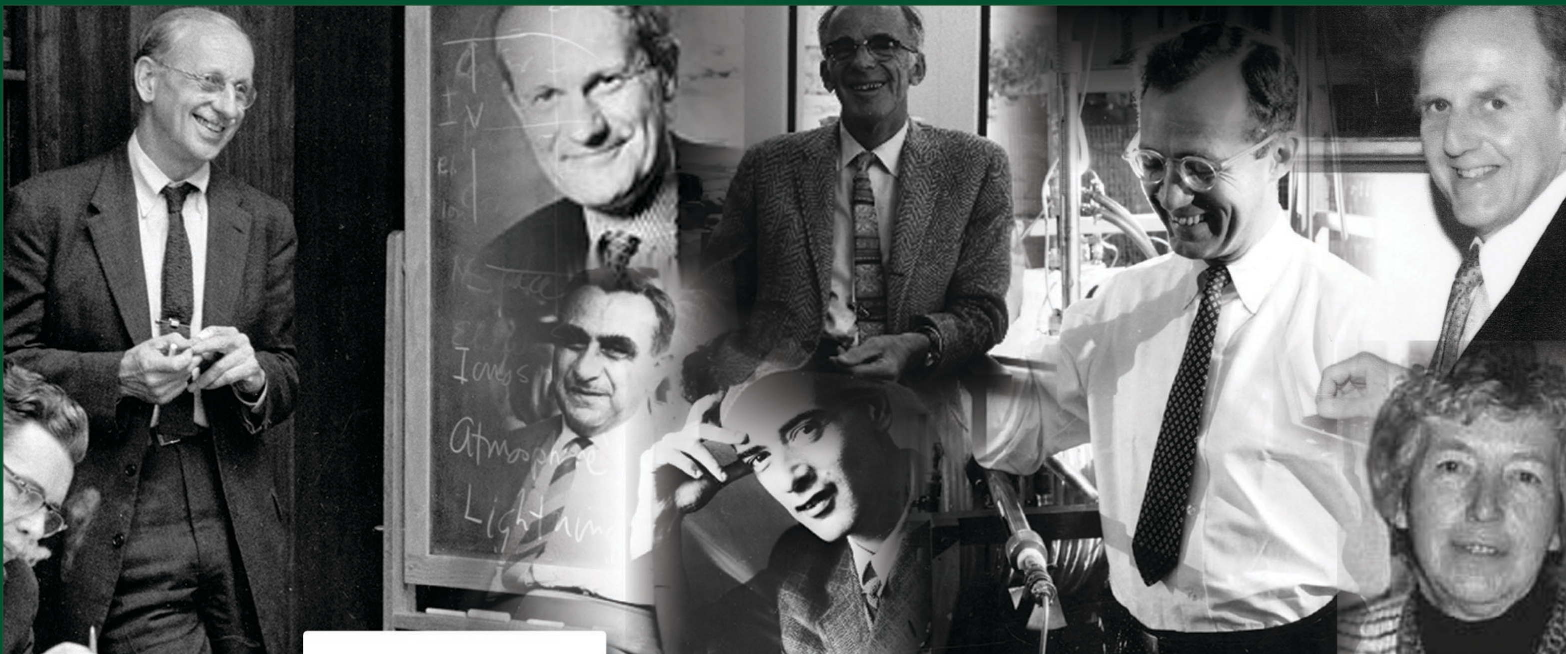
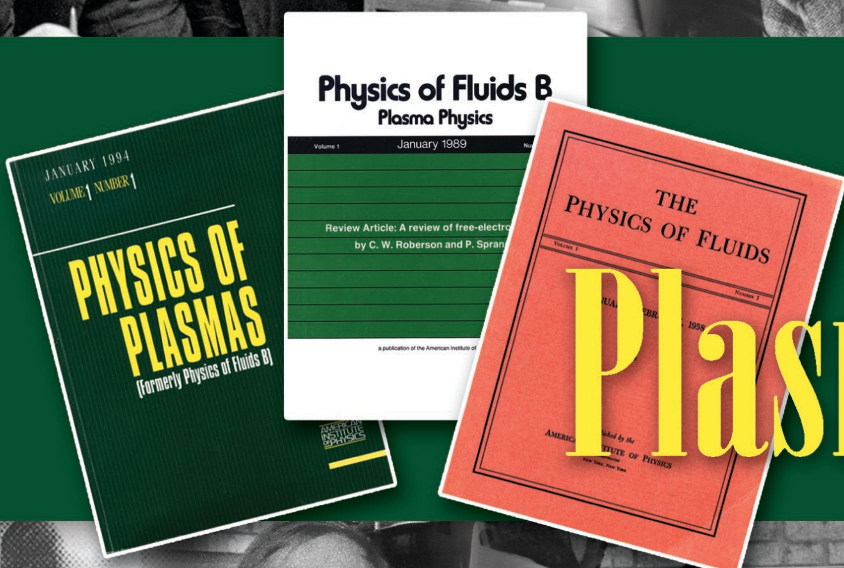
50 YEARS OF PLASMA PHYSICS





50 Years of Plasma Physics

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Selected Highly Cited Papers from 50 Years of Plasma Physics

A Special Publication
Prepared for the 50th Anniversary Meeting
of the APS Division of Plasma Physics

Dallas, Texas, November 2008

Editor

Ronald C. Davidson
Princeton Plasma Physics Laboratory, Princeton, New Jersey

Selected Papers Published in:

Physics of Fluids, 1958–1988

Physics of Fluids B, 1989–1993

and

Physics of Plasmas, 1994–2008

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Selected Highly Cited Papers from 50 Years of Plasma Physics

Contents

Credits—Cover Photographs

Grateful acknowledgment is given to those who granted permission to reprint the photographs used on the front cover of this special publication. Beginning with the photo in the top left-hand corner and reading clockwise, below are listed the person pictured and the source for each photograph:

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Inspecting the torus at John Jay Hopkins Laboratory's fusion research building are, from left to right: **Richard Courant, Hideki Yukawa, Marshall N. Rosenbluth, Marcus Oliphant, Niels Bohr, Edward C. Creutz, and Donald W. Kerst**, General Atomic, Division of General Dynamics Corporation
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Frontiers in Plasma Physics Research: A Fifty-Year Perspective from 1958 to 2008

This special anniversary publication has been assembled by the Editorial Office of *Physics of Plasmas* to feature many of the outstanding papers published by the journal and its predecessors that have significantly advanced the fundamental understanding of plasmas over the past fifty years. The abstracts of 221 highly cited papers are included in chronological order by subfield, reproduced as they appeared in the original issues.

The earliest papers included in this anniversary publication appeared in the first journal published by the American Institute of Physics (AIP) to include plasma physics, *Physics of Fluids*. The first issue of this journal appeared in January 1958, under the editorship of François N. Frenkiel. As noted by John T. Scott in his recent history of the *Physics of Fluids* [J. T. Scott, Phys. Fluids **20,** 011301 (2008)], the emphasis on plasma physics grew markedly from the first year of publication. In 1982, two editors replaced Frenkiel, with Fred L. Ribe taking on the role of Editor for the plasma physics papers. In 1989, the journal was divided into two separate publications, with the plasma physics papers appearing in *Physics of Fluids B—Plasma Physics*. Ronald C. Davidson became Editor of the journal in 1991, and in 1994, the journal was renamed again, as *Physics of Plasmas*. The covers of the first issues of each of these journals are reproduced on the front cover of this anniversary publication, along with a collage of photos in memory of some of the founding physicists of the field.

Selecting highly significant papers covering a fifty-year time period has been challenging, and an effort has been made to include papers that represent the diverse subfields of plasma physics. The selection of many papers will be obvious to the reader, while the selection of others may be somewhat surprising. Our apologies to those readers who have candidate papers that are not included. In any case, we believe you will agree that this anniversary publication indicates that plasma physics is a healthy and vibrant field of physics. We look forward to another fifty years of significant progress and landmark publications in *Physics of Plasmas*.

We wish to thank everyone in the production team at AIP, whose conscientious efforts made the concept for this anniversary publication a reality.

Ronald C. Davidson
Editor
Physics of Plasmas

Basic Plasma Phenomena, Waves, Instabilities

THE PHYSICS OF FLUIDS VOLUME 1, NUMBER 4 JULY-AUGUST, 1958

On the Stability of Plasma in Static Equilibrium*

M. D. KRUSKAL AND C. R. OBERMAN
Project Matterhorn, Princeton University, Princeton, New Jersey
(Received May 27, 1958)

Criteria useful for the investigation of the stability of a system of charged particles are derived from the Boltzmann equation in the small m/e limit. These criteria are obtained from the examination of the variation of the energy due to a perturbation, when subject to the general constraint that all regular, time-independent constants of the motion (including the energy) have their equilibrium values.

The first-order variation of the energy vanishes trivially, and the second-order variation yields a quadratic form in the displacement variable ξ (which may be introduced because of the well-known properties of this limit). The positive-definiteness of this form is a sufficient condition for stability. Several theorems are stated comparing stability under the present theory with that under conventional hydromagnetic fluid theories where heat flow along magnetic lines of force is neglected. Generalizations can be made to systems where the effect of collisions is included.

Phys. Fluids **1**, 275 (1958)

VOLUME 3, NUMBER 1 JANUARY-FEBRUARY, 1960

Test Particles in a Completely Ionized Plasma

NORMAN ROSTOKER AND M. N. ROSENBLUTH
John Jay Hopkins Laboratory for Pure and Applied Science,
General Atomic Division of General Dynamics Corporation, San Diego, California
(Received October 19, 1959)

Starting from the Liouville equation, a chain of equations is obtained by integrating out the coordinates of all but one, two, etc., particles. One "test" particle is singled out initially. All other "field" particles are assumed to be initially in thermal equilibrium. In the absence of external fields, the chain of equations is solved by expanding in terms of the parameter $g = 1/nL_D{}^3$. For the time evolution of the distribution function of the test particle, an equation is obtained whose asymptotic form is of the usual Fokker-Planck type. It is characterized by a frictional-drag force that decelerates the particle, and a fluctuation tensor that produces acceleration and diffusion in velocity space. The expressions for these quantities contain contributions from Coulomb collisions and the emission and absorption of plasma waves. By consideration of a Maxwell distribution of test particles, the total plasma-wave emission is determined. It is related to Landau's damping by Kirchoff's law. When there is a constant external magnetic field, the problem is characterized by the parameter g, and also the parameter $\lambda = \omega_c/\omega_p$. The calculation is made by expanding in terms of g, but all orders of λ are retained. To the lowest order in g, the frictional drag and fluctuation tensor are slowly varying functions of λ.

