GYROTRON

The gyrotron is a vacuum tube capable of delivering high levels of radio-frequency (RF) power at frequencies from several gigahertz to more than 300 GHz, which covers most of the microwave and millimeter wave band. Because of the structure of the RF fields in the cavity, the magnitude of the electric fields and the RF losses in the cavity walls are much lower in gyrotrons than in most microwave and millimeter wave vacuum tubes. As the RF increases, it is not necessary to reduce the size of the cavity and output waveguide. For these reasons, the gyrotron is the principal RF device for delivering high levels of RF power at frequencies between 30 GHz and 200 GHz.

Gyrotrons typically require a very high magnetic field to provide the cyclotron electron motion for power extraction, and most gyrotrons above 30 GHz require a superconducting magnet. This significantly increases system cost and complexity, limiting applications for these devices; however, recent advances in magnet technology are reducing this problem. Gyrotrons also have a narrow RF bandwidth, typically less than 1%, although gyrotron amplifiers are capable of wider bandwidths. Gyro-TWTs with 20% bandwidth have been demonstrated, and octave bandwidths are predicted with more complex circuits. Gyrotron oscillators produce more average or CW power levels since gyro-amplifiers are much more difficult to develop at higher frequencies due to the overmoded nature of the circuits. Still, gyro-amplifiers have significantly more capability than conventional tubes at millimeter-wave frequencies, and development of high-power gyroamplifiers is in progress at several locations around the world for use as high-power RF sources for accelerators and high-resolution radar.

Gyrotrons are used for electron cyclotron resonance heating (ECRH), electron cyclotron current drive (ECCD), and diagnostic measurements in fusion plasma devices. They are also being used for industrial heating applications such as ceramic sintering. Figure 1 is a photograph of Dr. Howard Jory, one of the pioneers in gyrotron development, holding a 28 GHz, 10 kW continuous wave (CW) harmonic gyrotron used for industrial heating. Behind him is a 110 GHz gyrotron rated at approximately 450 kW CW and 1 MW for pulses less than 1 s, that is used for electron cyclotron resonance heating. Communications and Power Industries, Inc. in Palo Alto, California manufactures both devices.

Research on gyro-type devices began in the 1950s when the astrophysicist R. Q. Twiss described an amplifying mech-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

