Low-Voltage, Sheet-Beam MMW Amplifiers

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***Abstract*—**The design and development of compact, slow-wave MMW amplifiers driven by low-voltage sheet beams will be discussed. A high-perveance sheet-beam gun has been designed to produce a 3.5-A, 19.5-kV beam having a cross section of 0.32 mm x 4 mm, suitable for driving a W-band amplifier at ~10 kW. A relatively simple sheet-beam circuit, an extended interaction klystron (EIK), is also being developed for integration with the gun and its permanent magnet solenoid. Both the basic gun design and the EIK circuit can be scaled to significantly higher frequencies.

I. Introduction And Background

SHEET-beam, slow-wave MMW amplifiers offer the prospect of considerably higher power and power density (output power per unit weight and volume) than can be achieved with comparable pencil beam devices, because significantly higher current can be transported through the circuit at a given voltage. Sheet-beam topologies are also attractive at MMW-THz frequencies because the very small planar features are amenable to lithographic microfabrication techniques (e.g., LIGA and deep reactive ion etching). Furthermore, by operating such devices at voltages ≤20 kV, many practical and operational advantages can be realized.

However, sheet-beam devices also pose some fundamental problems. Sheet electron beams are subject to instabilities, the circuits tend to be intrinsically overmoded, and a high degree of uniformity of both the beam and the rf field across the width of the sheet is necessary for strong and efficient beam-wave interaction. Thus, two major obstacles that must be overcome to achieve the full potential of sheet-beam amplifiers are 1) the formation and transport of a sufficiently high-perveance beam, and 2) the design and fabrication of suitable interaction circuits. Here, we will describe our techniques for addressing these problems.

II. Sheet Beam Generation And Transport

A key feature of our approach is the use of solenoidal magnetic focusing, which has usually been ruled out in sheet beam devices because of diocotron instability considerations or related **ExB** effects. The advantage of solenoidal focusing over the periodic permanent magnet (PPM) configurations that have typically been assumed for sheet beams is that a substantially higher field (and hence stronger focusing) can be achieved. Thus, higher current densities can be transported at lower beam voltages, leading directly to a shorter interaction length and higher power for a given voltage.

Because space-charge nonuniformities are the seed for the diocotron instability, it is very important that the electron gun be carefully designed to minimize distortions. We have designed a gun featuring a shielded cathode and single-plane electrostatic focusing that accomplishes this goal. MICHELLE [1] simulations (including realistic thermal effects) have shown that a 19.5 kV, 3.5 A beam having a cross section of 0.32 mm x 4 mm can be generated by this gun and transported stably over a distance of 5-6 cm (>4 diocotron e-folding lengths) in a uniform 9 kG field.[2] A permanent magnet configuration has been designed to generate this field, including the precise transition required to properly launch the beam into the 0.4-mm-high beam tunnel.

Beam generation and transport are illustrated in Figure 1. Here, a realistic thermal beam from a cathode at 1200 K has been assumed. The well-known curling of the edges of a sheet beam due to the **ExB** drift of electrons is evident in Fig. 1, ultimately leading to beam interception in the beam tunnel, but only after a transport distance of about 5 cm.

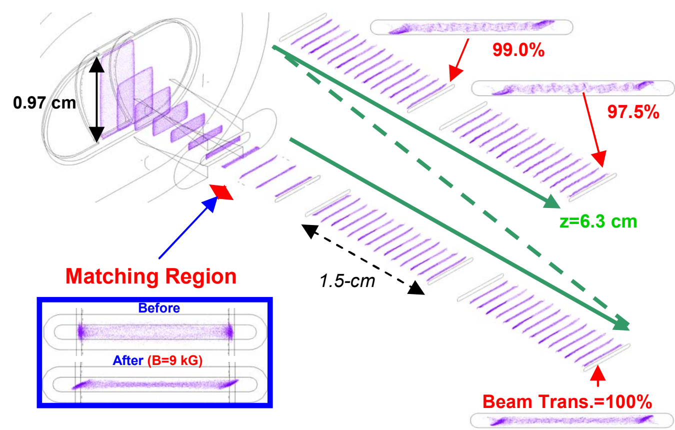

Figure 1. MICHELLE simulation of beam generation and transport in a uniform 9-kG field. Snapshots of the beam profile at various axial positions are shown.

If solenoidal transport of sheet beams over even longer distances is required, as it may be for traveling wave devices, it is possible to essentially eliminate this curling by properly designing the beam cross section.[3] Noting that the electric field is solely due to the beam space charge, the drift velocity can be written as

$$\mathbf{v} = c\frac{z \times \nabla\phi}{B}, \quad \nabla^2\phi = -4\pi q n(\phi),$$

where the potential ϕ depends only on the beam charge density distribution $n(\phi)$, subject to the condition that it be zero on the beam tunnel boundary. The beam profile will be

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constant if the drift velocity is perpendicular to the beam density gradient (parallel to the beam edge) at all points along the periphery of the beam. This equilibrium condition is satisfied by a uniform-density beam if the beam edge corresponds to an equipotential contour of the electrostatic field. In general, it is possible to find such an equilibrium for a specified beam tunnel cross section and beam fill factor (ratio of beam thickness to tunnel height). For large aspect ratio beams in a rectangular beam tunnel, the fill factor must be large to satisfy the equilibrium condition. Numerical solutions of stable beam cross section as a function of fill factor for a tunnel aspect ratio of 10 are shown in Fig. 2. A large beam aspect ratio can also be achieved at smaller fill factors by appropriately shaping the beam tunnel.

