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.

Reviews of Plasma Physics (Vol. 8)

Editor	M. A. Leontovich (translated from Russian by Dave Parsons)
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Reviewer	Glenn A. Gerdin

INTRODUCTION

This volume, which is a translation of the highly regarded Russian series "Voprosy Teorii Plazmy," contains four articles dealing with the application of magnetohydrodynamic (MHD) theory to the subjects of:

1. steady-state flow of a plasma fluid (first two articles)
2. two-dimensional computer modeling of a plasma focus (third article)
3. "plasma optics" or the properties of plasma-filled electrostatic and magnetic lenses for focusing ion beams (fourth article).

These articles represent the state-of-affairs in these areas as of 1974 with emphasis on the work reported in the Russian literature. The treatment is considerably expanded from the archival versions with several examples included to illustrate the phenomena being analyzed and the limitations of the approximations being made. The results are compared with experiments where possible to clarify the strengths and weaknesses of the theory; this enables the reader to form a comprehensive view of these topics.

The relevance of the topics selected to fusion research is somewhat more specialized than those of the earlier volumes of this series. The main motivation of the articles on steady-state flow of plasmas is the need for high current steady-state plasma accelerators to be used as high specific impulse rockets for spacecraft. However, applications to the modeling of plasma sources for heating and confinement, to magnetic divertor studies, and to direct energy conversion clearly exist. The plasma focus held the record for the most fusion neutrons emitted in a single pulse by a controlled fusion device until surpassed by the Princeton Large Torus in 1978. However, the plasma focus cannot be considered a mainline approach to fusion at present, although several exciting phenomena occur in the device, such as the generation of intense particle beams, which make it a subject of continuing interest. The article on plasma optics is probably of most interest to the fusion community since the focusing and transport of ion beams in plasmas is crucial to light ion inertial confinement fusion. Other important fusion applications of plasma optics include:

1. the direct conversion of charged-particle energy from fusion reactors
2. charged-particle diagnostics in a plasma environment
3. the study of the extraction region of ion beam sources for neutral beams.

The merits of these four articles are discussed in the following sections.

DISCUSSION OF ARTICLES

"Steady-State Plasma Flow in a Magnetic Field," A. I. Morozov and L. S. Solov'ev (103 pp., 27 refs.)

This first article consists of an analytical treatment of laminar or potential flow of plasmas in a magnetic field and hence is complementary to the following article by K. V. Brushlinskii and A. I. Morozov, which describes the nature of the computer calculations in this area. The application[a] of these calculations to plasma acceleration is clearly drawn in the first chapter. The role of the various terms in the ion force equation in the connection with ion acceleration is discussed and the conditions necessary for the existence of a steady-state electric field in a flowing plasma are presented. Also the effect of nonparallel electron and ion flow (two-fluid or Hall effect) is introduced and thus the reader is given an overview of what is to follow.

The next three chapters deal with single- and two-fluid potential flow calculations in axisymmetric systems and hence the formulation relies heavily on the use of both magnetic and fluid stream functions. This is analogous to the use of the magnetic flux (or stream) functions in the MHD equilibrium calculations (i.e., the Grad-Shafranov Equation) but in the flow calculations the inclusion of the $\rho(v\cdot\boldsymbol{\nabla})v$ term in the force equation requires the inclusion

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[a] The application to MHD power generation is limited since the plasma is assumed to be fully ionized throughout this article.

of the fluid stream function as well. Thus the resulting equations are quite lengthy and this reviewer found an earlier article by one of the authors (L. S. Solov'ev) in Vol. 3 of this series helpful in following this formulation.

These equations are simplified by such approximations as considering only an azimuthal magnetic field, narrow flux tubes, and/or weak axial or z dependence. Analytic expressions for the stream functions are derived or presented graphically where possible so the reader can gain an understanding as to the nature of the flow. Specific physical phenomena that can be described by these calculations even in a single-fluid approach are the existence of eddy currents and the shape of the critical surfaces where the flow becomes sonic. In the appendixes, the general equations for single- and two-fluid potential flow are derived for cylindrical, azimuthal, and helical symmetry.

