Technology Development for a mm-Wave Sheet-Beam Traveling-Wave Tube

Bruce E. Carlsten, Steven J. Russell, Lawrence M. Earley, Frank L. Krawczyk, James M. Potter, Patrick Ferguson, and Stanley Humphries, Jr., *Fellow, IEEE*

***Abstract*—A sheet-beam traveling-wave amplifier has been proposed as a high-power generator of radio frequency (RF) from 95 to 300 GHz, using a microfabricated RF slow-wave structure (Carlsten, 2002). The planar geometry of microfabrication technologies matches well with the nearly planar geometry of a sheet beam, and the greater allowable beam current leads to high-peak power, high-average power, and wide bandwidths. Simulations of nominal designs using a vane-loaded waveguide as the slow-wave structure have indicated gains in excess of 1 dB/mm, with extraction efficiencies greater than 20% at 95 GHz with a 120-kV, 20-A electron beam. We have identified stable sheet beam formation and transport as the key enabling technology for this type of device. Also, due to the high aspect ratio in the slow-wave structure, the RF coupling is complicated and requires multiple input and output couplers. The RF mode must be transversely flat over the width of the electron beam, which impacts both the vane design and the input and output coupling. In this paper, we report on new insights on stable sheet-beam transport and RF mode control in the slow-wave structure.**

***Index Terms*—Beams, electron beam focusing, electron tubes, millimeter wave power amplifiers, traveling-wave tubes.**

I. Introduction

A NEW need for high-frequency, high-power sources has been emerging for advanced radar and communications needs, with frequencies in the band between 100 and 300 GHz and peak powers as high at several hundreds of kilowatts, and with bandwidths of up to 10%. After investigation of different high-frequency gain mechanisms, including dielectric Cherenkov masers [2] and two-beam amplifiers, we determined that planar microfabricated traveling-wave tube (TWT) amplifiers could best satisfy the needs of these new missions [3]. This type of source consists of a very thin sheet electron beam passing through a periodic slow-wave structure that could be either single or double sided [4]. We have focused our technical efforts on understanding the underlying physics and technology of the double-sided interaction and developing a demonstration experiment. One promise of this technology is that with microfabrication technology, it is scalable to high frequencies at low-beam voltages (10 kV or less for amplification at 100 GHz, 20 kV for amplification at 300 GHz).

Manuscript received July 13, 2004; revised September 29, 2004. This work was supported in part by funds from the Laboratory-Directed Research and Development program at Los Alamos National Laboratory, operated by the University of California for the U.S. Department of Energy, and in part by the Proliferation Detection Technologies Program of the National Nuclear Security Administration's Office of Nonproliferation Research and Engineering.

B. E. Carlsten, S. J. Russell, L. M. Earley, and F. L. Krawczyk are with the Los Alamos National Laboratory, Los Alamos, NM 87545 USA (e-mail: bcarlsten@lanl.gov, srussell@lanl.gov, earley@lanl.gov, fkrawczyk@lanl.gov).

J. M. Potter is with the JP Accelerator Works, Los Alamos, NM 87544 USA (e-mail: jpotter@jpaw.com).

P. Ferguson is with the MDS Company, Oakland, CA 94611 USA (e-mail: mdsfer@netvista.net).

S. Humphries is with Field Precision, Albuquerque, NM 87192 USA (e-mail: humphries@fieldp.com).

Digital Object Identifier 10.1109/TPS.2004.841172

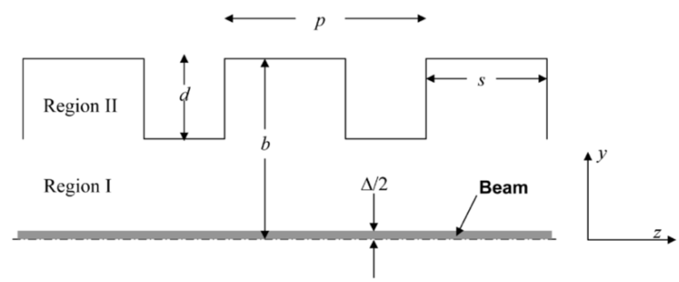


Fig. 1. Definition of terms used to describe planar ridged waveguide geometry.

Earlier work [5] has identified the key enabling technologies as: 1) the sheet beam formation and transport; and 2) the RF mode control in the structure. Our analytic and experimental program have focused on these two issues, mostly for the nominal parameters of a 20-A, 120-kV beam with elliptical cross section 1 cm by 0.5 mm, in a vane-loaded waveguide with period 0.5 mm, and vane tip–to–tip gap of 0.75 mm. This relatively high beam voltage was picked for our initial investigation because the higher beam voltage leads to a larger structure period and adds additional beam stability. This allows us to conventionally machine our test structures for faster turn around and stage our study of sheet beam transport stability.

The goal of this paper is to report on technology developments we have made on understanding the RF interaction, beam transport, and RF coupling and mode control. In Sections II, we will describe the main features of the interaction. Then we describe stable sheet beam transport, followed by one-dimensional (1-D), as well as two and one-half-dimensional, particle-in-cell (PIC) simulations verifying gain and saturated efficiency. Section VI describes experimental issues, including mode shaping in the slow-wave structure and RF coupling.

II. Description of the Interaction

The interaction is based on the ability to slow down the phase velocity in a waveguide by introducing vanes, as shown in Fig. 1. The geometry is defined by a period p, a vane height d, a vane separation s, and a vane tip separation $2(b-d)$. The geometry is assumed to be infinite horizontally (the dimension coming out

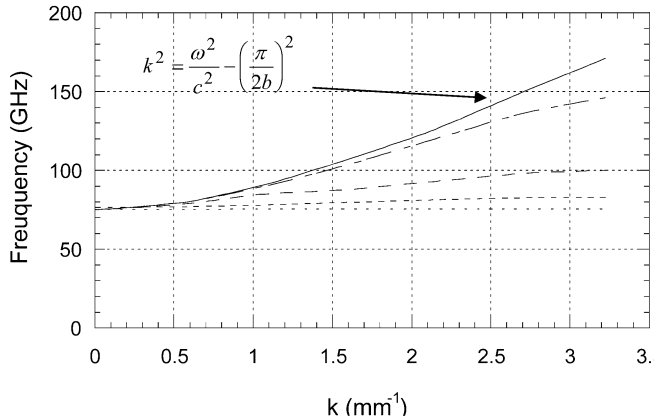


Fig. 2. Depression of the maximum frequency as the vane height is increased. Solid line corresponds to an empty waveguide, dot-dashed line to a vane height of 0.25 of the gap half-height, long dashed line to 0.5 of the gap half-height, medium dashed line to 0.75 of the gap half-height, and the dotted line to 0.9 of the gap half-height.

