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Research results establish that novel periodic magnetic focusing optics offer the opportunity to propagate much higher beam currents than previously achievable in slow-wave vacuum microwave devices. Several new sources for sheet electron beams have been designed and numerically analyzed, including 2 different thermionic electron gun designs as well as one approach that uses magnetic quadrupole optics for converting a conventional round beam into a large-aspect-ratio elliptical (i.e., sheet) beam. Round beam focusing by short period PPQM arrays was also studied. We have developed new understanding of the relatively unexplored area of hybrid electromagnetic waveguide mode dynamics. The dispersive properties of a slow wave grating system have been measured and compared with the theoretical model.

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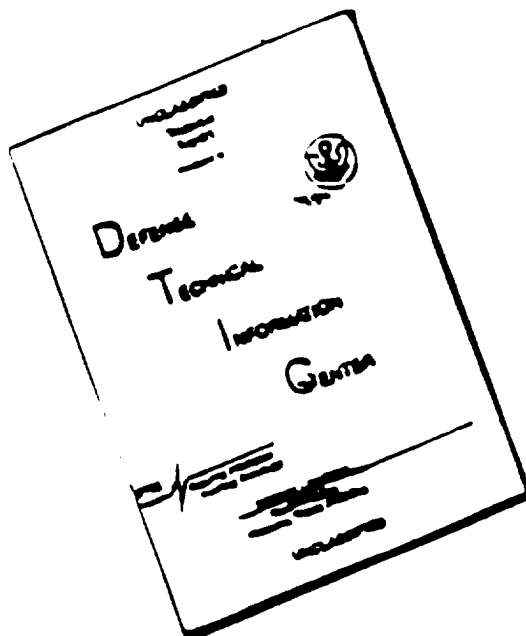
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# **Final Report**

**November, 1996**

**Low-Voltage Millimeter-Wave Cerenkov Amplifiers  
Grant: AFOSR-91-0381**

**Professor John H. Booske (PI/PD)**

**and**

**Professor John E. Scharer (co-PI)**

**University of Wisconsin-Madison  
Electrical and Computer Engineering Department  
1415 Engineering Drive  
Madison, WI 53706**

**OBJECTIVES:**

- To contribute to the fundamental knowledge and technology base for improved vacuum sources of high power, coherent millimeter-wave electromagnetic radiation.
- Focus on innovations to yield higher average power (up to ~10 kW) in wide-instantaneous-bandwidth ( $\Delta f/f \geq 20\%$ ) Ka-band (35 GHz) amplifiers, as well as higher average power (up to ~100 W) in W-band (95 GHz) travelling-wave-tube amplifiers (TWTAs).
- Specific objectives include research on: (1) the stable formation, focusing, and transport of high perveance electron beams, (2) the basic physics of grating-lined waveguides for high-average-power Ka-band TWTAs, and (3) the dynamics of multiple-round-beam arrays as an alternative electron beam configuration for higher-average-power W-band TWTAs.

**ACCOMPLISHMENTS/NEW FINDINGS:**

A number of important accomplishments have been realized by taking a fresh approach to the traditional desire for higher average power at ever-shorter wavelengths in compact systems based on existing technological capabilities. Specifically, we have focused on novel, high-perveance, electron beam configurations (sheet beams, multi-beams, periodic-permanent-quadrupole-magnet or PPQM focused round beams) and TWTA interaction structures compatible with those beam configurations, as well as with high-average power devices.

