An Examination of Ancillary Equipment for a Proposed 34.3 GHz High Power Gyrotron TWT Amplifier

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A short review of gyrotron developments and applications is given with attention to both theory and experiments. Parameters for a point design for a gyrotron TWT amplifier described in a previous article are listed again, and a detailed examination of ancillary equipment is made with emphasis on the availability of high voltage and handling facilities at Goldstone. A safety-interlock tree for insuring longer tube life under operating conditions is proposed, and a sequence for turn on/off of the proposed tube is given. In addition, reasoning for the expectation of multimode output is presented.

I. Introduction

Cyclotron Resonance Masers or gyrotrons are microwave amplifier tubes which show great promise for becoming the final amplifier stage for planetary radar transmitters and millimeter wave spacecraft uplinks. Impetus for their development is provided by current crowding at S-and X-band frequencies, the greater radar ranging and resolution available at higher frequencies with a given aperture antenna, particle accelerator technology augmentation, and fusion plasma heating applications. While high power (>10 kW CW) klystrons, twystrons, and TWTs perform excellently in the 1 to 18 GHz range, these conventional microwave tubes cannot be scaled to the 28 to 235 GHz range and maintain their high efficiency, high power parameters because of heat transfer problems in the relatively small electron interaction volume. Gyrotrons, on the other hand, can utilize overmoded cavities or waveguides and minimize the aforementioned, traditional high frequency scaling problems. In fact, the usual $P \propto 1/f^2$ (Ref. 1) scaling condition can be ignored and experimental research in the field has produced some exciting millimeter wave results: for example, 22 kW at $\lambda = 2$ mm and 1.5 kW at $\lambda = 0.92$ mm (Ref. 2), 10 kW at 8.9 mm (Ref. 3), and a pulsed oscillator which is 37 percent efficient at 28 GHz with a power output of 250 kW (Ref. 4).

The interaction mechanism responsible for microwave amplification in gyrotrons is azimuthal phase bunching due to the dependence of the electron cyclotron frequency on the relativistic electron mass. A hollow beam formed by a magnetron-injection gun (Ref. 5) is guided by a strong dc magnetic field into a cavity or waveguide close to cutoff and magnetic coupling to the RF fields therein produces amplification. It is the spinning or gyrating electron motion (Larmor orbital motion) caused by the guiding magnetic field from which the gyrotron derives its name. Like conventional tubes utilizing longitudinal electron bunching mechanisms, gyrotrons, which operate by azimuthal-phase bunching, can be divided into categories dependent upon the cavity or waveguide configurations used, for example, gyroklystrons which use cavities or gyroTWTs which use waveguides in the interaction volume. The mathematical analysis for the former is based upon solving the power emission integral while utilizing a relativistic correction to the cyclotron frequency and substituting for the perturbed electron distribution function via Vlasov theory arguments (Refs. 6, 7); the mathematical analysis for the latter is based upon solving for the dispersion relationship obtained from the determinant of the coupled electro-magnetic field wave equation matrix, after appropriate substitution for the electron and current densities via Vlasov theory arguments (Refs. 8, 9, 10).

In a previous article (Ref. 8), a point design for a gyrotron traveling wave tube amplifier was presented and ancillary equipment features (magnetic field, beam voltage and current, power dissipated in the collector, etc.) were listed. Since none of the power supply specifications exceeded the ratings of units already available at DSS 13 at Goldstone, it was proposed that, should a prototype be built by JPL or for JPL by a contractor, high power testing could be carried out and integration difficulties with existing systems examined at the test bed site without recourse to completely new support technology development or major high voltage equipment purchase. It was therefore suggested that a more detailed examination of required support apparatus be made with an eye to equipment protection systems and overall safety procedures. The following sections address not only these questions, as related to the previously presented point design, but also the output mode structure to be expected.

