plotted in Fig. 6. This indicates that bistablelike behavior may appear for some range of $\varphi_0$ when the transit time of the ring cavity and the period of the mode-locked pulse train are mismatched. The mismatching reduces the extent of overlap and thus the interaction between successive pulses in a pulse train. This could be the cause of the smoothing and the appearance of the bistability when the cavity length is mismatched.

Other nonlinear processes which are expected to occur in the fiber are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The threshold power of SBS in our single-mode optical fiber of length 120 cm was about 20 W, one order of magnitude lower than the onset of the bifurcations. But SBS is possible only in the direction opposite to the input beam, and therefore SBS is strongly suppressed for a pulse train of short pulses. On the other hand SRS can build up in the forward direction, and it actually occurred in our ring cavity at a few times higher input power level than the onset of the chaos.

In conclusion, the use of the mode-locked pulse train and the single-mode optical fiber was the key feature of the present experiment. In this system the bifurcations to the periodic and chaotic states in an all-optical system were realized.

We would like to thank Dr. K. Kato for the loan of a second-harmonic crystal and P. Davis for readings of this manuscript and helpful comments. This work was supported in part by a Grant in Aid for Scientific Research from the Ministry of Education of Japan.

[1]A. Szöke, V. Daneu, J. Goldhar, and N. A. Kurnit, Appl. Phys. Lett. 15, 376 (1969).
[2]S. L. McCall, Phys. Rev. A 9, 1515 (1974).
[3]H. M. Gibbs, S. L. McCall, and T. N. C. Venkatesan, Phys. Rev. Lett. 36, 1135 (1976).
[4]T. Bischofberger and Y. R. Shen, Phys. Rev. A 19, 1169 (1979).
[5]D. Ruelle and F. Takens, Commun. Math. Phys. 20, 167 (1971).
[6]J. B. McLaughlin and P. C. Martin, Phys. Rev. A 12, 186 (1975).
[7]K. Ikeda, Opt. Commun. 30, 257 (1979).
[8]K. Ikeda, H. Daido, and O. Akimoto, Phys. Rev. Lett. 45, 709 (1980).
[9]H. M. Gibbs, F. A. Hopf, D. L. Kaplan, and R. L. Shoemaker, Phys. Rev. Lett. 46, 474 (1981).
[10]F. A. Hopf, D. L. Kaplan, H. M. Gibbs, and R. L. Shoemaker, Phys. Rev. A 25, 2172 (1982).
[11]Masakatsu Okada and Kuniharu Takizawa, IEEE J. Quantum Electron. 17, 2135 (1981).
[12]B. Crosignani, C. H. Papas, and P. DiPorto, Opt. Lett. 6, 61 (1981).
[13]H. Nakatsuka, D. Grischkowsky, and A. C. Balant, Phys. Rev. Lett. 28, 910 (1981).
[14]D. J. Kuizenga, Opt. Commun. 22, 156 (1977).

# Realization of a Stable and Highly Efficient Gyrotron for Controlled Fusion Research

Y. Carmel,[a] K. R. Chu, M. Read, A. K. Ganguly, D. Dialetis,[b]
R. Seeley,[c] J. S. Levine, and V. L. Granatstein
*Plasma Physics Division, Naval Research Laboratory, Washington, D. C. 20375*
(Received 29 October 1982)

The innovation of adding a beam prebunching section at the input to the cavity of a millimeter-wave gyrotron oscillator has yielded outstanding improvements in mode control and device efficiency. These results constitute a technological breakthrough which greatly improves prospects of developing gyrotrons with megawatt average power ratings as will be required for bulk heating of plasma in controlled thermonuclear reactors.