- Research results establish that novel periodic magnetic focusing optics offer the opportunity to propagate much higher beam currents than previously achievable in slow-wave vacuum microwave devices. Theory and simulations establish that stable, edge-focused transport of linear sheet electron beams can be realized with periodically-cusped magnetic (PCM) focusing for very high current density beams ( $> 200 \text{ A/cm}^2$ ) even at low beam voltages (10 kV)—i.e., very high space-charge beams. Edge focusing options include offsetting the poles of the planar PCM array or using periodic permanent quadrupole magnetic (PPQM) edge focusing. Both options provide stable edge focusing with the former method requiring fewer magnet pieces and the latter method providing superior beam matching capability. An entire new class of higher-average-power coherent microwave and millimeter-wave sources can be based on this high-perveance electron-beam technology. Opportunities include both HPM as well as more conventional low-voltage ( $\leq 30 \text{ kV}$ ) vacuum microwave devices. Implementation is particularly appropriate for linear beam devices, including BWOs, TWTs, and klystron and free electron lasers. Hence, applications are envisioned for EW, ECM, high resolution tracking radar, remote sensing radar, and for air-, sea-, space- and land-based systems. Cost-effective improvements in devices for commercial microwave processing of materials are also envisioned.
- Several new sources for sheet electron beams have been designed and numerically analyzed, including 2 different thermionic electron gun designs as well as one approach that uses magnetic quadrupole optics for converting a conventional round beam into a large-aspect-ratio elliptical (i.e., sheet) beam. The latter method has several attractive features: (1) by varying the quadrupole parameters, one can substantially vary the

output beam characteristics (making this an ideal source for experimental research efforts), and (2) it will significantly extend the state-of-the-art understanding of quadrupole focusing physics, setting the stage for future research into periodic quadrupole focusing of intense electron beams and multi-beam arrays. Both simulation and experimental results with a 10 kV, 2 A electron beam confirm the feasibility of this approach.

- Round beam focusing by short period PPQM arrays was also studied. The focusing force from PPQM arrays can be an order of magnitude greater than that of conventional periodic permanent magnet (PPM) arrays for beam voltages from 10-40 kV. Analytic and numerical studies demonstrate the potential of this configuration but also show that beam ripple may be problematic. Experimental measurements are in good qualitative agreement with the predictions of envelope and PIC code simulations.
- We have developed new understanding (theoretical and experimental) of the relatively unexplored area of hybrid electromagnetic waveguide mode dynamics, including electromagnetic dispersion and mode-coupling physics (important for efficient launching and coupling to high-gain slow-wave hybrid modes), as well as the interaction physics between electron beams and these hybrid waveguide modes. In particular, this knowledge base is critical to designing high-average-power-compatible grating-based TWAs for use with sheet electron beams. Theoretical studies indicate that high gains (e.g., up to 6 dB/cm at 14 GHz) are possible with these modes and structures.
- The dispersive properties of a slow wave grating system have been measured and compared with the theoretical model and agree well for the shallow groove grating. A creative lab setup to measure the wave fields and dispersion relation using a moveable probe and coherent mixing was used. The lowest order mode in the backward wave regime and higher order modes were measured and good agreement with the theoretical predictions were obtained. For the deep groove grating, skin effect losses and the wave mismatch in the taper section of the grating were found to limit efficient coupling.
- The spontaneous emission round test beam curve for the shallow groove grating backward wave mode regime was obtained and is in good agreement with theoretical predictions. Next, the loop coupled multipass small signal gain for the backward wave regime with reflectors was obtained at 14.2 GHz in the Ku-band. The effect of beam spread on the gain and the classic doublet shape of gain/loss curve arising from Landau damping of the beam as the beam energy is scanned about the resonant beam energy was obtained. It was found that this small signal gain was in close agreement with our theoretical predictions of gain and the analytic predictions of the theory of Grover and Sprangle. Energy analyzer measurements found that the beam energy spread was about 4% due to beam optics alignment of the magnetic flux shield located in front of the electron gun. This research has been described in the Ph. D. thesis of J. Joe and has been submitted to the Journal Plasma Physics as a group paper.

