

30. Zherlitsyn, A.G. et al., Generation of intense microsecond-length microwave pulses in a virtual-cathode triode, *Sov. Tech. Phys. Lett.*, 11, 450, 1985.
31. Coleman, P.D. and Aurand, V.F., Long pulse virtual cathode oscillator experiments, in *Proceedings of the 1988 IEEE International Conference on Plasma Science*, Seattle, WA, 1988, p. 99.
32. Huttlin, G. et al., Reflex-diode HPM source on Aurora, *IEEE Trans. Plasma Sci.*, 18, 618, 1990, and references therein.
33. Davis, H. et al., Experimental confirmation of the redivron concept, *IEEE Trans. Plasma Sci.*, 16, 192, 1988; Davis, H., Enhanced-efficiency, narrow-band gigawatt microwave output of the redivron oscillator, *IEEE Trans. Plasma Sci.*, 18, 611, 1990.
34. Kwan, T.J. and Davis, H.A., Numerical simulations of the redivron, *IEEE Trans. Plasma Sci.*, 16, 185, 1988.
35. Kwan, T. et al., Beam bunch production and microwave generation in redivrons, *Proc. SPIE*, 1061, 100, 1989.
36. Madonna, R. and Scheno, P., Frequency stabilization of a vircator by use of a slow-wave structure, in *Proceedings of the 1990 IEEE International Conference on Plasma Science*, Oakland, CA, 1990, p. 133.
37. Zherlitsin, A., Melnikov, G., and Fomenko, G., Experimental investigation of the intense electron beam modulation by virtual cathode, in *Proceedings of BEAMS'88*, Karlsruhe, Germany, 1988, p. 1413.
38. Sze, H., Price, D., and Harteneck, B., Phase locking of two strongly coupled vircators, *J. Appl. Phys.*, 67, 2278, 1990.
39. Fazio, M., Hoerberling, R., and Kenross-Wright, J., Narrow-band microwave generation from an oscillating virtual cathode in a resonant cavity, *J. Appl. Phys.*, 65, 1321, 1989.
40. Gadestski, P. et al., The virtode: a generator using supercritical REB current with controlled feedback, *Plasma Phys. Rep.*, 19, 273, 1993.
41. Kitsanov, S.A. et al., S-band vircator with electron beam premodulation based on compact pulse driver with inductive energy storage, *IEEE Trans. Plasma Sci.*, 30, 1179, 2002.
42. Jiang, W. et al., High-power microwave generation by a coaxial virtual cathode oscillator, *IEEE Trans. Plasma Sci.*, 27, 1538, 1999.
43. Jiang, W., Dickens, J., and Kristiansen, M., Efficiency enhancement of a coaxial virtual cathode oscillator, *IEEE Trans. Plasma Sci.*, 27, 1543, 1999.
44. Didenko, A. et al., Investigation of wave electromagnetic generation mechanism in the virtual cathode system, in *Proceedings of BEAMS'88*, Karlsruhe, Germany, 1988, p. 1402.
45. Price, D. and Sze, H., Phase-stability analysis of the magnetron-driven vircator experiment, *IEEE Trans. Plasma Sci.*, 18, 580, 1990.
46. See Dumbrajs, O. and Nusinovich, G.S., Coaxial gyrotrons: past, present, and future (a review), *IEEE Trans. Plasma Sci.*, 32, 934, 2004, and the references therein.
47. Flyagin, V.A. et al., The gyrotron, *IEEE Trans. Microwave Theory Tech.*, MTT-25, 514, 1977.
48. Hirshfield, J.L. and Granatstein, V.L., The electron cyclotron maser: an historical survey, *IEEE Trans. Microwave Theory Tech.*, MTT-25, 522, 1977.
49. Twiss, R.Q., Radiation transfer and the possibility of negative absorption in radio astronomy, *Aust. J. Phys.*, 11, 564, 1958; Twiss, R.Q. and Roberts, J.A., Electromagnetic radiation from electrons rotating in an ionized medium under the action of a uniform magnetic field, *Aust. J. Phys.*, 11, 424, 1958.
50. Schneider, J., Stimulated emission of radiation by relativistic electrons in a magnetic field, *Phys. Rev. Lett.*, 2, 504, 1959.
51. Gaponov, A.V., Addendum, *Izv. VUZ Radiofiz.*, 2, 837, 1959; an addendum to Gaponov, A.V., Interaction between electron fluxes and electromagnetic waves in waveguides, *Izv. VUZ Radiofiz.*, 2, 450, 1959.
52. Hirshfeld, J.L. and Wachtel, J.M., Electron cyclotron maser, *Phys. Rev. Lett.*, 12, 533, 1964.
53. Gaponov, A.V., Petelin, M.I., and Yulpatov, V.K., The induced radiation of excited classical oscillators and its use in high-frequency electronics, *Izv. VUZ Radiofiz.*, 10, 1414, 1967 (*Radiophys. Quantum Electron.*, 10, 794, 1967).
54. Baird, J.M., Gyrotron theory, in *High-Power Microwave Sources*, Granatstein, V.L. and Alexeff, I., Eds., Artech House, Norwood, MA, 1987, p. 103.
55. Gaponov, A.V. et al., Some perspectives on the use of powerful gyrotrons for the electron-cyclotron plasma heating in large tokamaks, *Int. J. Infrared Millimeter Waves*, 1, 351, 1980.
56. See Gaponov, A.V. et al., Experimental investigation of centimeter-band gyrotrons, *Izv. VUZ Radiofiz.*, 18, 280, 1975 (*Radiophys. Quantum Electron.*, 18, 204, 1975).
57. Kisel, D.V. et al., An experimental study of a gyrotron, operating in the second harmonic of the cyclotron frequency, with optimized distribution of the high-frequency field, *Radio Eng. Electron Phys.*, 19, 95, 1974.
58. Litvak, A.G. et al., Gyrotrons for Fusion. Status and Prospects, paper presented at the 18th IAEA Fusion Energy Conference, Sorrento, Italy, 2000 (published online, available from <http://www-naweb.iaea.org/naweb/physics/ps/conf.htm>).
59. Granatstein, V.L. et al., Gigawatt microwave emission from an intense relativistic electron beam, *Plasma Phys.*, 17, 23, 1975.
60. Lawson, W. et al., High-power operation of a three-cavity X-band coaxial gyrokylostron, *Phys. Rev. Lett.*, 81, 3030, 1998.
61. Botvinnik, I.E. et al., Free electron masers with Bragg resonators, *Pis'ma Zh. Eksp. Teor. Fiz.*, 35, 418, 1982 (*JETP Lett.*, 35, 516, 1982).
62. Botvinnik, I.E. et al., Cyclotron-autoresonance maser with a wavelength of 2.4 mm, *Pis'ma Zh. Tekh. Fiz.*, 8, 1386, 1982 (*Sov. Tech. Phys. Lett.*, 8, 596, 1982).
63. Rapoport, G.N., Nematik, A.K., and Zhurakhovskiy, V.A., Interaction between helical electron beams and strong electromagnetic cavity-fields at cyclotron-frequency harmonics, *Radiotek. Elektron.*, 12, 633, 1967 (*Radio Eng. Electron. Phys.*, 12, 587, 1967).
64. Sprangle, P., Vomvoridis, J.L., and Manheimer, W.M., Theory of the quasioptical electron cyclotron maser, *Phys. Rev. A*, 223, 3127, 1981.
65. Nezhevenko, O.A., Gyrocons and magnicons: microwave generators with circular deflection of the electron beam, *IEEE Trans. Plasma Sci.*, 22, 756, 1994.
66. Budker, G.I. et al., The gyrocon: an efficient relativistic high-power VHF generator, *Part. Accel.*, 10, 41, 1979.
67. Bratman, V.L. et al., Millimeter-wave HF relativistic electron oscillators, *IEEE Trans. Plasma Sci.*, PS-15, 2, 1987.

