ANOMALOUS ELECTRON LOADING IN SLAC 5045 KLYSTRON AND RELATIVISTIC KLYSTRON INPUT CAVITIES*

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Abstract

Recent studies of RF breakup and instability in the SLAC 5045 klystrons have revealed that many production klystrons show loading of the input cavity by low energy electrons even under cold cathode no beam conditions. Sometime after the onset of the RF drive pulse, the input cavity absorbs a portion of the incident RF drive that would otherwise be reflected from the not-beam-loaded cavity. This power absorption is a function of drive level, and of axial magnetic field surrounding the cavity. No power absorption is present when the axial magnetic field is zero. This same phenomenon has been observed in the input cavity of relativistic klystron experiments being conducted as part of the SLAC-LBL-LLNL development program. The phenomenon may be associated with RF breakup and RF instability in SLAC 5045 klystrons, and with unstable pulse shortening in the relativistic klystron experiments. This paper outlines some old and new observations of microwave beam device malfunctions that probably are associated with low energy electron fluxes in the vacuum environments of microwave power devices.

1. Microwave Beam Device Design Methods

Early microwave tubes were designed using hand calculations and much cut and try experimentation. Many phenomena were observed that could be explained only loosely using field theory and beam dynamics arguments. Where phenomena limited tube performance, "fixes," arrived at by experiment, were used to move the effects away from normal tube operating conditions. As computational techniques were developed for solving Maxwell's equations and the beam dynamics equations, designs for microwave beam tubes could be optimized with modeling programs before devices were fabricated. As a result, high performance microwave beam tubes were produced that usually performed very close to the computer simulations. However, some RF output instabilities and other unsatisfactory phenomena persist in some microwave tubes that are not explained by any of the computer simulations. Consequently, cut-and-try methods supplemented by computational and analytical insight are still used to optimize most high power microwave devices.

2. Vacuum Environment in Microwave Beam Devices

Modern, high power microwave devices such as klystrons are constructed with very clean, low base pressure metals and ceramics. After assembly and bakeout to high temperature, usually 550°C a delivered tube is leak-tight to better than 10^{-10} Torr ℓ/s with a base pressure in the low 10^{-9} Torr range. Cathodes are usually of the dispenser type which maintain low base pressure both during processing and operation. Sometimes a dispenser cathode is a source of gas, and tubes with gassy cathodes have more instability problems than low base pressure tubes. Beam guiding is done with axial magnetic fields, and very high electric fields are used to produce space charge limited emission from cathode surfaces. The combination of high electric fields, magnetic fields, and RF exciting fields in microwave cavities, plus surfaces that support secondary emission, give rise to regenerative buildup of large, low energy electron fluxes that can damage performance.

3. Low Energy Charged Particle Activity in Microwave Tubes

The word 'multipactor' is used to describe a class of resonant phenomena in which a charged particle, usually an electron, is trapped by a restoring force and accelerated into a surface causing a collision that produces secondary electrons. In many cases, an RF field accelerates the secondaries away from the surface during one half cycle while a magnetic field bends them back toward the surface. If the secondaries strike the surface and create more secondaries, then electron flux may build up rapidly, and absorb energy from the RF field. This electron buildup and RF quenching is sometimes unstable and can result in random, bistable, and relaxation type periodic states that absorb RF energy. When this effect takes place in microwave cavities used to velocity modulate and bunch beams, the performance of a high gain microwave device is compromised. Several of the observed effects are described in the next sections.

