RESULTS OF SIMULATIONS OF HIGH-POWER KLYSTRONS*

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ABSTRACT

The MASK code is a 2-1/2 dimensional particle-in-cell code which has been applied to the simulation of a number of microwave devices. We discuss implementation of algorithms for the simulation of high-power klystrons. These algorithms use the cavity properties and the MASK results to find self-consistent solutions in both the linear (small signal) parts of the klystron as well as for the high-power cavities. The method is used to model the existing 35 MW tube and the 50 MW tube being built for the SLC project. Dependence of magnetic field profile and geometry on tube performance is discussed. Effects of radial beam dynamics on efficiency are described. Simulation results are compared to experimental data.

Introduction

A method for simulating the behavior of high-power klystrons using the particle-in-cell code MASK has been described elsewhere.[1,2] In this paper we describe the implementation of this algorithm and its application to the 35 MW XK5 tube currently in use at SLAC and the 50 MW 5045 tube which is in production for the SLC.

The algorithm models the beam dynamics in the drift tube region of the klystron, replacing the cavities by input ports with specified voltages and phases. These voltages and phases are calculated self-consistently by imposing the power balance equations. For the input and idler cavities the required values can be obtained from linear theory. For the last two cavities the values are obtained by iteration. Tubes of variable radius can be modelled by use of conducting blocks.

Implementation

This algorithm has been implemented by writing a controller which runs under COSMOS on the NMFECC system. This code sets up the MASK input files, runs MASK, reads the output files, calculates the new values of voltages and phases, and sets up the next input file for the new MASK run. In addition, a separate system of codes, running on the SLAC IBM 3081 system, is used to generate the input parameters for use in the MASK simulation. The EGUN code is used to model the klystron gun and calculate the electron current and velocity profile at the entrance of the drift tube. The POISSON code calculates the magnetic field from the measured currents used in the klystron electromagnets. Separate codes then translate the output of these codes into the formats required by MASK.

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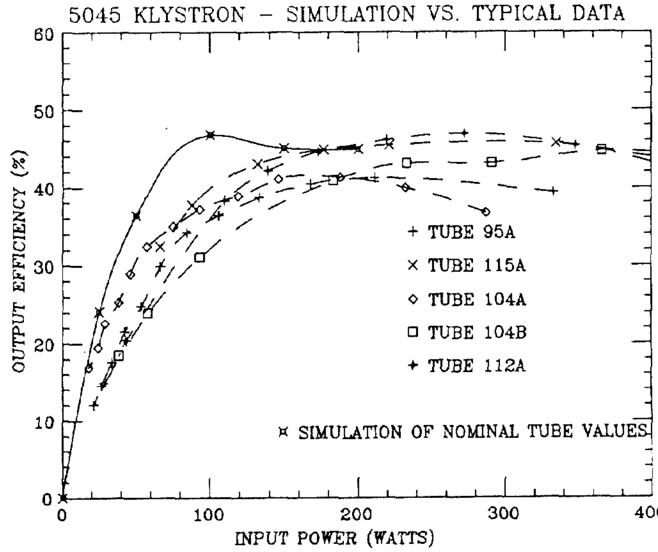
Results of the Simulations

Simulations have been made for the 35 MW XK5 and the 50 MW 5045 tubes. Figure 1 shows the simulation results for the 5045 using the nominal cavity tunings and magnetic field along with experimental results for several typical tubes. The results for peak efficiency for the 5045 tube lie within the range found in actual tubes, although the gain was about 2 db higher than the average. There was not much experimental data for the XK5 available; however, the calculated peak efficiency of 46% is similar to typical values.

FIGURE 1

5045 KLYSTRON – SIMULATION VS. TYPICAL DATA



These simulations used nominal values of the tube parameters. A problem in comparing simulation results to experiment is that many experimental values vary considerably from tube to tube. A very small change in the resonant frequencies of the cavities can result in a large change in the difference between cavity and operating frequencies. The variation in cavity parameters requires that the magnetic fields used for each tube be adjustable for optimal, stable operation.

It is also difficult to accurately measure the cavity R/Q values, and we are forced to calculate them by computer. This seems adequate for the axisymmetric cavities, but is not possible for the output cavity with a large, non-axisymmetric port.

To validate the code, data was obtained from a 50 MW klystron (tube 95A) which had been disassembled subsequent to window failure, and the cavity frequencies remeasured. The magnetic field values were calculated using the POISSON

