PREFACE

Turning adversity into good fortune has always been an attractive proposition. Spheromaks present this sort of appeal because spheromaks offer the possibility of turning what was previously considered catastrophic instability into the basis of a low-cost plasma confinement scheme. The essential idea is to harness magnetohydrodynamic instability in such a way as to let the plasma relax or self-organize into a toroidal confinement configuration which otherwise would have to be created artificially at great expense. The physics of the spheromak has intrigued its devotees because this physics depends on intrinsic three dimensionality and complexity.

This book assumes the reader has a modest background in plasma physics but no prior knowledge of spheromaks. It has been written to be as self-contained as possible and whenever possible complete mathematical derivations are provided from first principles. However, to show that spheromaks are not just algebra, there is ample discussion of the practical experimental issues that must be addressed in order to make real spheromaks.

Spheromak research to date has been primarily motivated by the goal of developing a controlled thermonuclear fusion reactor, but spheromak physics is quite interesting in itself because it provides a conjunction for many of the most pressing and least understood issues in contemporary plasma physics. Thus, spheromak physics has much relevance beyond fusion. This book considers spheromaks from the related points of view of fusion relevance and fundamental plasma physics.

The book is organized as follows: Chapters 1-3 provide an introduction and present basic concepts. Chapter 1 places spheromaks in context relative to other toroidal confinement schemes and gives a brief history of spheromak research. Chapter 2 discusses several standard magnetohydrodynamic concepts used throughout the book. Chapter 3 introduces and explores magnetic helicity, a delightful and fascinating concept which quantifies magnetic field topology and is at the heart of spheromak physics.

Chapters 4-7 show how spheromaks are created and give examples. Chapters 4 and 5 explain the Taylor relaxation principle (Chapter 4 derives Taylor relaxation for isolated configurations and Chapter 5 derives Taylor relaxation for driven configurations). This powerful principle shows that plasmas left to their own devices spontaneously self-organize into spheromak equilibria, but the principle also has an enigmatic aspect because it does not explain how this self-organization takes place. Chapter 4 gives arguments supporting the essential premise underlying Taylor relaxation, namely that magnetic helicity is much better conserved than magnetic energy when there is fine-scale dissipation. Chapter 6 shows how Taylor relaxation is related to the well-known magnetic energy principle. Chapter 7 surveys the various schemes that have been used to create laboratory spheromaks.

Chapters 8-13 discuss more subtle aspects of spheromak formation and sustainment. Chapter 8 puts this discussion in context by arguing that there is a close (but imperfect) analogy between spheromak physics and thermodynamics and that this analogy can be used to classify regimes. Chapter 9 derives relationships between the main parameters characterizing an isolated spheromak. Chapter 10 explores the various roles of the wall surrounding the spheromak. Chapter 11 considers an idealized driven spheromak and derives the parametric dependence of the spheromak energy, helicity, and impedance. Chapter 12 takes up the more realistic viewpoint that magnetic helicity is not exactly conserved, but instead dissipates somewhat and must therefore be replenished by an external source; this leads to the issue of dynamos and sustained fluctuations. Chapter 13 surveys confinement and transport, deviations from ideal behavior which provide the main limits on spheromak performance.

Chapter 14 discusses several practical issues relevant to making laboratory spheromaks. Chapter 15 gives an overview of several of the standard diagnostics used on laboratory spheromaks. Chapter 16 discusses spheromak applications, beginning with fusion confinement and then going on to several fusion-related and non-fusion applications. The book concludes with Chapter 17, a survey of spheromak-related phenomena in solar and space physics; many of the ideas discussed in earlier chapters reappear in this much larger venue.

As in most fields, the notation in spheromak literature has developed haphazardly and is not always consistent. For clarity, this book always uses ψ to denote poloidal flux, Φ to denote toroidal flux, and χ to denote the Helmholtz function related to force-free states. Another consistency problem is that variables in different contexts are often represented by the same symbol; for example ϕ can denote electrostatic potential or toroidal angle depending on the context. Similarly V denotes voltage or volume, etc. Rather than define a set of completely consistent, non-overlapping, but unfamiliar symbols, I have elected to use standard notation as much as possible, and state that ϕ is an angle or a potential at the beginning of each separate discussion. Following this approach, cylindrical coordinates are (r, ϕ, z) while spherical coordinates are (r, θ, ϕ) and it will be explicitly stated whether an analysis is in cylindrical or in spherical coordinates.

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