

# Simulation of Traveling-Wave Output Structures For High Power rf Tubes\*

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## Abstract

Travelling wave output structures can in principle provide higher efficiency and lower surface gradients than a single output cavity. We discuss simulations of TW structures designed for X-band klystrons to be used in the SLAC NLC. The PIC Code CONDOR [1] calculated efficiency over 50 percent for one such circuit. When the circuit was built in the SLAC XC7 klystron, the match was so poor that it had to be modified. When tested, the tube produced less than half the efficiency calculated. We subsequently found significant differences between the field distribution calculated by CONDOR versus that from the 3-D code MAFIA [2]. We have now developed a procedure which gives much better agreement between the 2-D and 3-D models. We use a  $\pi/2$  disk-loaded structure, with the waveguide coupling to an output cavity through an iris, rather than directly to the drift tube as in the XC7. The disk radii are tapered to produce an approximately constant gradient. The output coupling is adjusted to match to a uniform structure replicating the cell before the waveguide. The simulations predict 75 MW, 49 percent efficiency, with peak surface fields of 73 MV/m. from a 440 kV, 350 amp beam at 11.424 GHz.

## I. INTRODUCTION

The NLC design at SLAC requires a klystron producing at least 50 MW peak power at 11.424 GHz with a pulse length of at least 800 ns. A single gap output cavity would break down under these conditions. An extended output circuit should provide lower gradients and potentially higher efficiency. We have studied several disk-loaded travelling-wave output circuits at SLAC. Our main design tools have been the 1-D TWT code HARMON and the 2-D PIC code CONDOR. In CONDOR, we model the buncher cavities with the port approximation [3]. In the output section we model the actual geometry of the disks. The coupling to the waveguide is imposed as a port boundary condition on the outer wall of the last cell. This behaves like a radial transmission line whose impedance we can adjust. We can also adjust the coupling by adding a reactive phase to the impedance, or alternately tune the output cell by adjusting its dimensions:

There are two main difficulties we have encountered. For narrow band circuits, a very fine mesh may be required to accurately model the geometry. In addition, the non-axisymmetric nature of the coupling to the external waveguide is not always correctly modelled as a radial trans-

mission line. We discuss how these problems affected our early modelling attempts and the progress we have made in overcoming them.

## II. SLAC XC7 OUTPUT CIRCUIT

The output circuit that was used in the SLAC XC7 klystron originated with Phillips based on results from the 1-D HARMON code. The circuit had four cells plus a waveguide which intersected the drift tube directly, rather than through an iris to an output cavity. The intention was to operate in a  $2\pi/3$  mode. The operating conditions were 440 kV, microperveance 1.9. The cell radii were modified by the author based on the results of CONDOR simulations. A buncher section designed by Lien gave  $I_1/I_0$  of 1.5, much higher than previous bunchers used in the X-band klystrons. The 2-D simulations predicted efficiencies over 50 percent, with peak power of about 120 MW and peak surface fields under 100 MV/m. When the circuit was modelled with the 3-D code MAFIA, the match was poor, with a VSWR of 8:1. The fourth cell radius was then reduced to produce a better match. The circuit was mounted on a rebuilt version of the XC5 klystron. The tube produced about 50 MW, similar to the XC5 at short pulses, but performed more poorly than XC5 at long pulses. The rebuilt tube did not have the improved buncher used in the design. We believe that the discrepancy between the CONDOR simulations and the experiment was due to incorrect modelling of the 3-D effects of the waveguide. The analysis was complicated by the narrow bandwidth of the structure. This caused the simulations to be very sensitive to the mesh size. To deal with this problem we borrowed a method used in the MAGIC code. We partially fill the outer radius of the cell so that the average radius is much closer to the desired value.

We subsequently resimulated XC7, using the fourth cell radius as built rather than as initially designed, and using the actual buncher section. The code predicted 46 MW, agreeing fairly well with the experiment. Since XC5 and XC7 produced almost identical power for short pulses with very different circuits, the simulation agreement does not prove that the fields in the model were in good agreement with the tube. A MAFIA cold test of the circuit was compared to a CONDOR cold test, both driven by an antenna on axis upstream of the input cell. A frequency scan showed four resonant peaks, which would not be present for a true travelling wave structure. Thus the circuit was operating in a hybrid mode, partially standing wave and partially travelling wave. The actual operating point was about 100 MHz above the  $3\pi/4$  mode, about 200 MHz below the  $\pi$  mode.

