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ADVANCED MODELING OF KLYSTRONS WITH THE TESLA-FAMILY OF LARGE-SIGNAL CODES*

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Abstract

Klystron RF sources are widely used or proposed to be used in accelerators in the future. We present an overview of the main features and latest advances in the development of the TESLA-family of 2D large-signal codes, including parallel code TESLA-MB and a new, geometry-driven large-signal code TESLA-Z. The new capabilities are discussed and application of these codes to the modeing of advanced multiple-beam klystrons as a high power, broadband RF sources are presented.

INTRODUCTION

Klystrons remain very attractive as high-power RF sources used or potentially to be used in modern accelerators [1]. US Naval Research Laboratory (NRL) has successfully demonstrated several Multiple-Beam Klystrons (MBKs) [2]. Design and optimization of klystrons requires efficient simulation tools. One such tool is the code TESLA [3], which currently is used at NRL and in a few US tube companies. TESLA (Telegraphist's Equations Solution for Linear-beam Amplifiers) is a 2.5D large-signal code successfully applied to the modelling of single beam and multiple beam amplifiers having linear propagating beams. TESLA evolved from the code MAGY [4] and was developed as a result of collaboration of NRL, SAIC and the University of Maryland.

The 2D large-signal code TESLA algorithm [3] uses domain separation to reduce the simulation region to the volume occupied by the beam (e.g. beam-tunnel). The surrounding electromagnetic structure is treated as a set of external cavities whose eigen-modes and R/Q's are pre-computed using a 3D Computational Electromagnetic (CEM) code and coupled to the beam via the R/Q values. TESLA is a hybrid code. A frequency domain algorithm, which is based on an envelope approximation, performs integration of slowly varying fields until a converged solution is obtained. A time-advance algorithm is implemented in the code which handles operation in the transient and self-excitation regimes. The original, Fortran-77 implementation of the code TESLA was validated through comparisons to the PIC code MAGIC and with experimental data from single-beam and multiple-beam klystron measurements using approximation of identical beams [5].

Further modernization of the code TESLA included its rewriting from the original Fortran-77 to Fortran-95 language with modular programming and dynamical memory allocation used throughout. The F95 version of TELSA was subsequently improved by adding an algorithm for accurate treatment of slow and reflected particles [6].

Efforts to extend bandwidth using complex structures in single and multiple-beam klystrons (MBKs) have placed great challenges on large-signal computational tools. This is reflected in the fact that klystron designers routinely include structures with distributed circuit elements such as multi-gap coupled cavities, tuning irises and complex filter loading. TESLA algorithm was successfully extended to allow modelling of two-gap cavities: Fig. 1 shows good agreement between measurements and predictions of the large-signal code in the case of NRL MBK-2 design [7]. An overview [8] has more details about other additional capabilities of the code TESLA, including results of its application to the modelling of Inductive Output Tubes (IOTs) and Extended Interaction Klystrons (EIKs).

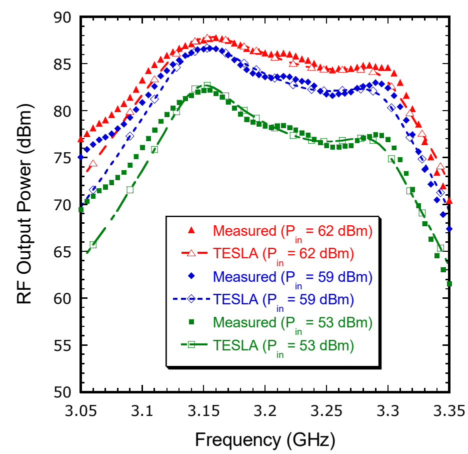

Figure 1: Comparison of experimental and predicted by TESLA bandwidth of the wide-band NRL MBK2 [7] at a few drive powers.