PACS numbers: 52.35.Hr, 52.50.Gj

Electron-cyclotron resonance heating (ECRH) has proven to be a promising method of heating of fusion research plasmas. This is due in part to the availability of a new type of powerful millimeter-wave source, the gyrotron, and in part to successful demonstration of ECRH in tokamaks,[1,2] bumpy torus devices,[3,4] and magnetic mirrors.[5,6] ECRH now constitutes a key phase in many fusion research programs. For example, the formation of the hot-electron ring in Elmo bumpy torus[7] and the creation and sustainment of the thermal barriers[8] in the tandem mirror depend critically on this method of heating. Further, localized rf power deposition in electron velocity space can lead to current generation[9–11] suggesting the possibility of a steady-state tokamak. Localized heating in real space, on the other hand, can stabilize tearing modes through control of temperature and current profiles.[12] As is well known, the main obstacle to low-frequency rf heating has not been the lack of powerful rf sources, but the effective coupling of rf power into the plasma. By contrast, the opposite is true in the case of ECRH, where efficient wave-plasma coupling has been demonstrated but realization of many important experiments still awaits the development of gyrotrons more powerful than those currently available. As controlled fusion experiments are scaled up to reactor size, gyrotrons capable of generating 1 MW or more cw will be required.

To generate megawatt power levels at the millimeter wavelength, a highly overmoded cavity is required[13] to provide a sufficiently large radiating volume. In addition, high interaction efficiency has to be achieved so as to minimize the heat deposition by the spent beam as well as maximize the output power. Megawatt peak power in a short-pulse gyrotron has been demonstrated[14]; however, the cavity mode in that device,[15] chosen to achieve good mode control, was characterized by large wall losses, and the pulse length was limited to ~100 $\mu$sec. A class of modes with relatively low wall losses are the $TE_{0n}$ modes in circular waveguide. Successful operation of gyrotrons with pulse lengths from 10 msec to cw has been achieved with $TE_{01}$ and $TE_{02}$ modes at power levels ~200 kW.[16] However, for megawatt cw operation, higher-order $TE_{0n}$ modes must be chosen and the difficulty of mode control is the primary technical barrier. Experimental investigations[17–19] of high-order $TF_{0n}$-mode gyrotrons have always shown a strong susceptibility to mode competition, a serious problem that often resulted in poor mode control and low efficiency. For this reason, the study of competing modes has received considerable attention.[18–23]

In this Letter, we report an innovative approach which has been employed to achieve a high-order-mode gyrotron with a remarkable degree of stability and a record efficiency of 63%. The approach involves the use of a carefully tailored complex resonator (Fig. 1), which is formed of two coupled cavities, a small cavity for mode control and a large cavity to provide the necessary radiating volume. When separated, each cavity is characterized by a discrete set of eigenfrequencies. If the dimensions of the two cavities are chosen such that the eigenfrequency of a low-order mode in the first cavity matches that of a high-order mode in the second capacity, strong coupling between the two cavities will result. Figure 2 (Ref. 24) illustrates the case under study where the low- and high-order modes were chosen to be, respectively, the $TE_{011}$ and $TE_{041}$ modes. The most likely competing modes are those close in frequency to the $TE_{041}$ mode of the more densely populated second cavity. These modes, however, will remain localized to the second cavity because of the absence of matching modes in the first cavity whose eigenfrequencies are much more widely spaced. Thus, by way of selective coupling, a desired mode in the second cavity has been isolated from its neighboring modes. The coupled $TE_{011}$-$TE_{041}$ mode distinguishes itself from other modes with a broad, double-peaked axial structure (Fig. 2). As discussed below, it is this unique feature that provides the basis for mode stability and efficiency

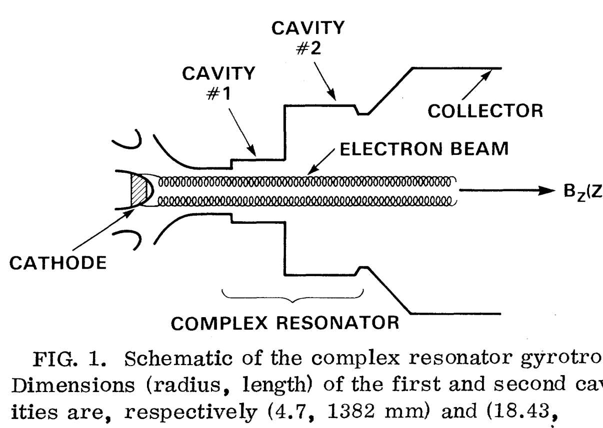


FIG. 1. Schematic of the complex resonator gyrotron. Dimensions (radius, length) of the first and second cavities are, respectively (4.7, 1382 mm) and (18.43, 23.24 mm).

