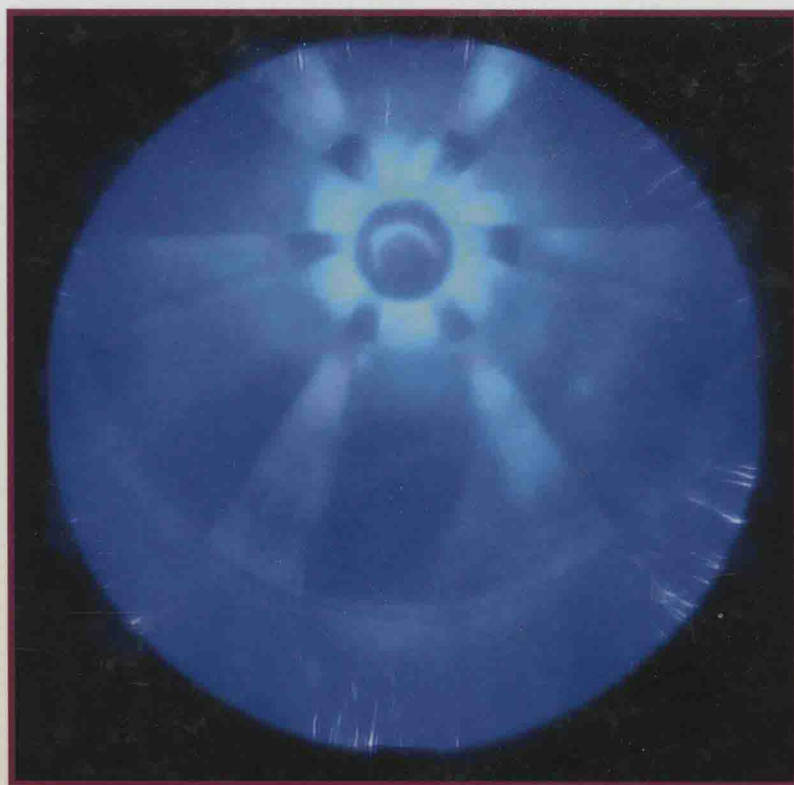


SERIES IN PLASMA PHYSICS

High Power Microwaves

Third Edition



James Benford
John A. Swegle
Edl Schamiloglu



CRC Press
Taylor & Francis Group

Series in Plasma Physics

High Power Microwaves

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James Benford

Microwave Sciences, Lafayette, California

John A. Swegle

J-Two, Aiken, South Carolina

Edl Schamiloglu

University of New Mexico, Albuquerque, New Mexico



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Al, Gerry, and Jennifer Swegle
Elmira and Selin Schamiloglu*