TESLA-MB MODELING AND STABILITY ANALYSIS OF MBKS

To allow accurate modelling of MBKs with non-identical beams and beam-tunnels, the TESLA algorithm was extended into a parallel code TESLA-MB [9]. This improved the accuracy of the model in cases where each beam in a multiple-beam device interacts with a local gap field whose distribution is consistent with the particular eigen-mode of the cavity. The parallel algorithm in TESLA-MB employs MPI-calls to combine sources on all

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gaps of the cavity and to drive the amplitude of the resonant mode. In response the amplitude of the mode drives the evolution of the gap-field of all the beam-tunnels to determine evolution of fields and particles inside them.

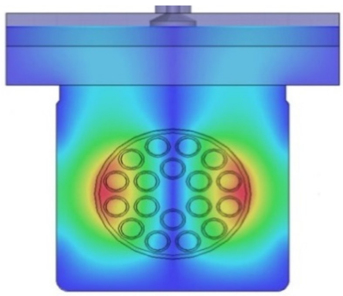

Figure 2: Front view of the HFSS model for a two-gap input cavity of MBK with the field profile shown here at the resonance frequency of its higher-order mode TM_{11}.

Recently TESLA-MB was successfully applied to a detailed study of the higher-order modes (HOMs) instability in the two-gap input cavity of the MBK-3 design [10]. According to the experimental data [11] the device was unstable at the beam-voltages much lower of its nominal value of 42 kV. Measured frequency of instability ~4.98 GHz indicated on the cavity's self-excitation on a frequency of its HOM TM_{11}. Shown of Fig. 2 field profile on the frequency of TM_{11} clearly illustrates the huge disparity in the values of R/Q's corresponded to different gaps of the 18-beams cavity.

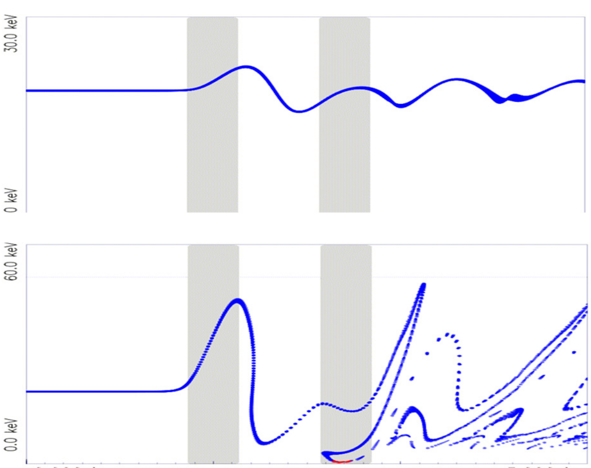

Figure 3: Energy evolution of particles travelling inside two-gaps input cavity of the MBK as shown here for the beam-tunnels #1 (upper) and #9 (lower), having lowest and highest values of R/Q correspondingly. The fraction of slow particles is shown here in red colour.

Application of the parallel code TESLA-MB allowed us to perform quasi-3D modelling of the MBK by using set of the actual (not averaged) values of R/Q's on all gaps and beam-tunnels of the device (see Fig. 3 for example).The predictions of the code were found to be in good agreement with the experimentally determined range of unstable operating voltages.

TESLA-Z: GEOMETRY-DRIVEN LARGE-SIGNAL KLYSTRON MODELING

Progressively lower Q cavities together with such advanced elements as filter-loading, frequency dependent loading and losses and multiple-gap cavities, rendered the usual assumptions in parametric codes inadequate As result, code TESLA wasn't able modelling of the broadband MBK-3 output structure with filter-loading element in it (Fig. 4).

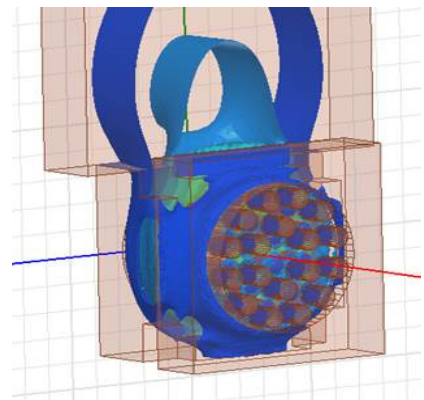

Figure 4: HFSS model for a two-gap output cavity of the NRL MBK-3 design [10,11] with an additional filter-loading element in it (not shown here).