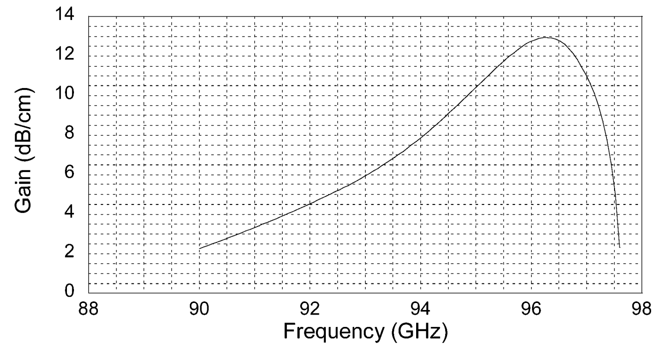


Fig. 3. Gain versus frequency for the nominal geometry at 95 GHz, as calculated with the modal code DETER.

of the paper) and the beam is thought of as very thin in the vertical (y) dimension. The geometry in Fig. 1 is used for a modal analysis [1]. Some results from that analysis are presented in this section.

In an empty waveguide, the RF mode phase velocity is greater than the speed of light. In an empty waveguide, the mode propagation number is given by $k^2 = (\omega^2/c^2) - (\pi/2b)^2$, where c is the speed of light and b is the guide half-height, and where the mode propagation is of the form $e^{j(\omega t - kz)}$, with frequency ω and axial wavenumber k. The phase velocity is simply $v_{\rm phase} = \omega/k$, which then must be always greater than the speed of light.

We assume the RF in a vane-loaded waveguide is in a TM mode, so the transverse magnetic field must be of the form

$$B_x = \sum_{n=-\infty}^{\infty} B_{x,n}(y) e^{-j(k+nk_w)z} e^{j\omega t} \tag{1}$$

where we have used Floquet's theorem to account for the periodicity in z and $k_w = 2\pi/p$. The Maxwell curl equations give us the nonzero electric field components in terms of B_x

$$E_z = \frac{j}{\omega\varepsilon_0\mu_0}\frac{\partial}{\partial y}B_x$$
$$E_y = -\frac{j}{\omega\varepsilon_0\mu_0}\frac{\partial}{\partial z}B_x. \tag{2}$$

The presence of the vanes does two things: 1) it introduces nonzero amplitudes of space harmonics (from Floquet's theorem); and 2) it depresses the extent of the pass band of the space harmonics. At a given frequency, there are, in general, multiple solutions in k. Each solution corresponds to one of the n values in (1). We can additionally consider a beam frequency, defined by $\omega_{\rm beam} = kv_{\rm beam}$. If the beam frequency is the same as the RF at a given wavenumber, the beam velocity is the same as the phase velocity, and synchronous energy exchange can occur. In Fig. 2, we plot the decrease of the pass band as the vane height is increased. Since the phase velocity of the RF mode is $v_{\rm phase} = \omega/k$, decreasing the frequency at a given wavenumber decreases the mode's phase velocity, eventually to the point that it is the same as the electron beam's actual velocity. Once that happens, synchronous energy exchange can occur between the beam and the RF mode. This interaction is with the fundamental forward mode [$n = 0$ in (1)]. By knowing the power flow and the field strength in the waveguide, a Pierce-type analysis could be done to estimate the growth in the RF mode [3]. However, we use the more exact modal analysis code DETER, described in [1], for gain and bandwidth calculations, as shown in Fig. 3. The maximum gain for our nominal parameters of a 20-A, 120-kV sheet beam with cross section of 1 cm by 0.5 mm in a vane-loaded waveguide with period of 0.5 mm is about 13 dB/cm. The gain is about 2/3 dB per structure period, which is consistent with lower-frequency, high-current TWTs. The waveguide vane parameters (as defined in Fig. 1) are $b = 1.05$ mm, $d = 0.608$ mm, $p = 0.5$ mm, and $s = 0.25$ mm. Significant gain extends over a bandwidth of a few GHz.

Our experimental investigation of this interaction is based on the parameters used in Fig. 3. To produce a sheet electron beam, we are using a 120-kV, 20-A electron gun, and form a 1-cm by 0.5-mm beam ellipse with a solenoid and a pair of quadrupoles, described more in Section IV. Alternatively, an elliptical solenoid can be used, replacing the normal solenoid and quadrupoles [6]. Stable elliptical beam focusing can be provided by either a PPM or a wiggler field configuration. Both are described more in Section III. A structure for synchronism at 95 GHz is then inserted into the wiggler for the interaction.

III. Stable Sheet-Beam Transport

The magnetic field for either a wiggler or PPM configuration is of the form $\vec{B} = -\vec{\nabla}\chi_m$, where $\chi_m = (B_w/k_z)\cosh(k_x x)\cos(k_z z)\{a\sinh(k_y y) + b\cosh(k_y y)\}$ and $k_x^2 + k_y^2 = k_z^2$. If $a = 1$ and $b = 0$, the field is known as a wiggler field (it can be visualized as a vertical field periodically varying, with the beam slightly moving back and forth horizontally). If $a = 0$ and $b = 1$, the field is known as a periodic permanent magnet (PPM) field (it can be visualized as an axial field periodically varying, with the beam slightly rocking back and forth between the vertical and horizontal directions). We are using Sharlemann's notation [7], and will also be following Bookse's development [8]. Those previous

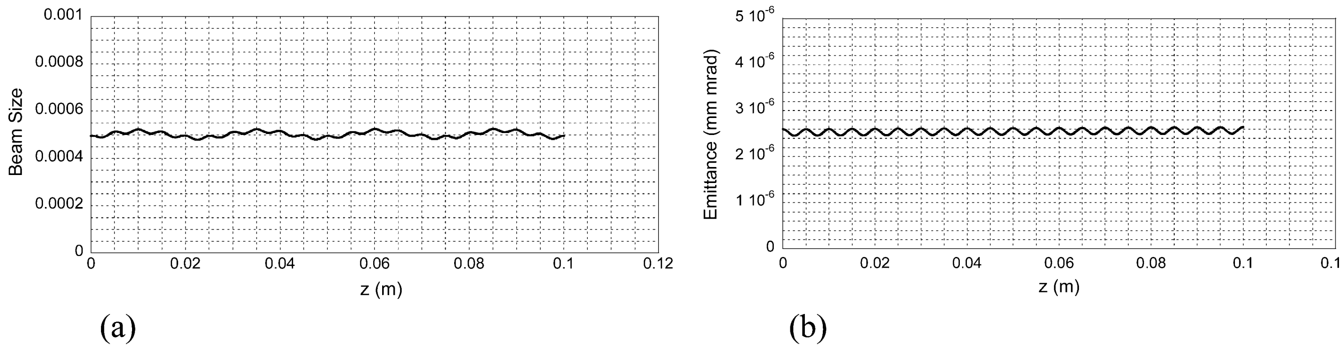


Fig. 4. Sheet beam calculation using PUSHER in a 2.5-kG wiggler field: (a) vertical beam envelope and (b) vertical beam emittance.

