Resonant Network Antennas for Radio-Frequency Plasma Sources

Theory, technology and applications

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Theory, technology and applications

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Part IV Technology, future developments, and appendices

Preface

Radio frequency plasmas provide the underlying technology for many of today's critical semiconductor industries. The demand for larger and more uniform plasma sources is reaching the limits of conventional capacitive and inductive RF plasma reactors, due to standing wave effects and the asymptotic impedance of large-area reactors. The inherent properties of resonant network antennas can overcome these limitations because of their spatially distributed internal resonances and real input impedance.

This book aims to show that resonant network antennas are versatile, alternative sources for inductively coupled and wave-driven plasma. The theory has developed alongside the technology (see also https://www.helyssen.com) to the extent that it is timely to document the progress in an accessible way, to aid antenna design for future RF plasma applications.

To maximize the usefulness of this book for the physicist, engineer, and student, we have taken care to provide all the necessary details for the reader. In particular:

- Equations are derived in full with all intermediate steps.
- Unfamiliar techniques, such as partial inductance calculations, the complex image method, and partial image theory are developed step-by-step from elementary principles by means of explanatory figures.
- The most useful and recurring antenna calculations are provided using a link to programs which reproduce the tensor solutions and many of the book's figures in appendix K.
- Basic concepts in plasma physics are explained, occasionally using a novel approach.

We assume an undergraduate science level familiar with complex numbers, complex impedance, and Maxwell's equations. The chapters and appendixes are cross-referenced throughout the book, but for the most part, the chapters can be read independently of each other. MKS SI units are used throughout. We use 'antennas' for the plural of 'antenna', with apologies to Latin scholars.

The readers will be grateful to Alex Howling, our illustrator, for bringing a touch of comic relief to each chapter.

Dr Philippe Guittienne
Dr Alan Howling
Professor Ivo Furno
Lausanne, Switzerland,
26 October 2023

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We are indebted to Rémy Jacquier, our master engineer, for his contribution to the construction of, and experiments on, the various plasma reactors. We are grateful to the former group leader and co-founder (with Alan Howling and Pierre-Jean Paris in 1989) of the Industrial Plasma Applications Group, Dr Christoph Hollenstein (now retired), for his foresight and generosity in supporting the fledgling Helyssen plasma sources at the CRPP. Our thanks also go to: Helyssen Sàrl director Alain Dannaoui, Gennady Plyushchev, Riccardo Agnello, Fabio Avino, Basile Pouradier Duteil, Cédric Vivien, Claudio Marini, Pierre Demolon, Renat Karimov, Simon Vincent, Marcelo Baquero, Christine Stollberg, Lyes Kadi, Christian Schlatter, Edith Grueter, Yves Martin, Stefano Alberti, Duccio Testa, Pierre Fayet, Sylvain Lecoultre, Antonio d'Angola, Alain Simonin, Stephane Béchu, Hamza Drissikamili, Zacharie Jehan, Arthur Wuhrmann, Benjamin Forster, Andrii Shytikov, the technical services and workshops, and the Swiss Plasma Center directorate, especially Professor Ambrogio Fasoli, for their continual support.

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Individual projects are acknowledged in full in the publications referenced throughout the book.