When $\lambda \ll 1$, the modification of the collisional-drag force due to the magnetic field, is negligible. There is a significant change in the properties of plasma waves of wavelength greater than the Larmor radius which modifies the force due to plasma-wave emission. When $\lambda \gg 1$, the force due to plasma-wave emission disappears. The collisional force is altered to the extent that the maximum impact parameter is sometimes the Larmor radius instead of the Debye length, or something in between. In the case of a slow ion moving perpendicular to the field, the collisional force is of a qualitatively different form. In addition to the drag force antiparallel to the velocity of the particle, there is a collisional force antiparallel to the Lorentz force. The force arises because the particle and its shield cloud are spiralling about field lines. The force on the particle is equal and opposite to the centripetal force acting on the "shield cloud." It is much smaller than the Lorentz force.

Phys. Fluids **3**, 1 (1960)

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 2 MARCH-APRIL, 1960

Electrostatic Instabilities of a Uniform Non-Maxwellian Plasma

OLIVER PENROSE
Imperial College of Science and Technology, London S. W. 7, England
(Received October 9, 1959)

A stability criterion is obtained starting from Vlasov's collision-free kinetic equations. Possible instabilities propagating parallel to an arbitrary unit vector **e** are related to a function $F(u) \equiv \Sigma_j \omega_j^2 \int d^3\mathbf{v}\, g_j(\mathbf{v})\, \delta(\mathbf{e}\cdot\mathbf{v} - u)$, where $g_j(\mathbf{v})$ is the normalized unperturbed distribution function, and $\omega_j \equiv (4\pi n_j e_j^2/m_j)^{\frac{1}{2}}$ the plasma frequency, for the jth type of particle. By using a method related to the Nyquist criterion, it is shown that plasma oscillations growing exponentially with time are possible if and only if $F(u)$ has a minimum at a value $u = \xi$ such that $\int_{-\infty}^{\infty} du\, (u - \xi)^{-2}[F(u) - F(\xi)] > 0$. A study of the initial-value problem confirms that the plasma is normally stable if no exponentially growing modes exist; but there is an exceptional class of distribution functions (recognizable by means of an extension of the above criterion) for which linearized stability theory breaks down. The method is applied to several examples, of which the most important is a model of a current-carrying plasma with Maxwell distributions at different temperatures for electrons and ions. The meaning of the mathematical assumptions made is carefully discussed.

Phys. Fluids **3**, 258 (1960)

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 3 MAY-JUNE, 1960

Resonance in a Plasma with Two Ion Species

S. J. BUCHSBAUM
Bell Telephone Laboratories, Inc., Murray Hill, New Jersey
(Received January 26, 1960)

When a high-density plasma column in an axial magnetic field possesses two (or more) ion species of different charge-to-mass ratios, there exists a plasma resonance condition which involves only the ion cyclotron frequencies. At reasonance, the two ion clouds oscillate transversely to the static magnetic field and 180 deg out of phase with each other, while the electrons remain relatively motionless. The ratio of the ion oscillatory energy to that of the electrons is of the order of the ratio of the ion-to-electron masses. Collisions between the two ion clouds randomize the large ordered velocities of the ions with great efficiency. Thus, by exciting this resonance, considerable ion heating may be realized. The effect of varying the relative concentration of the two ions is discussed.

Phys. Fluids **3**, 418 (1960)

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 5 SEPTEMBER-OCTOBER, 1960

Drift Instabilities in a Maxwellian Plasma

E. ATLEE JACKSON
Project Matterhorn, Princeton University, Princeton, New Jersey
(Received May 11, 1960)

The stability of two Maxwellian components of a plasma, which have different drift velocities, is investigated by means of a graphical solution of the dispersion relation. The graphical technique has the advantage of exhibiting the content of the dispersion relation in a transparent manner. By this method we determine the region of instability as a function of the perturbation wavelength λ and the relative velocity of the components, and show how this region depends on the ratio of the Debye lengths and plasma frequencies. In the case of an electron-proton plasma we obtain the maximum growth rate as a function of λ and the critical drift velocity as a function of the temperature ratios. The structure of the unstable region is also indicated by a few lines of constant growth rate.

Phys. Fluids **3**, 786 (1960)

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 6 NOVEMBER-DECEMBER, 1960

Plasma Motion Across Magnetic Fields

GEORGE SCHMIDT
Stevens Institute of Technology, Hoboken, New Jersey
(Received March 23, 1960)

The analysis of plasma flow problems in magnetic fields is usually based on a hydromagnetic fluid model. In low-density collisionless plasmas, however, the limitations of the applicability of this method are not clearly understood. In this paper a simplified self-consistent field method is used, with particle motion considered in the guiding center approximation. In this case the high "dielectric constant" of the magneto-plasma plays the role of the infinite conductivity of the fluid model. Several experiments are analyzed on the basis of this model, and the limitations and shortcomings of the hydromagnetic treatment discussed.