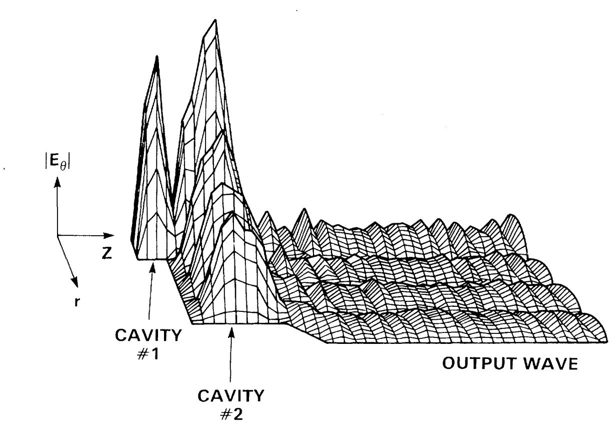


FIG. 2. Azimuthal electric field profile of the coupled $TE_{011}$-$TE_{041}$ mode.

enhancement.

In the linear regime, the strength of the beam-wave interaction is proportional to the square of the interaction length.[25] The desired $TE_{011}$-$TE_{041}$ mode, being the broadest in field structure, will therefore be most strongly coupled with the beam so as to require the lowest starting current. Viewed differently, the first cavity serves to prebunch the beam which in turn will preferentially excite the mode with the same frequency in the second cavity. In this manner, competition from other modes is essentially eliminated. In the nonlinear regime, prebunching of the beam in the first cavity can lead to efficiency enhancement in the second cavity. Because of its distinctively different field structure, the desired mode can be selectively optimized with respect to cavity lengths, dc magnetic field, and rf electric field profiles. This provides an additional measure to insure the dominance of the desired mode and further improve its efficiency.

An orbit-tracing code[26] was employed to evaluate the interaction efficiency as the electron beam traverses the complex resonator. For analytical convenience, uncoupled sinusoidal rf field profiles were assumed in both cavities to approximate the actual field shown in Fig. 2. The theory predicted suppression of the $TE_{241}$ mode and enhanced efficiency of the $TE_{041}$ mode due to prebunching of the electron beam. A main objective of the calculations was to determine (i) the optimum dimensions of the complex resonator, (ii) the optimum relative rf field amplitudes in the two cavities, and (iii) the optimum applied magnetic field profile so as to maximize the interaction efficiency. The dimensions of the resonator shown in Fig. 1 and the rf field profile shown in Fig. 2 were the results of extensive numerical optimizations. For the optimized configuration, a maximum theoretical efficiency of 57% was calculated in a linearly tapered magnetic field where the magnetic field strength increased by 15% along the beam path in the complex resonator.

The experimental setup is shown schematically in Fig. 1. The 70-keV beam generated by a magnetron injection gun had a perpendicular-to-parallel velocity ratio of 1.5. The system was immersed in an axial magnetic field produced by a superconducting magnet. The field increased monotonically from 2 kG at the gun to 13 kG at the resonator. In the resonator section, a conventional solenoid was used to linearly taper the field.

The output power was measured calorimetrically, with the efficiency defined as the observed millimeter-wave power divided by the electrical input power. The output mode was determined by measuring the frequency, and verified by a new technique of mode pattern visualization.[27]

Test results are shown in Figs. 3 and 4. Figure 3 is a "mode map," showing the regions in beam current, magnetic field parameter space in which oscillation occurred in the $TE_{011}$-$TE_{041}$ mode and its closest neighbor, the $TE_{241}$ mode. As can be seen, there is a quiescent region separating the two modes. This characteristic is fundamentally different from that observed with a single cavity,[18] where the two regions had a common boundary indicating that mode competition had occurred.