68. Sprangle, P. and Drobot, A.T., The linear and self-consistent nonlinear theory of the electron cyclotron maser instability, *IEEE Trans. Microwave Theory Tech.*, MTT-25, 528, 1977.
69. For a simplified analytical treatment, see Lentini, P.J., *Analytic Theory of the Gyrotron*, PFC/RR-89-6, Plasma Fusion Center, MIT, Cambridge, MA, 1989.
70. Nusinovich, G.S. and Erm, R.E., Efficiency of the CRM-monotron with a Gaussian axial structure of the high-frequency field, *Elektronnaya Tekhnika, Elektronika SVCh*, 8, 55, 1972 (in Russian). Recounted in Nusinovich, G.S., *Introduction to the Physics of Gyrotrons*, Johns Hopkins University Press, Baltimore, MD, 2004, p. 74.
71. Bratman, V.L. et al., Relativistic gyrotrons and cyclotron autoresonance masers, *Int. J. Electron.*, 51, 541, 1981.
72. Danly, B.G. and Temkin, R.J., Generalized nonlinear harmonic gyrotron theory, *Phys. Fluids*, 29, 561, 1986.
73. Chu, K.R. and Hirshfeld, J.L., Comparative study of the axial and azimuthal bunching mechanisms in electromagnetic cyclotron instabilities, *Phys. Fluids*, 21, 461, 1978.
74. As an example, see Kho, T.H. and Lin, A.T., Slow-wave electron cyclotron maser, *Phys. Rev. A*, 38, 2883, 1988.
75. Granatstein, V.L., Gyrotron experimental studies, in *High-Power Microwave Sources*, Granatstein, V.L. and Alexeff, I., Eds., Artech House, Norwood, MA, 1987, p. 185.
76. Temkin, R.J. et al., A 100 kW, 140 GHz pulsed gyrotron, *Int. J. Infrared Millimeter Waves*, 3, 427, 1982.
77. Carmel, Y. et al., Mode competition, suppression, and efficiency enhancement in overmoded gyrotron oscillators, *Int. J. Infrared Millimeter Waves*, 3, 645, 1982.
78. Arfin, B. et al., A high power gyrotron operating in the TE<sub>041</sub> mode, *IEEE Trans. Electron. Dev.*, ED-29, 1911, 1982.
79. See, for example, Carmel, Y. et al., Realization of a stable and highly efficient gyrotron for controlled fusion research, *Phys. Rev. Lett.*, 50, 1121, 1983.
80. See, for example, Luchinin, A.G. and Nusinovich, G.S., An analytical theory for comparing the efficiency of gyrotrons with various electrodynamic systems, *Int. J. Electron.*, 57, 827, 1984.
81. Anderson, J.P. et al., Studies of the 1.5-MW 140-GHz gyrotron experiment, *IEEE Trans. Plasma Sci.*, 32, 877, 2004.
82. Piosczyk, B. et al., 165-GHz coaxial cavity gyrotron, *IEEE Trans. Plasma Sci.*, 32, 853, 2004.
83. Kreischer, K.E. et al., The design of megawatt gyrotrons, *IEEE Trans. Plasma Sci.*, PS-13, 364, 1985.
84. Danly, B.G. et al., Whispering-gallery-mode gyrotron operation with a quasi-optical antenna, *IEEE Trans. Plasma Sci.*, PS-13, 383, 1985.
85. Flyagin, V.A. and Nusinovich, G.S., Gyrotron oscillators, *Proc. IEEE*, 76, 644, 1988.
86. Chu, K.R., Read, M.E., and Ganguly, A.K., Methods of efficiency enhancement and scaling for the gyrotron oscillator, *IEEE Trans. Microwave Theory Tech.*, MTT-28, 318, 1980.
87. Felch, K. et al., Long-pulse and CW tests of a 110-GHz gyrotron with an internal, quasi-optical converter, *IEEE Trans. Plasma Sci.*, 24, 558, 1996.
88. Blank, M. et al., Demonstration of a high-power long-pulse 140-GHz gyrotron oscillator, *IEEE Trans. Plasma Sci.*, 32, 867, 2004.
89. Gold, S.H. et al., High-voltage K<sub>a</sub>-band gyrotron experiment, *IEEE Trans. Plasma Sci.*, PS-13, 374, 1985.
90. Gold, S.H. et al., High peak power K<sub>a</sub>-band gyrotron oscillator experiment, *Phys. Fluids*, 30, 2226, 1987.
91. Gold, S.H., High peak power K<sub>a</sub>-band gyrotron oscillator experiments with slotted and unslotted cavities, *IEEE Trans. Plasma Sci.*, 16, 142, 1988.
92. Black, W.M. et al., Megavolt multikiloamp K<sub>a</sub> band gyrotron oscillator experiment, *Phys. Fluids B*, 2, 193, 1990.
93. Kreischer, K.E. and Temkin, R.J., Single-mode operation of a high-power, step-tunable gyrotron, *Phys. Rev. Lett.*, 59, 547, 1987.
94. Davidovskii, V.Ya., Possibility of resonance acceleration of charged particles by electromagnetic waves in a constant magnetic field, *Zh. Eksp. Teor. Fiz.*, 43, 886, 1962 (*Sov. Phys. JETP*, 16, 629, 1963).
95. Kolomenskii, A.A. and Lebedev, A.N., Self-resonant particle motion in a plane electromagnetic wave, *Dokl. Akad. Nauk SSSR*, 149, 1259, 1962 (*Sov. Phys. Dokl.*, 7, 745, 1963).
96. Bratman, V.L. et al., FELs with Bragg reflection resonators: cyclotron autoresonance masers versus ubitrons, *IEEE J. Quantum Electron.*, QE-19, 282, 1983.
97. Yovchev, I.G. et al., Present status of a 17.1-GHz four-cavity frequency-doubling coaxial gyrokystron design, *IEEE Trans. Plasma Sci.*, 28, 523, 2000.
98. Lawson, W., On the frequency scaling of coaxial gyrokystrons, *IEEE Trans. Plasma Sci.*, 30, 876, 2002.
99. Lawson, W., Ragnunathan, H., and Esteban, M., Space-charge-limited magnetron injection guns for high-power gyrotrons, *IEEE Trans. Plasma Sci.*, 32, 1236, 2004.
100. McCurdy, A.H. et al., Improved oscillator phase locking by use of a modulated electron beam in a gyrotron, *Phys. Rev. Lett.*, 57, 2379, 1986.
101. Freund, H. and Antonsen, T.M., *Principles of Free-Electron Lasers*, 2nd ed., Chapman & Hall, London, 1996.
102. Kapitsa, P.L. and Dirac, P.A.M., *Proc. Cambr. Phil. Soc.*, 29, 247, 1933.
103. Motz, H., Applications of the radiation from fast electrons, *J. Appl. Phys.*, 22, 257, 1951.
104. Phillips, R.M., The ubitron, a high-power traveling-wave tube based on a periodic beam interaction in an unloaded waveguide, *IRE Trans. Electron. Dev.*, ED-7, 231, 1960; Phillips, R.M., History of the ubitron, *Nucl. Instrum. Methods*, A272, 1, 1988.
105. Madey, J.M.J., Stimulated emission of bremsstrahlung in a periodic magnetic field, *J. Appl. Phys.*, 42, 1906, 1971.
106. Elias, L.R. et al., Observation of stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, *Phys. Rev. Lett.*, 36, 717, 1976.
107. Deacon, D.A.G. et al., First operation of a free-electron laser, *Phys. Rev. Lett.*, 38, 892, 1977.
108. Kroll, N.M., Morton, P., and Rosenbluth, M.N., Free-electron lasers with variable parameter wigglers, *IEEE J. Quantum Electron.*, QE-17, 1436, 1981.
109. See, for example, Fajans, J. et al., Microwave studies of a tunable free-electron laser in combined axial and wiggler magnetic fields, *Phys. Fluids*, 26, 2683, 1983.
110. Gold, S.H. et al., Study of gain, bandwidth, and tunability of a millimeter-wave free-electron laser operating in the collective regime, *Phys. Fluids*, 26, 2683, 1983.