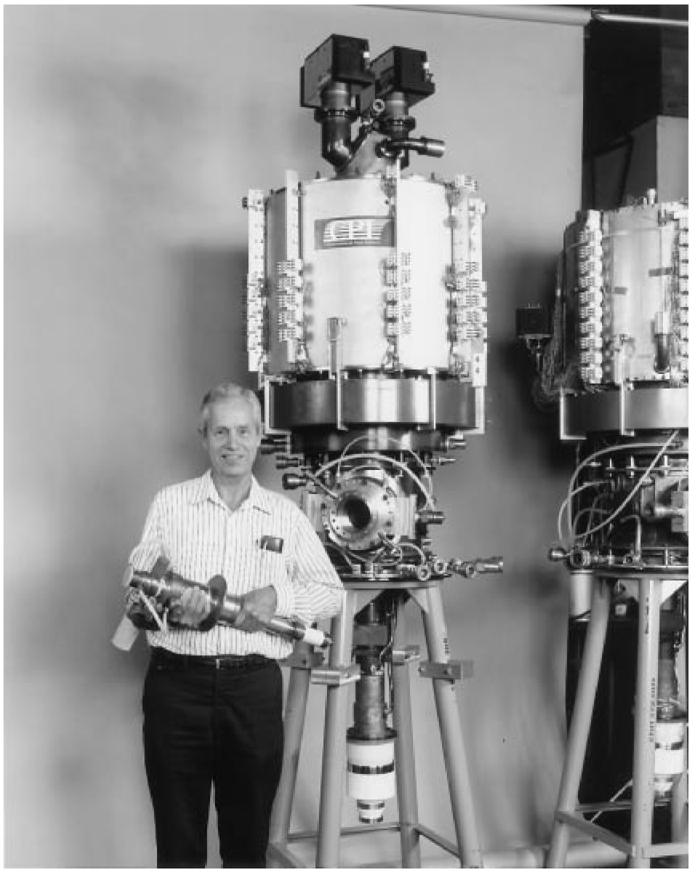

Figure 1. Dr. Howard Jory holds a 28 GHz, 10 kW CW harmonic gyrotron used for industrial heating. Behind him is a 110 GHz, 450 kW CW, 1 MW pulsed, gyrotron used for electron cyclotron heating of fusion plasmas.

anism for monochromatic radiation of angular frequency ω from stimulated emission of an ensemble of electrons (1). Twiss' formula predicted amplification for Cerenkov radiation and for cyclotron radiation. Working independently, Schneider described the stimulated emission of radiation from electrons in a magnetic field in 1959 using a quantum mechanical model (2). Also in 1959, Gaponov described this mechanism using a waveguide model (3).

The first experimental results describing a fast wave cyclotron interaction were reported by R. H. Pantell in 1959 (4). His device produced radiation between 2.5 and 4.0 GHz from a 1 kV, 3 μA electron beam. In the former Soviet Union, Gaponov and others were performing experiments in 1959 using a helical beam in a longitudinal magnetic field, but the efficiency was low. In 1963, M. Petelin presented the first theory involving helical beams at a conference in the Ukraine, which led to an experiment in 1964 that produced 200 W. In 1966, the power level reached 1 kW. A number of additional experiments were reported during the early 1960s (5–8), but the experiment that confirmed the cyclotron maser interaction was performed by J. L. Hirschfield and J. M. Wachtel in 1964 (9).

During the mid- to late 1960s, major advances were made by scientists in the Soviet Union, though much of this work went unreported in the Western World due to the political climate at the time (10). Soviet scientists embarked on a major program to develop megawatt gyrotrons and made major advances in electron mode selection, open resonators, and waveguides (11), ray tracing to optimize the interaction between the electron beam and the RF wave in the circuit, and large cross-section cavities utilizing whispering gallery modes (12). Whispering gallery modes are transverse electric modes where the number of azimuthal field variations significantly exceeds the number of radial field variations. Use of these modes was further facilitated by the development by S. N. Vlasov et al. of a quasi-optical device for converting the whispering gallery waveguide mode into a Gaussian mode that can be propagated in a narrow wave beam without waveguides (13). An equally important Soviet development was the magnetron injection gun, which generates the required electron beam for efficient gyrotron operation.

For a more complete historical description of gyrotron development, the reader is referred to three publications that cover the subject in more detail (14–16). The reader is also referred to a listing of journals in the bibliography that contain most of the published work in this area.

BASIC THEORY OF OPERATION

Gyrotrons exploit the negative mass instability to obtain azimuthal bunching of a cycloiding electron beam. A transverse electric field in the cavity modifies the energy of the electrons such that higher-energy electrons gyrate more slowly around the magnetic flux lines than do lower-energy electrons. A schematic cross section of a gyrotron beam is shown in Fig. 2. The beam is hollow with individual electrons rotating at the cyclotron frequency around magnetic field lines with orbit diameters equal to twice the Larmour radius. The Larmour radius is given by

$$R_l = \frac{\gamma m v_\perp}{e B_0}$$

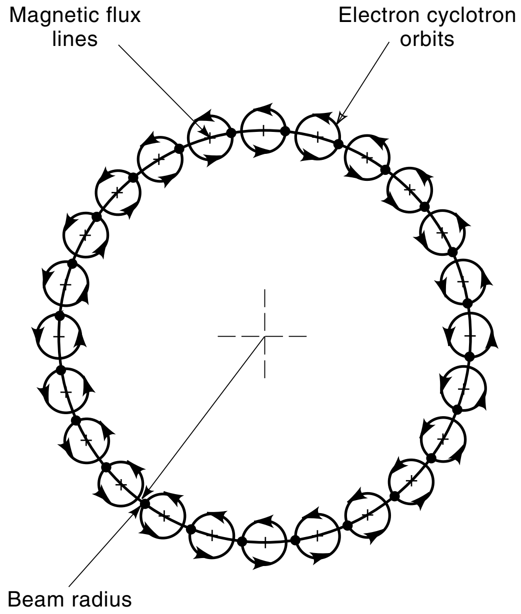

Figure 2. The cylindrical electron beam of the gyrotron consists of electrons orbiting around magnetic flux lines.