In Fig. 4, the efficiency and output power of the two modes are shown as a function of beam current. The points are for optimum values of the magnetic field (both at the cavity and the gun) and of the magnetic taper. The optimized output powers and efficiencies obtained in the $TE_{011}$-$TE_{041}$ mode combination are much greater than those found with $TE_{241}$. This is in contrast to the results with a single cavity, in which the highest powers and efficiencies were obtained in the $TE_{241}$. With the complex resonator, the maximum power, limited by the current of the electron gun, was 340 kW at an efficiency of 54%. At

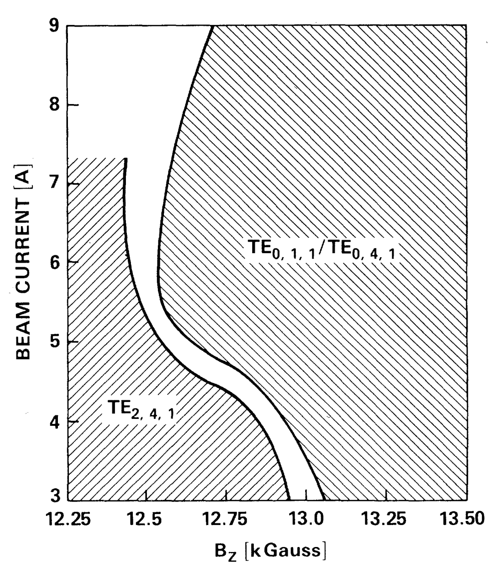


FIG. 3. Operating regimes of the $TE_{011}$-$TE_{041}$ mode and its closest neighbor, the $TE_{241}$ mode. No oscillations occurred in the unshaded region.

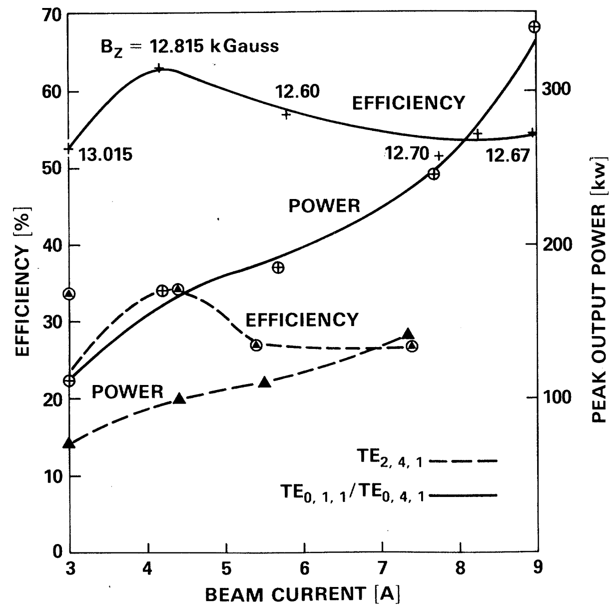


FIG. 4. Power and efficiency vs beam current for the two modes shown in Fig. 3. (Numbers on the upper curve are magnetic field values at the upstream end of the resonator.)

lower power (150 kW), efficiency was 63%, approximately 1.5 times greater than that obtained with a single cavity.[18] Remarkably, the device operated with an efficiency of greater than 50% over the entire range of 110 to 340 kW.

As theoretically predicted, the output was quite sensitive to the magnetic taper. For example, at the point of maximum power, a taper of 12% was required. With no tapering, less than 50 kW were obtained.

To summarize, a major physics issue—mode stability—in the development of high-power gyrotrons has been removed by the use of a complex resonator, and at the same time, a dramatic improvement in efficiency has been achieved. By applying the same technique to a still higher-order mode (e.g., $TE_{06}$), gyrotron power can be scaled up to surpass the megawatt level at wavelengths ≲3 mm. Concurrently, sophisticated window and beam collector technologies have been developed in industry to accommodate high-power cw operation.[28] In view of these encouraging developments, it is expected that the next generation of gyrotrons will meet the goal of the U. S. fusion program, viz., megawatt cw power at 120 GHz.

