Demonstration of a 600 kW Multiple-Beam Klystron Amplifier: A First-Pass Design Success

D.K. Abe,[1] K.T. Nguyen,[2] D.E. Pershing,[3] F.N. Wood,[3] R.E. Myers,[3] E.L. Eisen,[4] M. Cusick,[4] and B. Levush[1]
[1]*Electronics Science and Technology Division*
[2]*Beam-Wave Research, Inc.*
[3]*ATK Mission Research*
[4]*Communications and Power Industries, Inc.*

Introduction: Multiple-beam klystrons (MBKs) are a class of vacuum electronic amplifiers, in which the kinetic energy of axially streaming electron beams is converted to electromagnetic energy through the interaction of the beams with a series of resonant microwave cavities. With their potential to efficiently produce coherent, broadband, high-power microwave radiation in a compact package, MBKs are a promising device technology to provide the low-noise transmitter performance required by shipboard radar systems to operate in high-clutter environments (e.g., littoral zones) and to keep pace with evolving antiship cruise missile (ASCM) and tactical ballistic missile (TBM) threats. Nondefense applications of this technology include civilian radar, communications, and accelerators for high-energy physics.

As the name implies, MBKs make use of multiple electron beamlets, each of which propagates in a separate, parallel beam tunnel, but interact with electric fields in common regions such as cavity gaps. In this manner, the perveance of the individual beamlets can be low, facilitating stable-beam propagation and efficient beam-wave interaction without the adverse space-charge effects that could debunch the beam, while the total beam current can be high, facilitating high-power and broad-bandwidth operation.

In addition, MBKs possess a number of advantages over conventional single-beam klystrons of comparable power, including reduced operating voltages (typically 50% to 80%) which leads to shorter circuit lengths (typically 30% to 60%) and significantly lower weight. Furthermore, MBKs possess the low phase noise performance that is desirable for radar and communication applications.

MBK Design and Experiment: The inherent three-dimensional nature of the MBK creates design challenges for multiple-beam generation and transport, and the development of efficient radio-frequency (RF) interaction circuits. To address these issues, personnel from NRL and the U.S. industry formed a team to start an MBK development program in 2002.

In the first of a series of planned experiments, we have designed and successfully demonstrated a 600 kW, 40% efficient, S-band (3.24 to 3.30 GHz) fundamental-mode MBK[1,2] (Fig. 1). The eight-beam, four-cavity device was only 60 cm long and weighed approximately 23 kg (without the magnet). This is the first such device developed in the U.S. and is significant not only for the high-peak RF power achieved at a low cathode voltage (approximately 45 kV) and extremely compact size, but for the fact that all of the performance goals were met in a single hardware design pass.

To achieve such a "first-pass" design success, we have developed a simulation-based design methodology. Enabled in large part by advances in low-cost computer power, this methodology makes extensive use of a combination of NRL-developed and commercial two- and three-dimensional computational tools to model realistic device geometries. These new tools have sufficient accuracy and resolution to assess potential designs for their sensitivity to mechanical tolerances and fabrication methods, replacing costly, hardware-intensive "cut-and-try" methods.

The resulting MBK performed very close to design expectations.[3] Beam generation and transport were key technical challenges. We made extensive use of MICHELLE 3D, an NRL-developed electron gun/collector code, to design the beam optics in the cathode-anode region of the gun (Fig. 2(a)), model the transport of the beamlets through the interaction circuit (Fig. 2(b)), and design the electron beam collector

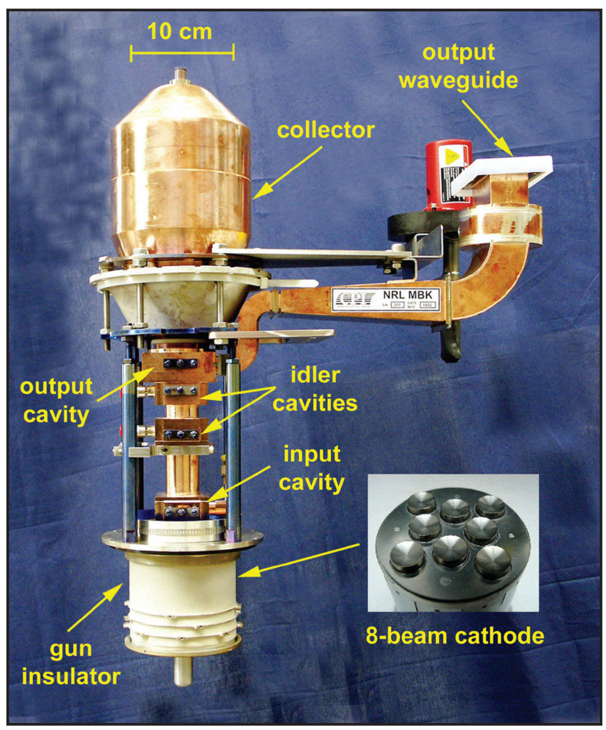

FIGURE 1
The NRL eight-beam, four-cavity, 600-kW MBK with a detail of the eight-beam cathode shown in the inset.