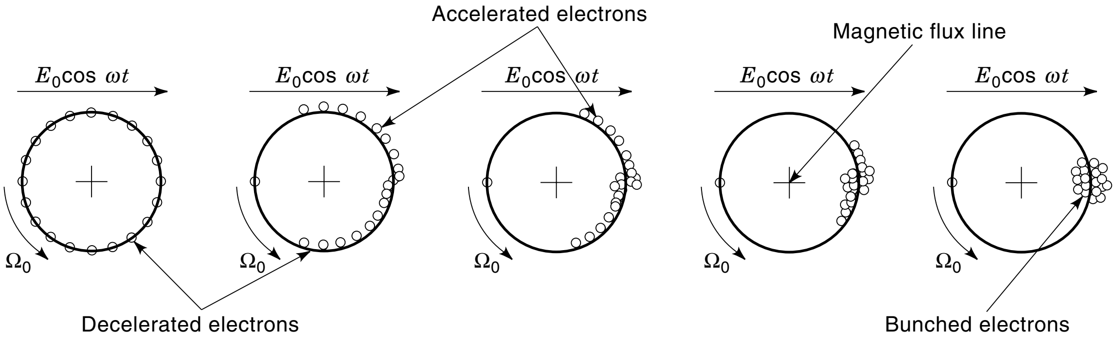

Figure 3. The cavity electric field interacts with the electrons orbiting around the magnetic flux lines. Each diagram is an integral number of cyclotron periods later in time as the electrons traverse the cavity. The force on the electrons is given by $\vec{F} = -e\vec{E}$.

where $\gamma = (1 - v_\perp^2/c^2 - v_z^2/c^2)^{-1/2}$ is the relativistic factor, m is the rest mass of the electron, $v_\perp$ is the velocity of the electron in the plane perpendicular to the direction of the magnetic field, v_z is the electron velocity in the direction parallel to the magnetic field, e is the charge of the electron, and B_0 is the applied magnetic field strength.

Figure 3 more closely examines the effect of the electric field on the individual electrons in a cyclotron orbit when the frequency of the electric field is equal to the cyclotron frequency. The cyclotron frequency is given by

$$\Omega = \frac{eB_0}{\gamma mc}$$

Most gyrotrons employ an interaction circuit that can be approximated by a right-cylindrical cavity. In the gyrotron interaction, only electron beam energy that is transverse to the axis of the cavity is extracted from the beam, so that the interaction is with the transverse (TE) modes of the cavity. For this geometry, the electric field components have the form

$$E_\theta = E_0 J'_m(k_\perp r)\sin k_z z\cos m\theta$$

$$E_r = \frac{m}{k_\perp r} J_m(k_\perp r)\sin k_z z\sin m\theta$$

where E_θ and E_r are the azimuthal and radial components of the electric field, respectively; J_m and J'_m are the Bessel function and Bessel function derivative, respectively; m is the azimuthal mode number of the electric field; $k_\perp = X'_{mn}/r_0$, where X'_{mn} is the nth root of the corresponding Bessel function derivative, and r_0 is the circuit radius; and $k_z = p\pi/L$, where p is the axial mode number of the circuit field (typically = 1), and L is the cavity length.