Author biographies

Philippe Guittienne

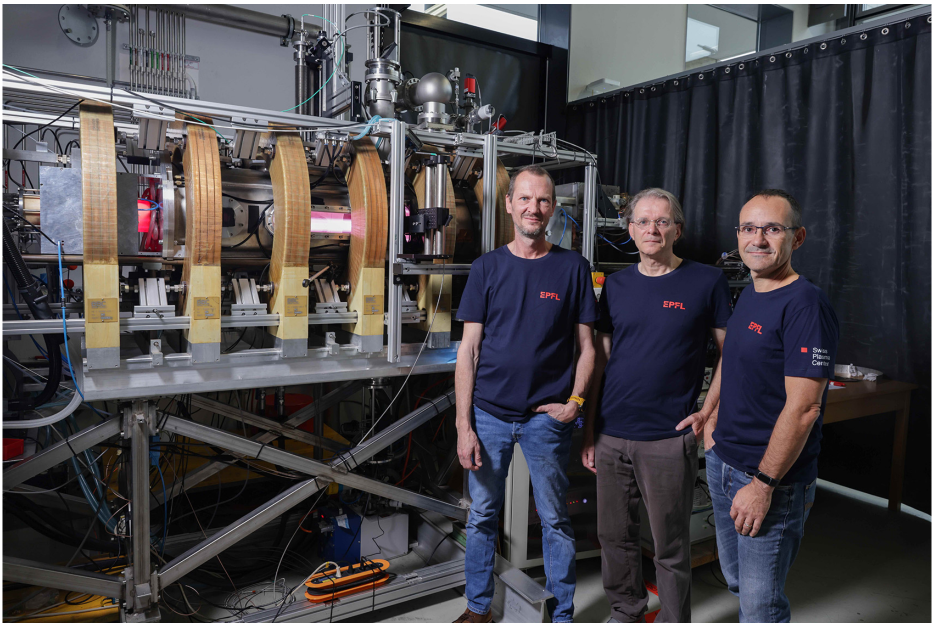
Dr Philippe Guittienne is currently a physicist at the Swiss Plasma Center (SPC) in the Basic Plasma Physics and Applications group under Professor Ivo Furno, and founder of the Helyssen Sàrl company in 2003. Following an engineering degree in physics (1997) and a doctorate (2002) in condensed matter physics at the EPFL on magnetization reversal in ferromagnetic nanostructures, he completely changed his field of interest to birdcages for helicon sources, inspired by the PhD on MRI of his future wife, Jacqueline. On the basis of this intuition, he founded the Helyssen Sàrl start-up in 2003, and started a collaboration with Dr Christoph Hollenstein's group at SPC for the development of resonant antennas as plasma sources. This topic turned out to be a fruitful field of research, and during the years it became a central part of the Industrial Plasma Group (now included in Basic Plasma Physics and Applications), and is, indeed, the subject of this book.

Alan Arthur Howling

Dr Alan Arthur Howling is an Adjoint Scientifique/Senior Scientific Collaborator, co-founder of the group for industrial plasmas in 1989 with Dr Christoph Hollenstein. He is currently a researcher and lecturer in the Basic Plasma Physics and Applications group under Professor Ivo Furno at the Swiss Plasma Center, EPFL, Lausanne, Switzerland. A Gordon Warter Open Scholarship in 1978 to Pembroke College, Oxford University, led to a physics (Natural Sciences) degree in 1981, followed by an MSc and Gordon Francis prize (1982) in the Science and Applications of Electric Plasmas at Wolfson College, Oxford University, and then a doctorate titled 'Fluctuations in the edge plasma of the TOSCA tokamak' (1985) at both Oxford and UKAEA Culham Laboratory, as it was then called. A postdoc on the TCA tokamak in the Centre de Recherches en Physique des Plasmas (CRPP), EPFL Lausanne, Switzerland from 1986 to 1989 was the springboard to RF industrial plasmas in 1989. Applied research topics included negative ion polymerization (silanions) and particle formation in silane RF plasmas; design of large-area RF capacitive plasma reactors for solar cells and flat panel displays, including showerhead uniformity, discharge equilibration, plasmoids, and electromagnetic analysis of symmetric and anti-symmetric modes; RF plasma deposition of amorphous and micro-crystalline silicon; RF plasma diagnostics and glass substrate charging; design of resonant ladder networks for RF plasmas, introducing partial inductance and complex image methods; high voltage design of satellite slip-rings; bio-plasma with Alexandra Waskow and the effect of humidity on dielectric barrier discharges; finally concentrating on writing this swan-song book before retirement on 26 October 2023.

