BOOK REVIEWS

Selection of books for review is based on the editor's opinions regarding possible reader interest and on the availability of the book to the editor. Occasional selections may include books on topics somewhat peripheral to the subject matter ordinarily considered acceptable.

Fusion Plasma Analysis

Author	Weston M. Stacey, Jr.
Publisher	Wiley Interscience Publishers, New York (1981)
Pages	376
Price	$32.95
Reviewer	Magdi M. H. Ragheb

An important document and a milestone in the history of fusion research is the "Magnetic Fusion Energy Engineering Act of 1980." It passed the House on August 26, 1980 by a vote of 365 to 7 and the Senate September 23, 1980 by a unanimous vote, and President Carter signed it into law on October 7, 1980. The purpose of this Act is to declare the policy of the U.S. toward magnetic fusion. It establishes a national goal of demonstrating the engineering feasibility of magnetic fusion by the early 1990s, to achieve at the earliest practicable time, but not later than the year 1990, operation of a magnetic fusion engineering device based on the best available confinement concept, and to establish as a national goal the operation of a magnetic fusion demonstration plant at the turn of the 21st century. The Act adopts the idea of the creation of a "Magnetic Fusion Engineering Center" for the purpose of accelerating fusion technology development. The magnetic fusion community expects the attainment of scientific breakeven by the year 1983, the operation of a "driven" magnetic fusion engineering device with some energy gain before the year 1990, the operation of a net-energy producing demonstration plant before the year 2000, attaining a "self-ignited" reactor around the year 2000, and operating a commercial fusion power plant just beyond the year 2000. Magnetic fusion is currently funded by the U.S. Department of Energy at a level of approximately $400 million per year.

Even though entitled *Fusion Plasma Analysis*, this book is concerned with the coupling between the plasma physics and the engineering physics aspects of magnetic confinement fusion, and is a most welcome publication at this time of heightened national interest in fusion energy engineering as expressed by the above-mentioned Act. The author, W. M. Stacey, Jr. from the Georgia Institute of Technology, formerly director of the Fusion Power Program at Argonne National Laboratory (ANL), is well positioned to analyze such a topic. The book has its own characteristic among previously published books and monographs on fusion energy,[1-10] in that the author tries to convey to the reader information at the level of current plasma experiments (e.g., tokamak fusion test reactor in the U.S., T-15 in the USSR, JT-60 in Japan, Joint European Torus in Europe) and ongoing work on fusion reactor conceptual designs. In that respect, it is a much needed addition to the existing fusion literature. The book is at the graduate level. A previous undergraduate course in plasma physics and another graduate one in electrodynamics,[11] as well as a mastering of vector calculus and some tensor analysis, would facilitate easy grasp of the content. The book is well organized, highly mathematically formulated, and is composed of 14 chapters with an incomplete list of supplemental reading updated to 1980. Some problems are given for each chapter. The author draws material from reports published at ANL, and the analysis mostly pertains to the tokamak concept, even though some aspects of the analysis apply to other magnetic confinement concepts.

Chapter I is an introduction in which the physical processes pertaining to fusion are reviewed. The deuterium-tritium (D-T), deuterium-deuterium (D-D), and D-^{3}He reactions are introduced, but other advanced-fuel reactions are ignored. From now on, the author concentrates on the D-T fuel cycle. A simple energy balance yields the condition for net energy release. The electron Debye length is defined, and the electrostatic shielding of the Coulomb interactions between charged particles is discussed. The concept of plasma frequency and the Rutherford scattering cross section are introduced. The analysis yields characteristic times for energy transfer for different particle interactions, and leads to the conclusion that ions will suffer a large number of collisions, on the average, before they undergo fusion, ". . . thus the effects of collisions on the plasma are quite important." Maxwell's equations are derived and the concept of magnetic pressure is introduced.

Several printing errors are discernible in this first edition of the book. For example, in Table 1.1, the thermonuclear energy release from the D-T reaction should be corrected from 17.4 to 17.6 MeV; on p. 5, the half-life of tritium should be corrected from 12.5 to 12.3 years; on the third line of p. 3, the ion density is n_1, and the electron density is n_2, rather than n, which is the total particle density ($n = n_1 + n_2$); on Fig. 15, the incident particle mass should be designated m_1 instead of m_2; on p. 17, "Stokes's theorem" should be corrected to "Stoke's theorem"; in Eq. 1-43, m_1 should be replaced by m_i; and in Fig. 1-3, kT/e should be replaced by kT_e.