In Fig. 3, each successive image is an integral number of RF periods later in time as the electrons traverse the cavity. Electrons accelerated by the electric field gain energy and, as a result of the relativistic mass increase, their angular velocity decreases as γ increases. Conversely, electrons decelerated by the electric field lose energy and gain angular velocity. This causes azimuthal bunching of the electrons, sometimes referred to as the *cyclotron resonance maser* (CRM) instability.

If the frequency of the electric field, ω, exceeds the cyclotron frequency, Ω, the bunch will eventually fall back in phase and more electrons will undergo deceleration than acceleration, as shown in Fig. 4. This will result in transfer of energy from the electrons to the electric field. Optimized performance of gyrotrons requires careful design of the circuit geometry and control of the magnetic field. The circuit geometry affects the frequency and choice of the mode for the electric field, as well as the strength and profile. The magnetic field affects frequency of the interaction, and the magnetic compression ratio affects the size and location of the beam as well as the transverse energy. In many cases the magnetic field is tapered; that is, it is modified in strength through the cavity, to optimize the efficiency of power extraction.

Harmonic gyrotrons operate at a multiple of the cyclotron frequency. As the harmonic number increases, beam placement becomes more critical, and the theoretical efficiency decreases. The advantage of harmonic gyrotrons is that the magnitude of the magnetic field is $1/n$ times that required for nonharmonic operation. This can eliminate the need for a superconducting magnet.

For a more complete description of gyrotron theory, both linear and nonlinear, the reader is referred to several excellent publications on the subject (16–18).

BASIC COMPONENTS

Figure 5 shows a schematic layout of a typical gyrotron oscillator. Basic components consist of an electron gun, input beam tunnel, circuit, output taper, collector, window, and

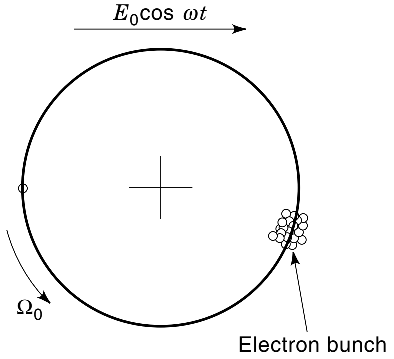

Figure 4. When $\omega > \Omega_0$, more electrons will be decelerated than accelerated, resulting in transfer of energy to the electric field.

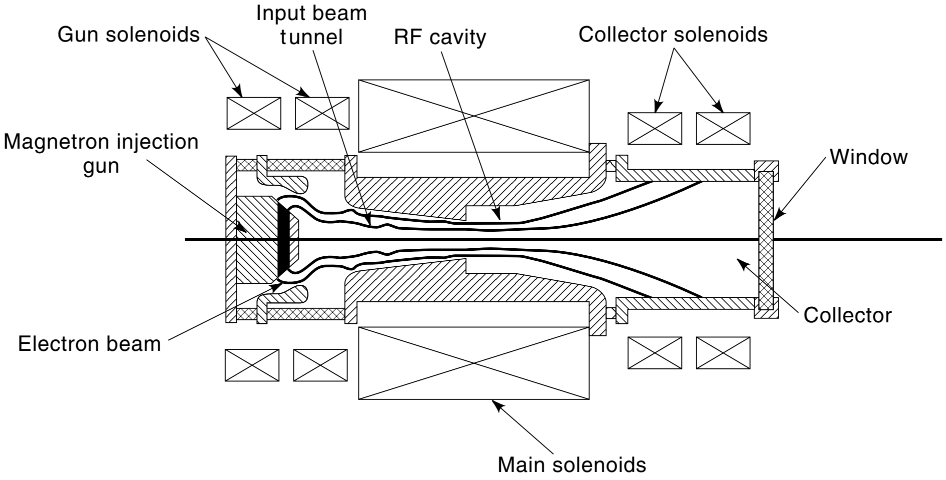

Figure 5. The basic components of a typical gyrotron are the electron gun, beam tunnel, cavity, output beam tunnel, collector, window, and magnet solenoids.

magnets. There are numerous variations of each of these components, depending on the operating characteristics of the gyrotron. The discussion that follows describes the most common types of components, including their purpose and performance characteristics.