**PROFESSIONAL PERSONNEL SUPPORTED BY AND/OR ASSOCIATED WITH  
PROJECT DURING THE SUPPORT OF THIS WORK**

Professor John H. Booske (faculty)

Professor John E. Scharer (faculty)

Dr. Richard True (Industrial Colleague, Litton Electron Devices, San Carlos, CA)

Dr. Glen Scheitrum (Industrial Colleague, Litton Electron Devices, San Carlos, CA)

Dr. Carter Armstrong (Industrial Colleague, Northrop Corp., Rolling Meadows, IL)

Mr. Mark Basten (Grad student)  
Mr. Jurianto Joe (Grad student)  
Mr. L. Lazaar Joseph (Grad student)  
Mr. Jim Anderson (undergraduate student)  
Mr. Ryan Thompson (undergraduate student)  
Mr. Len Rauth (undergraduate student)  
Ms. Keely Wagner (undergraduate student)  
Mr. Cubic Harris (undergraduate student)  
Mr. Mark McNeely (undergraduate student)  
Mr. Zachary Smith (undergraduate student)

#### PEER-REVIEWED JOURNAL PUBLICATIONS

"Experimental and Theoretical Investigations of a Rectangular Grating Structure for Low-Voltage Traveling Wave Tube Amplifiers," J. Joe, L.J. Louis, J.E. Scharer, J.H. Booske, M.A. Basten, submitted to *Plasma Physics*, 41 pages (1996).

"Magnetic Quadrupole Formation of Elliptical Sheet Electron Beams for High-Power Microwave Devices", M.A. Basten, J.H. Booske, and J. Anderson, *IEEE Trans. Plasma Sci., 5th Special Issue on High Power Microwave Generation* 22 [5], 960-966 (1994).

"Analysis of Rectangular Waveguide-Gratings for Amplifier Applications," B.D. McVey, M.A. Basten, J.A. Booske, J. Joe, and J.E. Scharer, *IEEE Trans. on Microwave Theory and Techniques*, 42, 995-1003 (1994).

"Wave Dispersion and Growth Analysis of Low-Voltage Grating Cerenkov Amplifiers," J. Joe, J. Scharer, J. Booske and B. McVey, *Physics of Plasmas* 1, 176-188 (1994).

"Periodic Magnetic Focusing of Sheet Electron Beams," J.H. Booske, M.A. Basten, A.H. Kumbasar, T.M. Antonsen, S.W. Bidwell, Y. Carmel, W.W. Destler, V.L. Granatstein and D.J. Radack, invited paper *Phys. of Plasmas* 1[5], 1714-1720 (1994).

"Periodic Focusing and Ponderomotive Stabilization of Sheet Electron Beams," J.H. Booske, A.H. Kumbasar, and M.A. Basten, *Phys. Rev. Lett.* 71 (24), 3979-3982 (1993).

Stability and Confinement of Nonrelativistic Sheet Electron Beams with Periodic Cusped Magnetic Focusing," J.H. Booske, B.D. McVey, and T.M. Antonsen, Jr., *J. Appl. Phys.* 73, 4140-4155 (1993).

"Wave Dispersion, Growth Rates and Mode Converter Analysis for a Sheet Beam Hybrid Mode Cerenkov Amplifier," S.F. Chang, J. Scharer and J. Booske, *IEEE Plasma Sciences* 20, 293-304 (1992).

"Linear Analysis of Sheet Beam Planar Grating and Dielectric Cerenkov Maser Amplifiers," J. Joe, S.F. Chang, J.E. Scharer and J.H. Booske, *Microwave and Optical Technology Letters*, 4, 443-446 (1991).

#### OTHER PUBLICATIONS

"Experimental and Theoretical Investigations of a Rectangular Grating Structure for Low-Voltage Traveling Wave Tube Amplifiers," J. Joe, L.J. Louis, J.E. Scharer, J.H. Booske, M.A. Basten, UW-CPTC 97-1 (1997).

"Analysis of Rectangular Waveguide-Gratings for Amplifier Applications," B. D. McVey, M. A. Basten, J. A. Booske, J. Joe, and J. E. Scharer, UW CPTC 93-3 (1993).

"Wave Dispersion, Growth Rates and Mode Converter Analysis for a Sheet Beam Hybrid-Mode Cerenkov Amplifier," S. F. Chang, J. E. Scharer and J. H. Booske, UW CPTC 91-12 (1991).