Chapter II starts with the Lorentz equation for the motion of a charged particle in electric and magnetic fields, and considers particle orbit theory. The motion of particles in a uniform magnetic field is studied, and the concepts of guiding center, gyrofrequency, and the Larmor radius are introduced. Then the analysis of the motion of a charged particle in a magnetic and perpendicular electric fields allows the discussion of the $\boldsymbol{E} \times \boldsymbol{B}$ drift. The constants of motion and adiabatic invariants are discussed, as well as the implications with respect to the confinement in magnetic fields. The grad-$\boldsymbol{B}$ polarization and curvature drifts are also discussed. The concept of the rotational transform and the safety factor are introduced for toroidal systems, as well as the diffusion coefficients and well-trapping of particles in tokamaks, particularly the collisionless or banana regime. In the collisional regime, the Pfirsch-Schlüter diffusion coefficient is considered. This leads to an estimate of the confinement times of tokamaks. The confinement in non-axisymmetric toroidal fields, drift currents, and magnetization current is briefly discussed.

Chapter III derives the equations describing the behavior of a plasma in the presence of Coulomb collisions. This includes the Boltzmann and the Vlasov (collisionless Boltzmann) equations. As these equations are complicated, and can only be solved in the simplest cases, a more tractable description of a plasma is obtained in terms of a distribution function for the velocity and the position of particle guiding centers: the drift approximations. When the collisional time scale is short compared to the time scale of the phenomena that affect the distribution function, one is justified in considering the change in the distribution functions due to collisions alone and then use this result in the Boltzmann or the drift-kinetic equations under the assumption that collisional effects are instantaneous on the time scale of interest. This results in a Fokker-Planck equation that provides a means of calculating the rate at which energy is transferred from a population of energetic ions to a background plasma, or the rate at which energy is transferred among the various ion species and electrons in a plasma. Four simpler collision operators that retain the properties of the Fokker-Planck operator are suggested.

A general fluid description of the plasma is developed in Chap. IV and several plasma models are formulated. From the Boltzmann equation, the moments equations yield the equations of continuity, momentum balance, energy balance, and energy flux for a multispecies fluid approximation. Summation over all species yields a one-fluid equation. A specialization to the one-fluid model: the magnetohydrodynamic (MHD) model is developed, and, for a relatively collisionless plasma, the anisotropic pressure tensor model is introduced.

The general properties of plasma equilibrium are now attacked in Chap. V, and the beta factor is defined. Axisymmetric toroidal plasma equilibria and the limit of large aspect ratio toroidal equilibrium are discussed. The equilibrium in situations in which the distribution function for one or more of the plasma species is anisotropic, and the change of magnetic fields and flux surfaces can change within a plasma are examined.

In Chap. VI, the author develops the theory of collisional transport from two points of view: the fluid and the drift-kinetic (guiding center) viewpoints. Classical collisional transport based on the multifluid balance equation, and neoclassical transport in a large-aspect ratio torus are surveyed. Comparison of Pfirsch-Schlüter and classical radial fluxes and scaling of diffusion and heat conduction coefficients is undertaken. The author develops a general formalism for transport across arbitrarily shaped flux surfaces. The neoclassical transport across flux surfaces in a large-aspect ratio, axisymmetric-toroidal plasma is treated. This analysis seems to be inconclusive, however: "Unfortunately when neoclassical transport theory has been applied to Tokamak experiments, the agreement has not been good." The measured energy confinement time is 10 to 100 times less than that predicted by neoclassical electron heat conduction. The ion energy confinement time inferred from experiment is generally within a factor of three of the value predicted on the basis of neoclassical ion heat conduction. "In part, this disagreement may be due to the failure of the calculation models to account for all the factors that are important in the calculation of the power balance and thus failing to arrive at a rigorous neoclassical prediction; for example, the effects of impurity and neutral influx and the transport of and radiation power loss by partially stripped impurity ions is usually not treated rigorously." The author gives expressions for the energy confinement time for ohmically heated tokamaks, including coefficients based on the trapped-particle-instability theory. He states: "It is possible to develop transport coefficients from the theory of current-driven drift waves and from the theory of torn magnetic surfaces that lead to an energy confinement scaling $\tau_E \sim na^2$ (the experimentally observed scaling for ohmically heated Tokamaks). However, the theories are preliminary, and no entirely satisfactory explanation for the observed energy confinement scaling can be made at this time." This topic appears to need extra effort by workers in the field and extensive research. The chapter concludes by exposing a model that uses a neoclassical transport coefficient for ion heat conduction, which agrees reasonably well with experiment, but that uses a "pseudoclassical" model based on the classical form and an empirical coefficient.

