STATUS OF HIGH POWER GYROTRON TECHNOLOGY*

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Gyrotron research and development is being driven by the requirements of microwave sources with capabilities beyond the state-of-the-art for both Controlled Thermonuclear Fusion Research (CTFR) and High Energy Physics (HEP). In projected CTFR studies, plasma heating will require microwave sources with average power $\gtrsim$ 1 MW at a wavelength $\lambda \approx 1$ mm. In projected HEP studies, high gradient accelerators for use in electron-positron colliders will require phase-controlled, microwave sources with peak power $\gtrsim$ 100 MW and pulse duration ~ 2 μs at 1 cm $\lesssim \lambda \lesssim$ 5 cm. This paper reviews recent progress toward meeting these requirements. Advances in both gyrotron average power capabilities and gyrotron peak power capabiliites are described. Progress in phase locking gyrotron oscillators and in reducing phase jitter in gyrotron amplifiers is reviewed. Finally, a design of a 10 GHz, 40 MW gyroklystron amplifier for the collider application will be described and compared with the design parameters of a conventional klystron with similar projected capabilities.

Gyrotron Oscillator Progress

High Average Power Gyrotrons

Gyrotrons which emit coherent radiation at the electron cyclotron frequency, ω_{ce}, can operate in a high order mode of a resonant cavity with good mode stability by matching the resonant frequency of that mode to ω_{ce}. Thus, gyrotrons have superior mode selectivity properties compared with other microwave tubes, and at a given wavelength, gyrotron cavities are generally much larger and can handle much higher levels of average power.

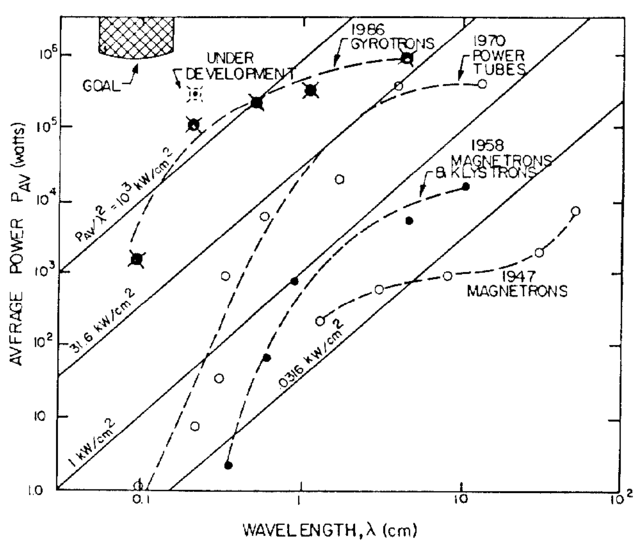

FIG. 1. Average power ratings of various types of microwave tubes plotted vs. wavelength.

In Fig. 1, the average power ratings of various types of microwave tubes are plotted vs. wavelength. It is apparent that for $\lambda \lesssim 3$ cm, gyrotrons have demonstrated far higher average power than any other type of microwave tube; at $\lambda \approx 1$ mm, the advantage in average power is several orders of magnitude. Gyrotron oscillators producing 200 kW of CW output power are commercially available at frequencies ranging from 28 GHz to 60 GHz.[1]

Nevertheless, the controlled fusion research program is demanding still further advances in microwave average power capabilities. The shaded area in the upper left corner of Fig. 1 indicates the microwave source requirement for Electron Cyclotron Resonance Heating (ECRH) in the Compact Ignition Torus (CIT), a next generation magnetic fusion experimental device planned for the 1990's. It is estimated[2] that 20 MW of ECRH power in the frequency range 240 GHz to 300 GHz will be required for several seconds. Of course, this power could be supplied by multiple sources, but even then, for reasons of economy, power level per tube $\gtrsim$ 1 MW is desired. Even greater challenge is presented by the recent concept of conducting ECRH at the second harmonic of the electron cyclotron frequency in the CIT, in which case the required frequency range could double (i.e., the frequency range of interest would be 480 GHz to 600 GHz).[3]