111. Latham, P.E. and Levush, B., The interaction of high- and low-frequency waves in a free electron laser, *IEEE Trans. Plasma Sci.*, 18, 472, 1990.
112. Instabilities can be convective and absolute, a subject beyond our scope here, but the classic treatment is Briggs, R.J., *Electron Stream Interaction with Plasma*, MIT Press, Cambridge, MA, 1964, chap. 2.
113. Liewer, P.C., Lin, A.T., and Dawson, J.M., Theory of an absolute instability of a finite-length free-electron laser, *Phys. Rev. A*, 23, 1251, 1981.
114. Kwan, T.J.T., Application of particle-in-cell simulation in free-electron lasers, *IEEE J. Quantum Electron.*, QE-17, 1394, 1981.
115. Kroll, N.M. and McMullin, W.A., Stimulated emission from relativistic electron passing through a spatially periodic transverse magnetic field, *Phys. Rev. A*, 17, 300, 1978; Sprangle, P. and Smith, R.A., Theory of free-electron lasers, *Phys. Rev. A*, 21, 293, 1980.
116. Friedland, L., Electron beam dynamics in combined guide and pump magnetic fields for free electron laser applications, *Phys. Fluids*, 23, 2376, 1980; Freund, H.P. and Drobot, A.T., Relativistic electron trajectories in free electron lasers with an axial guide field, *Phys. Fluids*, 25, 736, 1982; Freund, H.P. and Ganguly, A.K., Electron orbits in free-electron lasers with helical wiggler and an axial guide magnetic field, *IEEE J. Quantum Electron.*, QE-21, 1073, 1985.
117. Jackson, R.H. et al., Design and operation of a collective millimeter-wave free-electron laser, *IEEE J. Quantum Electron.*, QE-19, 346, 1983.
118. Freund, H.P. et al., Collective effects on the operation of free-electron lasers with an axial guide field, *Phys. Rev. A*, 26, 2004, 1982; Freund, H.P. and Sprangle, P., Unstable electrostatic beam modes in free-electron-laser systems, *Phys. Rev. A*, 28, 1835, 1983.
119. Parker, R.K. et al., Axial magnetic-field effects in a collective-interaction free-electron laser at millimeter wavelengths, *Phys. Rev. Lett.*, 48, 238, 1982.
120. Conde, M.E., Bekefi, G., and Wurtele, J.S., A 33 GHz free electron laser with reversed axial guide magnetic field, in *Abstracts for the 1991 IEEE International Conference on Plasma Science*, Williamsburg, VA, 1991, p. 176.
121. Pasour, J.A., Free-electron lasers, in *High-Power Microwave Sources*, Granatstein, V.L. and Alexeff, I., Eds., Artech House, Norwood, MA, 1987.
122. Orzechowski, T.J. et al., High gain and high extraction efficiency from a free electron laser amplifier operating in the millimeter wave regime, *Nucl. Instrum. Methods*, A250, 144, 1986.
123. Freund, H.P. and Ganguly, A.K., Nonlinear analysis of efficiency enhancement in free-electron laser amplifiers, *Phys. Rev. A*, 33, 1060, 1986.
124. Kroll, N.M. and Rosenbluth, M.N., *Physics of Quantum Electronics*, Vol. 7, Jacobs, S.F. et al., Eds., Addison-Wesley, Reading, MA, 1980, p. 147.
125. Colson, W.B. and Freedman, R.A., Synchrotron instability for long pulses in free electron laser oscillator, *Opt. Commun.*, 46, 37, 1983.
126. Colson, W.B., The trapped-particle instability in free electron laser oscillators and amplifiers, *Nucl. Instrum. Methods*, A250, 168, 1986.
127. Masud, J. et al., Sideband control in a millimeter-wave free-electron laser, *Phys. Rev. Lett.*, 58, 763, 1987.
128. Yu, S.S. et al., Waveguide suppression of the free electron laser sideband instability, *Nucl. Instrum. Methods*, 259, 219, 1987.
129. Yee, F.G. et al., Power and sideband studies of a Raman FEL, *Nucl. Instrum. Methods*, A259, 104, 1987.
130. Throop, A.L. et al., Experimental Characteristic of a High-Gain Free-Electron Laser Amplifier Operating at 8-mm and 2-mm Wavelengths, UCRL-95670, Lawrence Livermore National Laboratory, Livermore, CA, 1987.
131. Hester, R.E. et al., The Experimental Test Accelerator (ETA), *IEEE Trans. Nucl. Sci.*, NS-26, 3, 1979.
132. Orzechowski, T.J. et al., High-efficiency extraction of microwave radiation from a tapered-wiggler free-electron laser, *Phys. Rev. Lett.*, 57, 2172, 1986.
133. Allen, S.L. et al., Generation of high power 140 GHz microwaves with an FEL for the MTX experiment, in *Proceedings of the 1993 Particle Accelerator Conference*, Washington, D.C., 1993, p. 1551.
134. Lasnier, C.J. et al., Burst mode FEL with the ETA-III induction linac, in *Proceedings of the 1993 Particle Accelerator Conference*, Washington, D.C., 1993, p. 1554.
135. Vinokurov, N.A. and Skriniski, A.N., Institute of Nuclear Physics Preprint INP 11-59, Novosibirsk, 1977.
136. Leibovitch, C., Xu, K., and Bekefi, G., Effects of electron prebunching on the radiation growth rate of a collective (Raman) free-electron laser amplifier, *IEEE J. Quantum Electron.*, 24, 1825, 1988.
137. Wurtele, J.S. et al., Prebunching in a collective Raman free-electron laser amplifier, *Phys. Fluids B*, 2, 402, 1990.
138. Fajans, J. and Wurtele, J.S., Suppression of feedback oscillations in a free-electron laser, *IEEE J. Quantum Electron.*, 24, 1805, 1990.
139. Agafonov, M.A. et al., Generation of hundred joules pulses at 4-mm wavelength by FEM with sheet electron beam, *IEEE Trans. Plasma Sci.*, 26, 531, 1998.

# Appendix

## *High Power Microwave Formulary*

For plasma physics and much else, see the NRL Plasma Formulary, <http://www.ppd.nrl.navy.mil/nrlformulary/>. Much microwave information appears in *Microwave Engineers' Handbook*, Volumes 1 and 2, Artech House, Norwood, MA.

### A.1 Electromagnetism

- *Definitions of Q:*

$$1. \quad Q = 2\pi \frac{\text{average stored energy}}{\text{energy lost per cycle}} = \omega_0 \frac{\text{average stored energy}}{\text{power loss rate}}$$

$\omega_0$  is the center frequency of a cavity of resonant line width  $\Delta\omega$ ,

$$2. \quad Q = \frac{\omega_0}{2\Delta\omega}$$

$$3. \quad Q_p = \frac{\text{cavity volume}}{(\text{surface area}) \times \delta} \times (\text{geometrical factor})$$

The geometrical factor is typically of order unity.

4. The number of cycles in a pulse, the bandwidth, and the Q of the resonant system that produces a pulse are related by

$$N = 1/\text{percentage bandwidth} = Q$$

5. The radiated energy loss time constant from the cavity  $T_r$ , as the ratio of the stored energy to the power lost from the cavity, is

$$Q_r = \omega_0 T_r$$

6. If the cavity has highly reflecting ends with reflection coefficients  $R_1$  and  $R_2$ , then

$$T_r \approx \frac{L}{v_g (1 - R_1 R_2)}$$

- Skin depth:

$$\delta = \frac{1}{(\pi \sigma \mu \omega_f)^{1/2}} = \frac{1}{(\pi \sigma \mu_0 f)^{1/2}}$$

In copper,  $\sigma = 5.80 \times 10^7 (\Omega\text{-m})^{-1}$ ; skin depth at 1 GHz is 2.1  $\mu\text{m}$ .

**TABLE A.1**

Conductivities of Some Materials

Material	Conductivity ( $\Omega\text{-m}$ ) <sup>-1</sup>
Aluminum	$3.82 \times 10^7$
Brass	$2.6 \times 10^7$
Copper	$5.8 \times 10^7$
Gold	$4.1 \times 10^7$
Graphite	$7 \times 10^4$
Iron	$1.03 \times 10^7$
Lead	$4.6 \times 10^6$
Sea water	3–5
Silver	$6.2 \times 10^7$
Stainless steel	$1.1 \times 10^6$

## A.2 Waveguides and Cavities

**TABLE A.2**

Expressions for the TM and TE Field Quantities for a Rectangular Waveguide in Terms of the Axial Field Component, Derived from Equations 4.1 to 4.4

Transverse Magnetic, TM <sub>n,p</sub>	Transverse Electric, TE <sub>n,p</sub>
$E_z = D \sin\left(\frac{n\pi}{a}x\right) \sin\left(\frac{p\pi}{b}y\right)$	$B_z = A \cos\left(\frac{n\pi}{a}x\right) \cos\left(\frac{p\pi}{b}y\right)$
$B_z \equiv 0$	$E_z \equiv 0$
$E_x = i \frac{k_z}{k_\perp^2} \frac{\partial E_z}{\partial x}$	$E_x = i \frac{\omega}{k_\perp^2} \frac{\partial B_z}{\partial y}$
$E_y = -i \frac{k_z}{k_\perp^2} \frac{\partial E_z}{\partial y}$	$E_y = -i \frac{\omega}{k_\perp^2} \frac{\partial B_z}{\partial x}$
$B_x = -i \frac{\omega}{\omega_{co}^2} \frac{\partial E_z}{\partial y}$	$B_x = i \frac{k_z}{k_\perp^2} \frac{\partial B_z}{\partial x}$
$B_y = i \frac{\omega}{\omega_{co}^2} \frac{\partial E_z}{\partial x}$	$B_y = i \frac{k_z}{k_\perp^2} \frac{\partial B_z}{\partial y}$
$\omega_{co} = k_\perp c = \left[ \left( \frac{n\pi c}{a} \right)^2 + \left( \frac{p\pi c}{b} \right)^2 \right]^{1/2}$	

**TABLE A.3**

Cutoff Frequencies, Measured in GHz, for the Lowest-Order Modes of WR284 Waveguide

n	p	$f_{co} = \omega_{co}/2\pi$ (GHz)
1	0	2.079
0	1	4.407
1	1	4.873
1	2	9.055
2	0	4.159
2	1	6.059

TABLE A.4

Expressions for the TM and TE Field Quantities for Circular Waveguide in Terms of the Axial Field Components, Derived from Equations 4.1 to 4.4

