Analysis of Turbulence in Fusion Plasmas

Online at: https://doi.org/10.1088/978-0-7503-4856-0

IOP Series in Plasma Physics

Series Editor

Richard Dendy

Culham Centre for Fusion Energy and the University of Warwick, UK

About the series

The IOP Plasma Physics ebook series aims at comprehensive coverage of the physics and applications of natural and laboratory plasmas, across all temperature regimes. Books in the series range from graduate and upper-level undergraduate textbooks, to research monographs and reviews.

The conceptual areas of plasma physics addressed in the series include:

- Equilibrium, stability, and control.
- Waves: fundamental properties, emission, and absorption.
- Nonlinear phenomena and turbulence.
- Transport theory and phenomenology.
- Laser–plasma interactions.
- Non-thermal and suprathermal particle populations.
- Beams and non-neutral plasmas.
- High energy density physics.
- Plasma–solid interactions, dusty, complex, and non-ideal plasmas.
- Diagnostic measurements and techniques for data analysis.

The fields of application include:

- Nuclear fusion through magnetic and inertial confinement.
- Solar–terrestrial and astrophysical plasma environments and phenomena.
- Advanced radiation sources.
- Materials processing and functionalisation.
- Propulsion, combustion, and bulk materials management.
- Interaction of plasma with living matter and liquids.
- Biological, medical, and environmental systems.
- Low-temperature plasmas, glow discharges, and vacuum arcs.
- Plasma chemistry and reaction mechanisms.
- Plasma production by novel means.

A full list of titles published in this series can be found here: https://iopscience.iop.org/bookListInfo/iop-plasma-physics-series.

Analysis of Turbulence in Fusion Plasmas

Boudewijn Ph van Milligen
National Fusion Laboratory, CIEMAT, Madrid, Spain

Raul Sanchez
Department of Physics, Universidad Carlos III de Madrid, Leganés, Madrid, Spain

IOP Publishing, Bristol, UK

ISBN 978-0-7503-4856-0 (ebook)
ISBN 978-0-7503-4854-6 (print)
ISBN 978-0-7503-4857-7 (myPrint)
ISBN 978-0-7503-4855-3 (mobi)

DOI 10.1088/978-0-7503-4856-0

Version: 20221201

IOP ebooks

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Published by IOP Publishing, wholly owned by The Institute of Physics, London

IOP Publishing, No.2 The Distillery, Glassfields, Avon Street, Bristol, BS2 0GR, UK

US Office: IOP Publishing, Inc., 190 North Independence Mall West, Suite 601, Philadelphia, PA 19106, USA

Cover image: Transfer Entropy graph for the TJ-II stellarator. Image credit: Boudewijn Van Milligen.

Contents

Preface

Progress in science comes when experiments contradict theory.

—Richard P Feynman

When reviewing the literature on turbulence in fusion plasmas, one observes that while several books on the theory of turbulence are available [1–3] and also on general aspects of turbulent or anomalous transport [4], there are only few books focusing specifically on data analysis techniques for turbulence. We believe the reason for this is easy to understand: fusion plasmas constitute a hostile environment for measurement, making the measurement of turbulent quantities a significant challenge. Nevertheless, progress in the understanding of turbulence and its significance for the achievement of fusion as a power source is only possible when theoretical predictions are verified or falsified, and this requires measurement and analysis.

This book attempts to fill this gap by focusing not on the theory of turbulence—treated in profusion elsewhere—but on the analysis of turbulence measurements. It should be noted that this book provides a strictly personal view of the field and is not all-encompassing. Most of the material presented is based on personal work or work performed in close collaboration with others. Thus, this book does not intend to be a review of the field, and we extend our apologies to colleagues who may feel their contributions are underrepresented.

We have attempted to introduce the concepts used in the analysis of turbulence data in a gradual manner, providing explanations and emphasizing the underlying motivation for the approaches we followed. The book is organized in a manner that reflects our personal journey of discovery of the complexity of plasmas, gradually revealing ever more detail and understanding of the behaviour of these extreme systems.

The dynamics of present-day research require one to publish regularly, which has led us to write a considerable number of specialized, rather terse papers on this subject, usually with little space for explanation and context. This brings us to another reason for writing this book: we felt it was necessary to attempt to provide some insight into how these different pieces of the puzzle, published individually, fit together into a global view of turbulence in fusion plasmas. Many of the described methods and techniques are also used in, or could be applied to, fields other than fusion plasma research.