As impressive as the CW performance of the gyrotron oscillators has been, it is still far from meeting these projected requirements. The operating gyrotron oscillator which comes closest has been developed at Varian Associates at a frequency of 140 GHz.[4] Operating with electron gun voltage of 80 kV, this gyrotron has achieved 100 kW of CW output power (with 27% efficiency), 150 kW of output power for 100 ms, and 200 kW of output power for 1 ms. The main resonant cavity operates in the TE_{031} mode and is similar to that examined at MIT with 1 μs pulses.[5] Discrimination against spurious oscillation in the TE_{231} mode is achieved by prebunching the phases of the gyrating electrons in a TE_{021} cavity, which is strongly coupled to the main TE_{031} cavity. This coupled cavity technique for achieving superior mode stability in TE_{0n1} modes was pioneered at the Naval Research Laboratory.[6]

Another technique for achieving mode stability in very large gyrotron cavities is to employ whispering gallery modes ($TE_{m,n}$, m >> n). These modes have their field energy concentrated close to the cavity wall, and they can be preferentially excited by a hollow electron beam of large radius. A $TE_{15,2,1}$ gyrotron is presently under development at Varian Associates, again using an 80 kV electron gun; design goals are 400 kW of output power at 140 GHz, and operation is expected in the summer of 1987.[7] The design is similar to that used in a 1 μs pulsed experiment at MIT where output power up to 645 kW has been demonstated with efficiency $\sim$ 20%.[8] Further scaling up of gyrotron oscillators in average power and in frequency may require operation at harmonics of the cyclotron frequency and/or advanced techniques for cooling of the cavity walls.

In addition to continuing efforts to extend the capabilities of whispering gallery mode gyrotrons,

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other cyclotron maser oscillator configurations are also being considered. There is ongoing work on quasi-optical gyrotrons employing Fabry-Perot cavities [e.g., Refs. (9) and (10)], and on Cyclotron Auto-Resonance Masers (CARM's) which exploit a large doppler upshift to operate at frequencies far above ω_{ce} [e.g., Refs. (11)-(13)]. Free electron lasers are also being considered as candidate sources for ECRH in the CIT [e.g., Refs. (14) and (15)].

A Tunable High Peak Power Gyrotron Oscillator

Linear accelerators require high peak power microwave sources with relatively short pulse duration rather than high average power as required in the plasma heating application. Whispering gallery mode gyrotron oscillators with high peak power ouput have recently been studied at the Naval Research Laboratory.[16] The pulsed power for this study was provided by a "single-shot" 775 kV Febetron with a 55 ns pulse duration; the electron beam was drawn from a cold cathode by plasma induced field emission. The electrons are subsequently given a substantial increase in their transverse momentum by passing through a nonadiabatic dip in magnetic field produced by a "pump" magnet coil. Transverse momentum is then further increased between the "pump" magnet and the gyrotron cavity by adiabatic compression. The experimental configuration is sketched in Fig. 2.

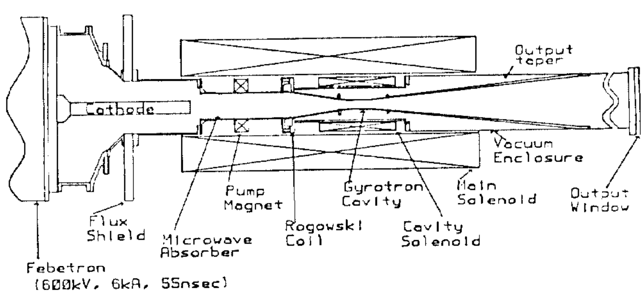

FIG. 2. Experimental configuration for a 100 MW K_a-band gyrotron oscillator study [from Ref. (16)].

At 35 GHz, approximately 100 MW of output power was produced in the TE_{621} mode with magnetic field in the cavity set at 24.4 kG. This power level corresponds to an efficiency of ~ 8% based on a current of 1.6 kA flowing through the gyrotron cavity. By tuning the cavity magnetic field, it proved possible to achieve a stepwise frequency tunability with the gyrotron operating at high power in a family of TE_{m21} modes. This tunability is shown in Fig. 3 where the observed operating frequency in modes with azimuthal eigennumber varying from four to ten is plotted vs. the axial magnetic field applied to the cavity. Stepwise tunability was achieved over a frequency range from 28 GHz to 49 GHz. It is interesting to note that tstepwise tunability is of interest in the plasma heating application.