#### STUDENT THESES RELATED TO THIS GRANT AND ITS SUPPORT

"Millimeter Wave Cerenkov Amplifiers," Jurdanto Joe, Ph.D. Thesis, Electrical Engineering, University of Wisconsin-Madison, 1996.

"Formation and Transport of High-Perveance Electron Beams for High-Power, High-Frequency Microwave Devices," M.A. Basten, Ph.D. Thesis, Electrical Engineering, University of Wisconsin-Madison, 1996.

"Waveguide excitation for linear gain millimeter wave amplifier," Lazaar Louis, M.S. in progress. Electrical Engineering, University of Wisconsin-Madison.

#### INTERACTIONS/TRANSITIONS:

a) Participation/presentations at meetings, conferences, seminars, etc.

A substantial time commitment was dedicated during 1994-95 by the co-PIs to the organization and hosting of the 1995 International Conference on Plasma Science in Madison, WI. This event, held in June 1995, attracted 580 attendees from Universities, National Laboratories, and Industry. A particular highlight of this event was a strong focus on Vacuum Electronics and High Power Microwave Generation. Particular advantage was obtained by co-location and integration with the 1995 Annual Tri-Service Vacuum Electronics Review. Professor John Scharer was the Conference Chairman and Professor Booske served on the Program Committee, as well as local coordinating chair for the Tri-Service Vacuum Electronics Review. Prof. Booske has been retained as Technical Area Coordinator for all Microwaves Generation and Microwave/Plasma Interaction papers for the 1997 and 1998 IEEE International Conferences on Plasma Science (San Diego, CA, and Raleigh, NC, respectively).

In addition, the following Conference papers/presentations were made during or in association with the support of this grant.

"Rectangular Grating Periodic Slow Wave Structure with Sheet Beam for Low-Voltage Amplifiers," Lazaar J. Louis, John E. Scharer, Mark A. Basten, John H. Booske, Bulletin of the American Physical Society 41, 1367 (1996).

"An investigation of the Applicability of Permanent Magnet Quadrupole Arrays for High-Power Microwave Tubes," J.H. Booske, M.A. Basten, L.J. Louis, J. Joe,

and J.E. Scharer, *IEEE International Conference on Plasma Science*, Boston June 3-5, Record 96CH35939, 291 (1996).

"Waveguide Coupled Rectangular Grating Periodic Structure for Low-Voltage Amplifiers," L.J. Louis, J. Joe, J.E. Scharer, J.H. Booske, and M.A. Basten, *IEEE International Conference on Plasma Science*, Boston June 3-5, Record 96CH35939, 291 (1996).

"Formation and transport of Low-Voltage, Space-Charge Dominated Sheet Electron Beams for High-Power Microwave Devices," M.A. Basten, J.H. Booske, L.J. Louis, J. Joe and J.E. Scharer, *IEEE International Conference on Plasma Science*, Boston June 3-5, Record 96CH35939, 290 (1996).

"Theoretical and Computational Characterization of Multi-Tone Helix Traveling Wave Tubes," M.H. Bettenhausen, J.E. Scharer, J.H. Booske, and C.M. Armstrong, *IEEE International Conference on Plasma Science*, Boston June 3-5, Record 96CH35939, 289 (1996).

"Experimental Studies and Analysis of Low-Voltage, Grating TWT Amplifiers," J.E. Scharer, J.H. Booske, J. Joe, L. Louis, and M.A. Basten, *IEEE International Conference on Plasma Science*, Boston June 3-5, Record 96CH35939, 233 (1996).

"High Power, Low Voltage, Millimeter-Wave Grating TWT Amplifiers with High Perveance Electron Beams," J.H. Booske, J.E. Scharer, J. Joe, M. Basten, L. Louis, M. Bettenhausen, *Vacuum Electronics Annual Review Abstracts*, Monterey May 21-23, VII-1 - VII-6 (1996).

"Formation and transport of sheet electron beams and multibeam configurations for high-power microwave devices," M.A. Basten, J.H. Booske, J. Anderson, J.E. Scharer, *Intense Microwave Pulses III Conference*, part of SPIE 1995 International Symposium on Optical Science, Engineering, and Instrumentation, 9-14 July, San Diego, CA (1995).

