{2,3,1}$ mode as a function of beam current at 3.5 kV and 8.38 T.

can be excited at very low voltage, less than 3.5 kV, with less than 7 W of beam power. Calorimetric measurements of the RF power indicate that the mode begins oscillating at 2 mA at 8.38 T and 3.5 kV with 100 mW of output power (cf. Fig. 2). At the experimental magnetic field corresponding to the minimum measured starting current, a starting current of 2 mA can be obtained using linear theory [12] with electron velocity-pitch factor $\alpha$ (ratio of transverse to longitudinal velocity of the electrons) of about two.

The low-voltage operation of the electron gun can be adequately explained through simulation of the electron gun using the EGUN electron optics code. Depicted in Fig. 3 is an EGUN simulation for 10-mA beam current at 3.5-kV beam voltage. The cathode magnetic field used in these experiments is estimated to be less than 0.22 T, corresponding to an electron-beam velocity-pitch factor with a steep slope and a transverse velocity spread of 8%. The calculation in Fig. 3 depicts that a large range of alpha values can be obtained by comparatively small changes in the cathode magnetic field.

Using a range of alpha values between two and five and with 12% transverse velocity spread, the starting currents for the first five discrete integer longitudinal modes ($TE_{2,3,q}$, where $q = 1, 2, 3, 4, 5$) have been calculated using linear theory [13] and are shown in Fig. 4. The experimental data in Fig. 4 are

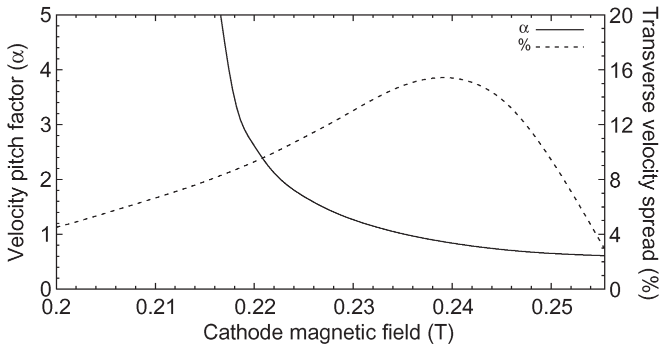


Fig. 3. Electron-gun simulation using EGUN electron optics code of the velocity-pitch factor (solid line) and transverse velocity spread (dashed line) for 10 mA, 3.5 kV, and 8.38 T.

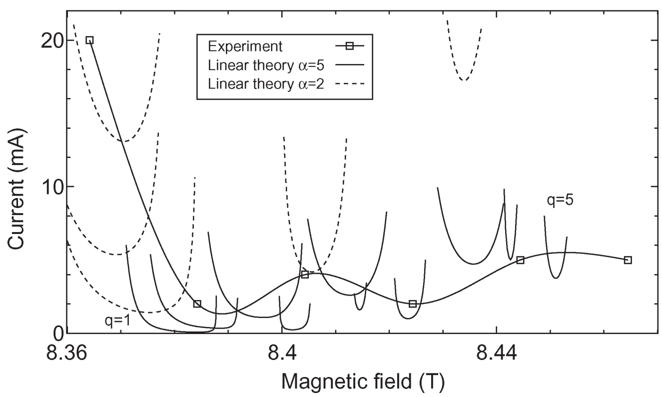


Fig. 4. CW start current data in the $TE_{2,3,q}$ series of axial modes at 3.5 kV compared to linear theory using $\alpha$ equal to two and five and with 12% transverse velocity spread.

a representative sample of continuous start current data as a function of magnetic field. This phenomenon is a result of axial mode hybridization of the $TE_{2,3,q}$ modes and, therefore, the data cannot be assigned to discrete modes [10]. The starting current calculation uses electron-beam parameters calculated by EGUN, cold-cavity electric-field profiles, cavity radius of 2 mm, and cavity-beam radius of 0.85 mm. We have systematically increased the EGUN-derived velocity spread according to [14] to account for cathode-surface roughness, thermal variations, and other effects not explicitly modeled in EGUN. While the experimental starting currents match well with linear theory for alpha equal to two at the lower magnetic fields, the calculation shows that a higher alpha is required to provide good agreement at higher magnetic fields.

