# Modeling Stability of Vacuum Electronic Devices With the Large-Signal Code TESLA-Z*

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**Abstract:** *We present a new approach to the study of the stability of Vacuum Electronic devices using the large-signal code TESLA-Z. The approach combines a precomputed complex impedance matrix for the structure Z with a TESLA computed admittance matrix Y of the beam-tunnel loaded with an electron beam. The gain matrix G for a given device then can be found as the product of the Z-matrix of the structure and admittance matrix Y of the beam-tunnel. Subsequent analysis of the eigenvalues of the gain-matrix G uses the Nyquist method to determine the stability of the device. We discuss details of the new algorithms and illustrate its application using available examples.*

**Keywords:** stability analysis; Nyquist criteria; structure impedance matrix; electron beam admittance matrix.

## Introduction

The stability of Vacuum Electronics Devices (VEDs) is an important issue, which become more urgent as designers of new VEDs push the boundaries of performance in bandwidth and power. It is highly desired to address the problem of potential instability at the design stage of the device. This can involve estimation of margins of stability controlling design tolerances. Traditionally, Particle-in-Cell (PIC) codes are used as a tool to check the stability of a given design. However, PIC code runs require a long run-time to ensure that enough time has elapsed for the instability to develop and reveal itself. Further, even if device is found to be stable for the given set of parameters, a single PIC code run cannot predict how close the device is to marginal stability. The usual practice is to vary parameters such as beam-current, beam-voltage and/or end-reflection coefficients to find input parameters that will make the device unstable. This process thus requires many time consuming runs.

In this work we report an alternative approach to stability study using a framework based on the large-signal code TESLA-Z [1] and its extensions. The approach allows one to predict stability margins and thresholds of instability [2].



## Extension of the TESLA-Z Algorithm to Include Stability Analysis of VEDs

The recently developed at NRL 2D large-signal code TESLA-Z is a general purpose, geometry-driven tool targeted at modeling of linear-beam VEDs based on a wide class of resonance and/or slow-wave structures (SWSs). The modeling approach is based on the representation of the VED's structure as a generalized network of ports (including actual input/output ports and interaction gaps) whose frequency dependent properties (response) can be fully characterized by a generalized impedance matrix ***Z*** representing the linear relationship between imposed currents and induced voltages at all gaps/ports:

$$\vec{V}_{gaps} = \hat{Z}(\omega) \cdot \vec{I}_{gaps} \qquad (1)$$

where ω is angular frequency.

The impedance matrix ***Z*** can be computed using a 3D Computational Electromagnetic (CEM) code (such as HFSS [3] or Analyst [4], for example) and then utilized by the large-signal algorithm in TESLA-Z to model VED's beam-wave interaction. Due to the geometry-driven nature of the approach employed in TESLA-Z, its algorithm allows modeling of a wide class of VEDs, including Travelling-wave Tubes (TWTs) and klystrons. The parallel extension of the TESLA-Z algorithm allows accurate modeling of multiple-beam devices, such as multiple-beam TWTs [5] and Multiple-beam Klystrons (MBKs) [6].

As a next step in the development of the algorithm we extend the code TESLA-Z to make it suitable for studying stability in various VEDs. In particular, we develop a way to find a gain matrix G for a given device and then analyze its eigenvalues *g* to determine the existence of unstable solutions. To find the gain matrix G, we first compute an admittance matrix Y of the beam-tunnel loaded with the electron beam. For this purposes we use the domain separation method in the TESLA-Z algorithm, which uses separate and independent field representations inside and outside of the beam-tunnel. This allows us to model beam-tunnel independently of the structure (outside to beam-tunnel region). By imposing unit voltage one by one on each gap of the structure we then can find the currents induced at each gap by the bunched electron beam. This allows us to represent the generalized response of the beam-tunnel in the form of an admittance matrix Y, where