The reader may wonder why we sometimes used rather old figures (from 20 years in the past, or more) to illustrate concepts and results. This is inherent in the scientific tendency to only publish novel results—if a result reproduces what has already been published, it is often not shown in more recent publications. Thus, although in many cases we could have produced similar graphs from more recent measurements, we have preferred to show published results whenever possible, with the advantage that the interested reader can obtain more details from the corresponding publication.

Organization of this book

Chapter 1 provides a general introduction to the study of turbulence in fusion plasmas, highlighting the many issues and remarkable phenomena occurring in these complex systems. Our interest in turbulence is motivated by the need to understand transport in fusion plasmas, in which turbulence is found to play an essential role.

Chapter 2 describes an initial characterization of turbulence, starting with standard analysis tools such as probability distributions, correlations, and Fourier spectra, and progressing to some more advanced techniques to detect structures in plasmas, such as the biorthogonal decomposition and (wavelet) bicoherence. These analyses already reveal some of the complexity that is the focus of this book.

Our general understanding of transport is based on the collective effects resulting from particles moving individually according to random (Brownian) motion. Chapter 3 reviews some aspects of probability theory (the theory of random variables). It is shown that the theory allows for a much broader range of behaviours than are usually considered by 'standard' transport theories, and that these 'alternative' descriptions fit some aspects of turbulence extraordinarily well. The associated analysis techniques are suited for the study of single turbulent time series, and allow quantifying complex behaviour, self-similarity, and long-range memory effects in a systematic way.

Chapter 4 then studies the *interactions* between turbulent variables using a technique originating in information theory, namely the transfer entropy. It is used both to study the causal relationship between fluctuating variables and to analyze the propagation of perturbations through a turbulent system. In other words, this chapter addresses the essential multivariate and/or spatio-temporal nature of turbulence.

Chapter 5 focuses on a specific yet important aspect of turbulence: intermittence or 'burstiness'. This property is analyzed using a technique from chaos theory. It is shown how the intermittence provides a new window on turbulent properties in the plasma interior.

Finally, chapter 6 summarizes the insights obtained in the course of the book and discusses some ideas for expanding and applying this work and future perspectives.

Acknowledgements

Both of the authors were introduced to the study of turbulence and anomalous transport by Benjamin Carreras, who has been a crucial influence in our careers, guiding our nascent understanding and always pushing us onward to do more. Among other notable achievements, Ben was among the first to recognize the importance of zonal flows in fusion plasmas [5, 6].

Modern science is not an individual endeavour and obviously much, if not all, of the work and results presented in this book are the fruits of collaborations with many people. In this respect, we should mention the TJ-II Team [7] at the National Fusion Laboratory of CIEMAT (Madrid, Spain), including Carlos Hidalgo, M Ángeles Pedrosa, Antonio López Fraguas, Teresa Estrada, Enrique Ascasíbar, Eduardo de la Cal, Edi Sánchez, Álvaro Cappa, Isabel García Cortés, Kieran McCarthy, José Luis de Pablos, Arturo Alonso, Emilia Solano, Elena de la Luna, Ignacio Pastor, Marian Ochando, and many others. Likewise, at the University of Carlos III in Leganés (Madrid, Spain), we would like to highlight collaborations with Luis García, Victor Tribaldos, José Ramón Martín-Solís, José Miguel Reynolds, José Angel Mier (now at University of Cantabria), Jacobo Varela, and others.

We have also collaborated with many people from across the world, among whom are Radu Balescu† from the Université Libre de Bruxelles (Belgium) [2, 8], David Newman from the University of Alaska at Fairbanks (USA), Diego del Castillo from ORNL (Oak Ridge, TN, USA), Paul Terry from the University of Wisconsin at Madison, the Wendelstein 7-X Team at Greifswald (Germany) [9] including Matthias Hirsch and Andreas Dinklage, Gustavo Grenfell, and Gregor Birkenmeier from the Max Planck Institute (Garching, Germany), Anantanarayanan (Chippy) Thyagaraja from UKAEA (UK), the JET Contributors [10] at Culham (UK), the HIBP Team—Alexander Melnikov and his team from the Kurchatov institute (Moscow, Russia) and the team from the Institute of Plasma Physics (Kharkov, Ukraine)—, Carlos Silva from IST (Lisbon, Portugal), and Paul Bons from Universität Tübingen (Germany).

We would like to thank all these people, and many others whom we have not mentioned explicitly, as this book could not have become a reality without their direct or indirect collaboration in this collective research effort spanning many decades and involving hundreds of people. We offer our apologies in advance to anyone who should have been included here and was inadvertently left out.