Phys. Fluids **3**, 961 (1960)

THE PHYSICS OF FLUIDS VOLUME 4, NUMBER 1 JANUARY, 1961

Longitudinal Ion Oscillations in a Hot Plasma

BURTON D. FRIED AND ROY W. GOULD*
Physical Research Laboratory, Space Technology Laboratories, Inc., Los Angeles, California
(Received July 21, 1960)

Linearized, longitudinal waves in a hot plasma include, besides the familiar electron plasma oscillations, in which the frequency ω is of order $\omega_p = (4\pi ne^2/m)^{\frac{1}{2}}$, also ion plasma oscillations with $\omega \approx \omega_p(m/M)^{\frac{1}{2}}$. The properties of the latter are explored using a Vlasov equation description of the plasma. For equal ion and electron temperatures, $T_e = T_i$, there exists a discrete sequence of ion oscillations, but all are strongly damped, i.e., have $-\text{Im}\,\omega/\text{Re}\,\omega \gtrsim 0.5$, and hence are not likely to be observable. The ratio $\text{Im}\,\omega/\text{Re}\,\omega$ can be made to approach zero (facilitating detection of the waves) by either increasing T_e/T_i or by producing a current flow in the plasma. In the latter case, $\text{Im}\,\omega$ can even be made positive (corresponding to growing waves), the current required for this being smaller the larger the value of T_e/T_i. This growing wave is just the familiar two-stream instability which is thus seen to be an unstable ion oscillation. It is also noteworthy that the ion oscillations, which for small k have the properties usually associated with an acoustic wave (longitudinal polarization, $\omega \propto k$), are obtained using a formalism which is sometimes designated as "collisionless."

Phys. Fluids **4**, 139 (1961)

VOLUME 4, NUMBER 4 APRIL, 1961

Convective Instability Induced by Gravity in a Plasma with a Frozen-In Magnetic Field

WILLIAM A. NEWCOMB
Lawrence Radiation Laboratory, University of California, Livermore, California
(Received September 22, 1960)

The convective instability induced by gravity in a compressible fluid layer is investigated in the special case of a plasma with a frozen-in magnetic field **B**. The necessary and sufficient condition for stability, which is here derived from the hydromagnetic energy principle, is that the density gradient should exceed a certain critical value that is independent of B. Thus the rigidity given to the plasma by the frozen-in field does not suffice to remove the instability but only to slow it down. The growth rates of the unstable displacements are calculated by means of a normal mode analysis and are shown to be inversely proportional to B when B is sufficiently large.

Phys. Fluids **4**, 391 (1961)

THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 4 APRIL, 1962

One-Dimensional Plasma Model

JOHN DAWSON
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received June 27, 1961; revised manuscript received December 27, 1961)

A one-dimensional plasma model consisting of a large number of identical charge sheets embedded in a uniform fixed neutralizing background is investigated by following the sheet motions on a high-speed computer. The thermalizing properties and ergodic behavior of the system are examined and found to be in agreement with the assumption that one is equally likely to find the system in equal volumes of the available phase space. The velocity distribution, Debye shielding, drag on fast and slow sheets, diffusion in velocity space, the Landau damping of the Fourier modes, the amplitude distribution function for the Fourier modes, and the distribution of electric fields felt by the sheets were obtained for the plasma in thermal equilibrium and compared with theoretically predicted values. In every case, except one, the drag on a slow sheet, the numerical results agreed with theory to within the statistical accuracy of the results. The numerical results for the drag on a slow sheet were about a factor of 2 lower than the theory predicated indicating that the approximations made in the theory are not entirely valid. An understanding of the cause of the discrepancy might lead to a better understanding of collisional processes in plasmas.

Phys. Fluids **5**, 445 (1962)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 1 JANUARY 1963

Plasma Electromagnetic Instabilities

R. N. SUDAN
School of Electrical Engineering, Cornell University, Ithaca, New York
(Received 22 August 1962)

A gyrotropic plasma with $T_\parallel/T_\perp \equiv \gamma < 1$, where $T_\perp$ and $T_\parallel$ are the transverse and longitudinal temperatures, is shown to be unstable to a perturbation in the form of a transverse wave with a wave vector $\mathbf{k}$ such that $k^2 < k_0^2 = \{\omega_c^2(1-\gamma)^2 + \omega_p^2(1-\gamma)/\gamma\}/c^2$, ω_c and ω_p are the gyro and plasma frequencies. For $T_\parallel > T_\perp$ such an instability arises only if $\omega_c^2/\omega_p^2 > 1/\gamma(\gamma-1)$ and then only for $k^2 < k_0^2$. However, in the latter case, the phase velocity of the instability exceeds c and the growth rate must be made to vanish because of relativistic considerations. No such instability arises for complete isotropy $T_\perp = T_\parallel$.

Phys. Fluids **6**, 57 (1963)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 2 FEBRUARY 1963

Excitation of Electrostatic Plasma Oscillations near the Ion Cyclotron Frequency

R. W. MOTLEY AND N. D'ANGELO
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 29 October 1962)

Oscillations near the ion cyclotron frequency have been excited in thermal cesium and potassium plasmas by drawing current in a filament along the axis of the plasma column. The oscillations appear to be electrostatic waves propagating radially from the filament. The waves are present if the electron drift velocity exceeds about 10 times the ion thermal velocity, in agreement with the prediction of M. N. Rosenbluth. The measured phase velocity is also in agreement with the phase velocity calculated from the fluid equations.