developments separated the PPM and wiggler analyzes, which will be combined here. The field is of the form

$$\begin{aligned} B_x &= -k_x \frac{B_w}{k_z} \sinh(k_x x)\cos(k_z z) \\ &\quad \times \{a \sinh(k_y y) + b\cosh(k_y y)\} \\ B_y &= -\, k_y \frac{B_w}{k_z} \cosh(k_x x)\cos(k_z z) \\ &\quad \times \{a \cosh(k_y y) + b\sinh(k_y y)\} \\ B_z &= B_w \cosh(k_x x)\sin(k_z z) \\ &\quad \times \{a \cosh(k_y y) + b\sinh(k_y y)\}. \end{aligned} \tag{3}$$

After small argument expansions and wiggle averaging [7]–[9], these transverse equations of motions are found

$$\ddot{x} = -\left(\frac{eB_w}{m\gamma}\right)^2 \frac{k_x^2}{2k_z^2}\left(a^2\frac{k_y^2}{k_z^2} + b^2\frac{k_x^2}{k_z^2}\right)x \tag{4}$$

and

$$\ddot{y} = -\left(\frac{eB_w}{m\gamma}\right)^2 \frac{k_y^2}{2k_z^2}\left(a^2 + b^2\right)\frac{k_y^2}{k_z^2}y \tag{5}$$

where we have dropped the cross terms (that go as ab).

Both configurations have identical vertical focusing, but since k_x is smaller than k_y, the wiggler focusing (the a term) will have greater horizontal focusing than PPM focusing (the b term). The cross terms are ugly, and have the potential to introduce non-simple-harmonic oscillator terms, which are negligible at 95 GHz [9], but could be significant at higher frequencies. The preaveraged equations of motion are fairly complicated; some of the averaged terms look like $\cos^2(k_z z)$ and some look like $\sin^2(k_z z)$, which means that the preaveraged equations of motion are more than just the driven Matthieu equation and have more complex regions of stability [9]. In particular, due to the increased transverse motion in the wiggler field, the stability limit for the wiggler field is only about three-quarters that for the PPM field. However, both fields lead to equivalently nice, stable flow at about one-quarter to one-third the Matthieu stability limit [9].

Direct integration of the particle equations of motion with the three-dimensional (3-D) code PUSHER [9] verifies the stable transport of the sheet beam with transverse emittance of 2.7 mm mrad, in the nominal design wiggler field of 2.5 kG, with no emittance growth, as shown in Fig. 4. Particles were evolved

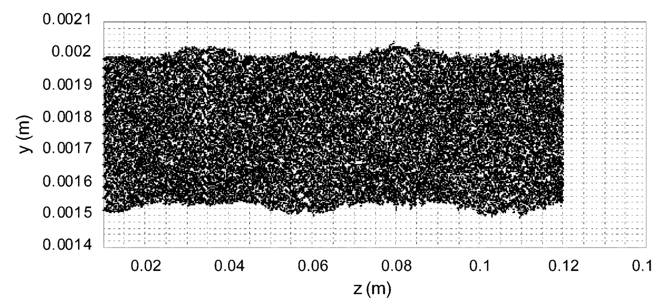


Fig. 5. Two and one-half-dimensional PIC simulations of wiggler transport using TUBE (no RF modulation).

using the exact external magnetic field in PUSHER, but the space-charge fields used the Lawson elliptical form [10]. The sheet beam transport analysis for these parameters reveals a rather unique situation: the horizontal beam transport is space-charge dominated, but the vertical beam transport is emittance dominated. Simulations with field errors show that mixing in even 10% PPM field components into the wiggler field ($a = 0.9$, $b = 0.1$) does not significantly degrade the transport.

A 2.5-D PIC simulation using the PIC code TUBE verifies the stable transport with the wiggler field, as shown in Fig. 5.

IV. PIC Simulations of the Interaction in 1-D and Two-Half Dimensions

For a comparison between the modal analysis code DETER and the PIC code TUBE, first we show in Fig. 6 results from a TUBE simulations in which the electrons in TUBE were constrained to move only axially (a 1-D simulation). In these calculations, the RF drive signal was imposed onto the electron beam through a standing-wave mode, and the traveling RF mode was launched by the bunching of the electron beam. The maximum gain is about 12 dB/cm, in reasonable agreement with the DETER gain of about 13 dB/cm (Fig. 3). The particles' energy is shown in Fig. 6(b), demonstrating both bunching and net energy loss. The extraction efficiency is about 24%.

The actual transverse dynamics reduce the gain and extraction efficiency slightly (gain still about 12 db/cm and about 22% extraction efficiency), as shown in Fig. 7. The initial beam expansion shown in Fig. 8 is due to the beam emittance of each beamlet. This beam emittance also increases the beam energy spread, and additionally mixes each particle's individual energy as the transverse motion due to the vertical emittance changes