List of Acronyms

ADS	Active Denial System	GA	General Atomics
AFOSR	Air Force Office of Scientific Research	GMBK	Gigawatt Multibeam Klystron
AFRL	Air Force Research Laboratory	GPS	Global Positioning System
AFWL	Air Force Weapons Laboratory	GPU	Graphics Processing Unit
A-K	Anode-Cathode	HAT	High-Power Amplifier Transmitter
ANSI	American National Standards Institute	HDL	Harry Diamond Laboratories
ARL	Army Research Laboratory	HE	High Explosive
ARM	Antiradiation Missile	HEMTT	Heavy Expanded Mobile Tactical Truck
ASAT	Antisatellite	HPM	High Power Microwaves
BASS	Bulk Avalanche Semiconductor Switches	HPPA	High Pulsed Power Antenna
BINP	Budker Institute of Nuclear Physics	HUD	Heads-up Display
BWG	Beam Waveguide	IAE	Institute of Applied Electronics
BWO	Backward Wave Oscillator	IAP	Institute of Applied Physics
CAEP	Chinese Academy of Engineering Physics	ICHE	Institute of High-Current Electronics
CARM	Cyclotron Autoresonance Maser	ICRH	Ion Cyclotron Resonance Heating
CERN	European Center for Nuclear Research	IED	Improvised Explosive Device
CFA	Crossed-Field Amplifier	IHCE	Institute of High-Current Electronics
CHAMP	Counter-electronics High-powered Microwave Advanced Missile Project	ILC	International Linear Collider
CIAS	Carbon-Impregnated Aluminosilicate	INPE	National Institute for Space Research
CLIC	Compact Linear Collider	IRA	Impulse Radiating Antenna
CONOPS	Concept of Operation	IREB	Intense Relativistic Electron Beam
COTS	Commercial-off-the-Shelf	IREE	Institute of Radio Engineering and Electronics
CSG	Competitive Strategies Group	ITER	International Thermonuclear Experimental Reactor
CSR	Cost Savings Ratio	JCTD	Joint Concept Technology Demonstration
CVD	Chemical Vapor Deposition	JDAM	Joint Direct Attack Munition
CW	Continuous Wave	JIEDDO	Joint Improvised Explosive Device Defeat Organization
DCM	Dielectric Cerenkov Maser	JINR	Joint Institute of Nuclear Research
DEW	Directed Energy Weapon	JNLWD	Joint Nonlethal Weapons Directorate
DSRD	Drift Step Recovery Diode	JSOW	Joint Standoff Weapon
EAST	Experimental Advanced Superconducting Tokamak	KdV	Korteweg de Vries
ECCD	Electron Cyclotron Current Drive	KE	Kinetic Energy
EC H&D	Electron Cyclotron Heating and Current Drive	KEK	High Energy Accelerator Research Organization
ECM	Electron Cyclotron Maser	KIT	Karlsruhe Institute of Technology
ECM	Electronic Countermeasure	KL-BWO	Klystron-Like Backward Wave Oscillator
ECRH	Electron Cyclotron Resonance Heating	LANL	Los Alamos National Laboratory
EED	Electro-Explosive Device	LBL	Lawrence Berkeley National Laboratory
EIRP	Effective Isotropic Radiated Power	LEO	Low Earth Orbit
EMC	Electromagnetic Compatibility	LEP	Large Electron-Positron
EMI	Electromagnetic Interference	LHC	Large Hadron Collider
EMP	Electromagnetic Pulse	LHH	Lower Hybrid Heating
EPFL	Ecole Polytechnique Federale de Lausanne	LIA	Linear Induction Accelerator
ERP	Effective Radiated Power	LLNL	Lawrence Livermore National Laboratory
ETA	Experimental Test Accelerator	LNA	Low Noise Amplifier
FCC	Federal Communications Commission	LTD	Linear Transformer Driver
FCG	Flux Compression Generator	MANPADS	Man-Portable Air Defense System
FEL	Free Electron Laser	MCG	Magnetocumulative Generator
FLAPS	Flat Parabolic Surface	MDO	Magnetron with Diffraction Output
FWHM	Full-Width-at-Half-Maximum	MIG	Magnetron Injection Gun
FZK	Forschungszentrum Karlsruhe GmbH		

