BOOK REVIEW

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.

Physics of Mirrors, Reversed Field Pinches and Compact Tori

Editors	Sergio Ortolani and Elio Sindoni
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Reviewer	Donald Rej

Since its inception in 1971, the International School of Plasma Physics has consistently attracted leaders in the field to deliver course lectures and participate in symposia and workshops sponsored by the school. To date, there have been 32 sessions, usually held in the Italian village of Varenna situated on the east shore of Lake Como. Proceedings from the course and workshop entitled "The Physics of Mirrors, Reversed-Field Pinches, and Compact Tori," convened in September 1987, has recently been published for the school and the Italian Physical Society. The book, in three hardbound volumes, is of the high technical standards expected from the school. It consists of a comprehensive compilation of 4 introductory, 41 course, and 25 workshop articles written by leading scientists, principally from Western Europe, the United States, the Soviet Union, and Japan. The editors, Sergio Ortolani [Consiglio Nazionale delle Ricerche (CNR) Padua] and Elio Sindoni (University of Milan), have nicely organized the book into three volumes: I. introductory lectures on all three topics and course articles on the reversed-field pinch (RFP) (454 pages); II. course articles on compact tori (CTs) and magnetic mirrors (507 pages); and III. workshop papers on all three topics (270 pages).

For the RFP research community, this is a timely publication, since their program has matured and recently reached an important crossroad. During the past 5 years, the number of operational RFP devices has tripled to 15. Impressive parameters have been obtained in these rather modest-sized machines: $n \leq 10^{20}$ m^{-3}, $T_e \leq 0.8$ keV, $T_i \geq T_e$, $\beta_\theta \leq$ 15%, and $\tau_E \leq 1$ ms. Moreover, large multimegaampere devices are under construction at Padua and Los Alamos National Laboratory (LANL). Articles have been written by principal scientists from virtually every major RFP group in the world: Colorado, Culham Laboratory, General Atomic, LANL, Nagoya, Padua, Tokyo, and University of Wisconsin. Both self-contained tutorial papers and detailed research articles can be found; therefore, this book should prove to be an indispensable resource not only for new staff and students assigned to these expanding programs, but also for veteran RFP scientists. There are review and research articles about fundamental RFP physics. For example, the theoretical bases and experimental observations of plasma relaxation or self-organization to the minimum energy state are reviewed. The impact of turbulent fluctuations on helicity transport and plasma heating is clarified by several authors. The intimate competition between resistive diffusion away from and relaxation toward the minimum energy state is studied. This competition is convincingly demonstrated with internal magnetic measurements of equilibria and fluctuations. With linear theory well established, recent studies with nonlinear three-dimensional magnetohydrodynamic (MHD) simulations have revealed that relaxation is a consequence of magnetic reconnection driven nonlinearly by kink instabilities.

The book contains a rich collection of technical papers about the RFP. Detailed descriptions of the experimental hardware for the major devices in operation or under construction are given. Recent experiments are reported. Density profiles have been effectively controlled with pellet injection on both the LANL ZT-40M and the Padua ETA-BETA II devices. The resistivity of an RFP is better understood, albeit still a controversial topic. In particular, the discrepancy between resistivities inferred from energy and helicity balance has been reconciled with a non-Spitzer term associated with helicity transport. Helicity dissipation in the edge appears to be critical. On the Culham Laboratory HBTX-1B device, edge obstructions such as limiters caused local increases in the edge plasma resistivity, which led to large increases in helicity dissipation, loop voltage, and power input to the ions.

Significantly improved plasma temperatures and confinement with reduced magnetic field errors are also reported by the HBTX-1B group. The RFP reactor is envisioned as a steady-state device that consequently must operate without the flux-conserving shell that normally surrounds plasmas in present-day devices. The effect of the resistive shell is a critical issue discussed in detail. With a resistive shell, equilibrium and field-error control are allowed; however, linear MHD theory predicts that the RFP is unstable with a growth time comparable to the shell current decay time. Rotation does not eliminate all the modes. The predicted instabilities have not been observed in experiments on the General Atomic Ohmically Heated Toroidal Experiment (OHTE) where RFP configurations were sustained for up to 15 ms with a 1.5-ms shell time constant.

There are several papers about the two configurations usually classified as CTs, the spheromak and the field-reversed configuration (FRC). Though these two concepts share the basic definition of CT in that no material objects link the toroid, their physics are substantially different. Spheromak equilibrium, stability, and confinement share more features with the RFP. For example, current-driven MHD modes are observed to relax the spheromak plasma toward a minimum energy state, while formation, transport, and sustainment processes tend to offset the relaxation. Comparisons between the spheromak and the RFP are emphasized in a complementary manner. Experimental results are presented from the Heidelberg, LANL, Princeton, and Osaka spheromaks as well as the objectives of a new device under construction in Manchester.