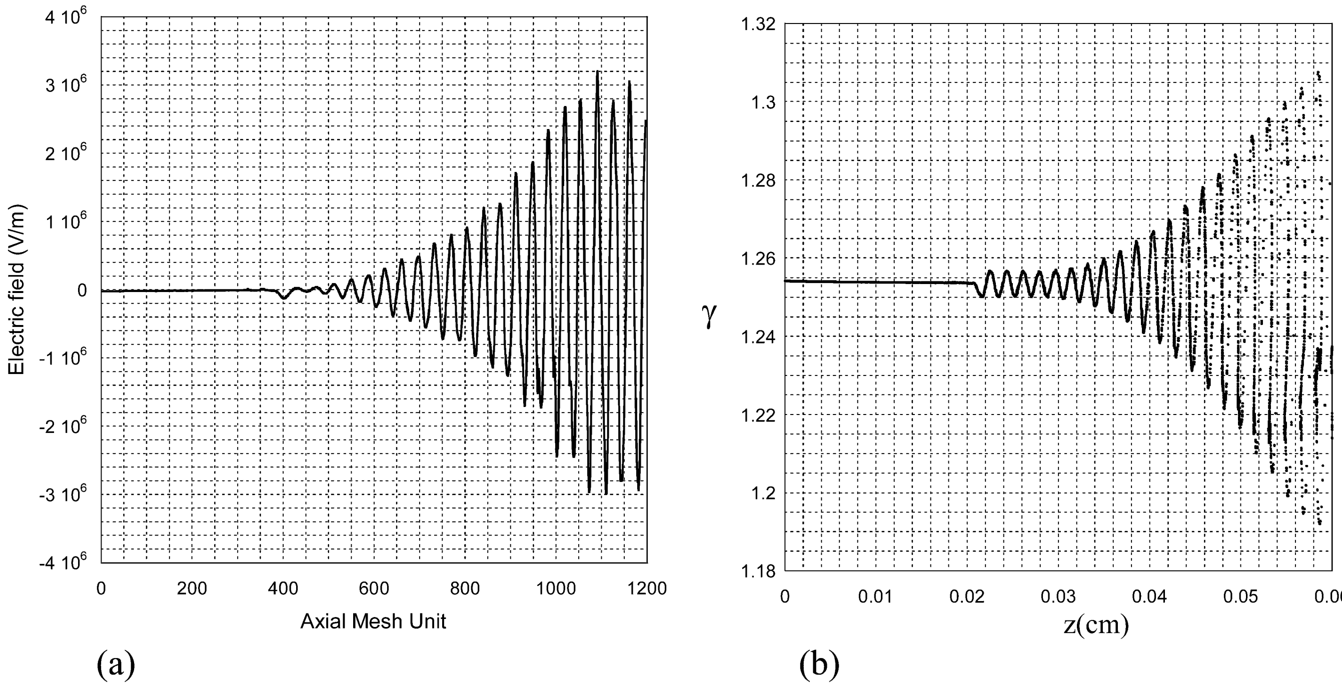


Fig. 6. A 1-D TUBE simulation of the nominal 120-kV geometry. (a) Axial electric field versus axial position (1 mesh unit is equal to 50 μm). (b) Electron relativistic mass factor versus axial position showing particle bunching and energy extraction, for an initial voltage modulation of 3 kV on the beam.

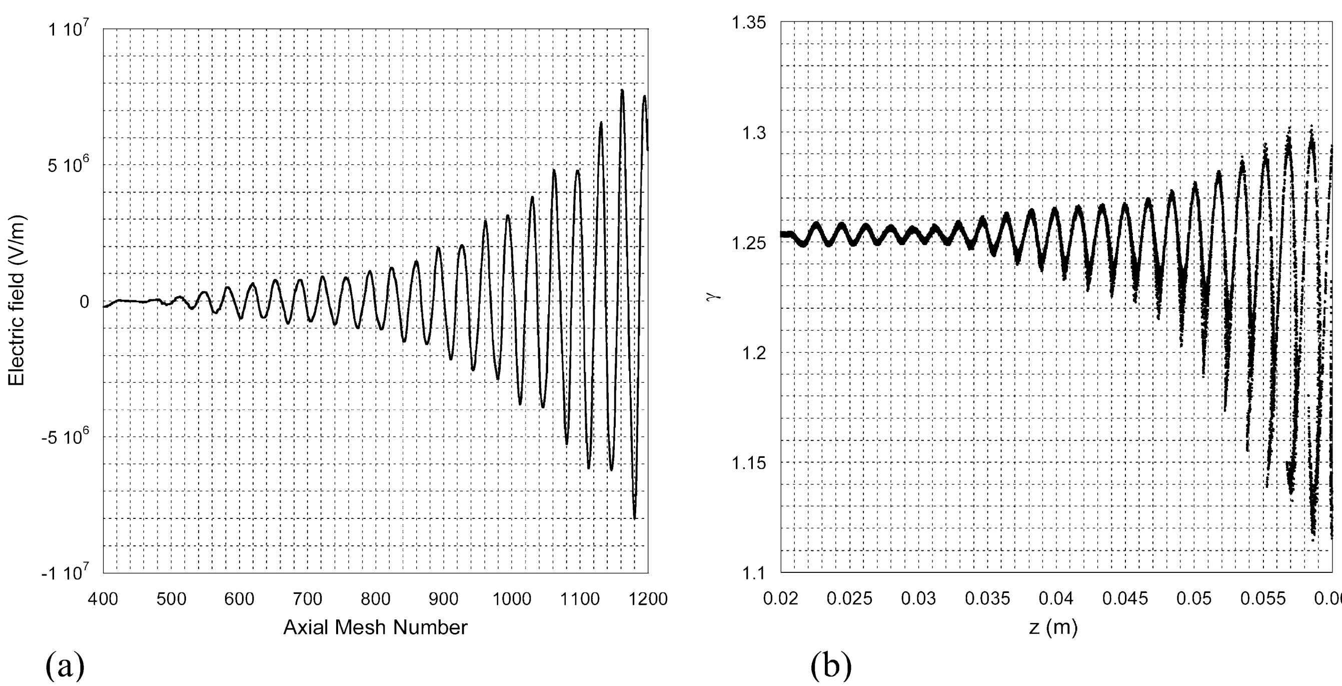


Fig. 7. Two and one-half-dimensional TUBE simulation of the nominal 120-kV geometry. (a) Axial electric field versus axial position (1 mesh unit is equal to 50 μm). (b) Electron relativistic mass factor versus axial position showing particle bunching and energy extraction.

each particle's potential depression. The vertical beam expansion in Fig. 8 at the end of the simulation volume is due to the beam emittance as the net velocity of the beam is decreased from the RF extraction (due to the fact that the beam is emittance dominated in the vertical plane). The transport is actually quite decent considering that after the RF interaction, the particle energies range from about 60 keV to about 150 keV (a final energy spread of about 90 keV).

V. 120-kV Experiment

The RF demonstration experiment concept is shown in Fig. 9. A 120-kV electron gun produces a cylindrical electron beam. This beam is then formed into a high aspect-ratio elliptical shape with a solenoid and quadrupole doublet. The elliptical beam is transported in a wiggler section, and an RF slow-wave structure is inserted into the wiggler structure for RF interaction.

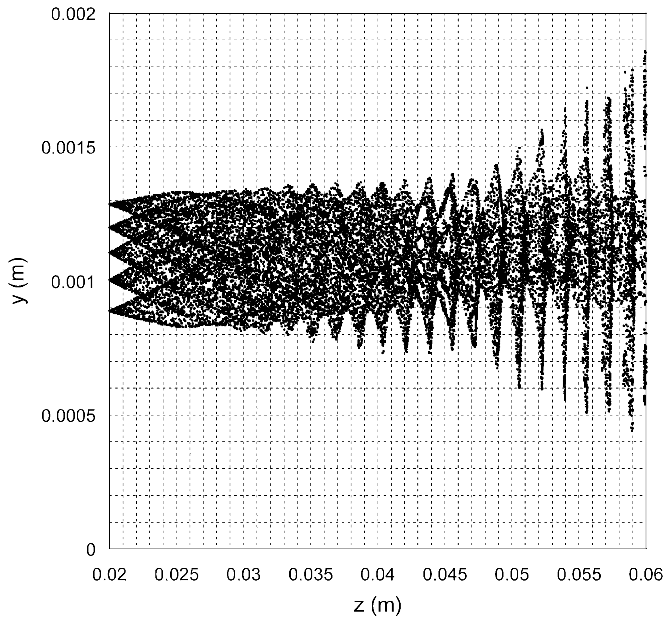


Fig. 8. Transverse particle motion for saturated extraction case using TUBE. Rapid initial vertical expansion of the beamlets is due to the beam emittance, which leads to an effective energy spread. Decreased beam velocity at the larger axial positions leads to beam expansion due to the emittance rather than the beam's space charge.