"Mode Coupling in Deep-Groove Grating-lined waveguides for TWT Amplifier Applications," J. Joe, J.E. Scharer, J.H. Booske, M.A. Basten, and L.J. Louis, 37th Annual Mtg., Amer. Phys. Soc.-Division of Plasma Physics, Louisville, KY, 6-10 Nov. (1995).

"Experimental Investigation of Magnetic Quadrupole Formation of Sheet Electron Beams and Transport in Periodic Magnet Arrays," M.A. Basten, J.H. Booske, R. Thompson, L. Rauth, C. Harris, and J.E. Scharer, 37th Annual Mtg., Amer. Phys. Soc.-Division of Plasma Physics, Louisville, KY, 6-10 Nov. (1995).

"Experimental Investigation of Deep Groove Grating Slow Wave Structure for Microwave Amplifier Application," J. Joe, J.E. Scharer, J.H. Booske, M.A. Basten, and L.J. Louis, *International Workshop on Crossed-Field Devices*, Ann Arbor, MI, Aug. 15-16 (1995).

"Stable Transport and Side-Focusing of Sheet Electron Beams in Periodically Cusped Magnetic Field Configurations," Jim Anderson, Mark A. Basten, Len Rauth, John H. Booske, Jurianto Joe and John E. Scharer, *IEEE International Conference on Plasma Science*, Madison June 5-8, Record 95CH35796, 64 (1995).

"Experimental Studies of Low-Voltage, Grating TWT Amplifiers," J. Joe, M.A. Basten, J.E. Scharer, J.H. Booske, and K. Wagner, 22nd IEEE International Conference on Plasma Science, June 5-8, Madison, WI (1995).

"Magnetic Quadrupole Formation of Low-Voltage Sheet Electron Beams for High-Power Microwave Devices," M.A. Basten, J.H. Booske, J. Anderson, J. Joe, and J.E. Scharer, 22nd IEEE International Conference on Plasma Science, June 5-8, Madison, WI (1995).

"Experimental Studies and Sheet Beam Transport for Low-Voltage, Grating TWT Amplifiers," J.E. Scharer, J.H. Booske, J. Joe, M.A. Basten, J. Anderson, and K. Wagner, 22nd IEEE International Conference on Plasma Science, June 5-8, Madison, WI (1995).

"Formation and Transport of Sheet Electron Beams and Multi-Beam Configurations," M.A. Basten, J. Joe, J. Anderson, J.H. Booske, and J.E. Scharer, 36th Annual Mtg., Amer. Phys. Soc.-Division of Plasma Physics, Minneapolis, MN, 7-11 Nov. (1994).

"Initial Experimental Investigation of Low-Voltage, Grating TWT Amplifiers," J. Joe, M.A. Basten, J.E. Scharer, and J.H. Booske, 36th Annual Mtg., Amer. Phys. Soc.-Division of Plasma Physics, Minneapolis, MN, 7-11 Nov. (1994).

"Cold Test, Spontaneous Emission and Gain in a Rectangular Cerenkov Amplifier," J.E. Scharer, J. Joe, J.H. Booske, M. Basten, and H. Kirolos, IEEE International Conference on Plasma Science, Santa Fe June 6-8, Record 94CH3465-2 185 (1994).

"Formation and Transport of PCM-Focused Sheet Electron Beams," M.S. Basten, J.H. Booske, J. Anderson, J.E. Scharer, IEEE International Conference on Plasma Science, Santa Fe June 6-8, Record 94CH3465-2 185 (1994).

"Sheet Beam Slow-Wave Amplifiers," H. Kirolos, J. Joe, M.A. Basten, J.H. Booske, J.H. Scharer, J. Anderson, R. True, G. Scheitrum, IEEE International Conference on Plasma Science, Santa Fe June 6-8, Record 94CH3465-2 228 (1994).