A general, geometry-driven approach to the modelling of advanced or broadband klystrons became necessary. In principal, to satisfy level of required generalizations, one could implement geometry-driven approach (such as finite-elements algorithms for cavity fields) inside the large-signal algorithm to make it applicable to a wider variety of klystrons. However, such implementation will highly complicate large-signal algorithm and probably will fully diminish its main advantage as being relatively simple, fast and efficient. Rather than add such capability into an existing large-signal algorithm one instead can utilize capabilities of highly developed Computational Electromagnetic (CEM) Codes (such as HFSS [12] or Analyst [13], for example) to find response of the given, arbitrarily complex resonance or slow-wave structure and, then use this response in the large-signal modelling of beam-wave interaction inside klystron or Travelling-wave Tube (TWT).

Following this idea we have developed new 2D large-signal code TESLA-Z [14], which utilized the best features of TESLA-family of algorithms, but fully relies on information provided by the CEM code in terms of generalized impedance matrix Z. Code TESLA-Z imports such Z-matrix data and uses it in its modelling of beam-wave interaction inside the beam-tunnel.

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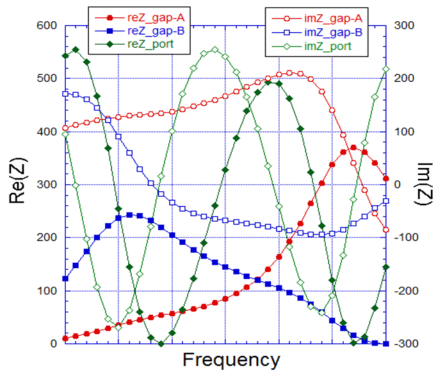

Figure 5: Computed by HFSS impedances on both gaps and port of output cavity of the MBK-3 design.

The TESLA-Z algorithm treats the input/output ports and interaction gaps of the structure as a set of generalized ports of a single network. Frequency dependent response of the given structure is represented in a view of impedance matrix Z, which can be computed on every frequency across the working band by exciting every gap/port one-by-one using sampling source current (as a feature available in 3D CEM code HFSS and used in [14]) and computing the induced voltages on all of the gaps in the given structure. The terms of the impedance matrix Z are easily computed as linear relationship between induced voltages and excitation currents. Figure 5 shows an example of the impedance profiles for the broadband, two-gap' MBK output cavity shown in Fig. 4 (gap-impedances here are averaged over all 18 beam-tunnels).

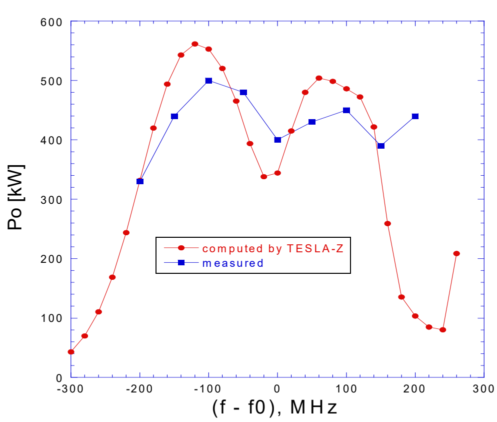

Figure 6: Comparisons of measurements with the bandwidth predicted by the parallel version of the code TESLA-Z for the NRL 18-beams 7-cavity MBK-3 design: Vb = 39.7 kV, Ib = 35.4 A, Pin = 200 W.

Parallel extension of the code TESLA-Z is capable of modelling with the full impedance matrix Z computed for all gaps of all 18 beam-tunnels of the MBK-3 device and containing full information about complex frequency response of its complete 7-cavity resonance structure. Such full Z-matrix was used by parallel version of the code TESLA-Z to perform accurate modelling of the MBK-3 design and to compare the obtained results with the available experimental data. Presented on Fig. 6 results of the TESLA-Z modelling are in a good agreement with the measured data and nicely reflect the broadband response of the 7-cavity MBK-3 design.

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