This work was supported in part by the U. S. Department of Energy. The authors would like to thank Mr. T. Smith, Professor I. Bernstein, Professor J. L. Hirshfield, Dr. A. Fliflet, and Dr. T. Antonsen for many helpful discussions.

---

[a]Also at University of Maryland, College Park, Md. 20742.

[b]Also at Science Applications, Inc., McLean, Va. 22102.

[c]Also at Jaycor, Alexandria, Va. 22304.

[1]V. V. Alikaev *et al.*, Fiz. Plazmy 2, 390–395 (1976) [Sov. J. Plasma Phys. 2, 212–215 (1976)].

[2]R. M. Gilgenbach *et al.*, Phys. Rev. Lett. 44, 647–650 (1980).

[3]R. A. Dandle *et al.*, in *Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978* (International Atomic Energy Agency, Vienna, Austria, 1979), Vol. 2, p. 365.

[4]M. Fujiwara *et al.*, in *Proceedings of EBT Ring Physics Workshop, Oak Ridge, Tennessee, 1979*, CONF-791228 (Oak Ridge, Tenn., 1979), p. 123.

[5]R. A. Dandle, in *Proceedings of EBT Ring Physics Workshop, Oak Ridge, Tennessee, 1979*, CONF-791228 (Oak Ridge, Tenn., 1979), p. 31.

[6]H. Ikegami and M. Hosokawa, in *Proceedings of EBT Ring Physics Workshop, Oak Ridge, Tennessee, 1979*, CONF-791228 (Oak Ridge, Tenn., 1979), p. 59.

[7]F. W. Baity, Jr., *et al.*, in Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1982 (to be published), paper no. CN41/L-1.

[8]D. Baldwin and G. Logan, Phys. Rev. Lett. 43, 1318 (1979).

[9]N. J. Fisch, Phys. Rev. Lett. 41, 873 (1978).

[10]T. Ohkawa, General Atomic Company Report No. GA-A13847, 1976 (unpublished).

[11]P. B. Parks and F. B. Marcus, Nucl. Fusion 21, 1207 (1981).

[12]H. Hsuan, private communication.

[13]K. J. Kim *et al.*, Int. J. Electron. 51, 427 (1981).

[14]A. A. Andronov *et al.*, Infrared Phys. 18, 385 (1978).

[15]V. A. Flyagin, private communication.

[16]K. Felch *et al.*, in *Proceedings of the IEEE International Conference on Plasma Science, Ottawa, Canada, 18–22 May 1982* (IEEE, New York, 1982), Vol. 45. Also A. V. Gaponov *et al.*, Int. J. Infrared Millim. Waves 1, 351 (1980).

[17]B. Arfin *et al.*, to be published.

[18]Y. Carmel *et al.*, Int. J. Infrared Millim. Waves 3, 645 (1982).

[19]R. J. Temkin *et al.*, Int. J. Infrared Millim. Waves 3, 427 (1982).

[20]Much of the recent gyrotron work has been reported in two special issues of the Int. J. Electron. (Oct. 1981 and Dec. 1982).

[21]K. E. Kreischer and R. J. Temkin, Int. J. Infrared Millim. Waves 1, 195 (1980).

[22]D. Dialetis and K. R. Chu, in *Infrared and Millimeter*

*Wave Book Series*, edited by K. J. Button (Academic, New York, 1982), Vol. 7.
[23]G. S. Nusinovich, Int. J. Electron. 51, 457 (1981).
[24]Figure 2 was obtained by T. Smith with a modified version of the partial-differential-equation solver developed by S. Eisenstat at Yale University.
[25]See, for example, K. R. Chu, Phys. Fluids 21, 2354 (1978).
[26]A. K. Ganguly and K. R. Chu, Int. J. Electron. 51, 503 (1981).
[27]Y. Carmel and G. Mourier, to be published.
[28]H. Jory, Varian Associates, private communication.