"Low Voltage Cerenkov Amplifiers with Periodically Focused Sheet Electron Beams," J. H. Booske, J. E. Scharer, M. A. Basten, J. Joe, H. Kirolos, R. True and G. Scheitrum, Monterey Tube Conference, Monterey, CA. May 10-12 (1994). Published in Conference Proceedings.

"Low-Voltage, Compact Sheet Beam Millimeter-Wave Cerenkov Amplifiers," J. H. Booske, J. E. Scharer, M. Basten, J. Joe, A. H. Kumbasar, B. D. McVey, and R. True, Vacuum Electronics Annual Review Meeting, Crystal City, VA, June 29-July 1 (1993).

"Finite Length Effects and Bandwidth in a Rectangular Cerenkov Amplifier," J. Joe, J. E. Scharer, J. H. Booske, M. Basten, Bull. Am. Phys. Soc. 38, 1939 (1993).

"Nonrelativistic Sheet Electron Beams for Microwave Devices," J. H. Booske, M. A. Basten, J. Joe, A. H. Kimbasar, J. E. Scharer, J. Anderson, UW-Madison, B.

D. McVey, LANL, R. True, G. Scheitrum, Litton, Bull. Am. Phys. Soc. 38, 1938 (1993).

"Experimental Investigation of a Cerenkov Amplifier Utilizing a Sheet Electron Beam," M. A. Basten, J. Joe, A. H. Kimbasar, J. H. Booske, J. E. Scharer, H. Kirolous, UW-Madison, B. D. McVey, LANL, R. True, G. Scheitrum, Litton, Bull. Am. Phys. Soc. 38, 1939 (1993).

"Cold Test and Spontaneous Emission in a Rectangular Cerenkov Amplifier," J. E. Scharer, J. Joe, J. H. Booske, M. Basten, and H. Kirolous, Bull. Am. Phys. Soc. 38, 1939 (1993).

"Analysis and Preliminary Experiments for Rectangular Grating Cerenkov Masers," J. E. Scharer, J. Joe, J. H. Booske, M. Basten and B. D. McVey, IEEE Plasma Conference, Vancouver, BC (1993).

"Experimental Investigation of a Cerenkov Grating Amplifier for Implementation with a Sheet Electron Beam," M. A. Basten, J. Joe, A. H. Kimbasar, J. H. Booske, J. E. Scharer and B. D. McVey, IEEE Plasma Conference, Vancouver, BC (1993).

"Sheet Electron Beam Confinement for Rectangular Cross-Section Cerenkov Amplifiers," J. H. Booske, B. D. McVey, J. Joe, J. E. Scharer, M. Basten, and A. H. Kimbasar, IEEE Plasma Conference, Vancouver, BC (1993).

"Analysis of a Rectangular Grating Cerenkov Maser," J. Joe, J. E. Scharer, J. H. Booske, B. D. McVey and M. Basten, IEEE Plasma Conference, Vancouver, BC (1993).

"Periodic Cusped Magnet Focusing of Sheet Electron Beams," J.H. Booske, B.D. McVey, J. Anderson, J. Joe, J.E. Scharer, T.M. Antonsen, Jr., Bull. Am. Phys. Soc. 37, 1462 (1992).

"Analysis of a Rectangular Grating Cerenkov Amplifier." B. McVey, J. Joe, J. Scharer, J. Booske, Bull. Am. Phys. Soc. 37, 1514 (1992).

"Low-voltage Cerenkov Amplifiers with Rectangular Cross-Section." J. Joe, J.H. Booske, B.D. McVey, J.E. Scharer, M. Yaklich, J. Anderson, Bull. Am. Phys. Soc. 37, 1515 (1992).

"Theoretical and Experimental Progress in Dielectric and Grating Cerenkov Masers with Pencil or Sheet Beams," J. Booske, J.E. Scharer, B.D. McVey, J. Joe, and S.F. Chang, IEEE Plasma Conference, Tampa, FL, June (1992).

"Theoretical and Experimental Progress in Dielectric and Grating Cerenkov Masers with Pencil or Sheet Electron Beams," S.F. Chang, J. Joe, J. Booske, and J.E. Scharer, Bull. Am. Phys. Soc. 36, 2340, Tampa, FL (1991).

