



Physics of Radio-Frequency Plasmas

Low-temperature radio-frequency (RF) plasmas are essential in various sectors of advanced technology, from micro-engineering to spacecraft propulsion systems and efficient sources of light. The subject lies at the complex interfaces between physics, chemistry and engineering. Focusing mostly on physics, this book will interest graduate students and researchers in applied physics and electrical engineering.

The book incorporates a cutting-edge perspective on RF plasmas. It also covers basic plasma physics, including transport in bounded plasmas and electrical diagnostics. Its pedagogic style engages readers, helping them to develop physical arguments and mathematical analyses. Worked examples apply the theories covered to realistic scenarios, and over 100 in-text questions let readers put their newly acquired knowledge to use and gain confidence in applying physics to real laboratory situations.

Pascal Chabert is Research Director within CNRS. He currently leads the Low-Temperature Plasmas group of the 'Laboratoire de Physique des Plasmas' at Ecole Polytechnique. His expertise is in plasma physics and plasma processing.

Nicholas Braithwaite is Professor of Engineering Physics at The Open University, where his research group works on the physics of 'technological' plasmas. He has been on the editorial board of the journal *Plasma Sources Science and Technology* since 1998.

CAMBRIDGE
UNIVERSITY PRESS
www.cambridge.org

ISBN 978-0-521-76300-4



9 780521 763004 >

Cover illustration: image courtesy of Vladimir Šamara.

Cover designed by Hart McLeod Ltd

Contents

<i>Acknowledgements</i>	page vii
1 Introduction	1
1.1 Plasmas	1
1.2 Plasma processing for microelectronics	3
1.3 Plasma propulsion	9
1.4 Radio-frequency plasmas: E, H and W-modes	14
1.5 What lies ahead	17
2 Plasma dynamics and equilibrium	18
2.1 The microscopic perspective	19
2.2 The macroscopic perspective	37
2.3 Global particle and energy balance	41
2.4 The electrodynamic perspective	45
2.5 Review of Chapter 2	55
3 Bounded plasma	59
3.1 The space charge sheath region	61
3.2 The plasma/sheath transition	72
3.3 The plasma region: transport models	78
3.4 Review of Chapter 3	90
4 Radio-frequency sheaths	96
4.1 Response times	97
4.2 Ion dynamics	102
4.3 Electron dynamics	110
4.4 Analytical models of (high-frequency) RF sheaths	116
4.5 Summary of important results	130
5 Single-frequency capacitively coupled plasmas	131
5.1 A constant ion density, current-driven symmetrical model	133
5.2 A non-uniform ion density, current-driven model	146

5.3	Global model	154
5.4	Other regimes and configurations	165
5.5	Summary of important results	174
6	Multi-frequency capacitively coupled plasmas	176
6.1	Dual-frequency CCP in the electrostatic approximation	177
6.2	Electromagnetic regime at high frequency	187
6.3	Summary of important results	218
7	Inductively coupled plasmas	219
7.1	Electromagnetic model	222
7.2	Impedance of the plasma alone	233
7.3	The transformer model	236
7.4	Power transfer efficiency in pure inductive discharges	241
7.5	Capacitive coupling	243
7.6	Global model	246
7.7	Summary of important results	252
7.8	Further considerations	253
8	Helicon plasmas	260
8.1	Parallel propagation in an infinite plasma	264
8.2	Helicon wave propagation in a cylinder	268
8.3	Conditions for existence of the helicon modes	276
8.4	Wave power absorption: heating	277
8.5	E-H-W transitions	283
8.6	Summary of important results	286
9	Real plasmas	287
9.1	High-density plasmas	288
9.2	Magnetized plasmas	293
9.3	Electronegative plasmas	298
9.4	Expanding plasmas	313
10	Electrical measurements	318
10.1	Electrostatic probes	319
10.2	Electrostatic probes for RF plasmas	340
10.3	A retarding field analyser (RFA)	348
10.4	Probing with resonances and waves	354
10.5	Summary of important results	365
	<i>Appendix: Solutions to exercises</i>	368
	<i>References</i>	375
	<i>Index</i>	383