Transverse Magnetic, TM <sub>n,p</sub> (B <sub>z</sub> = 0)	Transverse Electric, TE <sub>n,p</sub> (E <sub>z</sub> = 0)
$E_z = DJ_p(k_{\perp}r)\sin(p\theta)$	$B_z = AJ_p(k_{\perp}r)\sin(p\theta)$
$E_r = i \frac{k_z}{k_{\perp}^2} \frac{\partial E_z}{\partial r}$	$E_r = i \frac{\omega}{k_{\perp}^2} \frac{1}{r} \frac{\partial B_z}{\partial \theta}$
$E_{\theta} = i \frac{k_z}{k_{\perp}^2} \frac{1}{r} \frac{\partial E_z}{\partial \theta}$	$E_{\theta} = -i \frac{\omega}{k_{\perp}^2} \frac{\partial B_z}{\partial r}$
$B_r = -i \frac{\omega}{\omega_{co}^2} \frac{1}{r} \frac{\partial E_z}{\partial \theta}$	$B_r = i \frac{k_z}{k_{\perp}^2} \frac{\partial B_z}{\partial r}$
$B_{\theta} = i \frac{\omega}{\omega_{co}^2} \frac{\partial E_z}{\partial r}$	$B_{\theta} = i \frac{k_z}{k_{\perp}^2} \frac{1}{r} \frac{\partial B_z}{\partial \theta}$
$k_{\perp} = \frac{\omega_{co}}{c} = \frac{\mu_{pn}}{r_0}$	$k_{\perp} = \frac{\omega_{co}}{c} = \frac{v_{pn}}{r_0}$
$J_p(\mu_{pn}) = 0$	$J'_p(v_{pn}) = 0$

TABLE A.5

Relationship between the Power in a Given Mode, P, and the Maximum Value of the Electric Field at the Wall, E<sub>wall,max</sub>

Mode	
Rectangular	
TM	$P_{TM} = \frac{ab}{8Z_0} \left[ \left( \frac{n}{a} \right)^2 + \left( \frac{p}{b} \right)^2 \right] \frac{1}{\left[ 1 - \left( \frac{f_{co}}{f} \right)^2 \right]^{1/2}} \min \left[ \left( \frac{a}{n} \right)^2, \left( \frac{b}{p} \right)^2 \right] E_{wall,max}^2$
TE n, p > 0	$P_{TE} = \frac{ab}{8Z_0} \left[ \left( \frac{n}{a} \right)^2 + \left( \frac{p}{b} \right)^2 \right] \left[ 1 - \left( \frac{f_{co}}{f} \right)^2 \right]^{1/2} \min \left[ \left( \frac{a}{n} \right)^2, \left( \frac{b}{p} \right)^2 \right] E_{wall,max}^2$
TE n or p = 0	$P_{TE} = \frac{ab}{4Z_0} \left[ \left( \frac{n}{a} \right)^2 + \left( \frac{p}{b} \right)^2 \right] \left[ 1 - \left( \frac{f_{co}}{f} \right)^2 \right]^{1/2} \min \left[ \left( \frac{a}{n} \right)^2, \left( \frac{b}{p} \right)^2 \right] E_{wall,max}^2$

Continued.

TABLE A.5 (Continued)

Relationship between the Power in a Given Mode, P, and the Maximum Value of the Electric Field at the Wall, E<sub>wall,max</sub>

Mode	
Circular	
TM	$P_{TM} = \frac{\pi r_0^2}{4Z_0} \frac{E_{wall,max}^2}{\left[ 1 - \left( \frac{f_{co}}{f} \right)^2 \right]^{1/2}}$
TE p > 0	$P_{TE} = \frac{\pi r_0^2}{2Z_0} \left[ 1 - \left( \frac{f_{co}}{f} \right)^2 \right]^{1/2} \left[ 1 + \left( \frac{v_{pn}}{p} \right)^2 \right] E_{wall,max}^2$

Note: Min(x, y) is the smaller of x and y, and Z<sub>0</sub> = 377 Ω.

TABLE A.6

Standard Rectangular Waveguides

Band (Alternate)	Recommended Frequency Range (GHz)	TE <sub>10</sub> Cutoff Frequency (GHz)	WR Number	Inside Dimensions, Inches (cm)
L	1.12–1.70	0.908	650	6.50 × 3.25 (16.51 × 8.26)
R	1.70–2.60	1.372	430	4.30 × 2.15 (10.92 × 5.46)
S	2.60–3.95	2.078	284	2.84 × 1.34 (7.21 × 3.40)
H (G)	3.95–5.85	3.152	187	1.87 × 0.87 (4.76 × 2.22)
C (J)	5.85–8.20	4.301	137	1.37 × 0.62 (3.49 × 1.58)
W (H)	7.05–10.0	5.259	112	1.12 × 0.50 (2.85 × 1.26)
X	8.20–12.4	6.557	90	0.90 × 0.40 (2.29 × 1.02)
Ku (P)	12.4–18.0	9.486	62	0.62 × 0.31 (1.58 × 0.79)
K	18.0–26.5	14.047	42	0.42 × 0.17 (1.07 × 0.43)
Ka (R)	26.5–40.0	21.081	28	0.28 × 0.14 (0.71 × 0.36)
Q	33.0–50.5	26.342	22	0.22 × 0.11 (0.57 × 0.28)
U	40.0–60.0	31.357	19	0.19 × 0.09 (0.48 × 0.24)

Continued.

TABLE A.6 (Continued)

Standard Rectangular Waveguides

Band (Alternate)	Recommended Frequency Range (GHz)	TE <sub>10</sub> Cutoff Frequency (GHz)	WR Number	Inside Dimensions, Inches (cm)
V	50.0–75.0	39.863	15	0.15 × 0.07 (0.38 × 0.19)
E	60.0–90.0	48.350	12	0.12 × 0.06 (0.31 × 0.02)
W	75.0–110.0	59.010	10	0.10 × 0.05 (0.25 × 0.13)
F	90.0–140.0	73.840	8	0.08 × 0.04 (0.20 × 0.10)
D	110.0–170.0	90.854	6	0.07 × 0.03 (0.17 × 0.08)
G	140.0–220.0	115.750	5	0.05 × 0.03 (0.13 × 0.06)

## A.3 Pulsed Power and Beams

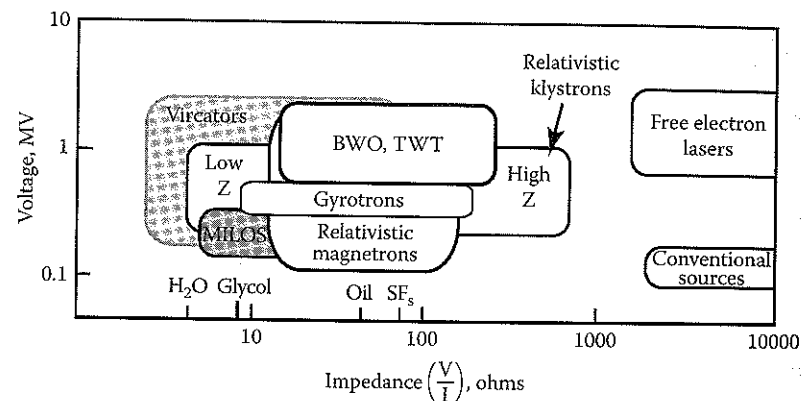


FIGURE A.1

Voltage and impedance of parameter space for HPM and pulsed conventional sources and optimum impedances for widely used pulse line insulators (water, glycol, oil, SF<sub>6</sub>).

- Below are optimum impedances of pulse-forming lines, maximizing energy density:

- Oil line, 42 Ω
- Ethylene glycol line, 9.7 Ω
- Water line, 6.7 Ω

- On the other hand, liquid energy density is largest for water (0.9 relative to mylar), intermediate for glycol (0.45), and lowest for oil (0.06).

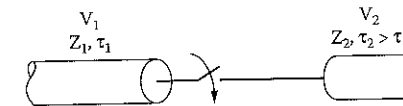
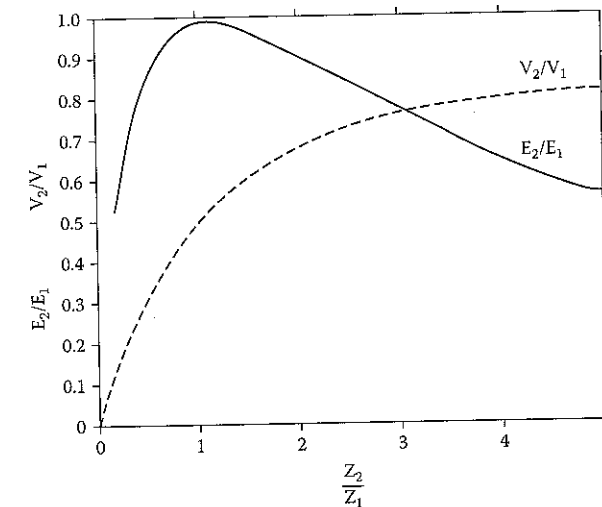


FIGURE A.2

Energy transfer and voltage ratios between transmission line (1) and load (2) as a function of impedance ratio.