Phys. Fluids **6**, 296 (1963)

VOLUME 6, NUMBER 4 APRIL 1963

Finite-Resistivity Instabilities of a Sheet Pinch

HAROLD P. FURTH AND JOHN KILLEEN
Lawrence Radiation Laboratory, Livermore, California
AND
MARSHALL N. ROSENBLUTH
University of California, San Diego, La Jolla, California, and *John Jay Hopkins Laboratory for Pure and Applied Science, General Atomic Division of General Dynamics Corporation, San Diego, California*
(Received 17 September 1962)

The stability of a plane current layer is analyzed in the hydromagnetic approximation, allowing for finite isotropic resistivity. The effect of a small layer curvature is simulated by a gravitational field. In an incompressible fluid, there can be three basic types of "resistive" instability: a long-wave "tearing" mode, corresponding to breakup of the layer along current-flow lines; a short-wave "rippling" mode, due to the flow of current across the resistivity gradients of the layer; and a low-g gravitational interchange mode that grows in spite of finite magnetic shear. The time scale is set by the resistive diffusion time τ_R and the hydromagnetic transit time τ_H of the layer. For large $S = \tau_R/\tau_H$, the growth rate of the "tearing" and "rippling" modes is of order $\tau_R^{-3/5}\tau_H^{-2/5}$, and that of the gravitational mode is of order $\tau_R^{-1/3}\tau_H^{-2/3}$. As $S \to \infty$, the gravitational effect dominates and may be used to stabilize the two nongravitational modes. If the zero-order configuration is in equilibrium, there are no overstable modes in the incompressible case. Allowance for plasma compressibility somewhat modifies the "rippling" and gravitational modes, and may permit overstable modes to appear. The existence of overstable modes depends also on increasingly large *zero-order* resistivity gradients as $S \to \infty$. The three unstable modes merely require increasingly large gradients of the *first-order* fluid velocity; but even so, the hydromagnetic approximation breaks down as $S \to \infty$. Allowance for isotropic viscosity increases the effective mass density of the fluid, and the growth rates of the "tearing" and "rippling" modes then scale as $\tau_R^{-2/3}\tau_H^{-1/3}$. In plasmas, allowance for thermal conductivity suppresses the "rippling" mode at moderately high values of S. The "tearing" mode can be stabilized by conducting walls. The transition from the low-g "resistive" gravitational mode to the familiar high-g infinite conductivity mode is examined. The extension of the stability analysis to cylindrical geometry is discussed. The relevance of the theory to the results of various plasma experiments is pointed out. A nonhydromagnetic treatment will be needed to achieve rigorous correspondence to the experimental conditions.

Phys. Fluids **6**, 459 (1963)

THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 9 SEPTEMBER 1964

Resonance Oscillations in a Hot Nonuniform Plasma

J. V. PARKER, J. C. NICKEL, AND R. W. GOULD
California Institute of Technology, Pasadena, California
(Received 20 April 1964)

A quantitative theory of resonance oscillations, such as observed by Dattner and others, is given. The first two moments of the collisionless Boltzmann equation assuming a scalar pressure are used in conjunction with a physically reasonable radial electron density profile to describe the oscillations of a hot nonuniform plasma cylinder. These equations coupled with Maxwell's equations assuming a scalar potential are solved numerically to yield the frequency spectrum of the plasma wave resonances. It is found that the frequency spectrum depends on the parameter $r_w^2/\langle\lambda_d^2\rangle$ where r_w is the radius of the plasma column and $\langle\lambda_d^2\rangle$ is the mean square Debye length of the electron plasma. New experimental observations of dipole and quadrupole spectra for two plasma columns of differing radii are reported and the results of these observations are in good agreement with the theory. The physical mechanism of the resonances is described.

Phys. Fluids **7**, 1489 (1964)

High-Frequency Electrostatic Plasma Instability Inherent to "Loss-Cone" Particle Distributions

M. N. Rosenbluth
General Atomic Division of General Dynamics Corporation
San Diego, California and University of California
San Diego, La Jolla, California
AND
R. F. Post
University of California Lawrence Radiation Laboratory
Livermore, California
(Received 12 October 1964)

It has been pointed out[1] that anisotropies in velocity space may lead to high frequency electrostatic instabilities in a plasma. The most widely studied model has been that of the two-temperature Maxwellian, for which a sufficient condition for stability is the rather unrestrictive one, $T_\perp/T_\parallel < 2$.[2,3] In this note we point out that a much wider class of distribution functions can be unstable—in particular those suitable for confinement in "open-ended" containment fields (e.g., mirror machines) which are characterized by a loss-cone. In such devices $f = 0$ for $v_\parallel > \gamma v_\perp$ where γ depends on the mirror ratio. In the bulk of the paper we discuss the case of an infinite homogeneous plasma in a uniform magnetic field and later make some remarks on finite systems and nonlinear effects.

Phys. Fluids **8**, 547 (1965)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 4 APRIL 1965

Experimental Studies of the Penetration of a Plasma Stream into a Transverse Magnetic Field

D. A. Baker and J. E. Hammel
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received 28 April 1964)

The interaction of a dense ($n \simeq 3 \times 10^{13}$ cm^{-3}), fast ($v \simeq 4 \times 10^7$ cm/sec) plasma stream with a transverse magnetic field is studied experimentally by injecting a plasma from a coaxial gun perpendicular to the magnetic field of a pair of mirror coils. The experiments show that the stream from such a gun can penetrate magnetic fields up to ~9 kG. A rapid field-plasma intermixing takes place and the injected stream crosses the magnetic field by electrically polarizing and producing an $\mathbf{E}\times\mathbf{B}$ drift. It was found that the forward motion of the stream can be stopped by draining the polarization charge by current flow along field lines to a shorting conductor located outside a magnetic mirror. Measurements of stream thickness normal to the magnetic field and the effectiveness of the depolarizing conductors have been made as a function of the strength of the transverse field. The exclusion of the plasma from high magnetic fields, and the variation of stream width with magnetic field intensity are due to plasma polarization effects rather than plasma diamagnetism. Observations on high energy electrons > 200 keV which are produced during the experiment are discussed.