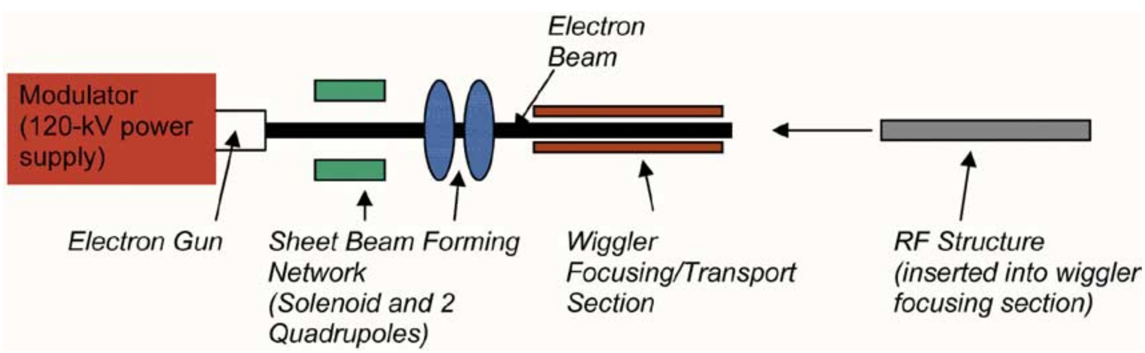


Fig. 9. Experimental schematic, showing beam formation section, transport section, and RF interaction structure.

The 120-kV electron gun used in the 95-GHz experiment was built by MDS Company, Oakland, CA, and uses a standard Pierce geometry with a Semicon cathode. A fully 3-D trajectory tracing simulation using AMAZE [11], is shown in Fig. 10, outlining the formation of a 1-cm by 0.5-mm elliptical beam by the solenoid and quadrupole doublet. The design of forming the sheet beam follows the work of Basten *et al.* in [12].

The placement of the beam line solenoid, quadrupoles, and wigger are shown schematically in Fig. 11.

We have identified the two major RF structure design issues to be: 1) maintaining a sufficiently flat RF mode transversely across the structure; and 2) providing well-matched coupling into and out of the RF structure. The motivation for having a flat RF mode is because all electrons across the sheet beam horizontally need to be bunched and decelerated at the same rate. However, because the total current decreases as we move horizontally from the center of the beam, there must be transverse power flow toward the side walls (because less RF power is extracted from the beam toward the horizontal edges). As a result, we believe that the optimum field shape will be somewhat different than completely flat. The ideal transverse mode shape will later be determined through 3-D MAGIC [13] simulations.

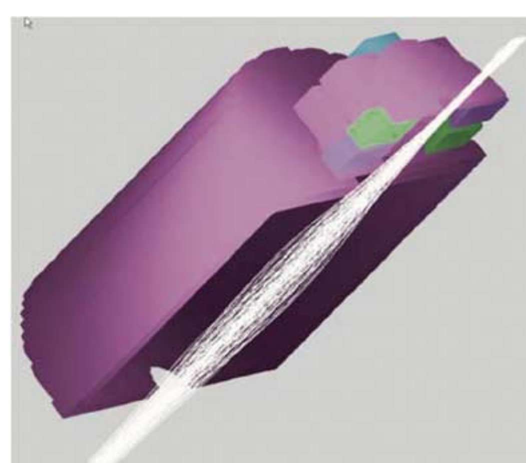


Fig. 10. AMAZE simulation of the sheet beam formation using a solenoid and a quadrupole doublet.

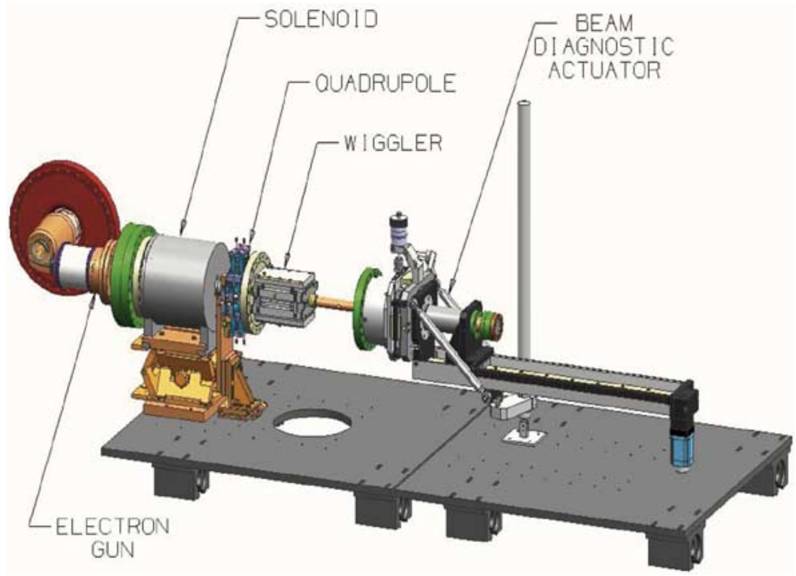


Fig. 11. Experiment schematic showing the beamline focusing optics.

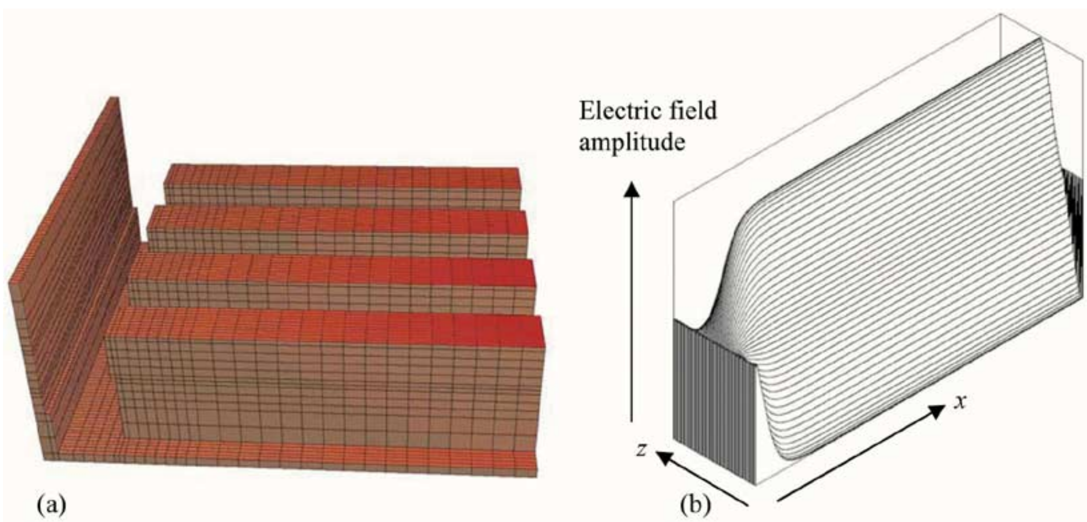


Fig. 12. Mode shape is achieved by capacitively coupling the vanes to the slow-wave structure endwalls. (a) MAFIA geometry of the vane to end-wall coupling, showing the wall undercut and the vane overcut. (b) RF mode field amplitude (vertical axis) plotted versus length along the SWS and horizontal position along the vanes for one vane period. Mode flatness can easily be kept more uniform than 1% over the width of the beam, if desired.