## Diodes and Beams

- Child–Langmuir current density, impedance:

$$J_{SCL} \left( \frac{kA}{cm^2} \right) = 2.33 \frac{[V_0 (MV)]^{3/2}}{[d (cm)]^2}$$

$$I_{SCL} (kA) = J_{SCL} A = 7.35 [V_0 (MV)]^{3/2} \left[ \frac{r_c (cm)}{d (cm)} \right]^2$$

$$Z_{SCL} (\Omega) = \frac{136}{\sqrt{V_0 (MV)}} \left[ \frac{d}{r_c} \right]^2$$



- Relativistic Child–Langmuir current density:

$$J \left( \frac{\text{kA}}{\text{cm}^2} \right) = \frac{2.71}{[d(\text{cm})]^2} \left[ \left( 1 + \frac{V_0(\text{MV})}{0.511} \right)^{1/2} - 0.847 \right]^2$$

- Diode pinch current:

$$I_{\text{pinch}}(\text{kA}) = 8.5 \frac{r_c}{d} \left[ 1 + \left( \frac{V_0(\text{MV})}{0.511} \right) \right]$$

- Parapotential current, impedance; magnetic insulation current  $I_z$  must exceed the parapotential current:

$$I_z > I_p(A) = 8500 \gamma G \ell n \left( \gamma + \sqrt{\gamma^2 - 1} \right)$$

where  $\gamma$  is a relativistic factor and  $G$  is a geometric factor.

$G = [\ell n(b/a)]^{-1}$ , coaxial cylinders of inner and outer radii  $b$  and  $a$  and  $G = W/2\pi d$ , parallel plates of width  $W$ , gap  $d$ .

$Z_p = V/I_p \approx 52G^{-1} \Omega$  for voltages  $\sim 1$  MV.

## A.4 Microwave Sources

TABLE A.7

Classification of HPM Sources

	Slow Wave	Fast Wave
O-Type	Backward wave oscillator Traveling wave tube Surface wave oscillator Relativistic diffraction generator Orotron Flimatron Multiwave Cerenkov generator Dielectric Cerenkov maser Plasma Cerenkov maser Relativistic klystron	Free-electron laser (ubitron) Optical klystron Gyrotron Gyro-BWO Gyro-TWT Cyclotron autoresonance maser Gyroklystron
M-Type	Relativistic magnetron Cross-field amplifier Magnetically insulated line oscillator	Rippled-field magnetron
Space-Charge	Vircator Reflex triode	

TABLE A.8

General Features of HPM Sources

Source	Operating Frequency	Efficiency	Complexity	Level of Development
Magnetron	1–9 GHz, BW $\sim 1\%$	10–30%	Low	High
O-type Cerenkov devices	3–60 GHz, somewhat tunable	10–50%	Medium to high	High
Vircator	0.5–35 GHz, wide BW ( $\lesssim 10\%$ ), tunable	$\sim 1\%$ simple $\sim 10\%$ advanced	Low	Medium
Electron cyclotron masers	5–300 GHz for gyrotrons, higher for CARMs	30% typical	Medium	High for gyrotrons Low for CARMs
FEL	8 GHz and up, tunable	35%	High	Medium to high
Relativistic klystron	1–11 GHz	25–50%	Medium to high	Medium

- Phase locking condition, known as Adler's relation:

$$\Delta\omega \leq \frac{\omega_0 P}{Q}$$



$\omega_0$  is the mean frequency of the two oscillators, which have the same  $Q$ . The injection ratio is

$$\rho = \left( \frac{P_i}{P_0} \right)^{1/2} = \frac{E_i}{E_0}$$

Subscripts  $i$  and  $0$  denote the injecting (or master) and receiving (or slave) oscillators. Phase locking occurs when the frequency difference between the two oscillators is sufficiently small. The timescale for locking is given by

$$\tau \sim \frac{Q}{2\rho\omega_0}$$

For  $\rho \sim 1$ , the locking range  $\Delta\omega$  is maximized and the timescale for locking is minimized.

TABLE A.9

Ultrawideband Band Regions

Bands		Percent Bandwidth, $100 \Delta f/f$	Bandwidth Ratio, $1 + \Delta f/f$	Example
Narrowband		<1%	1.01	Orion (Figures 5.31 and 7.24)
Ultrawideband	Moderate band (mesoband)	1–100%	1.01–3	MATRIX (Figure 6.11)
	Ultramoderate band (subhyperband)	100–163%	3–10	H-Series (Figure 6.16)
	Hyperband	163–200%	>10	Jolt (Figure 6.17)

## A.5 Propagation and Antennas

- *Power density:* Critical fluence for air breakdown for pulses longer than a microsecond:

$$S \left[ \frac{\text{MW}}{\text{cm}^2} \right] = 1.5\rho^2 (\text{atm})$$

where  $S$  is microwave power density and  $\rho$  is the pressure in units of an atmosphere. This corresponds to a critical field of 24 kV/cm at atmospheric pressure. The field due to microwave power density is

$$E(\text{V/cm}) = 19.4 [S(\text{W/cm}^2)]^{1/2}$$

$$S(\text{W/cm}^2) = E^2(\text{V/cm})/377$$

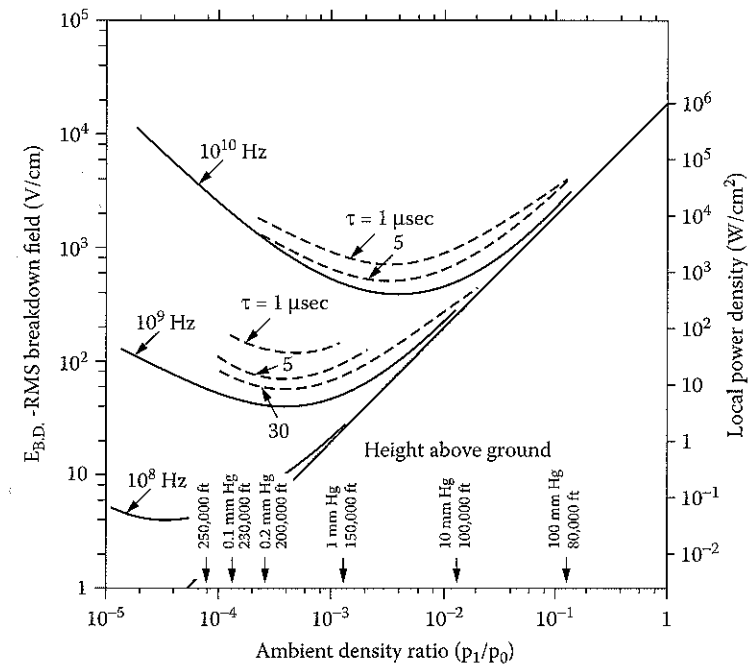


FIGURE A.3

Dependence of breakdown on pressure, frequency, and pulse duration.

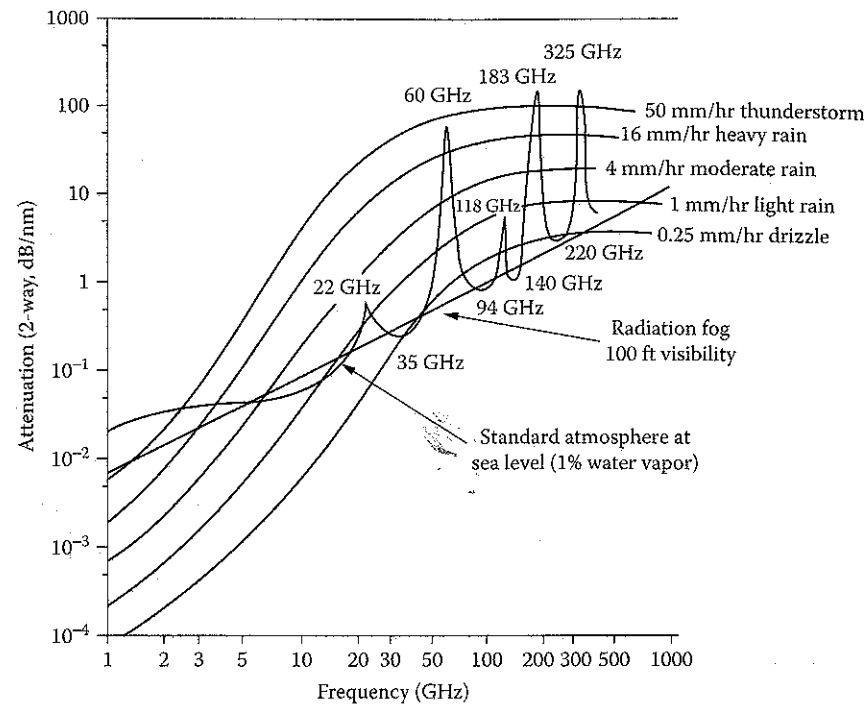


FIGURE A.4

Absorption in the air by water and oxygen molecules gives passbands at 35, 94, 140, and 220 GHz.

- **Directive gain:** The directive gain of an antenna is its ability to concentrate radiated power in a solid angle,  $\Omega_A$ , producing a power density  $S$  at range  $R$  due to power  $P$ :

$$G_D = \frac{4\pi}{\Omega_A} = \frac{4\pi}{\Delta\theta\Delta\phi} = \frac{4\pi R^2}{P} S$$

Beam widths in the two transverse dimensions are  $\Delta\theta$  and  $\Delta\phi$ . The gain,  $G$ , is  $G_D$  times the antenna efficiency and can be expressed in terms of wavelength and area,  $A = \pi D^2/4$ :

$$G = G_D = \frac{4\pi A\epsilon}{\lambda^2}$$

GP is the *effective radiated power* (ERP). The common way to describe gain is in decibels,  $G_{dB}$ . This value corresponds to an actual numerical value of

$$G = 10^{G_{dB}/10}$$

so a gain of 100 is called 20 dB.