Phys. Fluids **8**, 713 (1965)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 7 JULY 1965

Diocotron Instability in a Cylindrical Geometry

R. H. Levy
Avco-Everett Research Laboratory, Everett, Massachusetts
(Received 11 December 1964)

The diocotron (or slipping stream) instability of low density ($\omega_p \ll \omega_c$) electron beams in crossed fields is considered for a cylindrical geometry. For a simple density distribution, the normal modes of the electron beam correspond to a continuum of eigenvalues, plus two discrete eigenvalues. Work due to Case and Dikii appears to show that the continuous spectrum is not important in stability studies of this type. The condition for stability considering the discrete modes only is derived; under suitable geometrical and electrical conditions, it is shown that these modes can be stable. The analogy between the electromagnetic problem considered here and the problem of the stability of an ideal rotating fluid is discussed. It is shown that stability conditions derived for the latter problem depend on the possibility of axial perturbations; what this implies for the electron beam problem is briefly discussed.

Phys. Fluids **8**, 1288 (1965)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 8 AUGUST 1965

Universal Instability in Complex Field Geometries

Nicholas A. Krall and Marshall N. Rosenbluth*
General Atomic Division of General Dynamics Corporation,
John Jay Hopkins Laboratory for Pure and Applied Science,
San Diego, California
(Received 30 November 1964; final manuscript received 22 March 1965)

An inhomogeneous collisionless plasma in a magnetic field **B** is unstable to an electrostatic oscillation propagating nearly perpendicular to **B** but with a large phase velocity parallel to **B**. We study the stability of this mode in a more complicated plasma equilibrium, including magnetic shear, finite plasma length, currents parallel to **B**, temperature gradients, and gravity-simulated magnetic cusp or mirror curvature. We find that many of these equilibria are stable to this mode, which has been misnamed a "universal instability."

Phys. Fluids **8**, 1488 (1965)

Kelvin–Helmholtz Instability in a Fully Ionized Plasma in a Magnetic Field

Nicola D'Angelo
Plasma Physics Laboratory, Princeton University
Princeton, New Jersey
(Received 9 June 1965)

THE Kelvin–Helmholtz instability might arise in a stratified fluid if the different layers are in relative motion. We wish to examine the conditions of instability in a fully ionized plasma immersed in a magnetic field, **B**, under the assumption that the streaming velocity of the ions along the magnetic lines changes from point to point, in a direction perpendicular to **B**.

Phys. Fluids **8**, 1748 (1965)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 10 OCTOBER 1965

Finite Gyro-Radius Corrections to the Hydromagnetic Equations for a Vlasov Plasma

ALAN MACMAHON
*Lawrence Radiation Laboratory, University of California, Berkeley, California**
(Received 18 January 1965)

Velocity moments of the Vlasov equation are expanded systematically in m/e and equations obtained giving the fluid velocity transverse to **B** through second order. These equations include all "finite gyro-radius" effects. No *a priori* form is imposed on the velocity distribution. The transverse electric field $E_\perp$ is allowed to be large. For straight field lines the equations for purely transverse motion are closed. For weak instabilities ($E_\perp$ small) closed equations are obtained only for low plasma pressure.

Phys. Fluids **8**, 1840 (1965)

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 4 APRIL 1966

Electrostatic Instabilities in Finite Mirror-Confined Plasmas

R. F. POST
Lawrence Radiation Laboratory, University of California, Livermore, California
AND
M. N. ROSENBLUTH
General Atomics Division, General Dynamics Corporation, San Diego, California, and University of California, La Jolla, California
(Received 21 October 1965)

Three classes of electrostatic instabilities deemed likely to be encountered in magnetic mirror-confined plasmas are examined theoretically: (A) a convective type, maser-like in nature, with waves propagating essentially parallel to the field lines; (B) a nonconvective (absolute) instability, arising in the presence of radial density gradients; and (C) a limiting case of (B), not requiring radial density gradients for its stimulation. All three instabilities, which owe their origin to the loss-cone nature of the particle distributions, exhibit critical conditions for onset or growth that are sensitively dependent on the shape of the distribution functions. These conditions are least restrictive for plasmas that have reached a state of collisional equilibrium in confining fields of high mirror ratio. In this limit (C) disappears and the critical conditions imposed by (A) and (B) are not unduly restrictive. In particular, at high plasma densities it is required: (1) for adequate stability against (A), the length of the plasma between the mirrors must not be greater than about 300 to 500 ion-orbit radii, and (2) to satisfy conditions (on the radial density gradient) imposed by (B), the plasma dimensions transverse to the field must also be of the same order; i.e., the plasma must be roughly spherical. Examples are also given which show that the confinement of highly peaked distributions leads to required conditions of orders of magnitude more restrictive than those found for well-randomized distributions.