Since experimental situations probably require extensive computer calculations, the usefulness of these analytic calculations might appear limited. However this treatment does provide some nontrivial solutions for the testing of computer models and helps the reader attain a better understanding of MHD theory. Although phenomena such as the Hall effect are covered in elementary textbooks,[1] the more formal approach used here has broader application, which should make this article quite useful to anyone studying plasma flow.

"Calculation of Two-Dimensional Plasma Flows in Channels," K. V. Brushlinskii and A. I. Morozov (92 pp., 74 refs.)

As the computational analog of the analytic first article, one might expect that in the second article more space could be devoted to discussion of the results and comparison with experiments and this is indeed the case. In the introduction, the reader is presented with a comprehensive overview of the motivation for two-dimensional MHD calculations (i.e., as the logical next step as of 1974) and how the work presented here (steady state) relates to other two-dimensional MHD calculations including those of non-Soviet investigators (not steady state). In the next section, the experimentally observed asymmetry of the flow to polarity reversal is described, and a physical model of this phenomenon based on the Hall effect is presented. Next, the various phenomena that one would like to treat to simulate experiments are discussed, including ionization in the channel, nonfluidlike behavior of the ions, and the boundary conditions at the walls. Thus the reader is kept well aware of the relevance, strengths, and weaknesses of the results presented.

The analysis proceeds as follows: The basic MHD equations are presented and made dimensionless, the computation technique is described, and the results are presented and discussed. The computational technique used here of a Eulerian mesh along the flow and Lagrangian mesh transverse to the flow is often used in calculations where the radial dimension changes dramatically (e.g., theta pinch calculations).

Results are presented that demonstrate the effect of the inclusion of various terms of the generalized Ohm's Law for a fluid plasma. The existence of eddy currents in the flow (first discovered in computer calculations by the authors) and the decreasing size of the eddy-current volume with decreasing plasma conductivity are clearly demonstrated, as is the asymmetry of the flow to polarity reversal (i.e., the current distribution tends to run parallel to the anode), which is consistent with the physical model introduced earlier and with experiment. While no steady-state flow is found when the Hall effect is too strong and magnetic viscosity is neglected, finite viscosity stabilizes the flow. Compressional flow results and the results of simple ionization models are presented.

The article is written in a lucid manner and strongly complements the first article. In fact, the overview as to relevance of these types of calculations given in this article would have been welcome in the first article as well. Again these complementary articles should be very useful to the study of MHD flow.

"Two-Dimensional Magnetohydrodynamic Model for the Dense Plasma Focus of a Z Pinch," V. F. D'yachenko and V. S. Imshennik (100 pp., 47 refs.)

As pointed out in the introduction of this third article, several phenomena occurring in the plasma focus, such as the high neutron yield and beam generation, make it a subject of interest to fusion. The two-dimensional computer modeling of the plasma focus using a Eulerian mesh has been successful in explaining the motion of the current sheath and the current waveform[2-4] and the calculations presented here represent a logical next step in that a modified Lagrangian mesh is used. These calculations also represent the logical next step in the research of the authors who reported on the results of one-dimensional calculations modeling the radial collapse of a plasma focus in Vol. 5 of this series. As the authors point out in the introduction of this present article, the substantial mass ejection (up to 90%) along the z axis of the device makes a two-dimensional (r,z) calculation essential. Since the radial dimension becomes very small at pinch time, a Eulerian mesh may have only a few points remaining in the plasma unless long computer runs are possible. Even with the computational improvement of a modified Lagrangian scheme, during the period of maximum compression (called the "2nd compression" in this article) the ion mean-free-path becomes equal to the pinch radius so the single-fluid MHD formulation breaks down (although the electrons remain a fluid). However, up to this point, the MHD formulation is valid and so these calculations should provide a reasonable explanation of events up to the start of the pinch.

The article proceeds with a standard presentation of the MHD theory but includes a welcome derivation of the coupling of the circuit equation to the plasma using the Poynting vector. The numerical technique discussed next is called the "free-point method," which is a Lagrangian approach where the relationship between the points is rearranged on each time step. This avoids the distortion of the grid by the convective terms and yet gives adequate representation of the plasma at pinch time since the points still move with the plasma. The second chapter (30 pp.) is entirely devoted to a description of this method. While other investigators[5] were developing similar schemes in 1974, it is unique and these calculations represent the first where such a technique was applied to the severe challenge of modeling the plasma focus.