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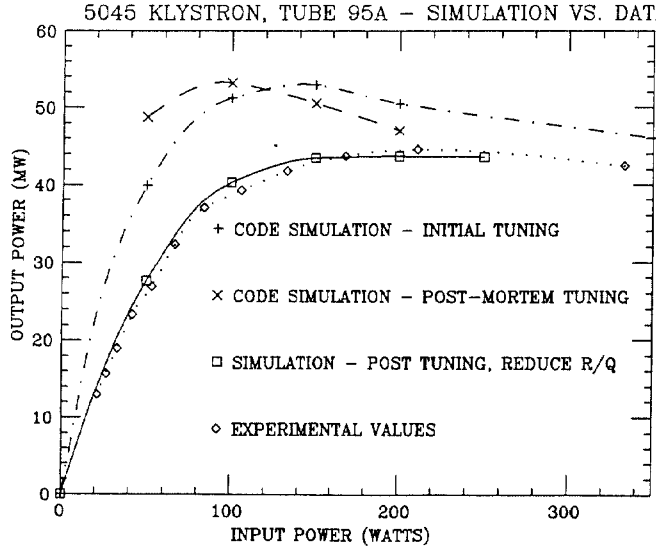
magnet design code, using the measured currents through the magnet coils and the measured geometry of the pole pieces. The beam voltage and current had been measured along with output power and gain versus rf input power. The only variables not directly measured were the Q and R/Q of the cavities. (Circuit-loaded Q values were measured for the first and last cavities, and R/Q was measured for an output cavity of the same geometry.) The remaining Q and R/Q values were calculated using SUPERFISH.

Calculated and experimental results are shown in Figure 2 for tube 95A. The input beam had energy 315 KeV at 343 A. The results are in approximate agreement with the measured values, although the peak power was about 18% higher than that measured, and the gain was about 2 db higher. Examining the sensitivity of the simulation to variations in the parameters suggests that this difference is larger than can be accounted for by the uncertainties in the cavity tunings and R/Q values. Thus there may be other loss mechanisms in the tube not modelled in the code. There are several possible effects which might result in lower gains and efficiencies. For example, beam aberrations or other differences between the actual input beam and that used in the simulation might result in poorer bunching in the experiment than in the code. Scattering of intercepted electrons back into the cavity might reduce the efficiency. Non-axisymmetric magnetic fields or instabilities might cause increased debunching, thus reducing gain and efficiency. Alternately, altered R/Q values due to multipactoring or other anomalous effects could increase losses.

It is also possible that there was a discrepancy between the way that input power was calculated in the experiment and the way that it was defined in the simulation. Cable attenuation and reflected power could have accounted for losses of between 1 and 2 db. This could explain the difference in gain but not in peak efficiency.

FIGURE 2

5045 KLYSTRON, TUBE 95A – SIMULATION VS. DATA



It is possible that numerical problems might contribute to the discrepancy. One of the problems with the simulation is that the induced currents calculated for the idler cavities are not completely stable. After the initial transient dies away, the value for the induced current gradually begins to grow and eventually diverges. This results in about a 10% uncertainty in the value of the induced currents, which will cause an uncertainty in the calculated cavity voltages, probably on the side of higher voltages. Thus the calculated gain would be too high.

We found that reducing the R/Q of all cavities by 20% from the nominal values gave an almost perfect fit to the data. Of course, this does not demonstrate that the discrepancy was actually due to incorrect or anomalous R/Q values, but it does indicate that the discrepancy can be accounted for in terms of physically possible loss mechanisms.

The results were found to be sensitive to the magnetic field behavior at the input. For example, when the magnetic field profile was shifted by 6 cm the peak output power was reduced to about 33 MW. In addition, the results were sensitive to the velocity distribution of the beam at the input.

Snapshots of the beam position and momentum-space distribution are shown in Figures 3 through 5 for the XK5 and 5045. The 5045 plots are for tube 95A discussed above, at peak power. The conducting blocks shown in the plot are used to simulate the variation in tube radius after the output cavity. The ports are located at the gaps between blocks. The output port was immediately after the last block, and is indicated by a heavier line. An examination of the beam trajectory shows that the bunching is as much or more in the radial dimension as it is in the longitudinal dimension. Maximum efficiency generally occurs when the beam trajectory can be adjusted so the edge of the beam comes as close as possible to the output gap.