Low energy charged particle effects are thought to play a part in two other klystron failure mechanisms. 'Backswing conduction' is observed in some klystrons: large reverse current is observed from anode to cathode when the normal reverse voltage transient characteristic of the pulse transformer drives the klystron cathode positive. This effect is discussed in the next section along with some secondary electron orbit calculations. Insulating surfaces inside vacuum systems tend to collect charged particles and can exhibit various unstable and destructive discharges. Most failed klystrons show evidence of charged particle activity on the vacuum side of ceramic cathode bushings even if the failure mode of the tube was not associated with any internal breakdown. In the extreme, ceramics can be punctured as the result charge buildup that overstresses the ceramic dialectric.[1]

4. Electron Loading Effects in 5045 Klystrons

RF Output Instabilities

An ideal klystron power saturation characteristic shows RF output power of the klystron monotonically increasing with increasing RF drive, saturating at rated output power, and then gently falling off as drive is increased beyond saturation. There are no glitches or jumps in the saturation characteristic, and the detected RF output pulse has a flat top with no instability, or periodic fluctuations. This condition is met at all cathode heater settings, and all beam transportable focus settings. About half of the present production of 5045 klystrons meet the above criteria. The other tubes exhibit various forms of RF output instability at various magnetic field, RF drive, and cathode heater settings that necessitate careful selection of operating point to meet specification performance. Figure 1 is a photograph of the production 5045 klystron.

In a klystron, electron beam loading provides most of the power absorption in the input cavity, and the cavity coupling is designed to accommodate this loading so that the cavity input is exactly matched at a specified beam current. With no beam current in the cavity, almost all the incident drive power is reflected back from the cavity input coupler. Under no beam conditions, some klystrons show input cavity power absorption at various drive and magnetic field levels, and at certain break points this absorption phenomenon is unstable. Input cavity multipactor, the generation of a low energy electron flux in the cavity, is the most probable cause of this effect. Since the power reflected from a klystron input cavity under normal beam operation is almost zero, a careful observation of reflected input power gives some insight into the additional loading and instabilities caused by secondary emission generated electron flux.

A common instability that shows up as a periodic amplitude modulation of the top of the detected RF output pulse is shown in Figs 2 and 3. The bottom trace of the scope photos is the detected RF output from a 5045 klystron. The top trace is the detected reflected power from the input cavity. Note that the reflected power from the input cavity has the same structure as the RF output pulse, indicating that the modulation structure occurs in the input cavity, or is present on the beam before the beam enters the input cavity. Small changes in magnetic field in the vicinity of the input cavity, or cathode region strongly affect both the magnitude and period of the perturbation. This kind of instability is also a function of cathode temperature with the magnitude of instability increasing with cathode heater excita-

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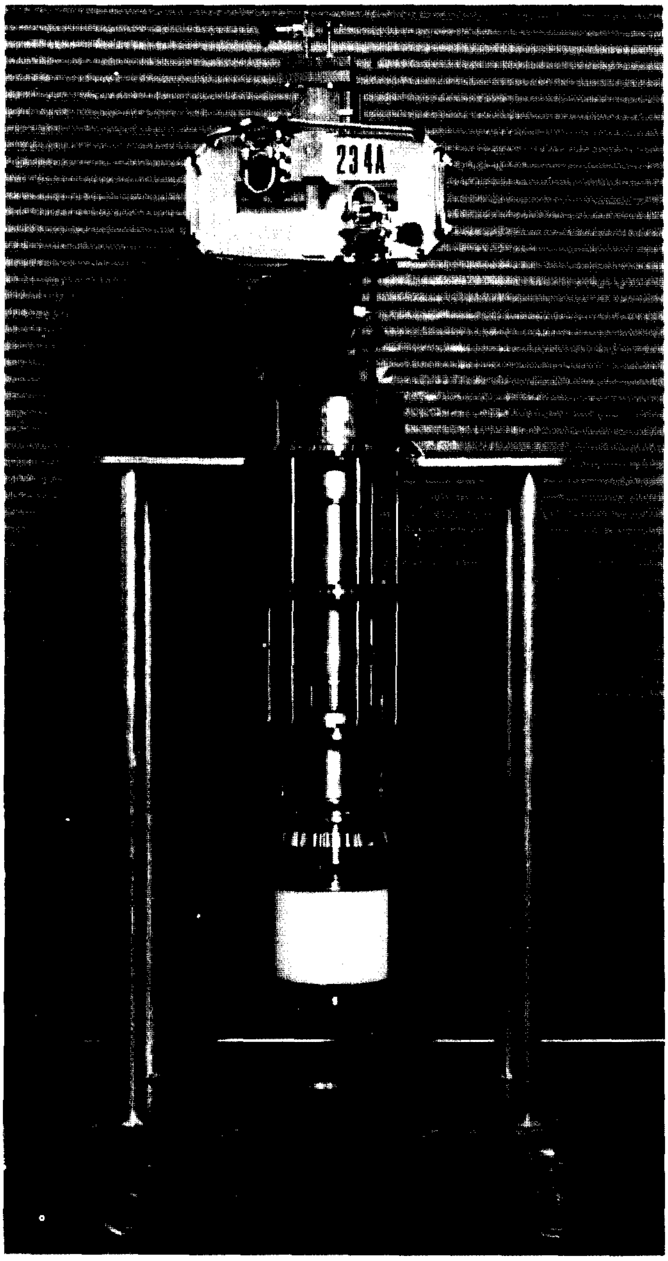