Average power measurements were made during the experiment using a laser calorimeter that was recalibrated for millimeter wavelengths. Fig. 5 depicts measured CW power data of the fundamental harmonic $TE_{2,3,q}$ modes around 233 GHz as a function of beam current and magnetic field. A calorimeter was used to measure the radiation, and the beam voltage was fixed at 3.5 kV. Over 12 W of average power was recorded at 50 mA with an efficiency in excess of 7%. The mode also exhibits an experimentally wide frequency-tuning range, shown in Fig. 6, nearly 2 GHz; this effect has been discussed in detail in [10] and [15] and has been interpreted in terms of smooth transitions between higher order axial modes of the resonator.

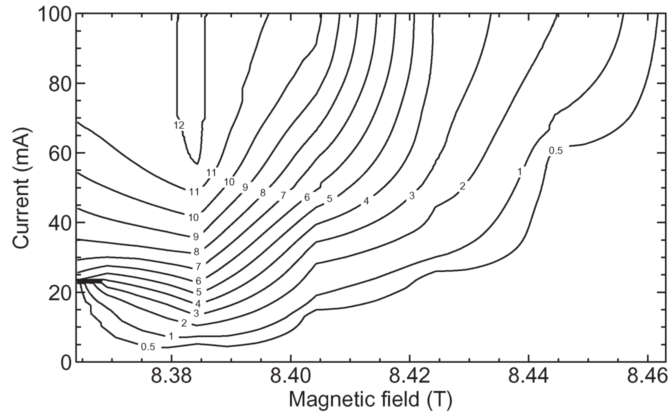


Fig. 5. Contour plot of measured CW power data of the fundamental harmonic $TE_{2,3,q}$ modes in watts as a function of beam current and magnetic field for an electron-beam voltage of 3.5 kV.

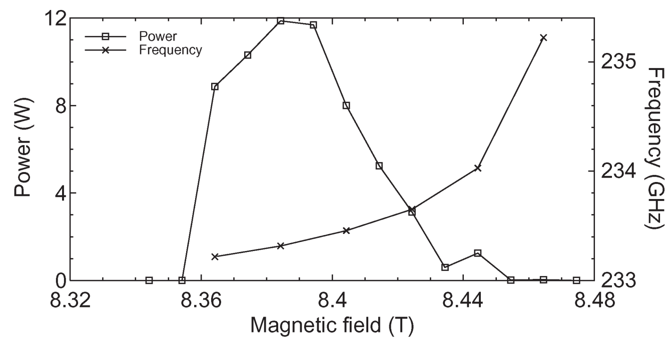


Fig. 6. CW output power and frequency in the $TE_{2,3,q}$ modes as a function of magnetic field for 50 mA and 3.5 kV.

## III. Conclusion

Gyrotron oscillators are capable of generating extremely high average powers (< 1 MW) over a wide frequency range (typically 24–170 GHz). One challenge is to further develop compact gyrotron oscillators for moderate average power applications of millimeter-wave and submillimeter-wave radiation. In this paper, we have significantly lowered the operating voltage of a millimeter/submillimeter wavelength gyrotron while still producing several watts of average power. The fundamental harmonic $TE_{2,3,1}$ mode at 233 GHz was excited with low beam power (7 W), at a voltage below 3.5 kV while oscillations started with 2 mA of beam current. Linear theory provides an explanation to the low experimental starting currents at low voltage, and the EGUN electron optics code described the operation of the diode gun. Future low-voltage gyrotron designs can then incorporate a more compact electron gun and electron-beam collector, and operate with significantly reduced cooling requirements.

## Acknowledgment

One of the authors, V. S. Bajaj acknowledges receipt of an NSERC PGS fellowship. The authors would like to thank A. Fliflet, S. Gold, K. Kreischer, D. Lewis III, I. Mastovsky, W. Mulligan, M. Shapiro, and J. Sirigiri for helpful discussions.

