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DIMOGA : Traveling-wave tube simulations including band edge and multiple-carriers operations

Damien F. G. Minenna^{*†‡§}, Yves Elskens[†], Frédéric André[‡], *Member, IEEE*, Jérôme Puech^{*}, Alexandre Poyé[†], Fabrice Doveil[†] and Telma Pereira[‡]

^{*}Centre National d'Études Spatiales, Toulouse, France

[†]Aix-Marseille Université, CNRS, PIIM, UMR 7345 Marseille, France

[‡]Thales AVS, Vélizy, France

[§]Email: damien.minenna@univ-amu.fr

Abstract—A new kind of time domain simulation for traveling-wave tube (TWT) is presented. The DIMOGA algorithm should be considered as an alternative to current particle-in-cell (PIC) and frequency approaches. To assess its validity, a comparison with a commercial Ku-band tapered helix TWT is performed. It shows an excellent agreement for the output power and the nonlinear phase shift at various frequencies. The algorithm is also tested near the band edge and for multitone simulations, both with success.

Index Terms—traveling-wave tubes TWTs, DIMOGA, simulation, band edge, multiple carriers, intermodulation, AM/AM, AM/PM, nonlinear signals, time domain, wave-particle interaction, Hamiltonian dynamics, N-body dynamics, communication systems, large-signal amplifiers.

I. INTRODUCTION

Traveling-wave tubes (TWTs) (see our recent historical review [1]) are high-power amplifiers mostly used for space communications. The physical process at the heart of the device is the wave-particle interaction, where by electrons transfer their momentum to amplify telecommunication signals, as, *e.g.*, in Landau damping. A synchronization process [2] occurs when the phase velocity of the wave (determined by the tube geometry) is close to the particle speed.

Nowadays, it is still difficult to simulate the output wave since TWTs modulate signals in amplitude (this is the role of an amplifier), in phase (knowing that the information is coded on this phase), and in frequency (harmonic and intermodulation generations). In addition, the large power of high frequency TWTs and their broad band spectrum generate critical instabilities. For example, spurious frequencies are generated very far from the drive frequency in the saturated nonlinear regime (where electron motion perturbations become significant) because of drive-induced oscillations.

Moreover, to improve the design of depressed collectors, we need accurate simulations of the electron distributions, allowing to lower the electric power used by the device, especially considering satellite payload for space systems.

II. THE ALGORITHM

Currently, there are two kinds of numerical approach to simulate the wave propagation in TWTs, each with typical benefits. The first kind relies on kinetic models in time domain such as particle-in-cell (PIC) codes based on kinetic

equations (like, *e.g.*, CST-PARTICLE, NEPTUNE or MAFIA). The second kind is based on specialized frequency models (like, *e.g.*, MVTRAD, CHRISTINE or TESLA). In contrast, we use a specialized time domain model relying on an N -body (*a.k.a.* many body or molecular dynamics) description [3], [4]. By definition, this description is deemed slower and computationally more expensive than PIC since all particles should be considered. We overcome this issue thanks to a drastic degrees-of-freedom reduction [5].

Our algorithm DIMOGA (for HAmiltonian DIScrete MOdel) is based on a rigorous theoretical model that respects Maxwell equations and Hamiltonian conservation properties, even with the number of degrees-of-freedom reduction. The heart of this model is the momentum exchange between the wave and particles, within the Hamiltonian formalism using a field decomposition. A particularity of DIMOGA is that it allows one-dimensional simulations, where generally time domain codes require to simulate the full tube in three dimensions. But its main advantage is that it considers all the fields in time (not just the wave envelope) as well as the electron dynamics (positions and velocities). This enables DIMOGA to work in nonlinear regime (trapping, chaos) and to inject any wanted type of wave, like multi-tones and telecommunication signals. A comparison with MVTRAD has already shown [3] a perfect agreement at power saturation in the middle of the transmission band of a basic tube without taper nor attenuators.

III. COMPARISON WITH MEASURES

The current version, that supports parallel computing (multi-core and multi-processor) on desktop computers or clusters, is able to perform a full simulation of industrial tubes. Figure 1 displays the RF output power (AM/AM) and the nonlinear phase shift (AM/PM) at $F = 11.7$ GHz for a commercial Ku-band tapered helix TWT, comparing DIMOGA with direct measurements. The computing time is less than 10 minutes to reach steady state on a small desktop computer (less than 800 US\$). It is a good progress compared to the 12 h needed with CST-PARTICLE [6].