The far field of a narrowband antenna begins at

$$L_{ff} = \frac{2D^2}{\lambda}$$

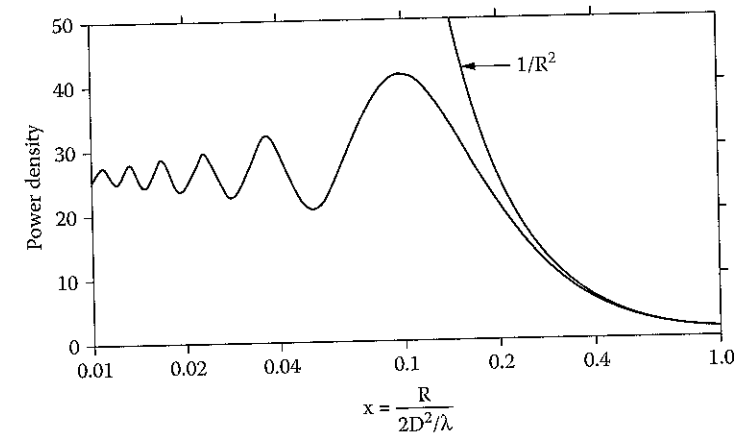


FIGURE A.5

Horn antenna intensity normalized to unity at  $2D^2/\lambda$ . Its general features are the same for most antenna types.

TABLE A.10

## Principal Antenna Types

Antenna	Gain	Comments
Pyramidal and TEM horn	$2\pi ab/\lambda^2$	For standard gain horn; sides $a, b$ ; lengths $l_e = b^2/2\lambda$ , $l_h = a^2/3\lambda$ $l = D^2/3\lambda$ ; $D$ = diameter
Conical horn	$5 D^2/\lambda^2$	
Parabolic dish	$5.18 D^2/\lambda^2$	
Vlasov	$6.36 [D^2/\lambda^2]/\cos \theta$	Angle of slant-cut $\theta$ , $30^\circ < \theta < 60^\circ$
Biconic	$120 \cot \alpha/4$	$\alpha$ is the bicone opening angle
Helical	$[148 N S/\lambda] D^2/\lambda^2$	$N$ = number of turns; $S$ = spacing between turns
Array of horns	$9.4 AB/\lambda^2$	$A, B$ are sides of the array

The diffraction-limited beam width is

$$\theta = 2.44 \lambda/D_t$$

This is the diffraction-limited divergence, giving the first null point of the Bessel function for a circular aperture and including 84% of the beam power. The size of this spot at range R is

$$D_s = \theta R = 2.44 \lambda R/D_t$$

## A.6 Applications

Electronics effects power coupled to internal circuitry, P, from an incident power density S is characterized by a coupling cross section s, with units of area:

$$P = S \sigma$$

For frontdoor paths,  $\sigma$  is usually the effective area of an aperture, such as an antenna or slot.

The Wunsch-Bell relation for the power to induce failure is

$$P \sim \frac{1}{\sqrt{t}}$$

where t is the pulse duration, applicable between >100 nsec and <10  $\mu$ sec.

TABLE A.11

Categories and Consequences of Electronic Effects

Failure Mode	Power Required	Wave Shape	Recovery Process	Recovery Time
Interference/disturbance	Low	Repetitive pulse or continuous	Self-recovery	Seconds
Digital upset	Medium	Short pulse, single or repetitive	Operator intervention	Minutes
Damage	High	UWB or narrowband	Maintenance	Days

## Power Beaming

The power-link parameter is

$$Z = \frac{D_t D_r}{\lambda R}$$

where  $D_t$  and  $D_r$  are the diameters of the transmitting and receiving antennas and R is the distance between the transmitter and receiver. For efficient transfer, the spot size must be  $\sim D_r$  and  $Z \geq 1$ . An approximate analytic expression, good for  $Z \sim 1$ , is

$$\frac{P_r}{P_t} = 1 - e^{-Z^2}$$

## Plasma Heating

Plasma heating resonant frequencies follow:

- Ion cyclotron resonance heating (ICRH)

$$f = f_{ci} = \frac{eB}{2\pi m_i}$$

- Lower hybrid heating (LHH)

$$f = f_{LH} \cong \left( \frac{f_{pi}}{1 - \frac{f_{pe}^2}{f_{ce}^2}} \right)^{1/2}$$

- Electron cyclotron resonance heating (ECRH)

$$f = f_{ce} = \frac{eB}{2\pi m_e}, \text{ or } f = 2f_{ce}$$

where  $m_i$  and  $m_e$  are the ion and electron masses, B is the magnitude of the local magnetic field,  $f_{pe} = (n_e e^2 / \epsilon_0 m_e)^{1/2} / 2\pi$ , with  $n_e$  the volume density of electrons and  $\epsilon_0$  the permittivity of vacuum, and  $f_{pi} = (n_i Z_i^2 e^2 / \epsilon_0 m_i)^{1/2} / 2\pi$ , with  $Z = 1$  the charge state of the ions in the fusion plasma. At the densities and field values necessary for fusion,  $f_{ci} \approx 100$  MHz,  $f_{LH} \approx 5$  GHz, and  $f_{ce} \approx 140$  to 250 GHz.

# Index

## A

- Active Denial (pain gun), 55–57
- Adler's relation, 173–174, 456–457
- Amplifier, 171, 326, 336
- Antenna, 202–214, 246–249
  - amplitude taper, 73
  - arrays, 210–212
  - atmospheric passbands, 208
  - breakdown, 206
  - dB, 204
  - far-field region, 205, 249
  - FLAPS, 55, 57
  - Gain, 204, 209
  - Horn, 213
  - linking parameter set, 24–25
  - narrowband, 208
  - regions, 203–4
  - side-lobes, 73–74, 205–6
  - SuperSystem, 31–32
  - Vlasov, 209–211
  - wideband, 212
- Anti-radiation missiles (ARMs), 53
- Applegate diagram (*see also* Klystron), 386–387
- Applications, 43–108
- ASAT (anti-satellite), 59
- A6 magnetron, 144, 261, 275, 277–279
  - dispersion relation, 144, 268

## B

- Beam pinching, 153
- Beam plasma frequency, 162
- Benford, G.
- Benford, J., 282, 282, 307
- Bessel functions, 122
- Brillouin layer, 159, 273
- Brown, W. 76
- Bunching, 161

- Buneman-Hartree condition, 268, 273–274, 280, 308
- role in relativistic magnetron pulse shortening, 294–295
- Burst mode, 21, 27, 39
- BWO (backward wave oscillator), 163–164
  - axially-varying slow-wave structure, 360
  - cross-excitation instability, 339–340
  - dispersion relation, 329, 332–334
    - references, 331
  - growth rate, 333
  - history, 322–323
  - low magnetic field operation, 359–360
  - magnetic field effect, 338
  - mode selection, 336
  - overbunch instability, 339
  - performance, 322, 346, 350–351
  - plasma-filled, 361
  - pulse shortening, 357–359
  - resonance BWO, 351–352
  - simulations, 342–343
  - slow-wave structures, 326
  - smooth-wall sections to enhance efficiency, 344–345
  - start current, 336–338
  - SuperSystem, 32,

## C

- Calorimeter, 220
- Cathodes, 191–195
  - CSi-coated, 193
  - emission mechanisms, 191
  - gap closure (*see also* pulse shortening), 192
  - materials, 192
  - outgassing, 193
  - thermionic, 193–194
  - transparent-cathode magnetron, 299–300
- Cavities, 144–148
  - modes, 145
  - power handling, 124–133
  - quality factor, Q, 146–148
  - reentrant, 139

Child-Langmuir diodes, 149–151, 195–197  
   relativistic (Jory-Trivelpiece), 152  
   Langmuir-Blodgett (cylindrical), 151–152  
 Chirp, 216  
 Choppertron, 402–403  
 CLIA (Compact Linear Induction Accelerator) (*see also* voltage adder), 288–290  
 Coaxial magnetron, 261  
 Compton regime of operation, 172, 486  
 Cost structure (*see also* power beaming), 82–85  
 Crossed-field devices, 259  
 Crossed-field amplifier (CFA), 168, 260, 314  
   history, 261  
   schematic diagram, 264  
 Cross-excitation instability, 339–340  
 Cutoff frequency, 114–115, 120, 381  
   circular waveguide, 122, 123  
   physical interpretation, 118–119  
   rectangular waveguide, 116, 117, 120  
 Cyclotron autoresonant maser (CARM), 166, 460, 473–475