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With no external waveguide, both MAFIA and CONDOR agreed well to URMEL calculations of the resonant frequencies. With the coupling, the two central resonances merged in a broad peak in the 2-D model, but not in the 3-D model or in the lab. Comparing both 2-D and 3-D models at the frequencies where each put the  $3\pi/4$  mode, we found a substantial discrepancy between the field amplitudes and phases. Retuning the output cell in the 2-D model (by adding tuning stubs) it was possible to recover the four peak resonant pattern, and, by careful adjustment, it was possible to get agreement with MAFIA for all the phase shifts to within .1 radian. The phases also tracked well when the codes were compared 100 MHz above the  $3\pi/4$  mode. However, the amplitudes still showed substantial differences. Although the number of nodes in the field patterns were the same, the location of the peaks was shifted. From our findings below, we believe the discrepancy is due to the strongly non-axisymmetric nature of the waveguide when coupled to the drift tube without an output cavity.

### III. CONSTANT GRADIENT $\pi/2$ STRUCTURE

We learned of a different approach that had been developed by Symons and Begum at Litton while designing a klystron for the DOD (through TRW). They used a four cell, disk-loaded structure, but with a  $\pi/2$  phase shift and with varying disk radii to maintain an approximately constant gradient for all cells. This structure also had a very broad bandwidth. This was not essential for SLAC, but makes the design simpler by making the results less sensitive to small changes in the dimensions. This circuit used a cavity with a coupling iris in the fourth cell rather than a waveguide only. The coupling was adjusted for the best match when looking into a long uniform structure replicating the cell before the waveguide (making both disks the radius of the downstream side). The tapered disk radii were predicted to compensate for the beam so as to give a good match with the beam present. A linear variation of beam energy with position was assumed. Symons' design assumed the beam energy became zero at the end of the circuit, but we assumed 50 percent. Symon also assumed constant rf current, but we assumed a linear decline to 30 percent. The disk radii were chosen to produce approximately uniform fields strengths for each cell, based on URMEL and SUPERFISH calculations. The cavity radii were adjusted to have  $\pi/2$  phase shifts at the operating frequency. There are some ambiguities in this process, as the phase shifts vary with radius, and the analysis of a periodic structure based on a single cell gives quite different results depending on which of the unequal disk radii is used. Fortunately the design is fairly robust.

The matching was done using a uniform structure, as described above. We modelled a five cell structure with input and output couplers and three inner cells identical to the cell before the waveguide. We did this with both CONDOR and MAFIA to see if we could obtain the same field distributions. In MAFIA, the radius of the coupler

cell and the aperture of the iris were varied to obtain the best match. For CONDOR, the radius and the impedance of the port was varied. In both cases the input and output cells were always adjusted to be identical. When we got the best agreement between CONDOR and MAFIA, the radius of the output cell in CONDOR was much closer to the value of the other cells than in MAFIA. Because CONDOR does not allow a variable mesh, the matching needs to be checked and possibly readjusted whenever the mesh size is changed. Alternately one can make small adjustments to the geometry of the structure to make it more closely approximate the results one would obtain with a very fine mesh. The mesh used was relatively coarse, with only six points modelling the rounded end of the disk. We obtained very good agreement between the 2-D and 3-D field distribution, with amplitudes agreeing to about 10 percent (normalized to the power level) and phases agreeing to better than .1 radian.

The first match we thought we found with MAFIA proved to be spurious. The reflection coefficient was very small but the fields in the cells were unequal. When an extra cavity was added, the reflection coefficient became larger. This is worth mentioning because the 2-D model continued to track the 3-D model closely when the extra cell was added. We obtained a true match with further variation of the cell parameters, and again were able to get good agreement between the 2-D and 3-D field patterns. Now the cell amplitudes were all nearly equal, and the reflection coefficient remained small when another cell was added.

We then studied the cold properties of the tapered circuit, using the matching conditions on the last cell determined above. We took care to keep the same mesh size so that the modelling of the last disk and cell would be unchanged. The tapered circuit was initially designed by Phillips using URMEL and SUPERFISH. The author made some small modifications to make the match better and the voltages more uniform.

Generally we have done cold test calculations with a single antenna, usually on axis or across one of the cavity gaps. We discovered that a volume phased array of antennas can give a much better approximation to the behavior of a beam. The array extends over a cylinder with radius equal to the beam, with constant radial current density. The phases change with phase velocity equal to the beam velocity. A further refinement is to taper this velocity, assuming a linear variation in beam energy through the circuit. The current can also be tapered linearly if desired. This new driver is a better design tool for the tapered circuits than a single antenna, making it more apparent whether the gradients are constant and whether the phase shifts are correct.