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MILO	Magnetically Insulated Line Oscillator	SAM	Surface to Air Missile
MIT	Massachusetts Institute of Technology	SAR	Specific Absorption Rate
MITL	Magnetically Insulated Transmission Line	SBK	Sheet Beam Klystron
MOPA	Master Oscillator/Power Amplifier	SCO	Split Cavity Oscillator
MPM	Medium Power Microwaves	SDI	Strategic Defense Initiative
MWCG	Multiwave Cerenkov Generator	SES	Switched Energy Storage
MWDG	Multiwave Diffraction Generator	SLAC	Stanford Linear Accelerator Center
MWS	Missile Warning System	SLC	Stanford Linear Collider
NAGIRA	Nanosecond Gigawatt Radar	SLED	SLAC Energy Development
NINT	Northwest Institute of Nuclear Technology	SLR	Sidelobe Ratio
NKCE	Nonkinetic Counter-Electronics	SNL	Sandia National Laboratories
NLC	Next Linear Collider	SOS	Semiconductor Opening Switch
NRL	Naval Research Laboratory	SPS-ALPHA	Solar Power Satellite by means of an Arbitrarily Large Phased Array
NUDT	National University of Defense Technology	SUSCO	Sectioned Un-Severed Cerenkov Oscillator
OC	Open Circuit	SWO	Surface Wave Oscillator
Pasotron	Plasma-Assisted Slow-Wave Oscillator	SWS	Slow-Wave Structure
PCM	Plasma Cerenkov Maser	TB-NLC	Two-Beam Next Linear Collider
PCSS	Photoconductive Solid State	TBA	Two-Beam Accelerator
PDA	Personal Digital Assistant	TE	Transverse Electric
PFL	Pulse Forming Line	TEM	Transverse Electromagnetic
PFN	Pulse Forming Network	TFA	Time-Frequency Analysis
PI	Physics International	TKA	Triaxial Klystron Amplifier
PIC	Particle-In-Cell	TM	Transverse Magnetic
PPM	Periodic Permanent Magnet	TPI	Tomsk Polytechnic Institute
PRF	Pulse Repetition Frequency	TR	Transmitter/Receiver
PRR	Pulse Repetition Rate	TTU	Texas Tech University
PV	Photovoltaic	TWT	Traveling Wave Tube
RCS	Radar Cross Section	UAS	Unmanned Aerial System
RDG	Relativistic Diffraction Generator	UAV	Unmanned Aerial Vehicle
REICO	Relativistic Extended-Interaction-Cavity Oscillator	UCAV	Unmanned Combat Air Vehicle
RF	Radiofrequency	UESTC	University of Electronic Science and Technology
RKA	Relativistic Klystron Amplifier	UM	University of Michigan
RKO	Relativistic Klystron Oscillator	UMD	University of Maryland
RMS	Root Mean Square	UNM	University of New Mexico
RPD	Receiver Protection Device	USAF	United States Air Force
RPM	Recirculating Planar Magnetron	UWB	Ultrawideband
RR-BWO	Resonant Reflector Backward Wave Oscillator	VEPP	Russian Electron-Positron Collider Concept
RWR	Radar Warning Receiver	VMD	Voltage Modulation Depth
S&T	Science and Technology		

Preface

This third edition has the following revisions compared to the second edition published in 2007:

- Every chapter has been significantly updated.
- The chapter previously called Ultrawideband Systems is titled Beamless Systems and includes nonlinear transmission lines.
- Chapter 10 now focuses entirely on vircators due to a resurgence of interest in them.
- Chapter 11 is a new chapter that covers gyrotrons, electron cyclotron masers, and free electron lasers.

As with previous editions, this book is meant to communicate a wide-angle, integrated view of the field of high power microwaves, or HPM. Our treatment of HPM is actually rather brief; by limiting the book's length to a manageable number of pages, we hope to encourage the reader to further explore the field, rather than skip to select sections of narrower interest, which often happens with lengthier tomes. Our presentation is broad and introductory with the flavor of a survey; however, it is not elementary. For the reader seeking greater detail, we have provided an extensive set of references and guidance to the literature with each chapter.

We anticipate that our readers will include researchers in this field wishing to widen their understanding of HPM; present or potential users of microwaves who are interested in taking advantage of the dramatically higher power levels that are being made available; newcomers entering the field to pursue research; and decision makers in directed energy weapons acquisitions and related fields, such as radar, communications, and high-energy physics, who must educate themselves in order to determine how developments in HPM will affect them.

This book has its origins in many short courses we have taught in the United States and western Europe. Over time, as we have continued to update and widen the scope of our classes, our outlook in the field of HPM has expanded considerably. Although we approached the field by initial investigations with particular HPM sources, we found ourselves asking questions with increasingly more global implications, which this book addresses:

- How does HPM relate historically and technically to the conventional microwave field?
- What applications are possible for HPM, and what key criteria will HPM devices have to meet in order to be applied?
- How do high power sources work? Are there really as many different sources as the nomenclature seems to indicate? What are their capabilities, and what limits their performance?
- Across the wide variety of source types, what are the broad fundamental issues to be addressed in the future?

