Recent Advances in Modeling of Traveling Wave Tubes
David Chernin*, John Petillo*, Thomas Antonsen, Jr.†, and Baruch Levush
Naval Research Laboratory
Washington, DC 20375 USA

Abstract — Traveling wave tubes (TWTs) remain the amplifiers of choice in many ground and space-based applications requiring the production of broadband high frequency microwave and millimeter wave power with high efficiency. All modern TWTs are designed using sophisticated computer-based design tools that are based on the fundamental physical laws governing the emission, transport, interaction, and collection of electron beams. This paper provides an overview of a state-of-the-art suite of modeling and design tools for the end-to-end simulation of coupled-cavity and helix traveling wave tubes.

Index Terms — TWT, electron gun, helix, coupled cavities, depressed collector, computer simulation, gain, bandwidth, stability

I. INTRODUCTION

The first traveling wave tube was built and successfully tested by Rudolf Kompfner in 1943. Following World War II, Kompfner joined John Pierce at Bell Labs where they jointly further developed the new invention to become a workhorse of the new communications age. Numerical methods were used virtually from the beginning, first to find roots of the small signal dispersion relation governing the interaction of a beam with a helix structure and later to simulate directly the transport and interaction of a beam with the helix circuit in order to predict large signal performance. Since the pioneering work of Pierce, Kompfner, Rowe, Birdsall and others in the US, Weinstein and Loshakov in the former Soviet Union and other prominent scientists, there have been have many researchers from many countries, based in industry, government, and Universities, who have further developed the art and science of computer modeling of TWTs.

Early work on computer simulation of TWTs was necessarily restricted to one-dimensional analyses, due to the modest speed and memory capacity of early computers. These models represent the beam as a collection of rigid, non-expanding disks or rings that are allowed to move only in the direction of beam propagation. The self-consistent expansion of the beam, under the forces of the rf, space charge, and magnetic focusing fields, however, is important to model correctly since the strength of the interaction of the beam with the circuit wave may depend sensitively on the transverse current distribution of the beam. Modern development of TWT design tools has focused on two- and three-dimensional models that incorporate significantly more sophisticated and accurate representations of the physics of beam generation, transport, and interaction.

A schematic of a helix traveling wave tube is illustrated in Figure 1; the helix delay line is replaced by a coupled cavity chain in coupled cavity TWTs. Its major components are an electron gun in which electrons emitted from a cathode are formed into a collimated beam and accelerated to a velocity approximately equal to that of the electromagnetic wave supported by the slow wave circuit (helix or coupled cavities). Once the spent beam exits the interaction region it enters a collector, which may consist of several stages to which negative voltages have been applied in order to recover the energy remaining in the beam.

In this paper we provide an overview and examples of the use of modern physics-based design tools for the end-to-end design and simulation of coupled-cavity and helix TWTs. These include 2D and 3D models for the electron gun, 1D and 2D models for the beam-circuit interaction, and 2D and 3D models for the collector. Other commonly used design tools for the analysis of the ‘cold test’ properties of the helix and coupled-cavity structures and for the design of the magnetic fields used to confine and transport the beam are now widely available commercial products and will not be reviewed here.

II. ELECTRON GUN MODEL

The current state-of-the-art in electron gun (and collector) models is represented by the MICHELLE code [1, 2], an electrostatic particle-in-cell, finite element code that may be operated as either a steady state or time-dependent 2D or 3D simulation model. MICHELLE has been widely and successfully applied to design high performance electron guns. A particularly complex 3D example is illustrated in Fig. 2, which illustrates the results of a MICHELLE simulation of a gridded electron gun. The simulation resolved the fields with up to 5.8 million elements using an

* Science Applications International Corp, McLean, VA
† University of Maryland, College Park, MD
unstructured conformal mesh and 75,000 rays. MICHELLE is the only code that has modeled a gridded gun with reasonable accuracy: about 3 percent for the current, ~9 percent for the beam radius waist, and ~4 percent for the beam waist’s axial position.

Recent work has included time dependent simulations for RF and photoemission guns. Time dependent space charge are important to capture in many designs.

The accurate modeling of thermionic emission and guns operating in the transition from space charge limited to temperature limited regimes requires the use of large numbers of particles. A parallel version of MICHELLE reduces run times in these cases.

Finally we mention that MICHELLE has been used within the ANALYST simulation framework to perform automated optimization of electron gun designs. An example will be shown in which this optimization process led to a significant improvement of a design that had already been manually optimized by an experienced electron gun designer.

III. BEAM-CIRCUIT INTERACTION MODEL

As the electron beam from the gun enters the interaction region it sees the electromagnetic field produced by the injected signal as it propagates from the input coupler on to the circuit structure and then to the output coupler. While it is possible to model the interaction of the beam with the circuit wave using first principles particle-in-cell methods in the time domain, a far more efficient and nearly as accurate approach employs the assumption that the fields in the slow wave structure are periodic in time; in the case of a single tone signal, that period is just the period of the input signal. When multiple discrete tones are present, this assumption requires that all frequencies be multiples of a common base frequency. This ‘frequency domain’ approach is the one taken in the CHRISTINE [3], CHRISTINE 3D [4] and CHRISTINE-CC suite of large signal simulation codes for modeling helix and coupled cavity TWTs.

Large signal codes like the CHRISTINE codes can be used to predict small and large signal gain, bandwidth, and efficiency as functions of various design parameters, including beam voltage, current, and radius, circuit length and pitch. These codes can also be used to optimize the values of these parameters, subject to various physical constraints using automated optimization algorithms.

One of the most important applications of beam-circuit interaction codes like the CHRISTINE codes is to assess the stability of a TWT design to out-of-band oscillation [5], both in the presence and in the absence of an in-band drive signal. In a helix TWT, one of the phenomena that limit output power is backward wave oscillation in which a spatial harmonic of a backward-going wave is synchronous with the beam and the beam current is large enough so that the resulting feedback produces spontaneous oscillation. An example will be presented in the Conference talk.

IV. COLLECTOR MODEL

Codes used for the design of electron guns can also be used to model electron collectors. MICHELLE has been for both steady state and transient analyses of collectors. The steady state analysis ignores the fact that the incoming beam is bunched, and so is correct only in some time-averaged sense. More accuracy is obtained when a complete RF cycle of the bunched beam is modeled in a fully time-dependent simulation. An example of both steady state and time-dependent analyses will be presented in the Conference talk.

V. SUMMARY

The development of modern TWTs has been facilitated by the application of a new generation of 1, 2, and 3D physics-based simulation codes. These codes incorporate sophisticated models for the generation, focusing, transport, circuit interaction, and collection of electron beams. When used as stand-alone models, or integrated with modern multi-variable optimization algorithms, the new codes now routinely produce reliable and robust designs, and physical insights into the operation of electron guns, circuits, and collectors for high performance TWTs and other vacuum electron devices. Two and three dimensional design and simulation capabilities will be essential for the design of a new generation of sheet beam amplifiers for very high power applications.

ACKNOWLEDGEMENT

This work was supported by the Office of Naval Research.

REFERENCES