

Preface

This book is intended to describe a systematic overview of the latest physical principles of fusion and plasma confinement. Students who learned the basics of quantum and analytical mechanics in university are introduced to the subject and may be interested in it as a future job option. Researchers in other fields may find commonalities and differences in the structure of the scientific principle of magnetic plasma confinement, which has been systematized through the 50 years of fusion research since its inception in 1958 (see Figure 0.1).

Academic fields have been developed in two ways. One is the case where object of purely intellectual curiosity exists and the field is formed to study it. Another is the case where a goal (such as to create a faster airplane, or predict the path of a typhoon) exists and the field is developed to resolve inherent physical issues in it. The relationship between physics and fusion falls into the latter category.



Figure 0.1 Opening ceremony of 22nd IAEA Fusion Energy Conference celebrating 50 years of fusion research on October 13, 2008, at Palais de Nations, Geneva

Earth” – deuterium, tritium, neutron, and helium are introduced and finally “Fusion cross section” is derived from the theory of nuclear reactions.

Chapters 3 to 9 are devoted to the principle of magnetic plasma confinement. In Chapter 3, the topological requirements of why the magnetic bottle should be a torus are discussed in relation to Poincaré theorem using the Euler index. This is followed by the introduction of “coordinates,” “field line dynamics,” “magnetic surface,” “flux coordinates,” and “ergodicity,” before describing 2-dimensional and 3-dimensional equilibrium using the machinery of analytical mechanics. Special emphasis is placed on the equivalence of integrability/symmetry in analytical mechanics and the existence of the magnetic surface.

In Chapter 4, particle orbit dynamics on the magnetic surface are discussed using the Lagrange–Hamilton formulation, noting the new variational principle, Littlejohn’s variational principle, to satisfy the Liouville theorem in guiding center phase space, as was established in the 1980s; in contrast to the guiding center equation by Alfvén, which does not conserve phase space volume. This variational principle is applied to guiding center motion in the flux coordinates and adiabatic invariants are introduced.

In Chapter 5, fundamentals of plasma kinetic theory are described. To clarify the difference between dynamics and kinetics, the conflict faced by L. Boltzmann’s Stosszahl Ansatz on the time-reversibility of Newton’s equation of motion and time-irreversibility of kinetic equations is discussed in comparison with Poincaré’s recurrence theorem. A similar but different problem appears in plasma physics. “Continuous spectrum and phase mixing” is discussed, which produces “Landau damping” from the time-reversible kinetic equation, the Vlasov equation. Coulomb collision in plasma is surveyed as collective phenomena. Finally, modern Gyro Kinetic theory is introduced which is cutting-edge research studying high temperature plasma turbulence.

In Chapter 6, the main subject is “stability.” After a general introduction to stability, the energy principle and stability criteria using the Euler–Lagrange equation are given to describe plasma instabilities such as Kink and Ballooning from the linearized magnetohydrodynamics (MHD) equation with an Hermitian linear operator. Dissipation at a rational surface produces “Tearing” – an instability associated with magnetic reconnection. The linearized MHD operator becomes non-Hermitian with equilibrium flow, which is a cutting-edge topic in confined plasma research.

In Chapter 7, the eikonal equation for plasma wave propagation and von Laue form of wave energy are introduced. Then drift waves and Alfvén resonance are considered: these are important in practical magnetic confinement research. Furthermore, the Hasegawa-Mima equation is introduced describing the nonlinear interaction among drift waves as a starting point of cutting-edge plasma turbulence research.

In Chapter 8, collisional transport of toroidal plasma in the collisionless regime is discussed. In collisionless plasma, a “self-generated current” or “bootstrap current” is produced by the pressure gradient, which is essential for the efficient steady operation of a tokamak fusion reactor. Neoclassical viscous force is produced by the distortion of velocity distribution function in the collisionless regime. A gen-

eralized version of Ohm's law includes bootstrap current expressed in terms of the thermodynamic forces. Cross-field neoclassical transport is also given.

In Chapter 9, the cutting-edge subject of turbulent transport in confined plasma is discussed. While introducing the basic concepts of dynamical systems, a basic picture of plasma confinement is shown. Heat diffusion in low mode confinement can be described by "Self-organized criticality (SOC)," which is an important concept in complexity science, while the Transport Barrier (TB) is a local relaxation of SOC driven by the flow shear to break the turbulent cell.

In Chapter 10, the characteristics of fusion as an energy source and its research status are briefly described.

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