## D

Deployment of space structures, 90  
 Diagnostics, 214–222  
   Calorimeter, 220  
   dispersive line, 216  
   energy, 220  
   frequency, 216  
   heterodyne, 216  
   magnetrons, relativistic, 285  
   phase, 220  
   power, 215  
   principal quantities, 215  
   time-frequency analysis, 219  
 Dickinson, R., 75, 81, 90, 91  
 Dielectric Cerenkov maser (DCM), 163–164, 361  
   history, 324  
 Diffraction coupling, 284  
 Diodes, 149–153, 195–197  
   beam pinching, 153  
   Child-Langmuir, 151, 195–197  
   Langmuir-Blodgett (cylindrical), 151–152  
 Directed Energy Weapons (DEW), 9, 45  
 Dispersion relation, 115  
   axially-varying slow-wave structure, 136–138  
   azimuthally-varying slow-wave structure, 139–144  
   electron cyclotron waves, 166, 464

free-electron laser, 484  
 magnetron, relativistic, 268  
 magnetron, rising-sun, 272  
 space-charge waves, 162–163  
 surface-wave oscillator (SWO), 329  
 waveguides, 114  
 Duty factor, 287

## E

E-Bombs, (*see also* HPM weapons) 53–54  
 ECCM (electronic counter-countermeasures), 48  
 ECM (electronic countermeasures), 44, 48  
 Efficiency  
   energy, 6  
   power, 7, 52  
   transfer, 180–182  
 Electromagnetic terrorism, 60  
 Electron beams, 148–157, 191–197  
   current-energy relationship, 155, 380  
   energy, in a drift tube, 155  
   fast rotational mode, 156–157  
   maximum power in a drift tube, 341–342  
   slow-rotational mode, 156–157  
 Electron cyclotron frequency, 166, 462  
 Electron cyclotron masers, 166  
   classification, 465  
   history, 459–460  
 Electron cyclotron waves, 166, 464  
 Electronic warfare (EW), 47–48  
 Electromagnetic coupling, 62–65  
 Emission, 194–195  
 ETA, ETA II, ETA III (Experimental Test Accelerator), 492  
 Explosive generator, (*see* flux compressors), 186

## F

Figure of merit  
   flux compressor, 186  
   UWB far voltage, 238, 248  
 Fill time for a cavity, 148  
 Floquet's theorem, 135  
 Flux compressors, 26–27, 54, 186–189, 314  
 Forward, R., 85  
 Free Electron Lasers (FEL), 99, 165, 480–496  
   dispersion relation, 484  
   electron orbits, 486–487  
   frequency scaling, 482–483  
   history, 480–481  
   optical klystron, 167, 492, 494–495

ponderomotive potential, 482, 488  
 repetitive operation, 492, 494  
 saturation of growth, 488  
 scatrons, 167  
 sheet beam, 494–495  
 sideband instability, 489–490  
 strengths and weaknesses, 497  
 synchrotron oscillations, 487  
 two-stage, 167  
 wiggler tapering, 488, 493  
 Frequency pulling, 171  
 Frequency pushing, 171  
 Free-space impedance, 125  
 Fusion, 91

## G

GAMMA accelerator, 346–347  
 Gap closure, 281  
 Gigawatt Multibeam Klystron (GMBK), 415–416  
   performance, 423  
 Grating lobes, 211  
 Group velocity, 120  
 Gyrocon, 460  
 Gyroklystron, 167, 460, 475–478  
   performance, 477  
   phase locking, 477–479  
   schematic, 476  
 Gyrotron, 166, 458–480  
   bunching mechanism, 463–464  
   efficiency, 467–469  
   field patterns, 466  
   high-average-power gyrotrons, 469–470  
   schematic, 470  
   history, 459–460  
   plasma heating, 96–97  
   quasi-optical, 460  
   relativistic gyrotron, 460, 470–473  
   schematic, 461  
   step tuning, 472–473  
   strengths and weaknesses, 497  
   theory, references, 464

## H

Hardening, 64–65  
 Hard-tube MILO, 310–311  
 HEIMDALL, 17  
 HPM (High Power Microwaves)  
   definition, 2  
   operating regimes, 3–9  
   origins, 3

HPM facilities, 222–230  
   indoor, 222  
   microwave safety, 226  
   outdoor, 224  
 HPM weapons, 8, 43–69  
   Active Denial, 55  
   ASAT,  
   compactness, 49  
   effects hierarchy, 47  
   effects on electronics, 65–69  
   first-generation, 4–59  
   fratricide and suicide, 53  
   history, 46  
   limitations, 47  
   missions, 59–60  
   NIRF, 56  
   nomographs, 60–61  
   Ranets-E, 11, 49–50, 323  
   SEPS, 57  
   Vigilant Eagle, 58  
   virtues, 46  
 Hull criterion, 157–159, 272–273

## I

Impedance, 275  
   free space, 125  
   generality, 26  
   optimum, 183  
   sources, 180–181  
   SuperSystem, 33  
 Impulse Radiating Antenna (IRA), 179, 209, 214, 246–250, 254  
 Instability, 160  
 International Linear Collider, 378  
 Inverted magnetron, 261, 301  
 Ionospheric mirror, 207

## K

Klystron, 165–166  
   Applegate diagram, 386–287  
   beam bunching, 384–388, 388–391  
   cavities, 381–384  
   characteristic impedance, 392  
   impedance, 391–394  
   circuit model, 391–394  
   classification, 376  
   drift-tube radius, 381  
   extended-interaction klystron, 377, 384  
   gain, 394  
   Gigawatt Multibeam Klystron (GMBK), 415–416, 423

- high-impedance, 375
  - cavity vs traveling wave section, tradeoff, 402
  - efficiency scaling with perveance, 423
  - fundamental limitations, 422–424
  - magnetic field, 380–381
  - MOK-2, 401
  - near-relativistic, 395–399
  - SHARK, SHARK-2, 400
  - SL-3, SL-4, 400–401
  - performance, 376, 396, 423
- history, 377–378
- low-impedance, 375
  - beam bunching, 388–391, 407–409
  - limitations, 424–425
  - magnetic field uniformity, 411
  - output mode converter, 409–410
  - performance, 376, 406, 413, 423
  - schematic diagram, 405
  - triaxial klystron, 417–421
  - wide gaps, 411
- magnetic field
  - Brillouin limit, 388
- modulation factor, 385
- periodic permanent magnet (PPM)
  - focusing, 397–399
- sheet-beam klystron, 416–417
- SLAC klystron, 377, 397–399
  - performance, 398
  - schematic diagram, 398
- stagger tuning, 384
- velocity modulation, 384–388
- Kopp, C., 53–54
- L**
- Langmuir-Blodgett diodes, 151–152
- Larmor radius, 462
- Larmor rotation, 166
- Laser pumping, 43
- Lethality, 64
- Lifter, 90
- Linear Induction Accelerator (see also voltage adder), 101–102, 189–190, 288–290
- M**
- MAGIC particle-in-cell code, 342–343, 416
- Magnetic mirroring, 462
- Magnetic moment, 361
- Magnetron injection gun, 261
- Magnetron, relativistic, 167, 259–260
  - axial current loss, 300–301
  - axial modes, 269, 283
- cavity schematic, 263
  - comparison with conventional magnetrons, 281
- computer simulation, 266
- dimensions, 270
- dispersion relation, 268
- electrode erosion, 287–290
- end caps, 282–283
- extraction, 283–285
- field patterns, 267
- history, 260–261
- performance, 276
- photographs, 269
- $\pi$ -mode operation, 266, 267
- rising-sun, 271–272, 285–286, 304
  - tunable, 285–286
- transparent cathode, 299–300
- $2\pi$ -mode operation, 266, 267
- 0-harmonic contamination, 303
- Magnets, 34, 224
- Magnetically insulated electron layers, 157–159
  - Hull-criterion, 157–159
- Magnetically-insulated line oscillator (MILO), 168, 260, 309–314
  - hard-tube MILO, 310–311
  - history, 261
  - schematic, 263
  - tapered MILO, 312–314
- Magnetically insulated transmission line (MITL), 185, 309
- Magnicon, 460
- Marx generator, 182–184
- Master oscillator/power amplifier (MOPA)
  - configuration, 173, 296, 356–357
- Maxwell's equations, 110
  - boundary conditions
    - conducting walls, 128–129
    - perfectly conducting walls, 111
- Medium power microwaves (MPM), 48
- Mesoband, 63, 236, 250–253
- Microwave safety, 226–229
- Mobile Test Device-1 (MTD-1), 290–291
- Microwave thermal rocket, 79–85
- Mode converters, 203–204
- Mode hopping, 339
- M-type devices, 159, 167–168, 262
  - classification, 170
- Multiwave Cerenkov generators (MWCGs)
  - history, 323
  - performance, 322, 346