Phys. Fluids **9**, 730 (1966)

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 6 JUNE 1966

Stability Limits for Longitudinal Waves In Ion Beam–Plasma Interaction

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(Received 22 September 1965)

The two-stream instability is examined for the case of an ion beam traversing a plasma. The dispersion equation for linearized, longitudinal waves in a plasma where collisions are negligible is used to find the restrictions on beam velocity, temperature, and density which will lead to growing waves.

Phys. Fluids **9**, 1084 (1966)

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 8 AUGUST 1966

Collisionless Damping of Hydromagnetic Waves*

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(Received 14 February 1966; final manuscript received 22 April 1966)

Numerical solutions have been obtained for the dispersion relation for hydromagnetic waves in an infinite, uniform, collisionless plasma. Except for the Alfvén (shear) mode, all hydromagnetic waves are strongly damped in plasmas of moderate or high β (fluid pressure/magnetic pressure). For β greater than about $\frac{1}{2}$, the damping factor $\mathcal{W} = -\mathrm{Im}\,(\omega)/|\mathrm{Re}\,(\omega)|$ is a few percent greater for the fast mode (except for special directions of propagation) and of order $\frac{1}{2}$ for the slow mode. The least damped (fast) magnetosonic mode exhibits two maxima in a plot of $\mathcal{W}$ versus the angle θ between the wave vector **k** and the static magnetic field: the first maximum occurs for θ between 20° and 40° and is associated with ion heating; the second occurs between 85° and 89° and is associated with electron heating. In addition, the modes associated with the "hose" and "mirror" plasma instabilities are considered in some detail.

Phys. Fluids **9**, 1483 (1966)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 3 MARCH 1967

Instabilities due to Temperature Gradients in Complex Magnetic Field Configurations

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(Received 25 July 1966)

An integral equation governing an instability due to ion temperature gradients is derived. In the presence of magnetic shear, localized non-convective normal modes of instability are shown to exist if the relative temperature gradient is larger than that of density, unless the shear is exceedingly strong, i.e., the field shears through a large angle in the distance in which the temperature drops. Quasi-modes which are less localized in the direction of the gradient can be constructed from these normal modes and a large thermal diffusion may be expected. Conversely the mass diffusion is shown to be rather slow so that it is reasonable to assume that an effective "divertor" should keep the actual heat loss quite small.

Phys. Fluids **10**, 582 (1967)

THE PHYSICS OF FLUIDS VOLUME 11, NUMBER 3 MARCH 1968

Drift Instabilities in General Magnetic Field Configurations

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(Received 5 October 1967)

A theory of low-frequency drift (universal) instabilities in a nonuniform collisionless plasma is developed for general magnetic field configurations including trapped particle effects, rather than the plane geometry which has previously received most attention. A type of energy principle shows that the special equilibrium distribution $F(\epsilon, \mu)$, of interest in minimum-B mirror configurations, is absolutely stable to these modes provided $\partial F/\partial\epsilon < 0$ together with a second condition on $\partial F/\partial\mu$. For equilibrium distributions not of this special form, in particular for a Maxwell distribution with a density gradient, the case of axisymmetric toroidal configurations with closed poloidal field lines is considered in detail. Three unstable drift modes are found, a flute-like mode, a drift-ballooning mode local to the region of unfavorable curvature, and a drift-universal mode. Stability criteria and growth rates for the modes are given. The equations also describe a recently discussed low-frequency trapped-particle instability.

Phys. Fluids **11**, 569 (1968)

THE PHYSICS OF FLUIDS VOLUME 14, NUMBER 4 APRIL 1971

Resonance Cones in the Field Pattern of a Radio Frequency Probe in a Warm Anisotropic Plasma

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(Received 29 June 1970)

An experimental and theoretical investigation of the angular distribution of the electric field of a short radio frequency probe in a plasma in a magnetic field is described. The field is observed to become very large along a resonance cone whose axis is parallel to the static magnetic field and whose opening angle is observed to vary with incident probe frequency, cyclotron frequency, and plasma frequency in agreement with simple cold plasma dielectric theory. The relationship of these cones to the limiting phase- and group-velocity cones which appear in the theory of plane wave propagation is discussed. The addition of electron thermal velocities (warm plasma effects) is examined in the limit of a large static magnetic field. A fine structure appears inside the cones and is shown to result from an interference between a fast electromagnetic wave and a slow plasma wave. This interference structure is observed experimentally and measurements of the angular interference spacing are shown to agree with the warm plasma theory. The use of measurements of the resonance cones and structure as a diagnostic tool to determine the plasma density and electron temperature in a plasma in a magnetic field is discussed.

Phys. Fluids **14**, 857 (1971)

Resistive instabilities in general toroidal plasma configurations

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(Received 20 August 1974; final manuscript received 18 February 1975)

Previous work by Johnson and Greene on resistive instabilities is extended to finite-pressure configurations. The Mercier criterion for the stability of the ideal magnetohydrodynamic interchange mode is rederived, the generalization of the earlier stability criterion for the resistive interchange mode is obtained, and a relation between the two is noted. Conditions for tearing mode instability are recovered with the growth rate scaling with the resistivity in a more complicated manner than $\eta^{3/5}$. Nyquist techniques are used to show that favorable average curvature can convert the tearing mode into an overstable mode and can often stabilize it.