In Chap. VII, a multifluid description of the plasma is used to analyze some wavelike phenomena in cold magnetized and unmagnetized plasmas. The Vlasov equation description of the plasma is used to study high-frequency wave phenomena. Langmuir waves and Landau damping, and the electrostatic waves' effects introduced by the fact that the plasma is hot, are treated. Dispersion relations are derived for the upper hybrid electron cyclotron wave, the electrostatic ion-cyclotron wave, and the lower hybrid wave. These are to be used later in the analysis of wave heating of plasmas.

In Chap. VIII, on stability, the processes by which a confined plasma can evolve to a state of lower free energy, in the process of converting free energy into kinetic energy, are considered. Free energy sources that can drive instabilities in a magnetically confined plasma,

1. relaxation of a non-Maxwellian, nonisotropic velocity distribution
2. relaxation of a spatial inhomogeniety or expansion
3. rearrangement of the magnetic field configuration,

are studied. The following constraints that inhibit transitions to states of lower energy are also studied:

1. The MHD, or perfect-conductivity constraint, freezes plasma to field lines to the extent that resistivity is negligible.
2. Conservation of magnetic moment constrains motion with characteristic frequencies less than the gyrofrequency.

3. The Liouville equation, or equation of state, constrains possible motions that do not change the entropy.

A number of specific instabilities and methods for analyzing the stability are examined: hydromagnetic instabilities, minimum-B stabilization, the pinch and kink instabilities, interchange or flute instabilities, resistive instabilities, drift wave instabilities, and loss-cone and drift-cone instabilities.

The next chapter reviews the processes for heating plasmas to thermonuclear temperatures: resistive heating, adiabatic compression, neutral beam injection, radiofrequency and microwave heating, and alpha-particle heating. Fueling is very briefly discussed since it is a "relatively undeveloped topic."

Chapter X deals with plasma radiations as power loss mechanisms and as diagnostic tools, particularly bremsstrahlung and cyclotron emissions. The formalism is developed using the Lienard-Wiechart potentials for an accelerated particle emitting radiation. Radiation from partially ionized impurity atoms is analyzed. The atomic processes considered are electron collisional excitation followed by radiative decay, electron ionization and radiative decay, electron ionization, and radiative recombination. Collisional deexcitation and three-body recombination are neglected in the analysis.

In Chap. XI, the particle, photon, and heat fluxes are the principal atomic processes thought to be involved in the plasma-wall interaction process are discussed. Surface phenomena expected to be important in fusion reactor plasma analysis are qualitatively discussed: reflection (backscatter and reemission), adsorption and desorption, vaporization and thermal shock, sputtering, blistering and flaking, electron emission, and nuclear transmutation. Impurity control through the use of limiters and divertors and the use of low-z materials as wall materials and coatings are treated. The author seems not to favor carbon for such uses, as "... carbon seems to be subject to intolerably high chemical sputtering, except in a temperature window around ~1000°C." A brief discussion of charged particle transport in a neutral gas and neutral particle transport in a plasma is exposed.

In Chap. XII, the plasma balance is described by a set of second-moment equations for each species with appropriate auxiliary equations to specify the heat and particle transport and with an appropriate specification of the energy source and loss terms. This is supplemented by an auxiliary set of equations of the various ion species present in the plasma. Power balances during the plasma operational phases: plasma breakdown and burn cycle are exposed and followed by the dynamic power balance during a tokamak burn cycle. The chapter is concluded by analyzing control mechanisms that can be used to maintain a steady-state power balance in a thermonuclear plasma: supplemental heating, injection of impurities, varying the confinement loss by varying the axial ripple in a tokamak are considered. "There are other, more subtle, effects associated with altering the spatial distributions, also. These topics are at an early stage of investigation."