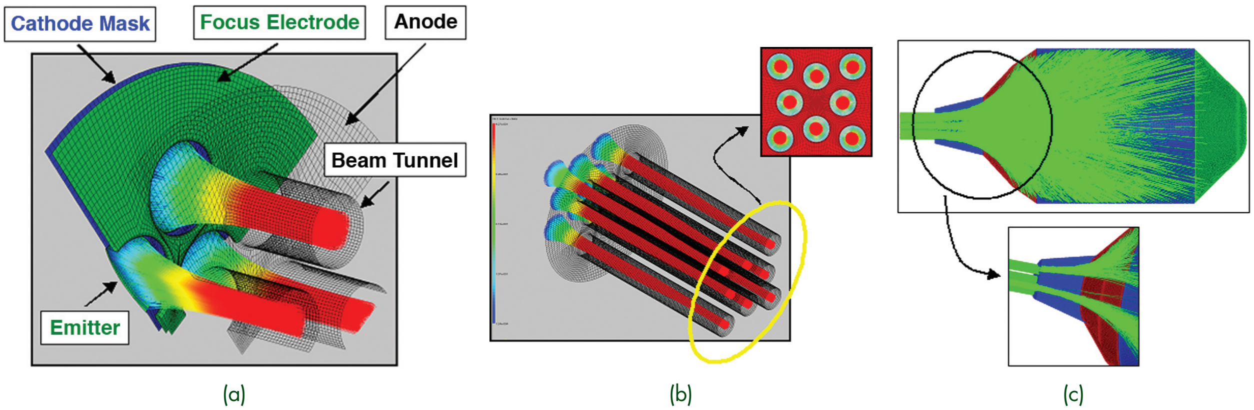

FIGURE 2
MICHELLE 3D electron-beam simulations: (a) quarter section of the eight-beam electron gun; (b) nonintercepting eight-beam transport in an axial magnetic field (inset: cross-sectional view showing the beamlets well-centered on the beam tunnels); (c) spent beam distribution in the collector, showing uniform deposition on the walls without particle reversals.

(Fig. 2(c)). To avoid electron interception on the walls of the beam tunnels, an external solenoidal magnetic field guides the eight off-axis beamlets. An innovative iron pole-piece design at the interface of the gun and circuit matches the beamlets into the highly uniform axial magnetic field in the interaction region (less than 0.2% measured variation in B_z). Very few beam electrons were lost to the walls: we measured greater than 99% beam transmission in the absence of an RF drive and greater than 97% transmission at saturation (maximum energy extracted from the beams). A reentrant pole piece shapes the magnetic field lines as they enter the collector, preventing potentially catastrophic virtual cathode formation and particle reversals.

The MBK generated a peak RF power of 600 kW at a frequency of 3.26 GHz with a corresponding gain of 25 dB and an electronic efficiency of 40%. Simulations using TESLA, an NRL-developed 2.5-D large-signal klystron code, are in excellent agreement with experiment. For example, Fig. 3 plots the measured and simulated output power vs frequency. The model accurately predicts the response of the MBK over a wide range of frequencies and in two very different regimes of amplifier operation (linear and nonlinear), validating our understanding of this complex nonlinear beam-wave interaction.

Summary: The successful demonstration of this eight-beam fundamental-mode MBK is an important first step in the development of a class of compact, high-power, broadband, low-noise amplifiers to improve the capabilities of Navy radar and communi-

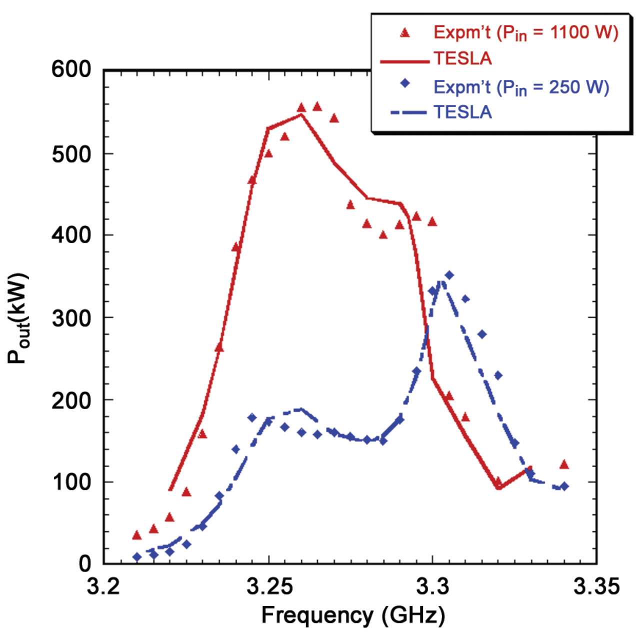

FIGURE 3
MBK output power vs frequency for drive powers corresponding to the linear (blue) and nonlinear (red) amplifier regimes of operation. The solid lines represent TESLA simulations and the discrete points are measured data.

cations systems. With the development of a validated complement of computational tools and a simulation-based design methodology, we are building the technological foundation to produce optimized, high-performance designs in a rapid and cost-efficient manner.

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