II. Support Equipment

The gyroTWT point design previously presented had the following important calculated characteristics: an output frequency of 34.3 GHz, a wave power of 354.36 kW CW, a beam voltage of 70.80 kV, a beam current of 9.50 A, a magnetic field strength of 13.07 kG, an interaction length of 34.90 cm for a total gain of 40 dB, a -3 dB bandwidth of 384 MHz, a drive power requirement of 35.44 W, and an electronic conversion efficiency in the lab frame of 52.7 percent. At DSS 13 (Venus Station), there is a 1 MW CW power supply capable of delivering the required amount of voltage to the magnetron-injection gun. This latter structure is composed of a thermionic emitting surface, a control electrode, and an anode. The relative potential differences are 30 kV between cathode and control electrode and 70 kV between cathode and anode (Refs. 5, 11). Beam current is controlled by the cathode temperature and, consequently, by the heater current. The heater supply should be a 100 W unit with low voltage, high current output. For purposes of cathode cooling and voltage holdoff, the cathode assembly (including some of the focusing magnets) should be immersed in an oil bucket with a small submersible pump for oil circulation.

General cooling requirements for body and collector will be similar to that of the 400 kW CW S-band klystrons presently used. The collector will have to dissipate 354 kW and either a depressed collector design or PPM defocusing using either Samarium Cobalt or perhaps bulkier, but less expensive materials, may be required. Local space charge effects can accelerate the "spent" hollow electron beam (Ref. 8) to about 140 keV. Impact of such energetic electrons on the copper collector surface results in X-ray generation beyond the safe-level attenuation capabilities of the collector tube. Hence, a lead shield about 0.3175 cm (1/8 in.) thick must surround the device.

As with other high power tubes, the interaction volume and the cathode region must be under fairly high vacuum (better than 1.333×10^{-4} N/m^2 (10^{-6} torr)). This is a condition imposed by the Vlasov theory which does not include a collision term in the "continuity" equation satisfied by the electron distribution function (Ref. 12). Also, the high vacuum inhibits breakdown or arcing between cathode and anode. At present, it is thought that Vac-ion® pumps are sufficient to obtain the desired vacuum. These units also have the added advantage of being useful as vacuum integrity diagnostics. Should vacuum integrity be lost, for any reason, the tube would have to be immediately shut down to prevent cathode surface poisoning.

Yet another area of crucial interest is the guiding magnet. This device is a solenoid which surrounds the interaction volume and keeps the electron beam focused in the tube length before the collector. A control of better than 1 percent over the magnet current must be exercised to maintain high efficiency (Refs. 8,9) and, typically, a range of 600-700 A at 30-60 V would be required to maintain the 13.07 kG field if a water-cooled copper solenoid were to be used. In addition, the magnet can be utilized as a "leaky" mirror to transfer longitudinal streaming energy into perpendicular Larmor orbital motion, thereby increasing the total energy available for conversion to microwaves. Hence, design constraints on the magnetron-injection gun, which would otherwise have to provide the required energy distribution from the start, would be eased.

At present, there is some debate whether the solenoid should be a conventional magnet composed of copper conductor with a hollow water channel for cooling or a superconducting magnet composed of Nb_3Sn embedded in a copper matrix. Since power dissipation will be the important parameter, if the superconducting solenoid does not give a factor of 1000 to 1 lower power dissipation than that achievable at room temperature, its advantage over a conventional copper magnet is doubtful. Another factor to be considered is that, for every watt of heat transfer in the cooled superconducting structure about 400 watts of power must be supplied at the refrigeration system input (Ref. 13).

The overall weight and dimensions of the gyroTWT are difficult to estimate without some experimentation. Considering magnets, cooling assemblies, lead shielding, and collector tube, the weight would probably not exceed 680.39 kg (1500 lb). This can be compared to the Varian tentative specification for the VGA-8000, a 28 GHz, 200 kW CW cyclotron resonance interaction oscillator. The latter's dimensions are 254 cm (100 in.) in length, 106.68 cm (42 in.) maximum diameter, and a total weight of 498.95 kg (1100 lb) (Ref. 11). The cranes and other weight handling fixtures at Goldstone should be sufficient for moving and positioning a tube of that size.

III. Special Considerations

To minimize power loss due to reflection at the output window (which is on beam axis), careful consideration must be given to the VSWR at that ceramic surface. Ideally, a VSWR of 1.1:1 or 1.2:1 should be used. Not only is this parameter important to power output, but the backwards wave amplification should be inhibited as much as possible so that additional backwards heating at the cathode assembly and at the drive window(s) does not occur. The extra cathode heating could be crucial in terms of beam current control since this latter is proportional to emitting surface temperature. It would not be desirable to attempt control of the beam current by increasing or decreasing the heater current and then discover that the cathode temperature remained essentially constant due to backwards heating as a result of a poor VSWR at the output window. Cathode cooling might then also become a problem. A reflected power monitor would be a useful device for measuring the VSWR.