Fig. 1. SLAC 5045 klystron, 2856 MHz, 3.5 μsec, 65 MW.

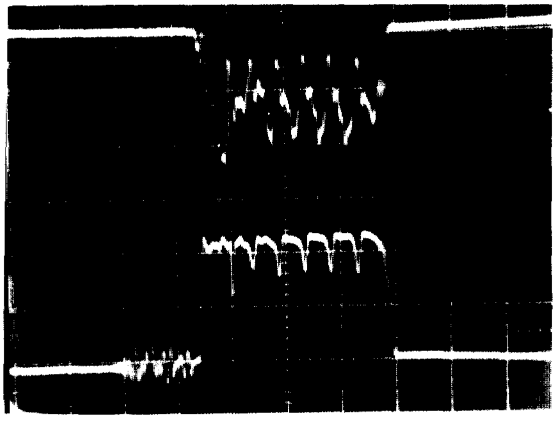

Fig. 2. Periodic relaxation instability (Tube 337C). Top trace: reflected power from input cavity. Bottom trace: power output.

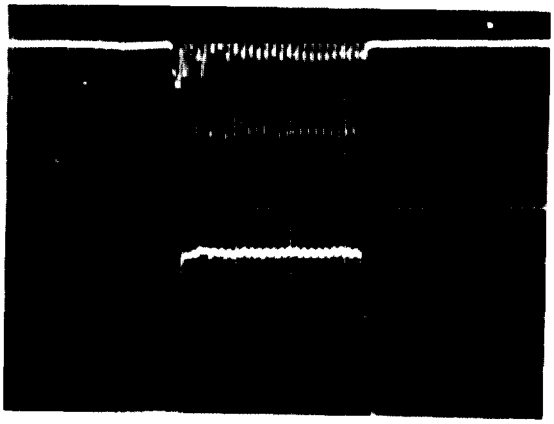

Fig. 3. Periodic relaxation instability (Tube 531A). Top trace: reflected power from input cavity. Bottom trace: power output.

tion. Some tubes are deliberately run at reduced heater power in the temperature limited region of the cathode to eliminate this instability.

This instability acts like a relaxation oscillation of a low energy electron production process such as multipactor. Starting conditions for the multipactor emission are affected by local pressure and surface temperature, both of which are increased by a hotter cathode. If the anomalous electron generation process starts immediately with application of RF drive, and is stable during the klystron RF output pulse, the effect is seen only as a slight increase in RF drive power to make up for the energy lost to the electron flux. If the effect is a function of RF drive level in the input cavity starting at some minimum electric field, and maybe having several electric field amplitudes that optimize electron flux production, the effect seen on the RF output beam pulse is steps and glitches in the saturation characteristic. If one of these steps, or glitches occurs in the region of saturation, an unstable amplitude RF output pulse can occur.

If the buildup of electron flux is self quenching due to field loading, a relaxation oscillation of the loading effect can occur that produces an amplitude modulation of the RF output. Observed frequencies of this modulation are between 5 and 20 MHz. Figures 2 and 3 show these effects.