Our design goal with two ans one-half-dimensional PIC calculations has been more generally to be able to finely control the transverse mode shape. The input/output coupler issue is also complex. It is hard to launch a flat mode in such an overmoded structure. This problem is aggravated because multiple output waveguides will be needed. Even oversized (so-called "tall") waveguides will breakdown if greater than 50 kW at W-band are passed through them. This requires multiple (8–10) output waveguides to be used for a high-power experiment.

In Fig. 12(a), we see an MAFIA calculation of one-quarter of the nominal 95-GHz slow-wave structure (SWS), and in Fig. 12(b), the field profile as calculated in MAFIA. A flat mode is achieved by capacitively coupling the vane ends to the side walls, tailoring the mode shape with a wall undercut, and a vane overcut.

Designing the input and output couplers turned out to be a harder problem than maintaining transverse mode flatness, especially for very wide structures (2-cm-wide or so for our 1-cm-wide sheet electron beam), due to overmoding of the structure. To solve this RF design issue, we first studied coupling into narrow structures, and we eventually developed a design capable of greater than 7.5% bandwidth. Such a design is shown in Fig. 13. The structure shown in Fig. 13 has a width only about one-quarter of the width of a structure properly designed for the sheet beam, as described in Section III. The concept is to introduce antisymmetric RF modes in both the upper and lower waveguide, and the transverse fields cancel as the two waveguides merge, leaving the desired mode in the SWS, as shown in Fig. 14. The VSWR is 1.55 or less over the 7.5% bandwidth, with at least 13 dB of isolation (and more typically 30–40 dB of isolation).

Recent work has indicated that the input coupler for the wide structure may be easier to design if only one input waveguide is still used entering from both the top and the bottom [14]. In this case, the input waveguides would need to expand to even a greater width, with internal shaping required to maintain a

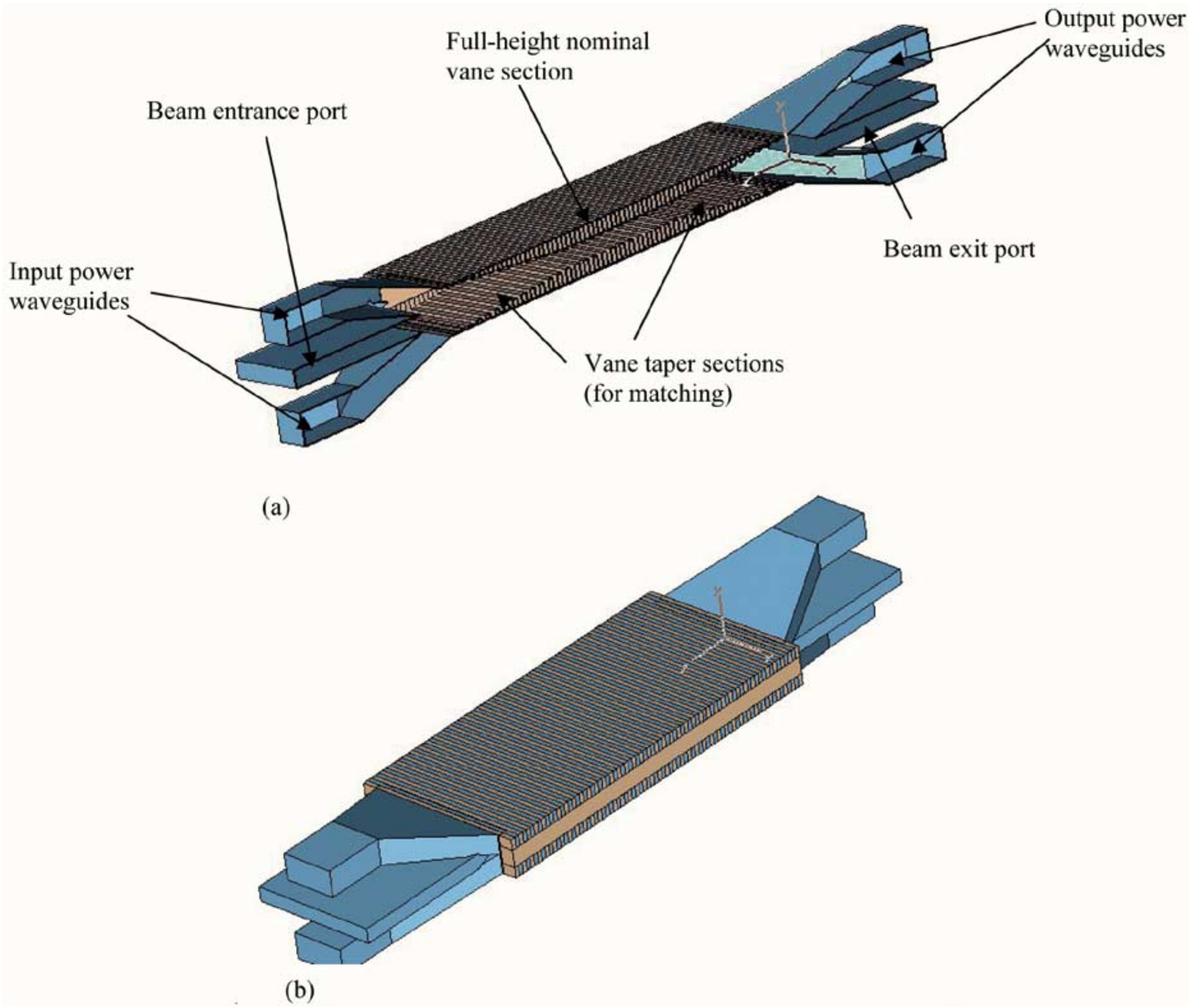


Fig. 13. Nominal coupler design for narrow SWS. (a) Interior view and (b) exterior view. Note even for the narrow structure, the input and output waveguides need to be expanded significantly to the width of the SWS.