For application to rf accelerators, however, tunability is of limited interest, but phase control is essential. Hundreds or even thousands of microwave sources will be requried to drive a large accelerator, and they must produce radiation with the proper phase to accelerate the electron or positron bunch as it passes by; phase control to an accuracy of about 1^0 is required. Phase locking of a single cavity gyrotron oscillator such as those described above has been demonstrated,[17] but the input power level required for locking was $\gtrsim$ 1% of the output power, while a "gain" of about 50 dB is desirable for the large accelerator application. Furthermore, separation of input and output channels is awkward in a single cavity device. Much better results with phase locking have been achieved in the gyroklystron configuration which is discussed below.

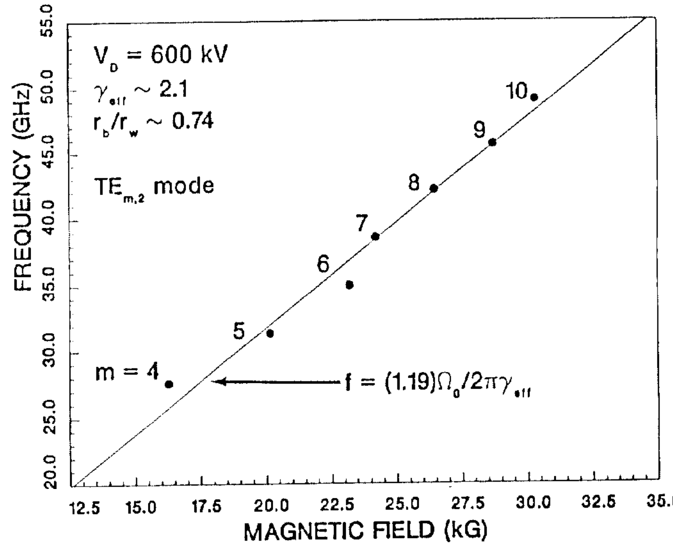

FIG. 3. Stepwise frequency tunability with the gyrotron operating at high power in a family of TE_{m2} modes. This tunability is shown where the observed operating frequency in modes with azimuthal eigennumber varying from four to ten is plotted vs. the axial magnetic field applied to the cavity [from Ref. (16)].

Gyrotron Studies

Measurements of Phase Noise and Phase Locking

A gyroklystron is similar in construction to a conventional klystron, being made up of a number of resonant cavities separated by drift spaces which are free of electromagnetic waves. However, in a gyroklystron, bunching takes place in the phases of the electrons in their cyclotron orbits rather than in the axial position of the electrons, and hence, no small gap reentrant cavities are required.

A 3-cavity gyroklystron has been operated at the Naval Research Laboratory. It is conservatively designed, employing rectangular fundamental mode cavities. Operating as a stable amplifier with a 30 kV electron gun, it has produced up to 54 kW of output power at 4.5 GHz.[18] A series of measurements of phase jitter has been carried out on this amplifier to determine the suitability of gyroklystrons for application to large linear accelerators.

A schematic of the 3-cavity gyroklystron and the phase detector circuitry is shown in Fig. 4. A 1 W, CW signal is coupled from a master oscillator into the gyroklystron input cavity. At the same time, a small sample of the master oscillator signal is fed to one arm of a balanced mixer through a coaxial cable line which contains a sliding short for adjusting phase. The second input to the balanced mixer is supplied with a portion of the gyroklystron output signal.

The IF output port of the balanced mixer yields a signal $S(\phi) = M\cos\phi + M\delta\sin\phi$, where M is the product of the electric field amplitude of the two input signals, ϕ is the mean phase angle between the two signals, and δ is the phase jitter. By adjusting the sliding short, the phase jitter can be found as $\delta = S(\pi/2)/S(0)$. Early measurements[20] recorded phase jitter of 20^0 during the pulse with a jitter frequency of about 6 MHz. This jitter was accompanied by a 1% ripple in beam current at about the same frequency. Installation of a capacitive filter between the cathode and final anode of the magnetron injection gun reduced the current ripple to 0.3% and the phase jitter to 0.75^0.[21]