There was an attempt made to correlate anomalous electron loading in a klystron input cavity with large RF output breakup observed in a few klystrons. In one klystron, input cavity components were coated with tin to reduce secondary emission, and at first, there seemed to be some improvement in the RF breakup, but the experiment was not conclusive. Breakdown in the klystron output cavity now seems to be the most likely cause of massive RF output breakup, and of course, damaged klystron output windows also show this breakdown characteristic.

Heater Hum Modulation

Another effect seen in all klystrons, but in some to a much greater degree is cathode heater hum modulation. The cathode heater is powered by 60 Hz AC, and although the heater coil is constructed to minimize stray field at the cathode surface, there is always some residual AC magnetic field in the cathode-anode and input cavity region. In a normal operating tube, this produces an output RF phase modulation of about 0.2°. Since the anomalous electron production is very sensitive to changes in magnetic field, it is not surprising to see increased AC phase modulation up to 1.5° in tubes that show other evidence of unstable anomalous electron production in the region of RF drive saturation.

Backswing Conduction in Klystron Anode-Cathode Gap

The klystron beam voltage on a pulsed klystron is delivered from a large stepup pulse transformer. This gives rise to a long, low amplitude reverse polarity backswing voltage that drives the klystron cathode positive for as much as 50 μsec. On a few klystrons, massive reverse conduction currents have been seen along with a rapid rise in the tube vacuum. This phenomenon is affected by the magnetic field profile in the cathode-anode region of the tube, and also seems to be dependent on cathode temperature and base vacuum in the region. Figure 4 shows the normal backswing voltage without conduction, and the loaded down voltage shape when the conduction occurs. This effect has been observed in pulsed microwave tubes for many years, and sometimes goes by the name "burning." One explanation has been "magnetron oscillation," and this does suggest a massive secondary emission buildup of electron flux on the curved anode housing surface that flows to the cathode when the cathode potential is positive.

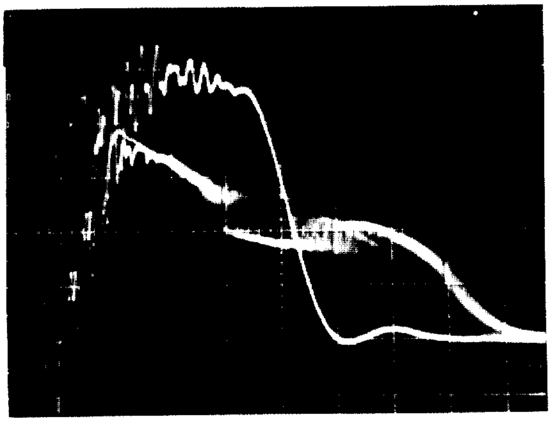

Fig. 4. Inverse avalanche breakdown.

We can investigate the motion of electrons leaving the klystron anode during the positive "backswing" of the beam voltage pulse if we consider the electron gun as a coaxial cylinder with the cathode as the inner conductor and the anode as the outer. With this approximation we can then determine whether the existing magnetic and electric fields are such that periodic motion can exist and whether or not an avalanche condition could arise due to such processes as secondary electron emission.

Assuming only radial electric fields E_r, and only axial magnetic fields B_z, we obtain a set of differential equations for the radial coordinate r, and the azimuthal coordinate θ:

$$\dot{\theta} = \frac{\omega_c}{2}\left(\frac{b^2}{r^2} - 1\right)$$

$$\ddot{r} = \frac{\alpha}{r} + \frac{{\omega_p}^2 b^4}{r^3} - r{\omega_p}^2 \quad .$$

Here ω_c is the cyclotron frequency, b is the radius of the anode, $\alpha = \eta V_0/\ln(b/a)$, $\eta = e/m_e$, a is the radius of the cathode, and ω_p is 1/2 the cyclotron frequency. We can solve the radial equation if we consider only small radial excursions for an electron leaving the anode, *i.e.*, $r = b - \epsilon$ and $\epsilon/r \ll 1$. Then the radial equation can be linearized to

$$\ddot{\epsilon} + \left(\frac{\alpha}{b^2} + {\omega_c}^2\right)\epsilon = -\frac{\alpha}{b}.$$