Chapter XIII studies how achievable plasma parameters interact with technological constraints in contemplated tokamak fusion reactors. A global power balance in a fusion plasma at steady state is used to estimate the energy confinement required in a 50% D–50% T plasma. The maximum power amplification factor (Q_p) for the plasma is defined and it is shown that a value of $Q_p \gtrsim 10$ is required for a "net power" reactor. The economic attractiveness of fusion reactors depends on the achievable power density, which is shown to depend on several factors: the ratio of plasma pressure to toroidal magnetic field pressure (β_t) and the geometric constraints on B_ϕ. The author turns his attention to the stability, technological, and geometric constraints that define the allowable range of tokamak reactor parameters. The toroidal magnetic field and magnet radiation shield are surveyed in detail. The use of NbTi and Nb_3Sn as superconductors for magnets is discussed, and the effect of radiation on the increase of resistivity of the superconductor stabilizer and their effect on the blanket and shield thickness are analyzed. He concludes that radiation damage considerations determine a minimum thickness of the blanket and shield to ~1 m. (This ignores leakage radiation through penetrations, however.) The author points out that the radiation damage to the insulators and their failure may be an important factor to be considered. Data on this effect are not available, however. Limitations on the maximum allowable field in the solenoidal ohmic heating coil and minimum design requirements for the magnetic flux that induces and maintains the plasma current are exposed. With respect to material constraints, the author maintains that fatigue failure (because of the pulsed nature of tokamak reactors) is the main lifetime-limiting factor for first walls. Other factors analyzed are: loss of ductility, creep, and swelling. He concludes that a representative upper limit for the neutron wall loading is in the range of 2 to 10 MW/m^2 (Note: on p. 306, line 6, $MW\text{-}yr/m^2$ should be corrected to MW/m^2) and a representative upper limit on the integrated neutron wall load is in the range: 3 to 30 $MW\text{-}yr/m^2$. The lower limit corresponds to the use of stainless steel, which implies an ~1.5-yr wall lifetime. He considers the allowable range of reactor parameters and turns briefly into a simple economic evaluation of the unit energy production cost. The analysis shows the strong economic incentive for developing advanced structural alloys that would allow the attainment of integral wall loadings $\gtrsim 10$ $MW\text{-}yr/m^2$. He warns the reader at the end of the chapter: "with a word of caution about taking any of the numbers too literally. The physics and technology data bases are not adequate for definitive specification of constraints, and the form of the constraints are design-specific."

In the last chapter, the author recognizes the fact that a tokamak is a low aspect ratio toroidal configuration, which "makes for difficulties in engineering design," as well as being a pulsed device, which implies engineering problems associated with thermal cycling and fatigue. He thus briefly considers the classical mirror concept, the tandem mirror, the Elmo Bumpy Torus (EBT), and the reversed field pinch (RFP). He discusses their major characteristics and their limitations. For example: "... the classical mirror will not lead to a net power producing reactor, although it can lead to a fusion source for materials testing and for producing fissile material from fertile blankets," "... the tandem mirror is attractive as a reactor concept from an engineering viewpoint. The long solenoidal configuration lends itself to relatively simple blanket designs and replacement/maintenance schemes. A mirror reactor should be able to operate in a steady-state mode, subject only to the necessity to replenish the plug and solenoidal plasmas, continuously heat the plug plasma, and control impurity accumulation," "... EBT has several potential advantages over a Tokamak as a reactor concept. The large aspect ratio of the EBT ($A \simeq$ 20-30) relative to the Tokamak ($A \simeq$ 3-4) implies a significantly simpler engineering design. The higher β-limits imply a higher power density and a more modest magnetic field requirement for a given power density ($P \sim \beta^2 B^4$). Finally the EBT could, in principle, operate in a steady-state mode (if impurity control is adequate) because there is no toroidal current that must be maintained," and ". . . the greatest physics uncertainty for the RFP concept is the toroidal field reversal itself. That self-reversal can occur is not in question; the reversed field pinch state has been observed in many experiments over the last 25 years. However, the time constants, relaxation mechanisms, and associated energy loss for setting the reversed field configuration are not well understood."

We believe the author succeeded in analyzing the engineering physics aspects directly affecting the plasma physics. We regret, however, that most of his analysis pertains to the tokamak concept, although this is understandable in view of the fact that the tokamak is now the principal line of development for fusion research. But the fact is that the tokamak concept has been chosen not on the basis of its merits as a potential fusion reactor, but mostly on historical grounds (this is analogous to the adoption of the light water reactor in fission technology): it was the first toroidal device to demonstrate a sufficiently long containment time. There exist today other concepts that demonstrated containment times above the Bohm value. Thus, the tokamak needs to be considered as a step in the advancement of fusion technology, not as a goal by itself. The same argument can be advanced regarding the D-T fuel cycle, which should be regarded as a step toward attaining the environmentally superior D-D or D-^{3}He and other advanced fuel cycles. We hope the author will be able to devote some space to expose this last topic in future editions of the book.

We strongly recommend the book for engineers and physicists in research laboratories or industry who aim at acquiring an up-to-date understanding of the engineering physics aspects of magnetic fusion energy directly affecting the plasma physics. The text is also recommended for advanced graduate courses on thermonuclear fusion, and is a "must" on the shelves of academic and research libraries.

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