

# SPURIOUS OSCILLATIONS IN HIGH POWER KLYSTRONS\*

B. Krietenstein, THD, Darmstadt, Germany, K. Ko, and T. Lee,  
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

U. Becker and T. Weiland, THD, Darmstadt, Germany

M. Dohlus, DESY, Hamburg, Germany

## Abstract

Spurious oscillations in high power klystrons are found to occur in the gun region, in the cavities in the main body of the tube, or in the drift tunnel. The criteria that determine whether a mode will oscillate is that its beam loading be negative, and that the power it extracts from the beam exceeds its losses to external loading and wall dissipation. Using the electromagnetic and particle-in-cell modules of MAFIA, we have devised numerical techniques with which the quality factors  $Q_b$ ,  $Q_e$  and  $Q_o$  can be evaluated and compared. Simulations involving a gun oscillation observed in the SLAC/DESY S-Band klystron will be reported.

## I. INTRODUCTION

Oscillations at frequencies other than the operating frequency are not uncommon in high power klystrons. The unwanted signals have been detected in the pulse transformer tank in the gun region, and also in the input and output RF couplers. They occur without the RF drive signal, and have the signature of high- $Q$  resonances in that their frequencies are not affected by variation in operating parameters, such as the focussing magnetic field. S-Band klystrons built at SLAC have experienced oscillations in the gun diode [1]), in the drift tunnel [2], and also in an output circuit of the double-gap type [3].

Spurious oscillations are undesirable since the electron beam couples to these modes as well as the desired signal frequency. If the amplitude of the spurious oscillation becomes very large the performance of the tube can be compromised. The main output signal may suffer from amplitude and phase instability which results in pulse shortening or decrease in efficiency. Thus, spurious oscillations can be a serious factor in limiting a klystron from reaching its designed performance if left unsuppressed. The identification and analysis of spurious modes are not easy to accomplish experimentally because the diagnostics are not set up to monitor such signals. Numerical modeling has proved to be valuable in microwave design and this paper describes the analytical efforts to address the spurious mode issue by computer simulation.

## II. COMPUTER ANALYSIS

The ability of modern electromagnetic codes to study RF modes in complex geometries, both in 2 and 3D, has enabled the klystron designer to identify spurious modes once their frequencies are known from measurements. Guided by the numerical solutions, he can then devise a method of suppression to be

incorporated into the next prototype. Ideally, it would be more cost-effective to catch potentially unstable modes in the design stage before fabrication and testing take place, thereby reducing the number of prototypes to be built. But this would require a complete analysis of the numerous modes that a klystron circuit can support, which is a nontrivial task. The analysis would have to include not only the vacuum RF properties, but also the mode interaction with the electron beam under a range of operating conditions, in order to determine if any of them is unstable or not.

Beam-field interaction can be modeled by the Particle-In-Cell (PIC) method, and 2D PIC codes such as CONDOR have been used quite routinely in klystron tube design to optimize the extraction of power from the beam [4]. In this application, one is concerned only with the main signal which is an axisymmetric mode so that, except for the input and output RF couplers, a 2D( $r, z$ ) geometry suffices. Spurious oscillations, on the other hand, are not limited to monopole modes, but have been observed to be dipole modes as well. Furthermore, external loading by coupling waveguides now plays an important role. PIC modules are available in 3D codes such as MAFIA, but their usage in klystron design has been restricted, largely because of the substantial computer resources such simulations demand. In this work, we will deal with a spurious mode that is axisymmetric so that only 2D calculations are required. We first formulate the criteria that determine oscillation in a way that is computationally efficient. Instead of treating the problem in one simulation, we consider separately three competing effects: beam-field interaction, external loading and wall dissipation. We use the electromagnetic/PIC modules of MAFIA [5] to analyse a gun oscillation problem and demonstrate the method with which to evaluate each effect. We next present the numerical results and discuss the efficacy of the approach.

## III. CRITERIA FOR OSCILLATION

There are two criteria that determine whether a mode can be driven to oscillate by a beam. The first and necessary condition is that the beam transfers power to the mode. The second condition is that the power lost by the mode to external loading and wall dissipation is less than the power obtained from the beam. As a result, there is a net gain in mode energy and the oscillation grows. Computationally, it is prohibitively expensive to model this power balance process. To begin with, one needs a disproportionately small grid step to resolve the skin depth due to finite wall conductivity. It also takes an unrealistic number of particles to maintain an electron beam flow over the long growth time of the instability.