Ivo Furno

Professor Ivo Furno is currently Adjunct Professor at the EPFL and leader of the Basic Plasma Physics and Applications (BPPA) group of the Swiss Plasma Center. He graduated in Nuclear Engineering from the Politecnico di Torino, Italy, in 1995 and then received his PhD from the EPFL with a thesis on 'Fast transient transport phenomena measured by soft x-ray emission in TCV tokamak plasmas'. He continued with a postdoc at the Los Alamos National Laboratory, where he studied magnetic reconnection on the Reconnection Scaling Experiment (RSX), before re-joining the EPFL in 2006. His research is marked by the use of human-scale, dedicated plasma devices to investigate the fundamental physics of plasmas under conditions ranging from fusion plasmas to plasmas of relevance for solar physics and to non-equilibrium cold plasmas for industrial and biological applications. For his work on turbulence in magnetized plasmas, he was awarded the Fellowship of the American Physics Society. On the TCV tokamak, he contributed to the development of the first experiments on the so-called snowflake divertor, and, recently, he led the TCV team that obtained the first experimental demonstration of electron cyclotron microwave beam broadening by plasma turbulence. Since he took over the responsibility of the BPPA group, he has obtained numerous grants to develop industrial applications in collaboration with national academic institutions as well as with industrial partners. He developed the Resonant Antenna Ion Device (RAID) and launched its scientific program to study the physics of helicon waves and negative ion volume generation in helicon plasmas. As part of the new SPC activities beyond fusion, he started collaborating with CERN in the field of wakefield acceleration for the next-generation particle accelerator. The SPC is today an active member of the AWAKE Consortium. A new laboratory for societal, e.g. biological, applications of plasmas, such as plasma agriculture and plasma sterilization, was launched by Furno to expand the SPC infrastructure into atmospheric pressure plasmas for fundamental life science projects. It was Furno who originally proposed writing this book, titled *Resonant Network Antennas for Radio-Frequency Plasma Sources*.



The authors in front of the RAID device: Philippe Guittienne, Alan Howling, and Ivo Furno.

Glossary

Greek terms

α	attenuation constant per section
α_m	a Fourier coefficient
β	phase change per section (rad)
β_m	a Fourier coefficient
$\beta_{1,2}$	wavenumber for H, TG modes (m^{-1})
γ	propagation constant
Δf	FWHM bandwidth (Hz)
δ	Dirac delta function
$\delta\omega$	a small difference in angular frequency from the resonance frequency (rad s^{-1})
$\Delta\omega$	the FWHM half-power bandwidth in angular frequency (rad s^{-1})
ε_0	permittivity of free space (F m^{-1})
ε_p	relative permittivity of unmagnetized plasma (–)
$\bar{\varepsilon}_p$	tensor relative permittivity of magnetized plasma (–)
ζ_m	a Fourier coefficient
η	power transfer efficiency
θ	angle of propagation with respect to the magnetic field
λ	wavelength (m)
μ_0	permeability of free space (H m^{-1})
ν	effective collision frequency (s^{-1})
ν_m	electron–neutral collision frequency (s^{-1})
ξ_m	a Fourier coefficient
ρ	free charge density (C m^{-3})
ρ_{dc}	DC electrical resistivity (Ω m)
ρ_p	plasma complex electrical resistivity (Ω m)
σ_{dc}	DC electrical conductivity (S m^{-1})
σ_{en}	electron–neutral collision cross-section (m^2)
σ_p	complex electrical conductivity of unmagnetized plasma (S m^{-1})
$\bar{\sigma}_p$	tensor electrical conductivity of magnetized plasma (S m^{-1})
τ	RF period $=2\pi/\omega$ (s)
Φ	total magnetic flux linkage (Wb)
ϕ	azimuthal angle in cylindrical coordinates (r, ϕ, z)
ω	angular (RF) frequency (rad s^{-1})
$\hat{\omega}$	$(\omega + j\nu)$
ω_0	resonance angular frequency for an ideal (lossless) circuit (rad s^{-1})
ω_0'	resonance angular frequency for a real (lossy) circuit (rad s^{-1})
ω_m	angular frequency of the mth normal mode (rad s^{-1})
ω_{ci}	ion cyclotron angular frequency (rad s^{-1})
ω_{ce}	electron cyclotron angular frequency (rad s^{-1})