Another difficulty commonly encountered in high power transmitter tubes is destructive arcing. The output waveguide, which leads to filters and the output horn antenna, is usually filled with nitrogen at one atmosphere pressure. Due to the high microwave power levels involved, arcing in this output waveguide can occur. Once the arc is formed, it generally propagates backwards toward the generator and hangs at the output window. Thermal gradients across the window lead to its shattering and the tube fails catastrophically (Ref. 14). Such failure results in cathode poisoning and other damage. The tube is then generally considered unsalvageable. However, a protection scheme using fiber optics and photodiodes to sense the propagating arc can be employed to shutdown the tube by taking the accelerating voltage off line. Signals from the optoelectronics trigger an SCR-controlled pulse forming network which turns on a Hg-plasma ignitron tube, thus shorting the accelerating potential. "Crowbar" systems of this type presently in use respond in less than 45 microseconds and terminate tube operation. Hence, the propagating arc never reaches the output window. It is clear that such a protection system will have to be employed in conjunction with other safety-interlocks in the 34.3 GHz gyroTWT system because of the high power output levels.

In fact, an entire safety-interlock tree (see Fig. 1) must be designed so that tube operation can be scrammed at the least sign of trouble. Overvoltage, undervoltage, magnet current, magnet coolant flow, oil flow, body and collector coolant flow, body current, collector current, forward and reverse power, water load temperature, arc detection, and drive power sensors must all be included so that failure of any one item will cause shutdown.

It is necessary to have a great deal of control over most of the above listed parameters, and deviation can potentially cause not only poor tube operation and unacceptable output results but also extensive failure leading to extremely costly repairs or actual scrapping of the tube. For example, the magnetic field strength is a highly important feature which must be strictly controlled to insure high power output and high efficiency (Refs. 8,9). Wandering of the magnet current cannot be tolerated since, not only will the previously mentioned two factors suffer greatly, but the electron beam itself may impact or graze a tube surface, causing local heating and/or melting. (Both effects of power loss and local heating have been observed by the author in a low power S-band gyromonotron experiment at the California Institute of Technology.) As backup features to a magnet current sensor, body and collector overcurrent sensors are required. Similarly, a loss of coolant or an interruption in its flow is insupportable because of physical damage to the tube resulting from overheating. Coolant flow sensors on both tube and magnet are required for that reason. Drive power monitors are also essential so that potential spot melting in the collector does not occur due to lack of beam modulation, which aids in electron spreading effects. This latter is a requirement for most conventional highpower microwave tubes. Forward and reverse power sensing is important for arc detection as well as monitoring of backwards cathode heating (Ref. 14). The reverse power detection, coupled with the light sensing diodes, makes it fairly certain that as soon as an arc is formed, it is detected either by direct visual confirmation or by a rapid rise in reflected power. By the same token, a power supply runaway condition resulting in overvoltage cannot be permitted because of potential cathode-anode arcing leading to destruction of the emitting surface. For these reasons, an interlock tree with all of these links is essential to insuring safe system operation and system longevity.

Some apparent redundancy is necessary to failsafe scramming if any one particular branch of the safety-interlock tree were to become non-functional during normal operation. In fact, the entire amplifier system (see Fig. 2) is highly interdependent and the nature of the interlock suggests a turn on/turn off procedure (see Fig. 3) that is similar to that used for other high power microwave tubes.

IV. Collector Output Mode Structure

The collector tube, through which the output power is emitted, must be radially larger than the interaction waveguide for reasons of high current intercept and greater heat dissipation (Ref. 8). Power densities due to the impacting electron beam may be on the order of 0.62 kW/cm^2 (4 kW/in.^{2}) which, by comparison, is considered a desirable level for the X-3075, a 500 kW CW S-band amplifier (Ref. 15). The high power millimeter wave output also mandates a waveguide radially larger than the interaction volume, so that breakdown or arcing is inhibited if not eliminated. However, use of the larger collector results in multimode output due to the lower cutoff frequencies of the principal modes of energy propagation. Circular polarization of the output is to be expected due to the cyclotron motion of the hollow electron beam and polarity will be dependent on the direction of the guiding magnetic field.