A recent comparison [7] with the Pierce four-waves theory has shown that our theoretical model should be more accurate near band-edge [8]. Indeed, Figure 2 displays the saturated output power over the complete tunable range of frequencies

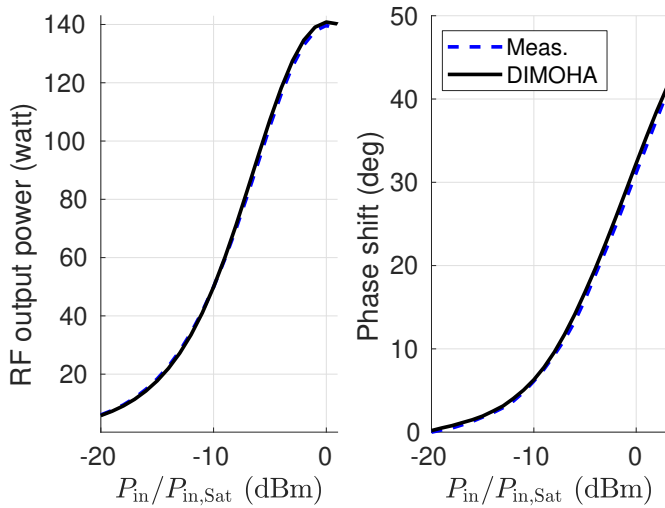


Fig. 1. Output power and nonlinear phase shift for a Ku-band tapered helix TWT and for DIMOHA at $F = 11.7$ GHz.

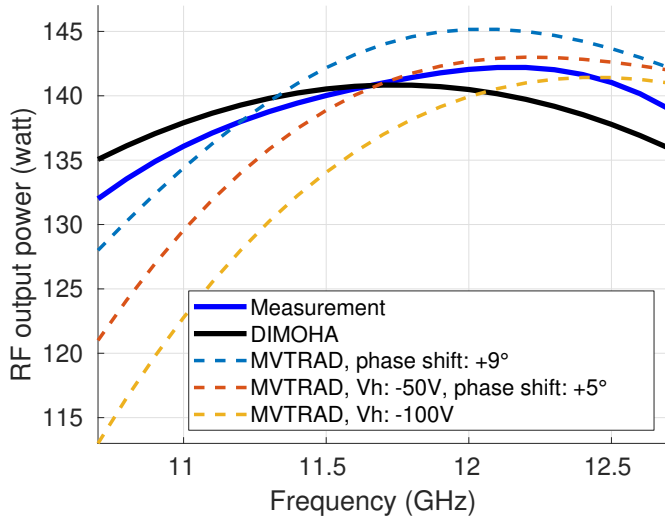


Fig. 2. Output power at saturation versus frequency for a Ku-band tapered helix TWT, DIMOHA and MVTRAD. As shown, the cathode potential V_h of MVTRAD is shifted by 0 to -100 V to adjust either the power output or the phase shift but not both at the same time. The phase shift of DIMOHA is identical to measurements (Fig 1).

for the same tube. A comparison with MVTRAD (that suffers the same shortcoming as Pierce's theory) is performed. The small variations near both edges between DIMOHA and the measurement result from our incomplete management of tube features, and we are working to reduce this discrepancy.

Electromagnetic waves for telecommunication signals are not simple sinusoidal waves and DIMOHA is able to simulate them without limitations. We propose here a single example where two-tones are injected in the same Ku-band TWT. Figure 3 displays the comparison of the frequency spectrum at the tube output : all intermodulation products are reproduced near the two original carrier waves and their second harmonics. For the second harmonics, we do not have an accurate calibration

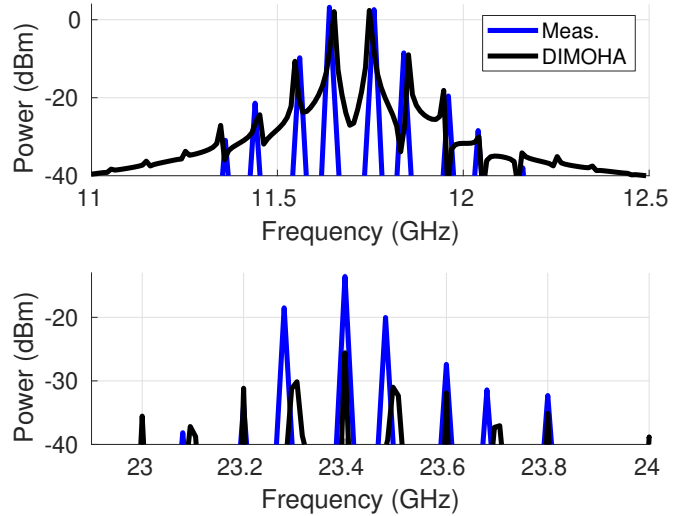


Fig. 3. Comparison of the output spectrum in two-carriers regime of DIMOHA (after $t = 100$ ns) and a Ku-band tapered helix TWT. Input: $F_1 = 11.65$ GHz and $F_2 = 11.75$ GHz at $P_{in,1,2} = -10$ dBm.

of the bench and this TWT is not adapted in this band. The computation time is about 5 h for 100 ns.

IV. PERSPECTIVES

We are currently working to improve the multitone simulations (including more complex nonlinear signal analysis) and to improve the modeling of tube defects (taper, attenuators, hot voltage standing-wave ratio (VSWR), etc.) for the characterisation of oscillations and reflections. In addition, a possible three-dimensional version of the algorithm is investigated. We also work on the electron distribution function with the aim to improve depressed collectors. Finally, we consider using the algorithm to study nonlinear and chaotic regimes in various aspects, including simulations of the 4 meters long TWT at Aix-Marseille Université, CNRS.

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