"Experiments and Analysis of Wave Absorption and Backscattering in Plasmas," J.E. Scharer, O.C. Eldridge, S.F. Chang, Y.S. Zhang, M.H. Bettenhausen, J. Joe, and N.T. Lam, Bull. Am. Phys. Soc. 36, 2340 (1991) Tampa, FL.

"Grating and Dielectric Cerenkov FEL Gain and Dispersion Analysis," J. Joe, S.F. Chang, J.E. Scharer, and J. Booske, IEEE Plasma Conference, Williamsburg, VA, June (1991).

"Low-Voltage Millimeter-Wave Cerenkov Source Research," J.H. Booske, J.E. Scharer, J. Joe and S.F. Chang, APS 35, 2146, Cincinnati, OH (1990).

"The Grating Cerenkov FEL Gain Analysis and a Design Comparison with the Dielectric Cerenkov FEL," J. Joe, S.F. Chang, J.E. Scharer, and J. Booske, APS 35, 2145, Cincinnati, OH (1990).

"An Optimization Analysis for a Dielectric Cerenkov Maser with Low Beam Voltage," S.F. Chang and J.E. Scharer, APS 35, 2145 (1990), Cincinnati, OH.

"An Optimization Analysis for a Dielectric Cerenkov Maser with Low Beam Voltage," S.F. Chang and J.E. Scharer, APS 35, 2145 (1990), Cincinnati, OH.

"An Efficient Method for Inclusion of Space-charge Forces in the PIANO 3D Multimode Simulation Code," J.E. Scharer and S.F. Chang, APS 35, 2146 (1990), Cincinnati, OH.

b) Consultative/advisory functions to other laboratories and agencies:

No formal such functions were conducted in matters related to this grant during the time of the grant.

c) Transitions:

Both Northrop-Grumman and Litton Electron Devices (San Carlos, CA) have been collaborating in our research, with expectations of implementing forthcoming research results into commercial technology. In particular, Litton has developed two strip (sheet) electron beam thermionic gun designs for use in possible future microwave tubes. The individual associated with this technology development is Dr. Richard True. An important, long-term collaborative relationship has been established with Northrop-Grumman (Rolling Meadows, IL) Corporation. This activity is being coordinated with Dr. Carter Armstrong. Several industrial research grants have already been made by Northrop-Grumman to our institution to supplement our work in this area. One of our former Ph.D. students, Dr. Mark Basten, has joined Northrop-Grumman as a scientist and engineer. The knowledge base he acquired related to our innovative work is expected to find its way into various technological ventures at Northrop-Grumman through Dr. Basten's contributions on current and future vacuum electronic systems development projects. Another of our prior undergraduate students (supported in part by this grant) is also being actively recruited for hire in the vacuum electronics industry.

**NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES**

None filed.

**HONORS/AWARDS SINCE THE BEGINNING OF THIS GRANT (OCTOBER 1, 1991):**

Professor Booske has received several Academic awards or honors:

UW Chancellor's Distinguished Teaching Award (1995)

Elected Fellow of the University of Wisconsin-Madison Teaching Academy (1994)

Co-winner (with undergraduate Jim Anderson) of UW-Heldale Faculty-Undergraduate Research Fellowship (1994) for work on "Stabilizing an Elliptical Sheet Electron Beam Using an Open Configuration of Periodic Cusped Magnets"

Awarded Early Tenure and Promotion (to Associate Professor) in 1994 (anything sooner than 6 years is considered "early"...Professor Booske was selected after 4 years at Madison).

ECE Holdridge Teaching Excellence Award (1994)

Elected to Senior Membership. IEEE (1993)

Elected Honorary Member of Kappa Eta Kappa EE Fraternity (UW-Madison chapter, 1993)

UW-Madison IEEE Professor of the Year (91-92)

U. Wisconsin-Madison Wisconsin Student Association's "Top 100" Educator Award (1991)