The FRC, an elongated CT without toroidal magnetic field, is a unique configuration in view of its high volume-averaged β (50 to 100%), natural divertor, and intrinsic applicability with advanced fuels. Impressive parameters are reported from very modest-sized devices: $n \leq 5 \times 10^{21}$ m^{-3}, $T_e \leq 0.2$ keV, $T_i \leq 0.8$ keV, $\langle\beta\rangle \leq 95\%$, and $\tau_E \leq 100$ μs. There are four course articles on the FRC, three by Americans (including one by this reviewer) and one by a Japanese. Regrettably, there are no contributions from either the Soviet or Chinese FRC groups. While small in number, the four papers complement one another and should serve as an adequate and concise introduction of FRC theory and experiments to nonspecialists. On the other hand, there is insufficient detail here to help researchers directly involved in FRC work. Theoretical topics include equilibrium and stability, with emphasis on the internal tilt mode. While predicted by theory, the virulent internal tilt has yet to be observed in the laboratory. Kinetic, rotation, and elongation effects may resolve this puzzle. The only destructive MHD mode observed is the $n = 2$ rotational mode, which can be controlled with helical or straight multipole fields. A new theory developed at Osaka University successfully explains most of the multipole stabilization data. Other experimental topics include formation, equilibrium, transport, axial translation, and compression heating. Two new devices are described. Confinement and stability at large plasma radius will be studied in the LSX device under construction at Spectra Technology, while high-power magnetic compression experiments on the FRX-C facility at LANL will concentrate on confinement at higher energy densities.

The international mirror program is well represented in this book. In addition to an excellent tutorial introductory lecture on the physics of magnetic mirrors, there are detailed course articles from leading American, Japanese, and Soviet scientists. Accordingly, this book should serve both as an introduction and a reference to plasma physicists interested in mirrors. Experimental results from tandem mirrors are presented. Confinement analyses, electrostatic potential measurements, and microstability on the Lawrence Livermore National Laboratory TMX-U and the Tsukuba GAMMA-10 devices are reported. Plasma equilibrium and stability in the TARA experiment at the Massachusetts Institute of Technology are reviewed. In particular, an $m = 1$ flute mode is stabilized with the addition of a magnetic divertor near the axial midplane of the central cell. Objectives and design details of the AMBAL-M device, under construction in Novosibirsk, are also presented. The stabilization of MHD activity is observed on the Wisconsin Phaedrus tandem mirror through the ponderomotive force generated during ion cyclotron resonance frequency (ICRF) heating. In addition, a comprehensive tutorial paper on the theory of ICRF waves in mirrors is authored by the Wisconsin group.

There is an informative review of the Soviet mirror program at the Institute for Nuclear Physics, where there is a concentrated effort to explore innovative axisymmetric configurations. Axisymmetry is attractive because neoclassical and resonant losses are absent; moreover, the configuration will be technically simpler, with longer plasmas, higher β, and larger B fields possible. In a theoretical paper, it is suggested that MHD stability may exist in nonparaxial systems (i.e., systems where the plasma radius is of comparable magnitude to the magnetic field scale length). In addition to AMBAL, there are articles about two other experimental programs. First results are presented from the gas dynamic trap device, a simple mirror operated with very strong mirror ratio (up to 100). The central cell is sufficiently collisional so that there is significant plasma density outside the plasma in so-called expander regions where there is good field-line curvature. Global MHD stability has been demonstrated with the expander plasma. The other program deals with the heating of mirror-confined plasmas with intense relativistic electron beams. An observed 30% heating efficiency is attributed to the two-stream interaction.

The application of magnetic mirrors as steady-state 14-MeV neutron sources received the attention of a number of authors. These sources are proposed to address fusion engineering issues such as material science, tritium breeding, and thermal hydraulics. Convincing arguments are made for compact, mirror-based devices capable of providing a 1 MW/m^2 flux over a 1-m^2 surface area with modest tritium consumption (0.15 kg/yr).

In summary, I found this book to contain a thorough collection of well-written introductory and tutorial articles about the theoretical and experimental physics associated with the RFP, CTs, and magnetic mirror. It should serve as a useful up-to-date reference for plasma physicists interested in any one of these topics. Furthermore, the book should prove to be an invaluable reference for every RFP scientist, because of its comprehensive collection of pertinent research articles about the RFP.

Donald Rej received his PhD in applied physics from Cornell University in 1981 for work with relativistic electron ring plasmas. Since that time, he has been a staff member in the Controlled Thermonuclear Research Division at LANL working on FRC CTs. His present research interests include FRC heating, confinement, and translation.