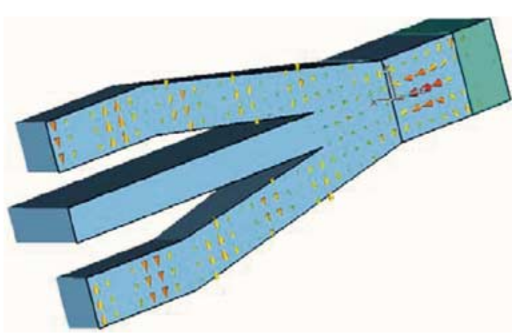


Fig. 14. Field pattern in the coupling waveguides, showing the field cancellation and net axial field component after combining.

transverse flat field inside them. Unfortunately, this solution is not acceptable for the output couplers in the final design, due to the power handling. However, this solution will be fine for initial, gain measurement experiments, which are intended to remain low power (100 W–1 kW). In Fig. 15, we show a choked waveguide (the small grey parts are undercuts and overcuts to make the field pattern within the choke area very flat). In Fig. 16, we see a two-input coupler design with the resulting flat input RF mode to the vane-loaded structure.

VI. Summary

We have identified the major technological problems in a high-frequency, sheet-beam TWT to be:

1) stable transport of the sheet beam itself;
2) transverse power flow in the RF structure;
3) maintaining control of the transverse mode shape in the slow-wave structure;
4) design of the input and output couplers.

In this paper, we have described how to achieve stable sheet beam transport with a wiggler focusing configuration for nominal beam parameters of 120 kV and 20 A, even under the conditions of a large energy spread induced by strong beam/RF interactions. The wiggler focusing is robust, does not degrade with minor field errors, and, for achievable periods, does not lead to a large beam ripple. We also have described how to control the transverse mode shape in the slow-wave structure by capacitively coupling the vanes to the side walls in the structure. In addition, we have shown an input/output coupling design that leads to very good bandwidth (7.5%) for a relatively narrow structure, and we have demonstrated how to extend this type of

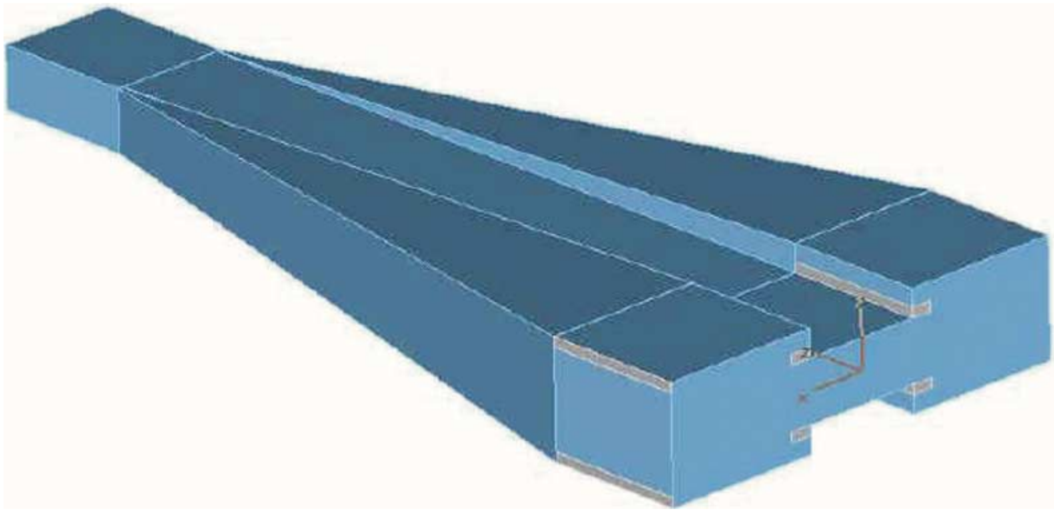


Fig. 15. Nominal choke waveguide design. Small grey part are tuned to provide a flat RF field within the choke region.

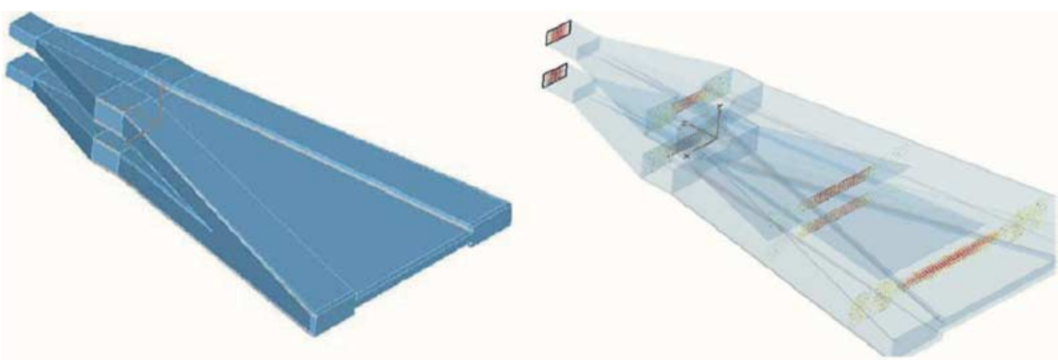


Fig. 16. Two input coupler design (without the beam inlet pipe). This design is similar to the one shown in Fig. 13, but the input waveguides are much wider to accommodate the wide SWS. The figure on the right shows the internal electric field profile, which can be made transversely very flat.

coupling design to a wide structure, suitable for a high aspect-ratio elliptical beam.

REFERENCES

[1] B. E. Carlsten, "Modal analysis and gain calculations for a sheet electron beam in a ridged waveguide slow-wave structure," *Phys. Plasmas*, vol. 9, pp. 5088–5096, Dec. 2002.

[2] ——, "Small-signal analysis and particle-in-cell simulations of planar dielectric Cherenkov masers for use as high-frequency, moderate-power broadband amplifiers," *Phys. Plasmas*, vol. 9, pp. 1790–1800, May 2002.

[3] ——, "Pierce gain analysis for a sheet beam in a rippled waveguide traveling-wave tube," *Phys. Plasmas*, vol. 8, pp. 4585–4591, Oct. 2001.

[4] H. P. Freund and T. M. Abu-Elfadl, "Linearized field theory of a Smith–Purcell traveling-wave tube," *IEEE Trans. Plasma Sci.*, vol. 3, pp. 1015–1027, Jun., 2004.

[5] B. E. Carlsten, S. J. Russell, L. M. Earley, J. M. Potter, P. Ferguson, and S. Humphries Jr, "MM-wave source development at Los Alamos," in *Proc. 6th Workshop High Energy Density High-Power RF*, vol. 691, AIP Conf. Proc., S. Gold and G. Nusinovich, Eds., Berkeley Springs, WV, 2003, pp. 349–357.