Alternatively, one argues that up to the instability threshold each power transfer acts independently, so therefore they can be

\*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

treated separately. We define the total quality factor  $Q_{tot}$  of a mode as:

$$1/Q_{tot} = 1/Q_o + 1/Q_e + 1/Q_b, \quad (1)$$

where  $Q_o$ ,  $Q_e$  and  $Q_b$  are the *wall loss*  $Q$ , the *external*  $Q$  and the *beam - loaded*  $Q$  respectively. If we express  $Q$  as

$$Q = \omega U/P, \quad (2)$$

where  $\omega$  is the angular frequency of the mode,  $U$  is the time-averaged stored energy and  $P$  is the power transferred, then Eq. (1) describes the power exchange between the mode and the beam, and the power loss by the mode to the circuit environment. If we take power gain as negative, it follows from Eq. (1) that the oscillation criterion is

$$Q_{tot} < 0. \quad (3)$$

Since  $Q_o$  and  $Q_e$  are always positive, then the sign and value of  $Q_b$  will determine unstable resonant modes. A necessary step before one can calculate the quality factors is the identification of the spurious mode, and this we will take up next.

#### IV. MODE IDENTIFICATION

One outstanding feature of spurious modes is their localization within some region of the klystron to form a resonant circuit. The most efficient way to search for resonances is with eigenmode solvers. Among the many solutions such solvers generate, one looks for modes in the proper frequency range that have diminishing fields towards the enclosing boundaries. Non-localized modes will form standing waves between opposing boundaries while localized modes will have exponentially decaying fields. A direct consequence is that localized modes will experience relatively small frequency shifts when different field conditions (*electric wall* :  $E_{tangential} = 0$  or *magnetic wall* :  $B_{tangential} = 0$ ) are imposed at the boundaries.

During the testing of the 150 MW S-band klystron that SLAC is building for DESY, a gun oscillation was discovered when a stable 1.365 GHz signal was detected at the sight window of the pulse transformer tank [1] (with no RF signal applied). Fig. 1 shows a MAFIA calculation of a mode at the same frequency that is localized inside the focus electrode. A small gap connects this small cavity to the main body of the gun diode. By comparison, Fig. 2 shows a nearby mode at 1.277 GHz that occupies the entire diode. Changing the top boundary from an electric to a magnetic wall results in a frequency shift and a different mode pattern for this mode. In contrast, the localized mode is relatively unchanged, indicating the presence of a high- $Q$  resonant structure. We conclude that it is a likely candidate responsible for the spurious oscillation and proceed to determine its  $Q$  factors.

#### V. Q DETERMINATION

##### Wall Loss- $Q_o$

Once a likely resonant mode is identified from the eigenmode spectrum, it is straightforward to calculate its  $Q_o$  by

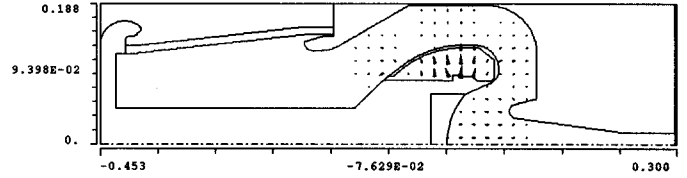


Figure 1. 1.365 GHz mode in the SLAC/DESY gun diode.

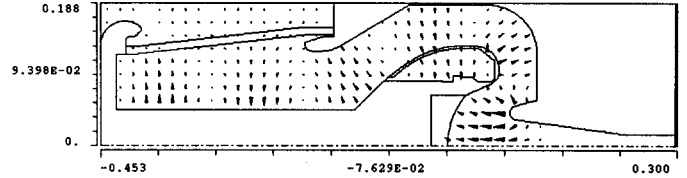


Figure 2. 1.277 GHz mode in the same geometry.

standard perturbation method. Most field solvers, including MAFIA, provide this result automatically via postprocessing. The time-average power absorbed per unit area at the wall is given by

$$\mu\omega\delta|H_{tangential}|^2/4, \quad (4)$$

where  $\delta$  is the skip depth  $(2/\mu\omega\kappa)^{(1/2)}$  and  $\kappa$  the finite conductivity of the wall material. From Eq. (2), then

$$Q_o = \omega U/P_w, \quad (5)$$

where  $P_w$  is the integral of Eq. (4) over the wall surface.  $Q_o$  due to copper loss typically ranges from several to tens of thousands at RF frequencies, and is not a major factor in determining  $Q_T$ . However, in situations where external loading is ineffective or not applicable, lossy wall material (e.g. stainless steel) is sometimes introduced in areas of high surface currents to provide additional Ohmic loss for mode suppression.