Experimental determination of the percentage of energy in a particular mode will be required. For purposes of comparison, the Varian VGA-8000 28 GHz 200 kW CW oscillator radiates its output in a 6.35 cm (2.5 in.) ID pipe principally in the TE_{01}, TE_{02}, TE_{03} modes (Ref. 11), but an examination of cutoff frequencies shows that energy will propagate in many other modes as well. Hence, measurable amounts of energy will be transmitted in modes other than the three already mentioned, and proper phasing and/or filtering in the antenna section will be required to achieve a particular signal for final ex-atmosphere transmission.

V. Conclusion

Most of the support equipment required for highpower microwave tubes is directly applicable to gyrotron devices. Differences between gyrotrons and conventional klystrons are generally internal, for example, the guiding magnetic field is of a higher order of magnitude, the output power can be taken directly off the beam axis, and a hollow beam from a magnetron injection gun is used to increase efficiency. Should a prototype tube at 34.3 GHz be built, testing at Goldstone appears to be feasible, since the main power supplies and handling facilities would be adequate for dealing with the demands of the gyrotron tube. Standard safety procedures could be used and the only development required appears to be perfection of techniques for accurately measuring multimode highpower output at Ka-band frequencies.

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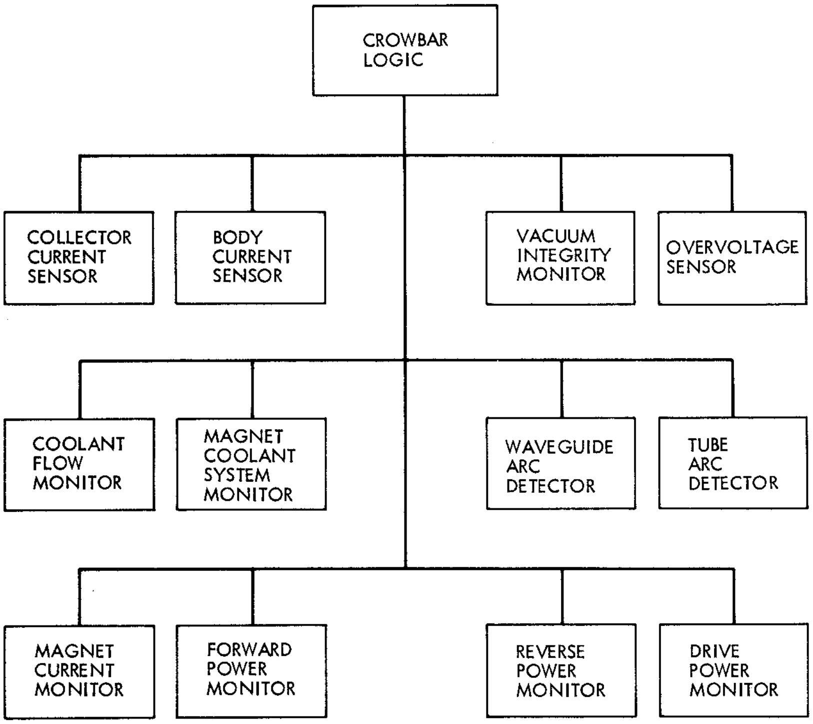