Symbols, abbreviations, and subscripts

$\bar{1}$	$N \times N$ identity matrix
1D, 2D	one-dimensional, two-dimensional
A	vector magnetic potential (Wb m^{-1})
A	vector column of upper-node voltages (V)
acw	anti-clockwise

ALD	atomic layer deposition
A_n	voltage phasor at the *n*th node of the upper stringer (V)
$\mathbf{B}$	(wavefield) magnetic flux density vector (T)
$\mathbf{B}$	vector column of lower-node voltages (V)
B	magnetic flux density magnitude (T)
$\mathbf{B}_0$, B_0	externally imposed constant, uniform magnetic flux density (T)
B_n	voltage phasor at the *n*th node of the lower stringer (V)
C	capacitance (F)
$\hat{C}$	capacitance matrix per unit length (F m^{-1})
CCD	charge-coupled device (CCD camera)
CCP	capacitively coupled plasma
c	contour
c	speed of light in vacuum
c	(subscript) collisional
cw	clockwise
CW	continuous wave; steady state
d	reactor height between a top-plate and a baseplate
d_s	source height above an interface
d$\mathbf{s}$	elemental length vector along a contour
D	connection configuration term
DC	direct current, time-constant value
DLC	diamond-like carbon
e	the base of natural logarithms, Euler's number (2.718…)
e	electron (subscript)
$\mathbf{E}$	(wavefield) electric field intensity vector (V m^{-1})
E-mode	coupling via the *E* field; see CCP
EM	electromagnetic
EM-mode	coupling via *EM* fields; see EMCP
EMC	electromagnetic compatibility
EMCP	electromagnetically coupled plasma
eq	equivalent circuit value
FTIR	Fourier transform infrared
FWHM	full width at half maximum
f	current feed point (subscript)
f	frequency (Hz)
f_{RF}	RF frequency (Hz)
f_{pe}	electron plasma frequency (Hz)
f_{pi}	ion plasma frequency (Hz)
f_p	plasma frequency (Hz)
$\hat{G}$	conductance per unit length (S m^{-1})
g	ground point (subscript)
h	height of an antenna above a baseplate
$\mathbf{H}$	magnetic field strength vector (A m^{-1})
H	helicon
H-mode	coupling via the *H* field; see ICP
$\mathbf{I}$	leg current column vector (A)
I	current (A)
ICP	inductively coupled plasma
Im	imaginary part
ISM	International Scientific and Medical standard