We believe that addressing these questions has profited us—and ultimately the reader—and that our perspectives are largely complementary: our primary research interests lie with different source

types. While James Benford works largely as an experimentalist, John Swegle is a theorist. The new coauthor since the Second Edition, Edl Schamiloglu, describes himself as an applied theorist.

The reader is encouraged to read Chapter 1, the introductory chapter, where we outline the historical trends that have led to the development of HPM and compare the capabilities of HPM with those of other domains, such as conventional microwaves and THz sources. A premise of this book is that the field can be divided into two sectors, which sometimes overlap: one applications-driven and the other technology-driven. Chapter 2 is entirely new and deals with both perspectives. Chapter 3 directly treats the applications of HPM. The other chapters are focused on technologies. Chapter 4 on microwave fundamentals is a guide to the major concepts used in later chapters. Chapter 5 on enabling technologies describes the equipment and facilities surrounding the sources in which microwaves are generated. These are the elements that make the system work by supplying electrical power and electron beams to the source, radiating microwave power into space, and measuring microwave properties. Chapter 6 deals with the ultrawideband or beamless technologies. Chapters 7 through 11 deal in detail with the major source groups. The Appendix contains the High Power Microwave Formulary. Finally, in the frontal matter we have included a List of Acronyms to assist the reader.

We thank our colleagues for helping in the preparation of this book: Gregory Benford, Steven Gold, John Luginsland, Dominic Benford, Bill Prather, David Price, Edward Goldman, Keith Kato, David Giri, Carl Baum, William Radasky, Jerry Levine, Douglas Clunie, David Price, John Mankins, Kevin Parkin, Richard Dickinson, Bob Forward, Bob Gardner, George Caryotakis, Daryl Sprehn, Mike Haworth, Sid Putnam, Yuval Carmel, Joe Butler, Sonya Looney, Michael Petelin, Ron Gilgenbach, Larry Altgilbers, Mike Cuneo, James McSpadden, and Mats Jansson.

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Finally, we thank Francesca McGowan of Taylor & Francis Group for shepherding us through this third edition.

Very special thanks go to our wives for their patience.

*James Benford
Microwave Sciences, Lafayette, California*

*John A. Swegle
J-Two, Aiken, South Carolina*

*Edl Schamiloglu
University of New Mexico, Albuquerque, New Mexico*

Authors

James Benford is the president of Microwave Sciences, Inc., in Lafayette, California. He does contracting and consulting in high power microwaves. His interests include high power microwave systems from conceptual designs to hardware, microwave source physics, electromagnetic power beaming for space propulsion, experimental intense particle beams, and plasma physics. He earned his PhD in physics from the University of California San Diego. He is an IEEE fellow and an EMP fellow. He has taught 26 courses in high power microwaves in 10 countries. In 2013, he coedited *Starship Century*, dealing with the prospect of star travel. Visit jamesbenford.com for papers on these topics.

John A. Swegle is currently employed at the Savannah River National Laboratory in Aiken, South Carolina, and also works as an independent consultant on high power microwaves. He began his career at Sandia National Laboratories in Albuquerque, New Mexico, where he was a member of the plasma theory group, and then moved to the Lawrence Livermore National Laboratory. He has obtained his PhD and MS degrees in plasma physics

from Cornell University and BSEE and MSEE degrees from the University of Washington, Seattle. He has served two terms as an associate editor of *The Physics of Plasmas*, and as an editor of a special issue of the IEEE *Transactions on Plasma Science*, devoted to high power microwaves. He has conducted short courses or extended workshops on the subject of high power microwaves in the United States, Europe, and China.

Edl Schamiloglu is a distinguished professor of electrical and computer engineering at the University of New Mexico. He earned his BS and MS degrees from Columbia University, New York, and his PhD from Cornell University in 1988. He is an IEEE fellow and an EMP fellow. His research interests are HPM source development and their effects on networked infrastructure. He is a recipient of numerous awards, most recently the 2013 IEEE NPSS Richard F. Shea Award and the 2015 IEEE NPSS Pulsed Power Science and Technologies' Peter Haas Award. He conducts numerous short courses and lectures all over the world.

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