FIGURE 3: 50MW KLYSTRON

ELECTRON POSITION–SPACE DISTRIBUTION

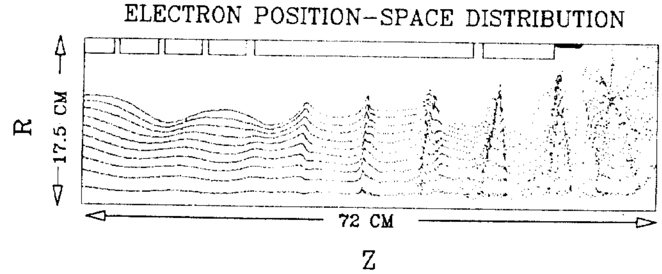


FIGURE 4: 35MW KLYSTRON

ELECTRON POSITION–SPACE DISTRIBUTION

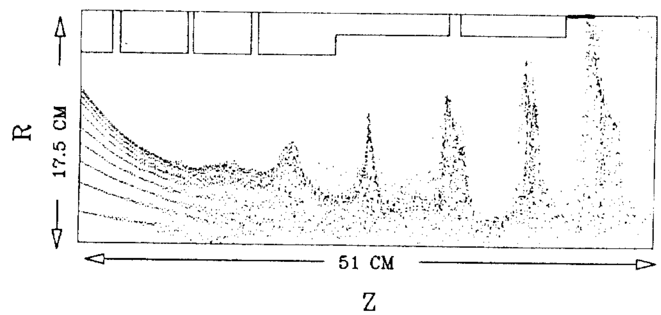
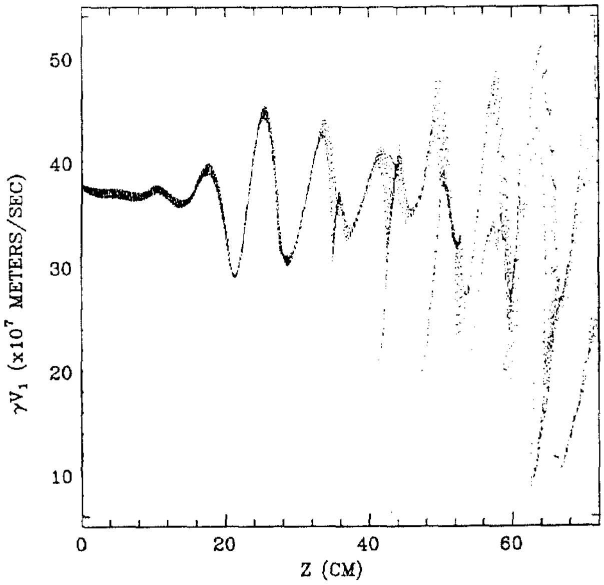


FIGURE 5: 5045 KLYSTRON
ELECTRON MOMENTUM-SPACE DISTRIBUTION



The most significant difference between the XK5 and 5045 (aside from the extra idler cavity in the 5045) is the input velocity distribution. The input beam for the 5045 was essentially "immersed flow", i.e., the beam was not spinning significantly. The XK5 beam had a large radial and angular velocity at input. Immersed flow results in a more uniform beam with less aberration and less scalloping. The magnetic fields used for the two tubes are also somewhat different in shape. The magnetic fields are chosen empirically to optimize efficiency and control interception. The beam expands radially at the output gap due to the effects of beam-cavity interaction and also because the magnetic field begins to drop off there. As the magnetic field continues to fall, the beam expands considerably in radius as the tube widens into the beam collector.

Some of the simulations predict beam interception of order 5–15% of the total current near the output cavity. This interception could result in a reflected beam which might be one cause of some of the observed instabilities. By varying the magnetic field near the output gap it was possible in the simulation to reduce the amount of intercepted current. This also reduced the output power, but by raising the Q of the output gap it was possible to restore the efficiency.

Limitations of the simulations

MASK requires that the boundary conditions at the input be metal walls, which introduces an error from the space charge of the beam. We approximately compensate for this by injecting the beam with its peak energy, rather than the space-charge depressed energy calculated by the EGUN code. Thus the reduction in energy due to the space charge is not inserted twice. However, ideally one would like to change the code to allow input beam (Neumann) boundary conditions.

The cavity fields are modelled as uniform across the gaps. Ideally, one would like to solve carefully for the resonant fields produced by the cavities and use them in the simulation (e.g., using a code like SUPERFISH). However, using a non-uniform form factor across the output gap to model the true gap fields more accurately did not make much difference in the results, even though the beam goes very close to the output gap. Thus we do not expect that a more exact treatment of the cavity fields would make a significant difference in the simulation results.

The problem of divergence of the idler cavity currents needs to be examined. Possibly some sort of smoothing or averaging of the induced currents may be needed to obtain more accurate values.

A limitation of the model is that it assumes steady-state behavior. Thus it is difficult to study the growth of instabilities. It may be possible to look specifically at transient behavior, at least to the extent of computing linear growth rates for different modes.

Another limitation of the simulation is that the port approximation to the cavities neglects the effects of higher harmonics. It may be possible to model the output cavity with a true simulation using a technique involving a variably-zoned mesh.

Future Research

An important question is the nature of the unstable behavior observed on certain of the 5045 tubes. The explanation for this behavior is not yet known. Data exist for some tubes showing stable behavior under some tube settings (e.g., magnetic fields, operating frequency) with unstable behavior for different settings. Modelling of these different conditions with simulations may shed some light on identifying features of beam behavior associated with instabilities.

A question of continued interest is the design of klystrons of higher efficiency. We have begun more systematic investigation of the effects on tube behavior of parameters such as magnetic field shape near the gun, cavity tunings (particularly those of the second and fifth cavities), and beam perveance. We are also interested in more fundamental design variations. For example, simulations of the Lasertron using a two-gap output cavity[3] predict substantially higher efficiencies than those attainable with a single output cavity. We wish to apply this technique with klystrons as well.

REFERENCES

1. S. Yu, P. Wilson, A. Drobot, "2-1/2 D Particle in Cell Simulation of High Power Klystrons," presented at the 1985 Particle Accelerator Conference, Vancouver, British Columbia, May 13-16, 1985.
2. S. Yu, "Particle in Cell Simulation of High Power Klystrons," SLAC/AP-34, 1984.
3. W. B. Herrmannsfeldt, "Lasertron Simulation with a Two-Gap Output Cavity," SLAC/AP-41, 1985.