The results of two versions of the code are presented, one with Spitzer resistivity and one with 100 × Spitzer resistivity to simulate the effect of anomalous transport. The criteria for the validity of anomalous transport are given in terms of the electron drift velocity, and it is found that the version with pure Spitzer resistivity should be valid for most stages. Since these calculations show that the boundary of the pinch becomes wavy (in r,z), the linear theory for Rayleigh Taylor ($m = 0$) instabilities with viscosity is analyzed and found in qualitative agreement with the calculations. This helps the reader understand the nature of the phenomena and such discussions are commendable.

Less commendable was the attempt to get a quantitative estimate of the neutron yield from the basis of these calculations. A thermonuclear model is assumed but since the validity of the computations break down shortly after pinch time the lifetime of the pinch cannot be determined. A model for the lifetime of the pinch based on the decay of the magnetic field in a detached current loop is not very convincing since the formation of such loops is beyond the scope of the calculations. The following discussion of the true nature of the neutron yield in a plasma focus, while somewhat consistent with observations from the Filippov-type of plasma focus, are not completely accepted in the plasma focus community.[6]

The conclusion strongly points to the need for a two-dimensional hybrid code treating the electrons as a fluid and the ions in a kinetic manner. While one-dimensional versions of such codes have been used to describe theta pinches, a two-dimensional version is clearly a formidable task.

In general, this reviewer found the article to be clear and thorough in its presentation and feels the article makes an important contribution to plasma focus theory.

"Plasma Optics," A. I. Morozov and S. V. Lebedev (159 pp., 42 refs.)

The fourth article presents an analytic approach to determining the ion-focusing properties of plasma-filled electrostatic and/or magnetic lenses. Since the plasma screens out electrostatic fields used in conventional vacuum ion optics, new approaches must be developed as presented in this article. Charge neutrality of the beam is assumed throughout and self-magnetic fields of the beam are neglected so that results can be based on single-particle orbit calculations. While the effects of self-magnetic fields may limit the use of such lenses, recent experimental results from Cornell[7] indicate that single-particle orbit effects can describe the focusing properties of a plasma magnetic dipole lens for focused current densities on the order of 100 A/cm^2. Also they found the theoretical limit to be the ion Alfven current (somewhat similar criteria are presented in the last section of this article), which is 782 kA for a 300-keV proton beam. Thus the results presented in this article should have a wide range of applicability even in the realm of light ion fusion.

The problem is simplified by the use of the nonrelativistic paraxial ray equation (PRE) for single-particle trajectories. Both axial and annular lens systems are considered so the PRE involves particles that make small radial derivations from the axis or the initial annular surface, respectively. The magnetic and electric potentials are determined by power series expansions in the radial direction from potentials specified on these surfaces. The weak field approximation is made (where the maximum velocity increment gained by the particle in the lens is much smaller than the incident velocity, v_0) and expressions for the focal lengths of various field configurations are derived in a power series of $(Mv_0^2)^{-1}$ where M is the mass of the ion. Aberrations are included by treating the nonlinear terms in the PRE and simple examples are worked out to illustrate the technique.

Multiple-lens, multiply connected (i.e., toroidal) charge acceleration systems are considered as is two parameter focusing. Finally the effects of finite electron pressure and criteria for the neglect of self-magnetic fields are presented.

While the theoretical analysis of realistic lens systems requires computer calculations, there is always a need for nontrivial analytic results to test the computer calculations and to help scientists and engineers understand the nature of these focusing systems. The clear, careful, and logical manner of this article should make it valuable to anyone with the problem of focusing ion beams in a plasma environment.

SUMMARY

The thorough and lucid presentation of the topics in these articles should make them of great use[b] and also indicates excellent editing. Since this actually is a translation, high praise should be given to the efforts of the translator, Dave Parsons, and those of the translation editor, the late Herbert Lashinsky.

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[b] However, the reviewer cautions the reader to check the equations. For example, Eq. 2.41 of the article on "Plasma Optics" should be linear in (eH_θ/Mc), not squared, and this error propagates farther on.