##### External Loading- $Q_e$

Of the various methods to determine the external  $Q$  of a mode, we will choose the one which is the most direct. We load the eigenmode from the previous calculation as the initial conditions to a time-domain simulation. As opposed to the eigenmode analysis which assumes a closed cavity, power flow across the boundaries are now permissible via ports that are terminated in matched loads. In the gun-diode of Fig. 1, one port is the outer boundary of the pulse transformer tank at top left, while the other is at the entry into the drift tunnel to the bottom right. With the ports open, the initially confined electromagnetic fields can radiate through these apertures and decay. After the initial transient has subsided, one can calculate the decay time constant  $\tau_e$  from the field values at successive time intervals. The external loading effect is then determined directly from the relation

$$Q_e = \omega\tau_e/2. \quad (6)$$

##### Beam Loading- $Q_b$

The beam loading of a mode comes about because the mode induces bunching in the beam which then interacts with the mode field to produce energy exchange. In the absence of losses,

we can use energy conservation and equate the rate of change of stored energy to the power transfer between the mode and the beam. We arrive at an expression for  $Q_b$  similar to Eq. (2), namely,

$$Q_b = \omega U / P_b. \quad (7)$$

The time-average power flow  $P_b$  is given by the integral over the beam volume

$$P_b = \frac{1}{T} \int_t^{t+T} \int_V \vec{J}_m \cdot \vec{E}_m dV dt \quad (8)$$

where  $J_m$  is the induced current density,  $E_m$  is the electric field of the mode, and  $T$  its period. The facility to evaluate  $P_b$  is currently under construction in MAFIA, but we can alternatively find  $Q_b$  from the time constant the same way it is done in determining  $Q_e$ .

## VI. GUN OSCILLATION SIMULATION

As noted before, the computation of  $Q_b$  requires a full PIC simulation that includes relativistic and space charge effects [6]. The MAFIA PIC module has this capability so we use it to model the gun oscillation problem. The MAFIA simulation consists of a dc beam, a static field between cathode and anode, a focussing magnetic field and the RF mode under consideration. The injection parameters for the beam at the cathode are taken from previous EGUN [7] results, while the MAFIA static module provides the gradient  $E_s$  and the magnetic field  $B_o$ . The RF mode  $E_m$  is taken from the eigenmode calculation as before.

Without the RF mode, the PIC module essentially reproduces the beam optics results from EGUN. The RF mode is then added with its amplitude scaled to a small fraction of the static field amplitude. This way the RF mode serves as a test field that modulates the lowest order beam equilibrium. Fig. 3 shows a time snapshot of the simulation. The beam is constituted of fifteen rays and the field ratio used is  $E_m/E_s = 0.1$ . Note that the gun diode is much smaller than previously considered. We provide the justification for the reduced geometry below.

In the absence of external loading and wall loss, the RF mode is basically a standing wave resonance. A resonant circuit is essentially unchanged if shorted properly at one of its node points. The region from the focus electrode to the pulse transformer tank does not play a part in beam-loading except for the energy stored there. Fig. 3 shows the placement of a shorting plane which removes this part of the circuit but leaves the frequency and field pattern of the RF mode unchanged. The geometry is now smaller, and because the total stored energy is less, any time constant related to it also is faster, both of which is good for simulation. However, one needs to scale by the proper ratio of the stored energy in the full geometry to that in the reduced one to obtain the physically correct values.

## VII. NUMERICAL RESULTS

The calculations from the previous sections on the localised 1.365 GHz mode are summarized in Table 1. For comparison, the results on the 1.277 GHz mode are also given. As expected, the  $Q_o$ 's do not play a role. The 1.277 GHz signal has negative

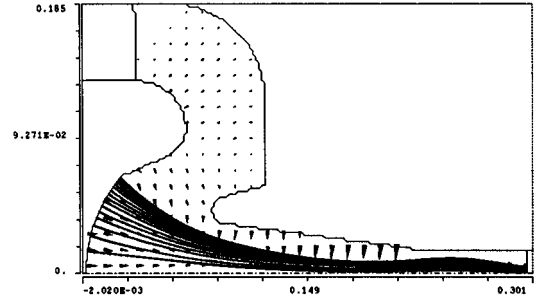


Figure 3. Reduced geometry for the PIC simulation.

beam loading, but is negligible when compared with the heavy external loading, so the net result for  $Q_{tot}$  is positive. On the other hand, the 1.365 GHz signal couples so weakly to external loads that the stronger negative beam loading leads to a negative  $Q_{tot}$ , and results in oscillation. After the gap at the focus electrode in the SLAC/DESY klystron gun was shorted to eliminate the 1.365 GHz unstable mode, the klystron was processed up to full power without experiencing the previously observed gun oscillation.

Frequency [GHz]	$Q_o$	$Q_e$	$Q_b$	$Q_{tot}$
1.277	25500	45	-1340	46
1.365	13300	5000	-728	-910

Table 1. Calculated  $Q$ 's for the 1.365 and 1.277 GHz signal.

## VIII. SUMMARY

We have presented an analytical method to study spurious oscillation by computer simulation, and have applied it to a gun oscillation problem with encouraging results. Further generalization of this approach to other klystron oscillations, including those in which 3D effects can be important, is being considered.

## Acknowledgements

We thank D. Sprehn for useful discussions. One of the authors (B. Krietenstein) also acknowledges R. Ruth for his generous hospitality and support during his stay with the ATSP Dept. at SLAC.

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