We also used a current array with the exact current and phase distribution (with no radial variation) produced by the simulation with beam. The result agreed very closely to the full beam simulation. This calculation is

much faster than the particle simulation. It is also useful in checking the results with a finer mesh, and may be used for 3-D simulations with MAFIA, which otherwise would be very costly.

The preliminary CONDOR results from the tapered circuit are highly encouraging. With almost no experimentation, the design produced 49 percent efficiency (75 MW). The peak surface field was 73 MV/m. The beam was 350 amps at 440 keV, perveance 1.2, with  $I_1/I_0 = 1.5$ . The rf current was produced with an imposed velocity and density modulation. Wright has designed a buncher which is predicted to produce  $I_1/I_0=1.6$ .

Table 1.  
Field Pattern in the Output Structure (Hot)

Cell	$E_z$ on axis (MV/m)	Phase Shift (radians)	Peak Surface Field (MV/m)
1	14.7	—	38.1
2	14.6	-1.66	60.4
3	14.6	-1.85	60.6
4	20.5	-1.04	72.8

#### IV. FUTURE WORK

We will redo the simulation with a buncher-modulated beam. We will perform a parameter study to further optimize the performance. We will model the tapered structure on MAFIA to assure that the field pattern is being represented correctly by CONDOR.

#### V. CONCLUSIONS

It is possible to represent a disk-loaded output structure reasonably well with a 2-D model, if one couples the waveguide to a cylindrical cell through an iris, uses a broad band circuit, and uses 3-D modelling to verify the field patterns. We have designed a circuit using a  $\pi/2$  mode tapered to give a constant gradient which simulations predict will give high efficiency with moderate gradients.

#### IV. REFERENCES

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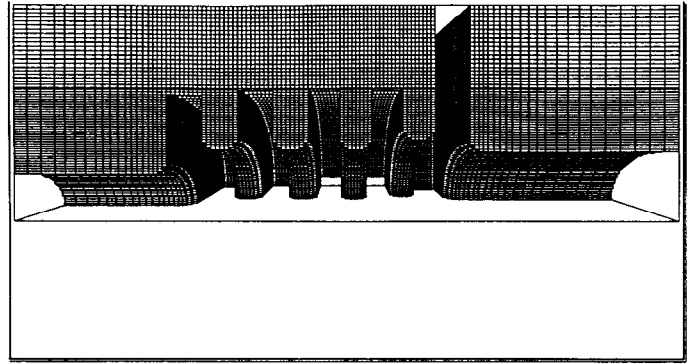


Figure 1. MAFIA simulation of XC7 output structure.

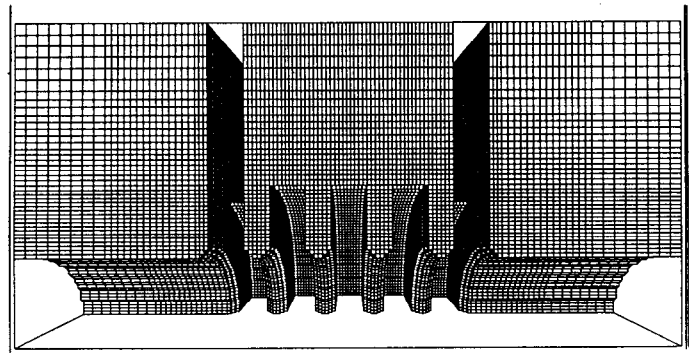


Figure 2. MAFIA simulation of 5 cell coupler used to match the  $\pi/2$  structure into the waveguide

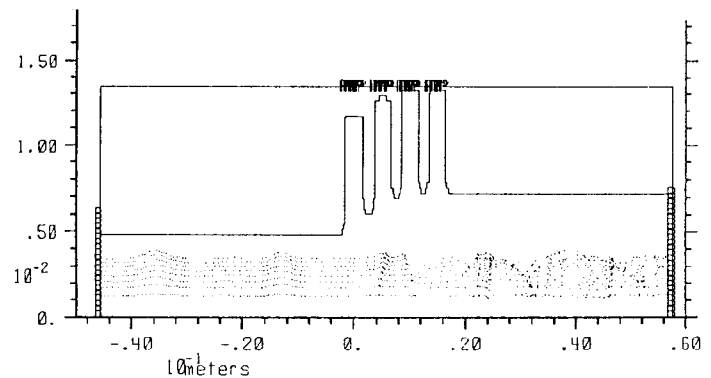


Figure 3. CONDOR simulation of  $\pi/2$  structure (not to scale). Electron position space distribution is shown. Horizontal scale is Z, vertical is R.