Fig. 1. Safety-interlock tree

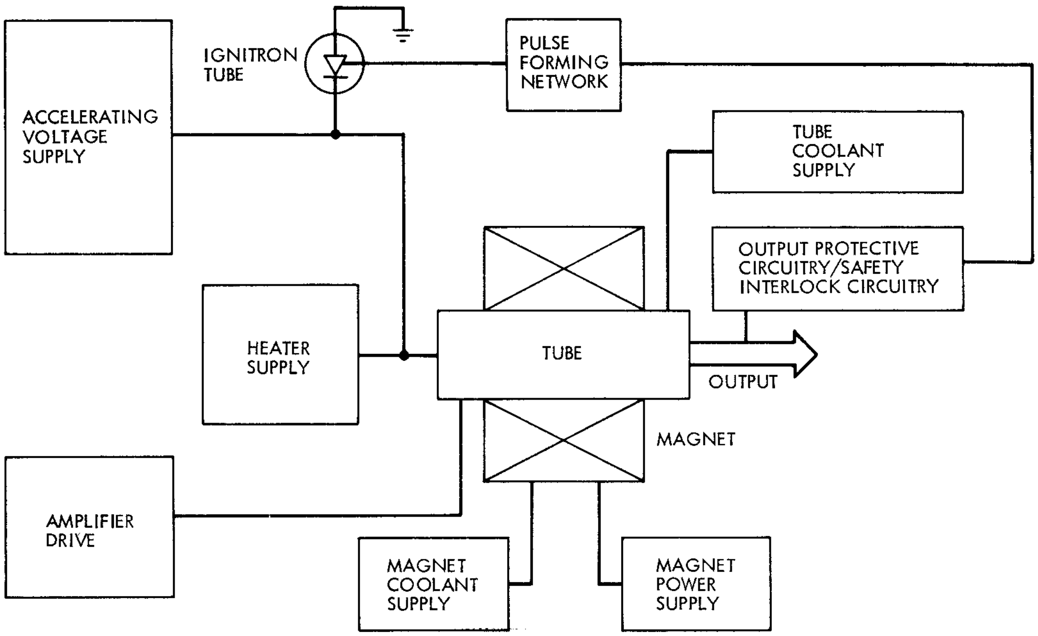

Fig. 2. System diagram: 34.3 GHz gyrotron TWT amplifier

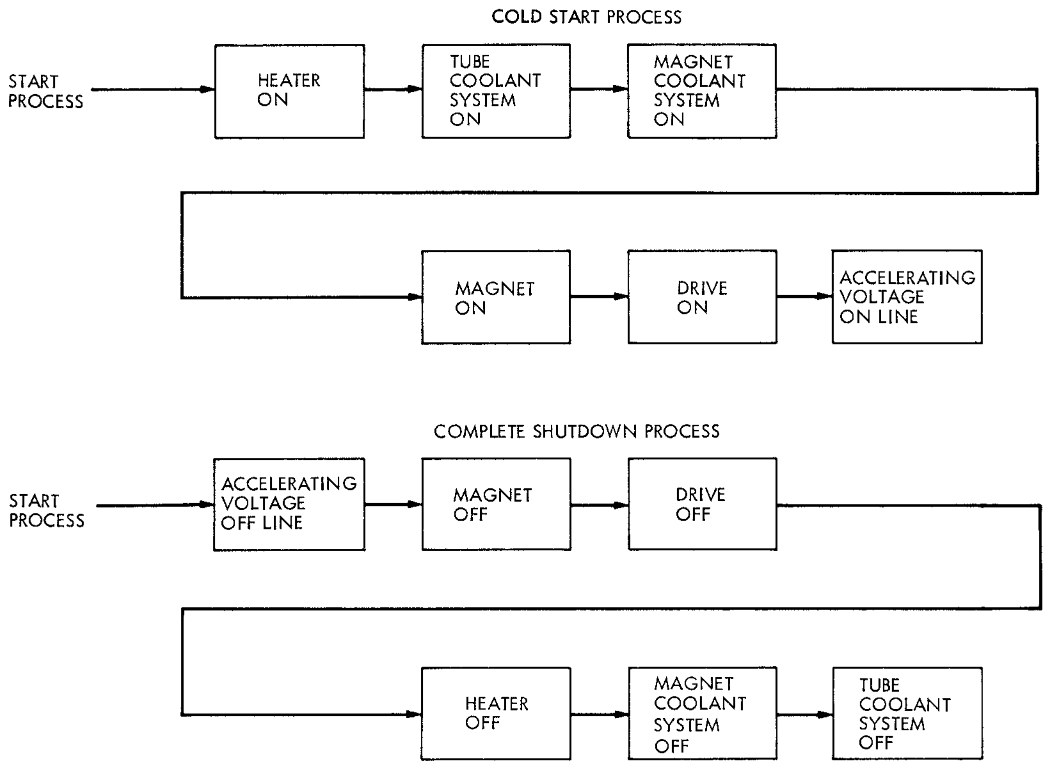

Fig. 3. Turn on/off sequences