[6] S. Humphries, S. Russell, B. Carlsten, L. Earley, and P. Ferguson, "Circular-to-planar transformations of high-perveance electron beams by asymmetric solenoid lenses," *Phys. Rev. Special Topics—Accel. Beams*, vol. 7, pp. 060 401-1–060 401-10, 2004.

[7] E. T. Scharlemann, "Wiggle plane focusing in linear wigglers," *J. Appl. Phys.*, vol. 58, pp. 2154–2161, Sep. 1985.

[8] J. H. Booske, B. D. McVey, and T. M. Antonsen Jr, "Stability and confinement of nonrelativistic sheet electron beams with periodic cusped magnetic focusing," *J. Appl. Phys.*, vol. 73, pp. 4140–4155, Sep. 1993.

[9] B. E. Carlsten, S. J. Russell, L. M. Earley, F. Krawczyk, J. M. Potter, P. Ferguson, and S. Humphries Jr, "Stable sheet beam transport for high-frequency microwave devices," Phys. Rev. Special Topics—Accel. and Beams., submitted for publication.

[10] J. D. Lawson, *The Physics of Charged-Particle Beams*. Oxford, U.K.: Clarendon , 1977, pp. 156–160.

[11] "MAGNUM, OMNITRAK, and TRAK Software," Field Precision, Albuquerque, NM.

[12] M. A. Basten, J. H. Booske, and J. Anderson, "Magnetic quadrupole formation of elliptical sheet electron beams for high-power microwave devices," *IEEE Trans. Plasma Sci.*, vol. 22, no. 5, pp. 960–966, Oct. 1994.

[13] *MAGIC User's Manual*, Mission Research Corp., Santa Barbara, CA, 1999.

[14] S. Tantawi, private communication, 2004.

Bruce E. Carlsten received the B.S. degree in physics from the University of California, Los Angeles, in 1979, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 1985.

In 1982, he joined the Los Alamos National Laboratory, Los Alamos, NM, and has published research in the areas of electron beam emittance growth and compensation, intense electron-beam physics, electron beam bunch compression, coherent synchrotron radiation, RF and induction accelerators, sheet beam transport, klystrons, and traveling-wave tubes. He is currently a Project Leader at Los Alamos for the sheet beam traveling-wave tube development program.

Steven J. Russell received the Ph.D. degree in physics for Michigan State University, East Lansing, in 1998, with a focus in accelerator beam physics.

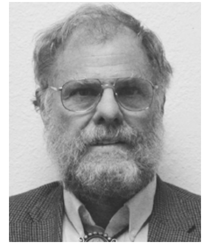
He joined the Los Alamos National Laboratory, Los Alamos, NM, as a student during the summers of 1990 and 1991 to work on the Advanced Free Electron Laser (AFEL) project. In 1992, he joined Los Alamos National Laboratory as a Graduate Research Assistant for an extended stay to work on his Ph.D. thesis. Upon graduating, he was hired as Staff at Los Alamos National Laboratory, and has continued his research in accelerator physics, specifically on the behavior of electron beams. Since 2002, he has be working to develop sheet electron beams for milimeter-wave vacuum tube devices.

Lawrence M. Earley received the M.S. degree in electrical engineering from Stanford University, Stanford, CA, in 1979, and the degree of engineer in electrical engineering from Stanford University in 1981 as part of the AFTER (Air Force Thermionic Engineering Research) Program.

He has over 25 years experience in high-power microwave generation at Los Alamos National Laboratory, Sandia National Laboratories, and Hughes Aircraft Company EDD, including developing high-power microwave generators (magnetrons, backward wave oscillators, MILOs, vircators, TWTs, FEMs, and klystrons). He has extensive experience with pulsed power, electron beams, and RF diagnostics, and precision measurements for frequencies up to 300 GHz. He has extensive experience on RF accelerator structures including RFQs, side-coupled, drift tube linacs, and LIAs. He has over 25 publications in the field of RF, microwaves, and pulsed power.

Frank L. Krawczyk was born in Delmenhorst, Germany, in 1960. He received the Diploma in physics from University of Kiel, Germany, in 1986, and the Ph.D. degree in physics from Hamburg University, Hamburg, Germany, in 1990.

While working on the Ph.D. degree (1986–1989), he was with the DESY National Laboratory, Hamburg, Germany before joining the Computational Electromagnetics Laboratory (TEMF), Darmstadt University, Darmstadt, Germany, as a Research Assistant (1989–1992). He joined the Los Alamos National Laboratory (LANL), Accelerator Physics Group, Los Alamos, NM, as a postdoctorate, in 1993. Since 1995, he has been mainly responsible for 3-D RF-designs and testing of resonators and power couplers for projects at LANL.



James M. Potter received the Ph.D. degree from the University of Illinois, in 1975.

He has over 40 years experience in linear accelerator design and testing. He also has extensive experience in high-power RF and microwave system design and testing, computer control and data acquisition, and high-power high-voltage systems in connection with applications to linear accelerator systems. He is the founder and President of JP Accelerator Works, Inc., Los Alamos, NM, a small business engaged in design and fabrication of linear accelerators and related system components.

Patrick Ferguson received the B.A. degree in physics from San Jose State University, San Jose, CA, in 1962, the M.S. degree in physics from California State University, Northridge, in 1970, and the Ph.D. degree in electrical sciences from the University of California, Los Angeles, in 1975.

He has 33 years of experience in electron device development, twenty of which as an independent consultant. He developed the first 40% bandwidth high-power coupled cavity TWT, a 100-GHz, 500-kW gyrotron oscillator, and a 100-MW X-band klystron for particle acceleration. He founded the MDS Company, Oakland, CA, in July 1991, and presently serves as its President.

Stanley Humphries, Jr. (M'75–SM'90–F'93) received the B.S. degree in physics from the Massachusetts Institute of Technology, Cambridge, and the Ph.D. degree in nuclear engineering from the University of California, Berkeley.

He spent the first part of his career as an experimentalist in the fields of plasma physics, controlled fusion, and charged particle acceleration. A notable contribution was the creation and demonstration of methods to generate and to transport intense pulsed ion beams. His current work centers on simulations of electromagnetic fields, biomedical processes, and material response at high pressure and temperature. He is a Professor Emeritus in the Department of Electrical and Computer Engineering, the University of New Mexico, Albuquerque, and President of Field Precision, Albuquerque, NM, an engineering software company. He is the author of over 150 journal publications and the textbooks *Principles of Charged-particle Acceleration* (Wiley, New York, 1986), *Charged Particle Beams* (Wiley, New York, 1990), and *Field Solutions on Computers* (CRC Press, Boca Raton, 1997).

Dr. Humphries is a Fellow of the American Physical Society.