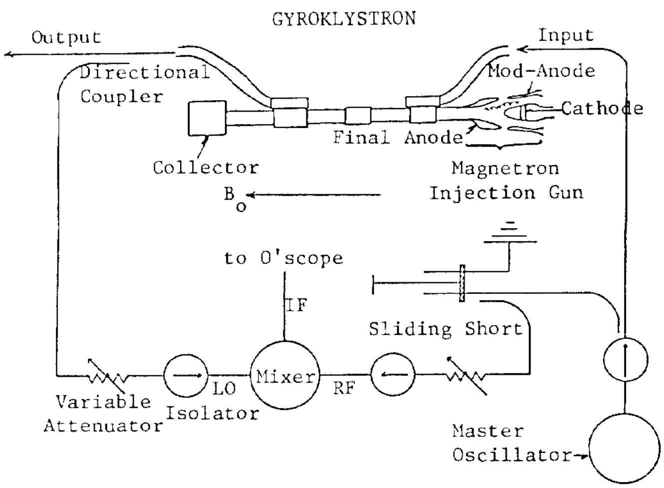

FIG. 4. Schematic of the 54 kW, 4.5 GHz, 3-cavity gyroklystron and the phase detector circuitry [from Refs. (19) and (20)].

Pulse to pulse jitter was also measured because of its relevance to starting many amplifiers with synchronized phase. This measurement was made by observing the mixer output for many pulses at a fixed time interval after the start of each pulse. Pulse to pulse phase jitter was measured as $< 0.25^0$.

While these measurements of phase jitter $< 1^0$ are encouraging, it should be noted that they were made in a relatively low power gyroklystron. However, since phase jitter can be reduced by feedback circuitry if required, there is promise that even much higher power gyroklystrons can be operated with phase jitter sufficiently small for the large linear accelerator appplication.

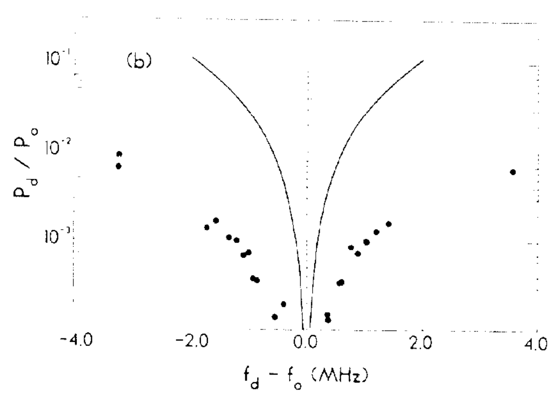

FIG. 5. Phase locking of the free oscillations in the output cavity by a small signal introduced into the input cavity. Results are shown where the ratio of input drive power to output power, P_d/P_o, is plotted vs. the frequency difference between the two signals [from Ref. (21)].

The 4.5 GHz gyroklystron could also be made to operate with the output cavity freely oscillating; this was accomplished by mechanically tuning the resonant frequency of the output cavity. The phase locking of the free oscillations in the output cavity by a small signal introduced into the input cavity has been studied.[22] Results are shown in Fig. 5 where the ratio of input drive power to output power, P_d/P_o, is plotted vs. the frequency difference between the two signals; magnetic field was slightly tapered along the axis so that the input cavity abosrbed radiation effectvely at the drive frequency. The solid line in Fig. 5 shows the level of P_d/P_o that would be expected in a single cavity oscillator according to Adler's theory.[23] It is clear tha the premodulation of the electron beam produced in the buncher cavities and drift spaces greatly reduces the level of drive power required for phase locking. Phase locking is observed with drive power almost 40 dB below the output power. Since microwave tubes which drive rf accelerators must be controlled in phase but not necessarily in amplitude, it would be possible to use either stable gyroklystron amplifiers or phase locked gyroklystrons with their output cavities in free oscillatioh.

Development of a Gyroklystron for Linear Supercolliders

Development of high peak power gyroklystron amplifiers is underway at the University of Maryland; the purpose of this development project is specifically to evaluate the applicability of gyroklystrons to driving linear supercolliders. The first amplifier has been designed to operate at a frequency of 10 GHz with peak power in the range 36 MW to 48 MW. The design of this tube is substantially completed and operation is expected in 1987.