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**Melissa K. Hornstein** (S'97–M'05) received the B.S. degree in electrical and computer engineering from Rutgers University, New Brunswick, NJ, in 1999, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT), Cambridge, in 2001, and 2005, respectively.

From 2000 to 2005, she was a Research Assistant at the MIT Plasma Science and Fusion Center and the Francis Bitter Magnet Laboratory. She was involved in the development of a novel submillimeter-wave second-harmonic gyrotron oscillator for nuclear magnetic-resonance spectroscopy via dynamic nuclear polarization as well as other projects in the millimeter and submillimeter regime. Since 2005, she has been with the Naval Research Laboratory, Washington, DC, as an NRC Postdoctoral Fellow in the Plasma Physics Division. Her research interests include terahertz and millimeter sources and their applications, such as materials processing.

**Vikram S. Bajaj** received the B.A. degree in biochemistry and the M.S. degree in chemistry concurrently from the University of Pennsylvania, Philadelphia, in 2000. He is currently working toward the Ph.D. degree at the Department of Chemistry (Physical Chemistry Division), Massachusetts Institute of Technology (MIT), Cambridge.

Since 2000, he has been a Research Fellow at the MIT Francis Bitter Magnet Laboratory, where his work involves structure determination of biomolecules through solid-state nuclear magnetic resonance (NMR) and the development of dynamic nuclear polarization for sensitivity enhancement in NMR spectroscopy.

**Robert G. Griffin** received the B.S. degree in chemistry from the University of Arkansas, Fayetteville, in 1964, and the Ph.D. degree in physical chemistry from Washington University, St. Louis, in 1969. He did his postdoctoral research in physical chemistry at the Massachusetts Institute of Technology (MIT), Cambridge, with Professor J. S. Waugh.

In 1972, after completing his postdoctoral training, he assumed a staff position at the MIT Francis Bitter National Magnet Laboratory (FBML). In 1984, he was promoted to Senior Research Scientist, and was appointed to the faculty in the Department of Chemistry, MIT, in 1989. In 1992, he became Director of the FBML and is concurrently Director of the MIT–Harvard Center for Magnetic Resonance, where he has been an Associate Director since 1989. He has published more than 300 articles concerning with magnetic-resonance methodology and applications of magnetic resonance (NMR and EPR) to studies of the structure and function of a variety of chemical, physical, and biological systems. In the last decade, this research has focused on the development of methods to perform structural studies of membrane and amyloid proteins and on the utilization of high-frequency ($>$ 100 GHz) microwaves in EPR experiments and in the development of dynamic nuclear polarization/NMR experiments at these frequencies.

Prof. Griffin has served numerous advisory and review panels for the National Science Foundation and the National Institutes of Health.

**Richard J. Temkin** (M'87–SM'92–F'94) received the B.A. degree in physics from Harvard College, Cambridge, MA, and the Ph.D. degree in physics from the Massachusetts Institute of Technology (MIT), Cambridge.

From 1971 to 1974, he was a Postdoctoral Research Fellow in the Division of Engineering and Applied Physics, Harvard University. Since 1974, he has been with MIT, first at the Francis Bitter National Magnet Laboratory, and later, at the Plasma Science and Fusion Center (PSFC) and the Department of Physics. He is currently a Senior Scientist in the Physics Department, as an Associate Director of the PSFC, and Head of the Waves and Beams Division, PSFC. His research interests include novel vacuum electron devices such as the gyrotron and free-electron laser, advanced high-gradient electron accelerators, quasi-optical waveguides and antennas at millimeter wavelengths, plasma heating, and electron-spin-resonance spectroscopy. He has been the author or coauthor of over 200 published journal articles and book chapters and has been the Editor of six books and conference proceedings.

Dr. Temkin is a Fellow of the American Physical Society and The Institute of Physics, London. He is the recipient of the Kenneth J. Button Prize and Medal of The Institute of Physics, London, and the Robert L. Woods Award for excellence in vacuum electronics research.