# Observation of Raman Scattering of High-Frequency Phonons by Spin States

M. Englehardt, U. Happek, and K. F. Renk
*Institut für Angewandte Physik, Universität Regensburg, D-8400 Regensburg, West Germany*
(Received 24 August 1982)

High-frequency acoustic phonons in an $Al_2O_3$ crystal at low temperature were generated at one frequency (891 GHz) by excitation of $V^{4+}$ impurity ions with a far-infrared laser, and detected at another frequency (874 GHz) by fluorescence from $Cr^{3+}$ ions. A strong detector signal was observed, giving evidence that inelastic phonon scattering occurred. The dependence on magnetic field and temperature indicated that the effect was due to Raman scattering of phonons by spin states.

PACS numbers: 63.20.Kr, 78.30.Gt

In this Letter we report on a first direct observation of Raman scattering of phonons by spin states at low crystal temperatures. To observe a phonon frequency shift we have generated monochromatic phonons of one frequency, and detected phonons of another frequency. By application of recently developed techniques of high-frequency phonon spectroscopy, phonons were generated by use of a far-infrared laser[1-3] and detected by phonon-induced fluorescence.[4] Since the cross section increases strongly with frequency,[5] high-frequency phonons are most suitable for the study of Raman scattering.

The principle of our experiment, performed on an $Al_2O_3$ crystal containing $V^{4+}$ and $Cr^{3+}$ impurity ions, is shown in Fig. 1. Monochromatic phonons are generated by far-infrared excitation and relaxation of $V^{4+}$ ions. Far-infrared laser radiation at a frequency $\nu_{FIR}$ (891 GHz) is absorbed in the wing of a broad absorption line[6,7] which is due to an electronic transition between the ground state and the lowest excited state of $V^{4+}$. Since the $V^{4+}$ ions are excited to forced electronic vibrations by the monochromatic far-infrared radiation, it is expected that the generated acoustic waves have exactly the same frequency $\nu_{FIR}$ as the far-infrared radiation.

Phonons at a detector frequency $\nu_{det}$ (874 GHz), which corresponds to the separation of the $\bar{E}$ and $2\bar{A}$ levels[4] of optically excited $Cr^{3+}$ ions, are detected by $R_2$ fluorescence (Fig. 1). Since the $\bar{E} \rightarrow 2\bar{A}$ absorption line is very narrow (0.5 GHz),[8] the detector responds only to phonons in a very narrow frequency band. Surprisingly, phonon generation by excitation of $V^{4+}$ ions with a far-infrared laser yielded an $R_2$ signal, even though the detector frequency $\nu_{det}$ was different (by 2%) from the generator frequency $\nu_{FIR}$. This shows that inelastic scattering of the monochromatically generated phonons occurred.

Before we present further results the experiment will be described in more detail. The $Al_2O_3$ crystal (size $3\times3\times5$ mm$^3$) contained 0.3 wt.%

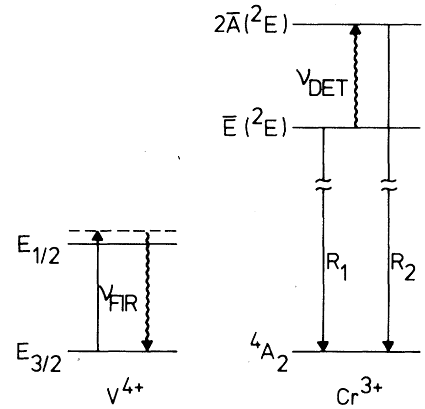


FIG. 1. Energy levels of $V^{4+}$ and $Cr^{3+}$ ions in $Al_2O_3$ and principle of monochromatic phonon generation and detection. Generator frequency $\nu_{FIR}$ and detector frequency $\nu_{det}$ are different.