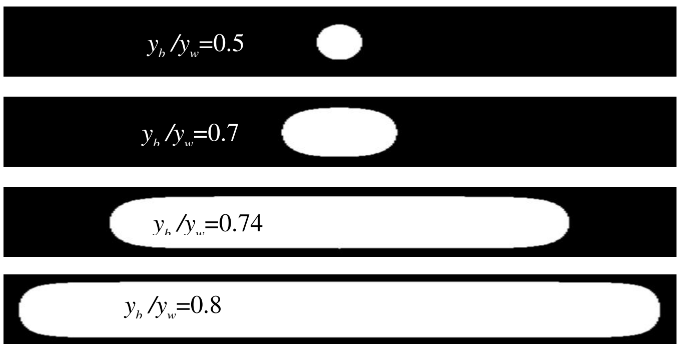

Figure 2. Stable uniform beam cross section as a function of beam thickness (relative to tunnel height).

III. Extended Interaction Klystron

A highly scalable extended interaction klystron (EIK) circuit has been designed [4] for the sheet beam gun shown in Fig. 1. The circuit consists of several multi-gap cavities, with excellent field uniformity across the width of the beam and high gain per unit length. A W-band circuit consisting of two 5-gap cavities, shown in Fig. 3, is only 1.1 cm long. This circuit has several important features. First, to facilitate operation at low beam voltages, the cavities are designed for the 2π-mode. As shown in Fig. 4, the gap field is quite uniform with little field leakage into the intergap regions, which is critical for efficient beam-cavity coupling. Second, the cavity design can easily be adjusted to accommodate sheet beams of a wide range of aspect ratios. Third, the cavity *R/Q* is relatively high (about 50 Ω for the configuration shown) and can be adjusted by adding or subtracting gaps (since it is proportional to the number of gaps).

MAGIC-3D [5] simulations of this circuit show a saturated gain of 22 dB at an ouput power of 10 kW. Higher gain can be achieved by adding buncher cavities, while keeping the overall circuit length <1.8 cm. Test cavities have been fabricated at 91 and at 220 GHz using relatively inexpensive techniques (electric discharge machining and slitting saws).

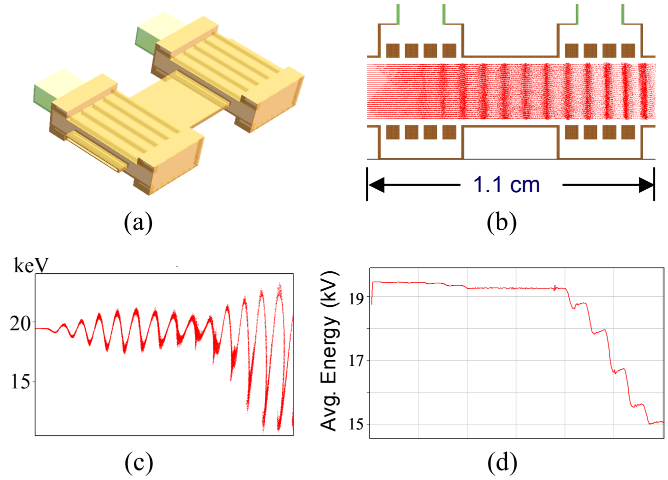

Figure 3. MAGIC-3D simulation of a W-band sheet-beam EIK. a) Two-cavity circuit configuration. b) Electron spatial distribution snapshot. c) Energy per particle vs. axial distance. d) Average kinetic energy vs. axial distance, showing 23% interaction efficiency.

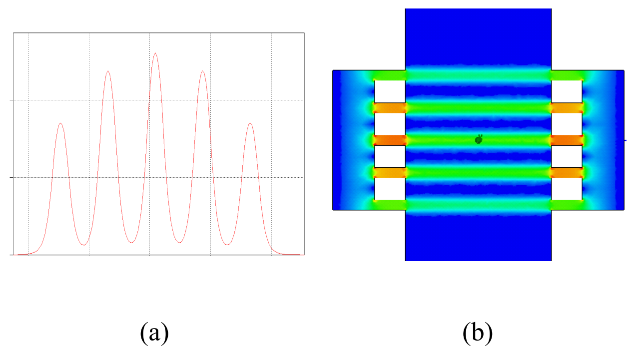

Figure 4. (a) RF electric field vs. axial length along axis.
(b) RF field distribution in midplane of cavity structure.

IV. Conclusions

Based on these results, the development of high-power-density sheet-bam amplifiers at ~100-300 GHz is feasible. Work is underway at NRL to demonstrate such devices, first by building a beam stick (gun, magnet, 1.8-cm-long beam tunnel, and simple collector), which is in progress, and then by integrating the W-band EIK circuit.

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