Because of the high power level, and because only a fraction of the electron velocity is directed along the tube axis, a relatively large electron energy (500 keV) had to be chosen to avoid excessive potential depression of the beam with respect to the circuit walls. The ratio of transverse to axial velocity must be taken greater than unity to make high device efficiency possible; a value of $v_\perp/v_\parallel = 1.5$ was chosen. This choice led to a Larmor radius so large that the beam cannot easily fit into a drift tube which is cutoff to the fundamental mode. Then, the TE_{011} circular mode was chosen for the gyroklystron cavities. The drift tubes can be made sufficiently small to cutoff the TE_{01} mode; lower order modes (viz., TE_{11}, TM_{01}, and TE_{21}) are suppressed by slotting the drift tubes to prevent the flow of axial wall current. A photograph of a slotted drift tube is shown in Fig. 6. This design concept was presented at the Particle Accelerator Conference in 1985.[24]

The complete gyroklystron is sketched in Fig. 7, which shows the gyroklystron circuit to be composed of four cavities. The rotating annular electron beam is generated by a Magnetron Injection Gun (MIG) whose design optimization is described in the literature.[25] The peak dc electric field on any electrode in the gun is $\leq$ 91 kV/cm. Axial velocity spread in the circuit region is a minimum of ~ 6% when beam current is 160 A. For a beam current of 240 A, axial velocity spread rises to ~ 8%.

Based on this electron beam, the gyroklystron circuit design was optimized using a partially self-consistent code developed by K. R. Chu.[26] The dimensions and Q of each cavity, and the length of each drift space are optimized for maximum device efficiency at a current of 160 A while making sure that operation is below the threshold current for any mode in the buncher cavities. The output cavity will self-oscillate when there is no input signal, but will operate stably when the incoming electron beam is prebunched. The circuit dimensions and other design details are described in another paper at this conference.[27] A calculated gain curve is plotted in Fig. 8 for the case of beam current I = 160 A. Peak output power of 36 MW is predicted at a saturated gain of 63 dB.

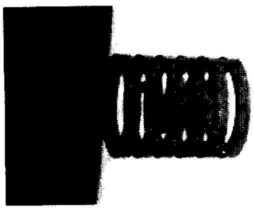

FIG. 6. Slotted drift tube.

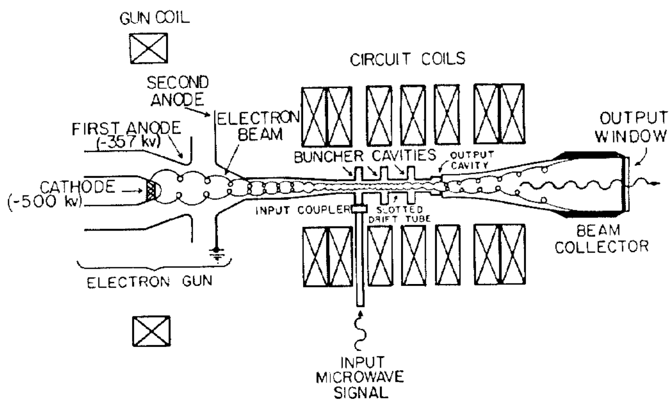

FIG. 7. Sketch of the 40 MW, 10 GHz gyroklystron [from Ref. (27)].

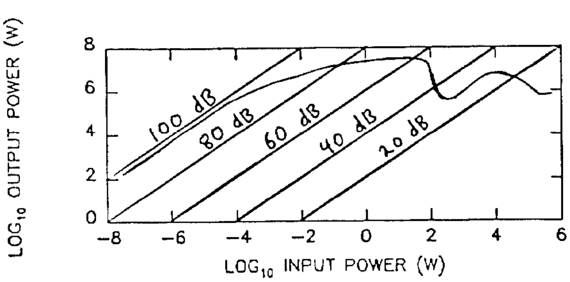

FIG. 8. Calculated gain curve plotted for the case of beam current I = 160 A. (Curve provided by P. Latham.)