Last but not least, we should mention the unwavering support and patience of our families. Boudewijn would like to thank his wife, Deysi Coromoto, and his daughter María for providing a joyful and interesting life and his mother Emma and sisters Marjolein and Ingrid in The Netherlands for their steadfast encouragement with this project. Raul would also like to thank his wife, Estefanía Cuevas, his mother Carmina, his brother Ruben, and his wife Sonia, and his two wonderful nephews, Ivan and David, for keeping his sanity in check while doing science and teaching.

References

[1] Yoshizawa A, Itoh K and Itoh S I 2003 *Plasma and Fluid Turbulence: Theory and Modelling* 1st edn (Boca Raton, FL: CRC Press)

[2] Balescu R 2005 *Aspects of Anomalous Transport in Plasmas* (Bristol: Institute of Physics))

[3] Scott B D 2021 *Turbulence and Instabilities in Magnetised Plasmas: Fluid Drift Turbulence* vol 1 (Bristol: IOP Publishing)

[4] Horton W 2017 *Turbulent Transport in Magnetized Plasmas* 2nd edn (Singapore: World Scientific)

[5] Diamond P H, Liang Y-M, Carreras B A and Terry P W 1994 Self-regulating shear flow turbulence: a paradigm for the L to H transition *Phys. Rev. Lett.* **72** 2565

[6] Ware A S, Terry P W, Diamond P H and Carreras B A 1996 Transport reduction via shear flow modification of the cross phase *Plasma Phys. Control. Fusion* **38** 1343

[7] Hidalgo C *et al* 2022 Overview of the TJ-II stellarator research programme towards model validation in fusion plasmas *Nucl. Fusion* **62** 042025

[8] Klages Rainer, Radons Günter and Sokolov Igor M (ed) 2008 *Anomalous Transport: Foundations and Applications* (New York: Wiley)
[9] Beidler C D *et al* 2021 Demonstration of reduced neoclassical energy transport in Wendelstein 7-X *Nature* **596** 221–6
[10] Joffrin E *et al* 2019 Overview of the JET preparation for deuterium-tritium operation with the ITER like-wall *Nucl. Fusion* **59** 112021

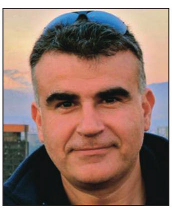
Author biographies

Boudewijn van Milligen

Boudewijn van Milligen studied physics at the University of Utrecht in The Netherlands, where he also obtained his PhD thesis. This thesis was based on work performed at the FOM Institute for Plasma Physics, then located in Rijnhuizen, and JET in the UK, among others, thus starting a life-long career in which international collaborations have always been predominant. The thesis work, performed under the motivating guidance of Niek Lopes Cardozo, aroused his interest in transport studies and unusual transport phenomena.

Following a six-month holiday break in Venezuela and elsewhere, he started work at the CIEMAT institute in Madrid, Spain, with financing from the European Commission. After an initial phase in which he was involved in the data acquisition systems for the TJ-I tokamak and the TJ-IU stellarator, he refocused his attention on data analysis. Under the guidance of Carlos Hidalgo and Benjamin Carreras, this turned out to be an extremely fruitful area. Over the years, he has explored data from many fusion devices around the world, using a wide range of data analysis methods, with the purpose of clarifying the physics underlying transport and turbulence, as reported in this book.

Raul Sanchez



Raul Sanchez studied theoretical physics at the Universidad Complutense de Madrid, where he also obtained his PhD thesis. In this work, performed under the direction of Professor Luis Garcia at Universidad Carlos III de Madrid (UC3M), he developed a fast and accurate solver to calculate ideal MHD ballooning stability in arbitrary magnetic configurations. This was the basis of the widely used COBRA code, which he later developed while already working as a post-doc at Oak Ridge National Laboratory (ORNL) in the USA. He remained associated with ORNL for almost a decade until finally relocating back to Madrid as a physics professor at UC3M. During his time at ORNL he co-developed the ideal MHD equilibrium code SIESTA with Steve Hirshman, his advisor at the time and one of the several people that showed him the joy of working in plasma physics.

In parallel with his work in magnetohydrodynamics, he also developed a strong interest in plasma turbulence after meeting Benjamin Carreras and David Newman at ORNL. This collaboration, that remains active and fruitful to this day, introduced him to the complexity of turbulence and the turbulent nature of complex systems. With the help of many collaborations and friends, this has been a topic that has kept him busy and entertained many days and many nights.