Electron Gun

The function of the electron gun is to produce the electron beam required for interaction with the desired operating mode in the circuit. The gun must produce an electron beam that will be located at the proper radius for efficient interaction with the cavity electric fields and must contain most of its energy in cyclotron motion. Most gyrotrons employ a magnetron injection gun (mig) that emits electrons from a cathode placed in a region of crossed electric and magnetic fields. This geometrical configuration causes the individual electrons to spiral around the magnetic field lines as they are accelerated by the electric field toward the circuit. This development was pioneered in the Soviet Union in the 1960s and made rapid development of gyrotrons possible (19).

Gyrotron cathodes typically operate temperature-limited, which means that the amount of current emitted from the cathode is primarily determined by the temperature of the emitting surface. The reader is referred to the excellent treatment of cathode emission mechanisms presented by A. S. Gilmour, Jr. (20). Typical cathode temperatures are between 950 °C and 1000 °C.

Gyrotron guns come in two basic types, mod anode and diode. A mod anode gun contains an electrode near the emitting surface to module the electron beam; that is, it uses an applied voltage to modify the characteristics of the beam. This electrode is maintained at a voltage between the cathode and ground and can have a significant effect on the beam characteristics and, hence, the performance of the gyrotron. By varying the voltage on this electrode, the user can control the output power by varying the amount of transverse energy that is present in the electron beam. Most commercially available gyrotron oscillators using mod anode guns operate at cathode voltages between -60 kV and -80 kV with mode anode voltages ranging from 15 kV up to about 30 kV above cathode potential.

A diode gun possesses no intermediate electrode, so the cathode voltage or the magnetic field controls gyrotron operation. Because the cathode power supply must also supply the current in the beam, it cannot be modified as easily as a mod anode supply, so diode guns typically operate where RF power is turned on or off by pulsing of the cathode power supply. For applications where it is not necessary to modify the operating characteristics of the tube, this represents a lower-cost gyrotron and power supply configuration.

Magnetic Solenoids

The circuit requires an electron beam where the electrons are orbiting the magnetic field lines at a frequency near that of the RF frequency of the cavity. For gyrotrons operating at frequencies above 30 GHz, this typically requires a superconducting solenoid to generate the required magnetic field in the circuit. An exception can occur if the circuit is operating at a harmonic of the cyclotron frequency. The requirement of a superconducting solenoid limits applications for gyrotrons to those where the additional weight and complexity do not present a severe burden; however, advances in superconducting magnet design and technology are rapidly reducing this problem. Gyrotrons are now being considered for mobile or airborne applications that were previously considered impractical.

In addition to the solenoids required to produce the cavity magnetic field, other solenoids can be present around the electron gun and collector regions. Solenoids around the electron gun modify the amount of transverse energy in the beam or its size in the circuit. These coils are typically operated at room temperature because the fields in the electron gun are typically a few hundred gauss. The ratio of strength of the magnetic field in the circuit to that in the electron gun is referred to as the *beam compression.* This value plays an important role in the design of the electron gun and the combination of electric and magnetic fields required for efficient circuit interaction. Beam compressions of 10 to 20 are typical.

Solenoids around the collector are used to distribute the power deposited by the electron beam exciting from the circuit. The fringing magnetic fields from superconducting coils impose a magnetic field in the collector that is higher than in other linear beam tubes. This field prevents the electrons from spreading due to space charge and results in a relatively thin beam of electrons impacting a small region of the collector. This can result in excessive localized heating of the surface and possible destruction of the gyrotron. The collector coils are used to "buck" the field from the main solenoid and spread the electron impact area over a larger region of the collector. In some more advanced applications, an oscillating power supply drives one or more solenoids to sweep the beam back and forth along the collector surface.

Beam Tunnel

The beam tunnel must perform two important functions. First, it must prevent RF fields from the circuit from traveling back toward the electron gun. RF fields in the electron gun can severely affect the electron beam and cause excessive current on the body of the tube or the mod anode. It can also result in heating of the cathode emitter, which will affect the beam current. Either condition will adversely affect tube operation.