The solution for this equation is

$$r = b\left[1 - \frac{\alpha}{\omega^2 b^2}(\cos\omega t - 1)\right]$$

and

$$\theta = -\frac{\alpha\omega_c t}{\omega^2 b^2}\left(1 - \frac{\sin\omega t}{\omega t}\right)$$

where $\omega = \left[\eta V_0/b^2\ln(b/a) + \eta^2 B^2\right]^{1/2}$, V_0 is the backswing voltage, and $\eta = e/m_e$ is assumed negative for electrons.

Using these equations and substituting the parameters applicable to the 5045 klystron we obtain periodic (cycloidal) trajectories which can lead to an avalanche condition through secondary electron emission. This multipactor-like mechanism is certainly a plausible explanation for the phenomenon seen on some klystrons where the backswing voltage is suddenly quenched after reaching some peak value accompanied by a deterioration of the tube vacuum.

5. Relativistic Klystron Experiments

As part of the general development of next generation linear colliders, very high power X band microwave sources are being developed as a collaboration among SLAC, LBL, and LLNL. A number of klystron experiments have been carried out and are described in Ref. 2. Unstable pulse shortening of the RF output pulse was observed in several of these experiments. Unstable reflected energy was also observed from the input cavities of these devices, and the apparent multipactor effect was studied in some detail. The behavior of the input cavity reflected power was similar to the multipactor effect seen in 5045 klystron input cavities. The effect was a function of magnetic field in the cavity. An iron ring input cavity was constructed which partially shielded the axial field in the input cavity. This field reduction increased the multipactor threshold above the normal field operating point in the cavity. This field depression plot is shown in Fig. 5. Subsequent testing at sustained higher rep rate showed that the multipactor effect could be cleaned up, and also that at higher excitation levels, the multipactor could be made to disappear.

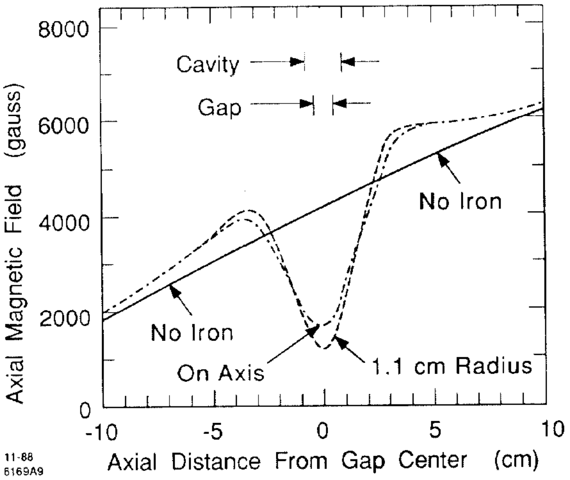

Fig. 5. Relativistic klystron input magnetic field profile.

6. Conclusions

This paper has presented some of the observed instability and failure mechanisms that plague high power microwave devices. These effects have been around since klystrons were first made, and various "fixes" have moved the most damaging effects away from the operating points of existing klystron designs. As we proceed with the design of the next generation of higher power and higher frequency microwave devices, we will need to understand these failure mechanisms in a more analytic way, and develop design procedures and computer models to avoid these limitations.

References

1. "Breakdown Phenomena in High Power Klystrons," by A. E. Vlieks, *et al.*. Invited paper presented to the XIIIth International Symposium on Discharges and Electrical Insulation in Vacuum, June 1988; SLAC-PUB-4546, March 1988.
2. "Relativistic Klystrons," by A. E. Vlieks and G. A. Westenskow. Invited paper presented at the 1989 Particle Accelerator Conference, Chicago, Illinois, March 1989. SLAC-PUB-4861, March 1989.