I_n	current phasor in the nth leg (A)
i_{line}	current phasor of current along the line (A)
i_{rf}	current phasor of injected RF current (A)
i_0	amplitude of the first harmonic of shell current density (A m^{-1})
i_s	shell current density (A m^{-1})
J_m	first kind of Bessel function, of order m (see Y_m)
J_n	current in the nth upper stringer section (A)
j	$\sqrt{-1}$
K_n	current in the nth lower stringer section (A)
$\mathbf{k}$	wavenumber vector (m^{-1})
k	magnitude of the wavenumber vector $\mathbf{k}$ (m^{-1})
k_0	wavenumber in vacuum; $k_0 = \omega/c$ (m^{-1})
k_d	wavenumber in a dielectric (m^{-1})
k_z	axial wavenumber, along z (m^{-1})
$k_\perp$	perpendicular wavenumber, perpendicular to z (m^{-1})
k_{B}	Boltzmann's constant ($1.38 \cdot 10^{-23}$ J K^{-1})
LHS	left-hand side
L	self partial inductance (H)
$\hat{L}$	self partial inductance per unit length (H m^{-1})
L_{leg}	self partial inductance of a leg (H)
L_{str}	self partial inductance of a stringer segment (H)
L^{loop}	loop self inductance of a wire loop, coil, or solenoid (H)
$\hat{L}^{\text{loop}}$	loop self inductance per unit length of a transmission line (H)
L_i^{loop}	contribution to loop self inductance of the ith wire segment (H)
l	length of a wire, or an antenna leg
leg	leg (or rung) across the ladder width; or a birdcage leg
MRI	magnetic resonance imaging
$\hat{M}$	mutual partial inductance matrix per unit length (H m^{-1})
M_{ij}	mutual partial inductance between wire filaments i and j (H)
m	mode number
m	azimuthal periodicity
m_e	electron mass (kg)
mes	measured, or measurement
NMR	nuclear magnetic resonance
N	total number of legs
N	refractive index
nc	(subscript) non-collisional, or collisionless
n_{e0}	time-constant electron number density (m^{-3})
OTR	oxygen transmission rate (c.c. m^{-2} atm $^{-1}$ day^{-1})
PEC	perfect electric conductor
PECVD	plasma-enhanced chemical vapour deposition
P_{rf}	RF input power (W)
$\bar{P}$	Maxwell's potential coefficient matrix (V)
p.u.l.	per unit length (signified by a hat above the symbol)
q	magnitude of the electron charge; $q = +1.602 \cdot 10^{-19}$ C
Q	quality factor
RAID	Resonant Antenna Ion Device
Re	real part
res	resonance (subscript or superscript)
RF, rf	radio frequency

RHS	right-hand side
R	resistance, real impedance (Ω)
$\hat{R}$	resistance per unit length (Ω/m)
R, r	radius (m)
r	resistance (Ω)
$\mathbf{S}$	Poynting's vector $\mathbf{E} \times \mathbf{H}$ (W m^{-2})
S	area (m^2)
S_n^J	source current at the nth node of the upper stringer (A)
S_n^K	source current at the nth node of the lower stringer (A)
sccm	a gas mass flow rate in standard cubic centimetres per second
Scrn	algebraic terms depending on currents induced in a PEC screen
SiO_x	silicon oxide with intermediate stoichiometry; $x = 1–2$
SLM	a gas mass flow rate in standard litres per second
str	stringer, along the length of a ladder
T	absolute temperature (K)
T_e	electron temperature
T	Trivelpiece–Gould mode (subscript)
T–G	Trivelpiece–Gould mode
TM	transverse magnetic
$\bar{U}_L$	lower shift matrix
V_{pp}	peak-to-peak voltage (V)
V_{rf}	phasor of the applied RF voltage (V)
v	velocity (m s^{-1})
υ	phase velocity (m s^{-1})
W-mode	coupling via helicon wave fields
$\bar{X}$	$N \times N$ matrix for parameters X_{nm}
$\mathbf{X}$	column vector array for parameters X_n
X	reactive (imaginary) impedance (Ω)
$\hat{\mathbf{x}}$	unit vector along the x-axis
Y	complex admittance (S)
Y_{eq}	complex equivalent circuit admittance at resonance (S)
$\hat{\mathbf{y}}$	unit vector along the y-axis
Y_m	second kind of Bessel function, of order m (see J_m)
Z	complex impedance (Ω)
Z_{str}	stringer complex impedance (Ω)
Z_{leg}	leg complex impedance (Ω)
Z_{c}	characteristic impedance of a transmission line (Ω)
$Z_{\mathrm{in}}^{\mathrm{eq}}$	equivalent circuit complex input impedance (Ω)
$Z_{\mathrm{in}}^{\mathrm{res}}$	complex input impedance at resonance (Ω)
$\hat{\mathbf{z}}$	unit vector along the z-axis