The second function of the beam tunnel is to prevent parasitic oscillations between gun and circuit. Parasitic oscillations result in excessive body or mod anode current and can prevent tube operation. In some cases, dielectric material with a high RF loss is used to load out any electromagnetic fields present.

Circuit

The RF circuit typically consists of a right circular cylinder whose radius v_0 is chosen such that

$$v_0 = \frac{cX'_{mn}}{2\pi f}$$

where X'_{mn} is the nth root of the Bessel function derivative for the TE_{mn} cavity mode, c is the speed of light, and f is the operating frequency. The gyrotron operates near the cut-off frequency of the circuit, and the equation for the circuit radius is the equation for the cut-off frequency for a waveguide of radius v_0. The cavity mode depends primarily on the desired RF frequency and output power level. The application for the tube can also play an important role. The first commercial gyrotrons used TE_{01}, TE_{02}, or TE_{03} modes because they were reasonably close to the fundamental mode, did not couple to nonsymmetric modes that could travel down the beam tunnel toward the electron gun, and had very low RF loss in the circuit walls. More than 100 gyrotrons at frequencies between 28 GHz and 100 GHz and power levels up to 340 kW CW were produced by Varian Associates, Inc. (now Communications and Power Industries, Inc.) from 1978 through 1990. These tubes were used for electron cyclotron resonance heating (ECRH) of plasmas in magnetic confinement fusion research. Gyrotrons of this type have also been developed in Germany, China, Japan, France, and Russia (21).

As the demand for higher-power tubes increased, gyrotrons that used whispering gallery modes were developed. Whispering gallery modes allow the electron beam to be larger and minimize mode competition from other circuit modes. These modes also have reasonable RF power dissipation in the circuit. This work was pioneered in the former Soviet Union beginning in 1968.

Designers of high-power gyrotrons must balance a large number of factors to achieve a circuit configuration that will provide the power and frequency required with reasonable efficiency while avoiding parsitic mode competition, instabilities, and excessive RF power densities on the circuit walls. For additional information on the design of high-power gyrotron circuits, the reader is referred to Ref. 22.

Output Taper

Most all gyrotron circuits are open-ended toward the collector, and the RF power diffracts into the output taper. The output taper is usually a shallow, tapered section of waveguide that terminates the circuit interaction and transmits the RF power toward the collector. The waveguide radial dimensions must be increased in such a way that the purity of the output mode is not compromised. For gyrotrons where the RF power is extracted along the axis of the tube, the output taper continues to increase the radial dimension until the desired collector radius is achieved. The requirement to maintain mode purity often conflicts with the necessity of achieving the collector radius within a reasonable distance. The size of the collector is driven by the necessity to dissipate the spent electron beam without incurring excessive power densities on the walls, which could lead to melting or loss of vacuum integrity.

For gyrotrons with average RF power levels exceeding 200 kW, particularly those employing whispering gallery circuit modes, it is more expedient to extract the RF power radially to allow more freedom in collector design. For these tubes, the output taper transmits the circuit power to an RF launcher for eventual extraction from the vacuum envelope. This removes further requirements on the output taper to maintain mode purity and allows the designer more freedom in transitioning to the collector region.

Collector

Typical linear beam devices rely on termination of the magnetic field and space charge depression to spread the spent electron beam in the collector. Most of these devices employ an iron polepiece to terminate the magnetic field at the entrance to the collector. While this works well for solid electron beams, it does not apply to gyrotrons. Because of the high magnetic fields required in gyrotrons, this is often not practical, particularly when superconducting solenoids are used. Forces imposed by nearby iron on the superconducting coils would dramatically increase the complexity and cost of the magnet. As a result, sufficient magnetic fields exist in the collector to limit spreading of the electron beam from space charge forces. In addition, the beam used in gyrotrons is typically a thin cylindrical beam with high current density. This also exacerbates the problem of beam dissipation in the collector. Power densities up to 500 W/cm^2 are typical: 1000 W/cm^2 is considered the upper limit.