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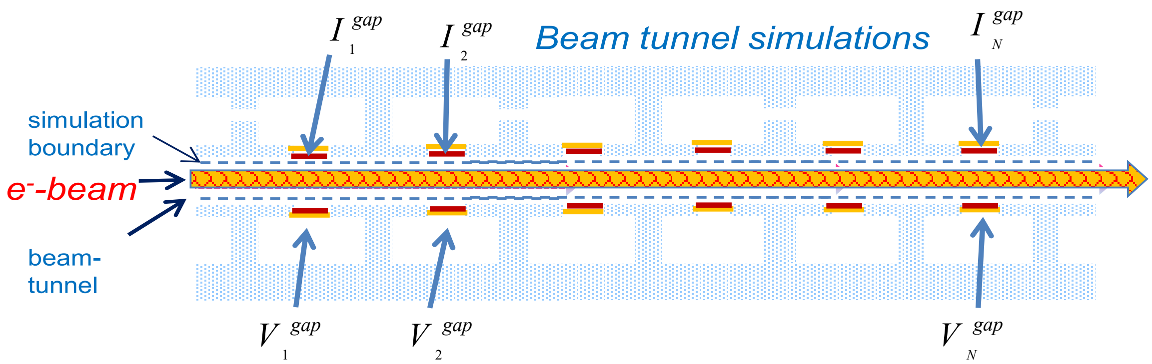

**Figure 1.** Schematic view of the slow-wave structure with the beam-tunnel and electron beam propagating inside of it.

$$\vec{I}_{gaps} = \hat{Y}_b(\omega)\cdot\vec{V}_{gaps} \qquad (2)$$

Combining formulas (1) and (2) give us:

$$\vec{V}_{gaps} = \hat{Z}(\omega)\cdot\hat{Y}_b(\omega)\cdot\vec{V}_{gaps}$$

or

$$\vec{V}_{gaps} = \hat{G}(\omega)\cdot\vec{V}_{gaps} \qquad (3)$$

where the product of the ***Z*** and ***Y*** matrices becomes the gain matrix ***G***. The elements of the matrix ***G*** are complex, analytic functions of frequency. Threshold of unstable solutions correspond to values of complex frequency for which an eigenvalue ***g*** of the gain matrix satisfies ***g****=1*.

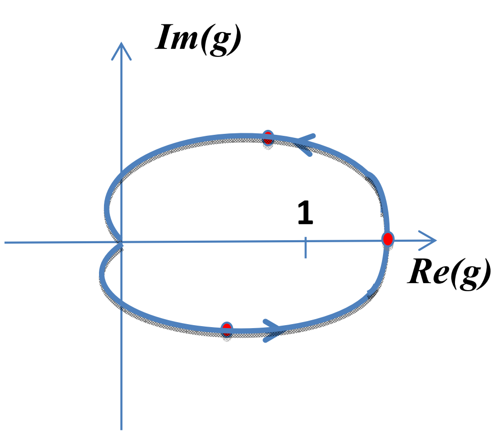

**Figure 2.** Schematic plot for evolution of the Real and Imaginary parts of the gain-matrix eigen-value ***g*** on the complex plane as it traced in frequency; here is shown the case when during such evolution eigenvalue ***g*** encircles unit to indicate that analyzed system became unstable.

As both the ***Z*** and ***Y*** matrices are computed for real frequency, we use Nyquist's method to determine if there are any complex frequencies in the upper-half plane giving ***g****=1*. To do this, we plot the eigenvalues ***g*** in the complex plane as the real frequency is varied through the band of interest. According to Nyquist's method [7], the net encirclement of ***g***=1 (see Fig.2), gives the number of unstable solutions.

The procedure of computing the beam-tunnel admittance matrix ***Y*** and then finding the matrix ***G*** together with its subsequent analysis has been implemented in the TESLA-Z algorithm. It was verified and then validated by comparisons with available data on stability of experimental devices. We will present examples of successful predictions of instability using this approach.

DISTRIBUTION A: Approved for public release, distribution is unlimited.

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