- pulse shortening, 348–349
  - slow-wave structure, 348
- Multiwave diffraction generators
  - history, 323
  - performance, 322
  - pulse shortening, 348–349, 358–359
  - slow-wave structure, 348
- Myrabo, L., 81
- N**
- NAGIRA, 28–31, 34, 70, 350
- Negative-energy waves, 160
- Next Linear Collider (NLC), 378, 416
- Normal mode, 115
- O**
- Optical klystron, 167, 492, 494–495
- Orion, 34, 224–226, 260, 290–292, 296
- Oscillator, 171, 326
- O-type devices, 159
  - O-type Cerenkov devices, 321
    - classification, 333–335
    - comparison, 345–346
    - design flow diagram, 327
    - history, 322–324
    - limitations, 361–364
    - mode selection, 336
    - output coupling, 327
    - performance, 321–322
    - pulse shortening, 357–359
    - classification, 170
    - slow-wave structures, 328–330
- Overbunch instability, 339
- P**
- Pain gun (Active Denial), 55
- Parapotential current, 309
- Parkin, K., 79, 84
- Particle accelerators, 97–103
  - CLIC (Compact Linear Collider), 101–103, 197
  - International Linear Collider, 101–102
  - RF breakdown, 102–103
  - wakefield acceleration, 101
- Passband, 138
- Periodic permanent magnet (PPM) focusing, 397–399
- Perveance, 280
- PF scaling, 4–6
- Phase focusing, 265
- Phase-locked array, 296
- Phase locking, 173–174, 297–299
- Phase shifters, 211–212
- Phase velocity, 119–120
- Photoinjector, 99
- Photoemission, 194
- Pinched-beam diode, 153
- Plasma Cerenkov maser (PCM), 322, 361
- Plasma-filled BWO, 361
- Plasma heating, 91–97
  - ECCD (electron cyclotron current drive), 92
  - ERCH, (electron cyclotron resonance heating), 92
  - microwave sources, 96–97
- Positive-energy waves, 160
- Power beaming, 8–9, 71–78
  - cost, 82–85
  - power-link parameter, 71–73
- Poynting vector, 125
- Prime power, 19–22, 29–30
- Priming, oscillators, 174
- Pulsed microwave compression, 197–202
  - binary, 198
  - SES method, 198–200
  - SLED method, 198, 202
- Pulse forming line (PFL), 34, 182–183,
- Pulse forming network (PFN), 183–185, 224
- Pulse shortening, 3, 5, 6, 8, 10, 52, 220, 255, 287, 290, 315,
  - klystrons, 402, 420–421, 424, 426
  - multiwave Cerenkov generator, 348–349
  - multiwave diffraction generators, 348–349
  - relation to efficiencies, 52, 293–296
  - relativistic magnetrons, 287, 290, 293–296
  - TWTs, 348, 353–354, 356–359
- Pulsed Power, 22–23, 34, 180–191
- Q**
- Q-factor (quality factor), 63, 146–148, 452
- R**
- Radar, 69–71
- Raman regime of operation, 173, 486
- Ranets-E, 11, 49–50, 323
- Rayleigh hypothesis, 139
- Receiver protection devices (RPD), 63
- Rectenna, 74–76

Reditron, 436, 437, 449–451  
 Reflex oscillations, 442  
 Reflex triode, 169–170, 436, 447  
 Relativistic diffraction generators  
   history, 323  
   performance, 322, 346  
   pulse shortening, 359  
 Relativistic klystron amplifier (RKA), 378  
 Reltron, 375–376, 412–414  
   bunching cavity, 395  
   limitations, 425–426  
   performance, 376, 415  
   photograph, 413  
   schematic diagram, 394  
 Rocket equation, 78–79

**S**

Sail, microwave propelled, 85–91  
   beam-riding, 90  
   desorption pressure, 87–88  
   experiments, 86–87  
   interstellar, 90  
   missions, 88–90  
   orbit-raising, 88–89  
   spinning, 80–81  
 Saturation, 161  
 Scatrons, 167  
 Sideband instability in FELs, 489–490  
 Sheet-beam klystron, 416–417  
 Shortstop Electronic Protection System (SEPS), 57  
 SINUS generator, 323, 481  
   NAGIRA, 28–29, 70  
   O-type sources, 346, 349–351, 364  
   SuperSystem, 34, 39  
   vircator, 454  
 Skin depth, 128–129  
 SLAC klystron, 377, 397–399  
 Slow waves, 133  
 Slow-wave structures, 133–144, 163  
   axially-varying, 134–139  
     dispersion relation, 136–138  
     Floquet's theorem, 135  
     passband, 138  
     Rayleigh hypothesis, 139  
   azimuthally-varying, 139–144  
     dispersion relation, 140–144  
   BWOs, 326  
   multiwave Cerenkov generator (MWCG), 348  
   multiwave diffraction generator (MWDG), 348  
 Smooth-bore magnetron, 157, 277–278

Sneak-through, 208  
 Space-charge depression, 153  
 Space-charge devices, 159, 168–170  
   classification, 170  
 Space-charge-limited flow  
   cylindrical diodes (Langmuir-Blodgett diodes), 151–152  
   cylindrical drift tube, 438–439  
     annular beam, 153–155, 380, 439  
     solid beam, 155, 439  
     triaxial klystron, annular beam, 417–418, 439  
   planar diodes (Child-Langmuir diodes), 149–151  
 Space-charge waves, 161–163  
   fast and slow, 331  
 Space propulsion, 78–91  
   deployment of large structures, 90–91  
   launch from orbit, 85–90  
   launch to orbit, 78–85  
   orbit-raising, 88–89  
 Space Solar Power (SSP), 76–78  
 Split-cavity oscillator (SCO), 378  
 Start current, 171  
   BWOs, 336–338  
 SUPERFISH code, 419–420  
 Superposition, 115  
 Super-radiant amplifiers, 172  
 SuperSystem, 27–41  
   Antenna and mode converter, 31  
   BWO, 32  
   specifications, 27  
 Surface resistance, 129  
 Surface-to-air missiles (SAM), 58  
 Surface wave oscillator (SWO), 323  
   dispersion relation, 329  
   references, 331  
   large diameter, 352–353  
 Susceptibility, 64  
 Switches  
   opening, 185–186  
   PFL's and PFN's, 185  
   UWB solid-state, 242–246  
   UWB spark gaps, 239–242  
 Systems, 13–42  
   Active Denial, 55–57  
   block diagrams, 14  
   combinatoric explosion, 15, 17–18  
   component linking, 17  
   definition, 13  
   DS110B, 251–252  
   GEM II, 245–246  
   H-Series, 240–242, 251–253  
   issues, 25–27  
   Jolt, 253–255

linking parameter set, 17  
 MATRIX, 250–251  
 NAGIRA, 28–31, 34, 70  
 NIRE, 56–57  
 Orion, 34, 224–226, 260, 290–291, 296  
 Prototype IRA,  
 Ranets-E, 11, 49–50, 323  
 Shortstop Electronic Protection System (SEPS), 57  
   sub-optimization, 15–16  
 UWB, 250–255  
 Vigilant Eagle, 58–59

## T

Transparent-cathode magnetron, 299–300  
 Traveling wave tube, 163–164, 322, 353–357  
   dispersion relation  
     references, 331  
   gain, 340  
   history, 322–324  
   pulse shortening, 358  
 Triaxial klystron, 417–421  
   performance, 423  
 Two-beam accelerator (TBA), 399–400, 402  
 Two-Beam Next Linear Collider (TB-NLC), 403  
 TWOQUICK particle-in-cell code, 322  
 Twyston, 377

## U

Ubitron (*see also* free-electron laser, FEL), 165  
 Ultrawideband, 235–258  
   antennas, 212–214, 246–249  
   classification of pulses, 236–237  
   definition, 235–238  
   Impulse Radiating Antenna (IRA), 179, 209, 214, 246–250, 254

## V

Vigilant Eagle, 58–59  
 Vircator, 436–458, 168–169  
   cavity vircator, 438, 451–453  
   coaxial vircator, 436, 438, 454–456  
   double anode, 448–449  
   efficiency, effect of anode thickness, 445

extraction, 445–447  
 feedback vircator, 436, 438, 453–454  
 flux compressor-driven, 26–27, 54, 187–188  
 history, 437–438  
 limitations, 458  
 phase locking, 456–458  
 reditron, 449–451  
 strengths and weaknesses, 497  
 Virtode (*see* Feedback vircator)  
 Virtual cathode, 439–444  
 Virtual cathode oscillator (*see* Vircator)  
 Voltage adder (linear induction accelerator, LIA), 101–102, 189–190, 288–290

## W

Wave equation, 112  
 Waveguides, 112–133  
   attenuation due to conducting walls, 131–132  
   circular waveguides, 121–124  
     cutoff frequency, 122–123  
     fields, mathematical expression (TE and TM), 122  
     fields, mode patterns, 124  
     power flow, 126–127  
   overmoded, 133  
   power handling, 124–133  
   rectangular waveguides, 115–121  
     cutoff frequency, 116–117  
     fundamental mode, 117  
     fields, mathematical expression (TE and TM), 117  
     fields, mode patterns, 118  
     power flow, 125–127  
     WR number 117–118  
   single-mode, 133  
   transverse-electric (TE) modes, 113–114  
   transverse-magnetic (TM) modes, 113–114  
   wall heating, 130–133  
 Whispering-gallery modes, 465  
 Wood's anomaly, 334–335  
 WR number, 117–118  
 Wunsch-Bell relation, 65–66

## X

X-ray safety, 229–230