For gyrotrons at lower average power levels, these complications may not be a critical issue. For these devices, the output taper conducts the RF power to the collector with high mode purity, and the collector also serves as the output waveguide. In some cases, a downtaper is employed at the end of the collector to reduce the tube diameter before the output window. For these devices, the designer must also be concerned about modes that can be trapped in the collector between the uptaper from the circuit and the downtaper to the window.

For gyrotrons exceeding 500 kW of average power, radial RF power extraction allows the designer more freedom in collector design. The size of the collector can be based on the dissipation requirements of the spent beam alone. As a result, collectors for high-power gyrotrons often constitute a major portion of the device. In Fig. 1, the collector of the 500 kW CW gyrotron behind Dr. Jory begins above the output window. The designer must balance low power densities with the increasing size, weight, and cost of large collectors.

RF Launcher System

The RF launcher system converts the circular cavity/waveguide mode to a quasi-optical Gaussian mode. This development was pioneered in the Soviet Union and allows transmission of the beam with very low loss using a series of metallic mirrors. Modern computer codes and integration with computer numerically controlled (CNC) mills and lathes allow precise control of the power in the RF beam. Modern designs convert the power from the circuit into the desired Gaussian mode with greater than 95% efficiency. The conversion of the waveguide mode to a quasi-optical Gaussian-type mode also results in a more convenient RF mode for most user applications.

Figure 6 shows a typical RF launcher configuration consisting of a waveguide launcher and two mirrors internal to the gyrotron. The exit angle of the RF power from the launcher is at the waveguide bounce angle, and the mirrors concentrate the power into a small circular beam and tailor the distribution of power within the beam as required by the output window.

Output Window

A dielectric window is used to extract the RF power from the vacuum envelope of the gyrotron. Common window materials are alumina and sapphire; however, berllia oxide, boron nitride, silicon nitride, and other materials have been used in special devices. At higher average power levels, the thermal characteristics of standard materials is such that the heat deposited in the ceramic cannot be adequately removed by cooling around the edges as in most linear beam devices. Figure 7 shows a schematic diagram of a double disk window that uses a dielectric fluid to convectively face-cool the disks.

The power-handling capability of the window is the major factor limiting output power for high average power gyrotrons. For tubes utilizing Gaussian mode output, internal mirrors are carefully designed to shape the beam profile for optimum window performance. In addition, new materials, such as chemically vapor deposited (CVD) diamond, are being studied to provide extremely high thermal conductivity and low dielectric loss.

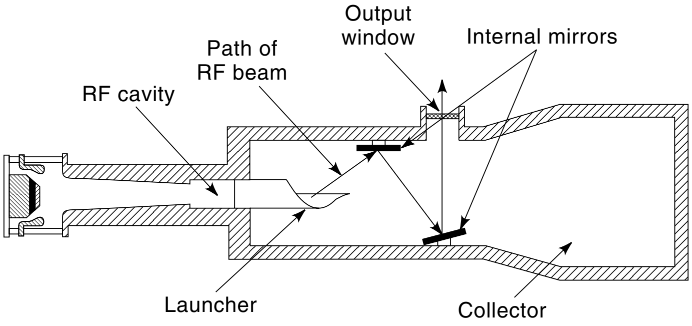

Figure 6. The Gaussian mode launcher converts the waveguide mode to a quasi-optical beam, and the internal mirrors shape the RF beam profile.