The design parameters of this X-band gyroklystron are summarized in Table I where they are compared with the parameters of a conventional klystron which is being developed at the Stanford Linear Accelerator Center.[28] It is very interesting to note that although the gyroklystron has somewhat higher operating frequency, gain, and output power, the maximum gradient at the electron gun electrodes is much lower. The maximum gradient for the gyroklystron is 91 kV/cm compared with 300 kV/cm for the conventional klystron. The reason for this large difference is somewhat difficult to enunciate because the electron gun configurations are so different; viz., a double-anode, temperature-limited, MIG producing a hollow beam of spiralling electrons in the case of the gyroklystron, and a Pierce gun producing a solid beam of streaming electrons in the case of the conventional klystron. Nevertheless, it is worthwhile noting that the gyroklystron has larger cathode area and smaller electron beam perveance, and these are usually factors which lead to lower gradients at the gun electrodes.

The lower gradients in the gyroklystron gun imply that one could scale the gyroklystron to operate at higher voltage and higher output power. For example, one could produce a gyroklystron design using a similar TE_{01} circuit to that described above while increasing the voltage and current both by 60% to keep relative electrostatic potential depression in the circuit region constant. This might produce an increase in output power to a level ~ 100 MW. The electron gun for such a gyroklystron would have gradients at the electrons larger than 91 kV/cm but still well below the 300 kV/cm value that characterizes the conventional klystron design in Table I.

TABLE I. A comparison of design parameters of an X-band gyroklystron with an X-band conventional klystron. The numbers in parentheses in the gyroklystron column refer to operation at 240 A.

	Gyroklystron	Conventional Klystron
Frequency (GHz)	10	8.568
Voltage (kV)	500	330
Current (A)	160 (240)	152
Saturated Gain (dB)	$\gtrsim$ 60	50
Peak Output Power (MW)	36 (48)	30
Pulse Duration (μs)	1.5	1.0
Efficiency (%)	45.5 (40)	60
No. of Cavities	4	4
Current Density in Interaction Ckt. (A/cm^2)	67.2 (101)	330
Beam Area Convergence Ratio	12:1	36:1
Cathode Area (cm^2)	28.6	16.6
Current Density at Cathode (A/cm^2)	5.6 (8.4)	9.2
Max. Gradient at Electrodes (kV/cm)	91	300
Perveance (μp)	0.45 (0.68)	0.8

It might also be possible to develop higher power gyroklystrons that would operate with a higher order cavity mode (e.g., TE_{02}) and drift spaces of larger cross-section. Such devices could have the same 500 kV voltage and approximately the same current density as the gyroklystron in Table I. However, cathode area and total current would be much larger. Scaling in this fashion would require a more complex circuit design to supress spurious modes especially in the drift spaces.[24]

Finally, it should be noted that the pulse duration in the gyroklystron in Table I is considerably larger than the ~ 110 ns pulse length that would be required for the collider application at X-band, and much larger peak power is therefore attainable in principle by use of a pulse compression circuit. This power multiplication technique is in fact being invoked up to a factor of 16 in conceptual designs of linear colliders.[29] A pulse compressor design that is well matched to the gyroklystron since it functions best with the TE_{01} mode has been described by Farkas.[30]

Summary

High power gyrotron technology is in a state of rapid development. During this year (1987) a 400 kW CW gyrotron oscillator at 140 GHz is expected to become operational representing a four-fold advance in average power capability. However, even this demonstration will fall far short of the perceived requirements for high average power millimeter wave sources for plasma heating in advanced magnetic fusion experiments (viz., power $\gtrsim$ 1 MW and frequency in the range 240 GHz to 600 GHz). Promising concepts for further research and development in high average power, high frequency gyrotrons include whispering gallery mode oscillators operating at cyclotron harmonics, and quasi-optical gyrotrons using Fabry-Perot cavities, and free electron lasers.

Also, during 1987 one expects the first demonstration of a high peak power, X-band gyroklystron amplifier that would be relevant to driving linear supercolliders. Peak power in the range 36 MW to 48 MW is predicted with pulse duration of 1.5 μs. Using pulse compression, this gyroklystron might deliver peak power on the order of 600 MW. The design parameters of the gyroklystron promise that further scaling up in peak power and/or frequency should be feasible. However, it should be kept in mind that the 36 MW gyroklystron represents a thousand-fold advance in peak power over existing gyroklystron capability, and thus, the proof of the pudding will be in the results of the upcoming experimental demonstration.

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