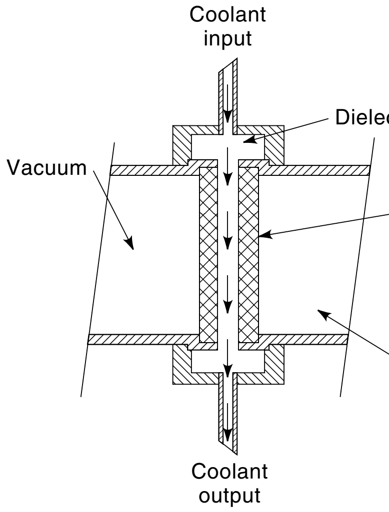

Figure 7. In the double-disk window, a dielectric fluid flows between the ceramic disks for enhanced cooling.

AMPLIFIERS

While most gyro devices are oscillators, research is in progress to develop gyroamplifiers as drivers for linear accelerators (23) and for high-frequency, high-resolution radar (24). While oscillator design is relatively straightforward, amplifier design presents several challenges. Since the circuits are typically overmoded, it becomes more difficult to prevent RF leakage through the drift regions between cavities. Also, the high cavity Q factors characteristic of gyrotron output cavities limits the bandwidth that can be achieved. While several amplifier configurations have been studied, the gyroklystron and the gyro-TWT (traveling wave tube) have achieved the most success.

The gyroklystron consists of two or more cavities separated by drift spaces cut off for the operating mode. An azimuthal drift is imposed on the electrons by a sinusoidal energy modulation in the first cavity. These drifts are enhanced by intermediate buncher cavities, and the output cavity extracts the power from the azimuthally bunched electron beam. Most gyroklystrons employ cavity modes that are above the fundamental TE_{11} circular waveguide mode. Extreme care must be used to ensure that any RF power converted from the cavity mode to the TE_{11} mode is not allowed to propagate through the drift spaces and cause spurious oscillations. This also limits the circuit modes that can be used to those close to the fundamental (typically TE_{01} or TE_{02}) circuit modes. Bandwidths for gyroklystrons are typically less than 1%. Operating efficiencies greater than 30% are common, and gains range from 20 to 40 dB.

In the gyro-TWT, an azimuthally bunched helical beam interacts with a traveling wave. If the periodicity and velocity of the electron bunches are such that synchronism occurs between the electrons and the traveling wave, cumulative bunching and energy extraction can occur. These amplifiers have considerably larger bandwidths than gyroklystrons; however, they operate at lower efficiency (<20%) and generally produce less power.

Research has also been performed on gyro backward wave oscillators, gyrotwystrons, and gyropeniotrons. The reader is referred to the additional reading list for information on these devices.

FUTURE DEVELOPMENT

Most gyrotron research is focused on increasing the output power of the device, primarily for ECRH and ECCD of fusion plasmas. It is anticipated that several hundred megawatts of RF power will be required for heating these plasmas. It is desirable to maximize the output power of the individual gyrotrons to reduce the number of gyrotrons required. The current goal is to develop gyrotrons producing 1 MW of CW power at frequencies between 100 GHz and 170 GHz (27–29). Much of this research is focused on individual components, such as the RF window (30) and depressed collectors for energy recovery (31–33). Other researchers are investigating alternative cavity configurations (33–35).

Amplifier research is focused on developing gyro-amplifiers for high-resolution radar and for high-power linear accelerators. Current research goals for radar applications include bandwidth enhancement, increased efficiency, increased output power, and gains exceeding 30 dB. It is anticipated that peak powers approaching 100 kW and average powers exceeding 10 kW will be required. Accelerator applications do not require large bandwidths, but peak powers exceeding 100 MW at frequencies between 11 GHz and 20 GHz will be needed. High efficiency and reasonable gain will also be major goals. Advances in gyrotron components, such as windows, electron guns, launcher systems, and depressed collectors, will also be applicable to amplifier development.

Research is also in progress to develop gyrotrons for industrial heating applications, particularly for sintering of fine grain ceramics. Studies indicate that microwave and millimeter sintering can produce extremely high heating rates or selective heating in multiphase systems leading to novel ceramic materials with compositions and microstructures not possible using standard techniques (36). Several experiments are in progress to develop sources for these applications (37,38). It is anticipated that other applications will materialize when efficient, cost-effective sources are available.

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