Phys. Fluids **18**, 875 (1975)

Effects of finite plasma beta on the lower-hybrid-drift instability

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(Received 27 May 1976)

The local dispersion relation for the lower-hybrid-drift isntability is derived in a fully self-consistent manner including the finite-beta effects associated with (a) transverse electromagnetic perturbations ($\delta\mathbf{B}\neq 0$), and (b) resonant and nonresonant ∇B_0 electron orbit modifications. Moreover, the analysis is carried out for arbitrary values of local $\beta = 8\pi n(T_e + T_i)/B_0^2$, T_e/T_i, $\omega_{pe}^2/\omega_{ce}^2$, and V_E/v_i. (Here, V_E is the cross-field $\mathbf{E}\times\mathbf{B}$ velocity, and v_i is the ion thermal speed.) For all parameter regimes studied, the net effect of finite plasma beta is to reduce the maximum growth rate γ_m of the lower-hybrid-drift instability. The details, however, vary, depending on plasma parameters. For example, if $T_e \ll T_i$ and $V_E < v_i$, then the maximum growth rate is reduced by a factor $(1+\beta_i/2)^{-1/2}$, relative to the value obtained when $\beta_i = 8\pi n T_i/B_0^2 \to 0$. On the other hand, for $T_e \approx T_i$, there exists a critical value of plasma beta (β_{cr}) such that the lower-hybrid-drift instability is completely stabilized ($\gamma < 0$) for $\beta > \beta_{cr}$.

Phys. Fluids **20**, 301 (1977)

Kinetic theory of tearing instabilities

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(Received 20 December 1976)

The transition of the tearing instability from the collisional to the collisionless regime is investigated kinetically using a Fokker–Planck collision operator to represent electron-ion collisions. As a function of the collisionality of the plasma, the tearing instability falls into three regions, which are referred to as collisionless, semi-collisional, and collisional. The width Δ of the singular layer around $\mathbf{k}\cdot\mathbf{B}_0 = 0$ is limited by electron thermal motion along $\mathbf{B}_0$ in the collisional and semi-collisional regimes and is typically smaller than ρ_i, the ion Larmor radius. Previously accepted theories, which are based on the assumption $\Delta \gg \rho_i$, are found to be valid only in the collisional regime. The effects of density and temperature gradients on the instabilities are also studied. The tearing instability is only driven by the temperature gradient in the collisional and semi-collisional regimes. Numerical calculations indicate that the semi-collisional tearing instability is particularly relevant to present day high temperature tokamak discharges.

Phys. Fluids **20**, 1341 (1977)

Finite length thermal equilibria of a pure electron plasma column

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(Received 30 May 1978)

The electrons of a pure electron plasma may be in thermal equilibrium with each other and still be confined by static magnetic and electric fields. Since the electrons make a significant contribution to the electric field, only certain density profiles are consistent with Poisson's equation. The class of such distributions for a finite length cylindrical column is investigated. In the limit where the Debye length is small compared with the dimensions of the column, the density is essentially constant out to some surface of revolution and then falls off abruptly. The falloff in density is a universal function when measured along the local normal to the surface of revolution and scaled in terms of the Debye length. The solution for the shape of the surface of revolution is simplified by passage to the limit of zero Debye length.

Phys. Fluids **22**, 278 (1979)

Collisionless plasma expansion into a vacuum

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(Received 5 October 1978)

Particle simulations of the expansion of a collisionless plasma into vacuum are presented. The cases of a single-electron-temperature plasma and of a two-electron-temperature plasma are considered. The results confirm the existence of an ion front and verify the general features of self-similar solutions behind this front. A cold electron front is clearly observed in the two-electron-temperatures case. The computations also show that for a finite electron-to-ion mass ratio, m_e/m_i, the electron thermal velocity in the expansion region is not constant, but decreases approximately linearly with $\xi = x/t$, where x is distance and t is time. A self-similar solution, derived from the relation $T_e n_e^{1-\gamma} = \text{const}$, where T_e is the electron temperature, n_e is the electron density, and γ is a constant (instead of the isothermal assumption made in earlier theories), yields a linearly decreasing ion acoustic speed, $c \simeq c_0 - (\gamma - 1)\xi/2$, and comparison with computer simulation results show that the constant $\gamma - 1$ is proportional to $(Zm_e/m_i)^{1/2}$, where Z is the ion charge number.

Phys. Fluids **22**, 1384 (1979)

Waves and transport in the pure electron plasma

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(Received 21 September 1978; accepted 3 October 1979)

Investigations of low frequency waves and transport in a plasma consisting almost purely of electrons are presented here. This plasma is trapped in a cylindrical system with radial confinement supplied by a strong axial magnetic field and axial confinement supplied by electrostatic fields. Very long containment times are possible. Classical transport due to electron-neutral collisions has been investigated and good agreement with the theory of Douglas and O'Neil is obtained. Externally launched diocotron waves are investigated. The modal frequencies agree well with linear theory, but the damping is governed by nonlinear effects. Experimental scaling laws for the damping rates are given. Measurements of spatial transport due to these modes are also presented. A signature of this process is that the transport is strongly localized spatially.

Phys. Fluids **23**, 63 (1980)

Guiding center drift equations

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(Received 16 March 1979; accepted 18 January 1980)

The equations for particle drift orbits are given in a new magnetic coordinate system. This form of the equations separates the fast motion along the magnetic field lines from the slow motion across the lines. In addition, less information is required about the magnetic field structure than in alternative forms of the drift equations.

Phys. Fluids **23**, 904 (1980)

Experiments on vortex dynamics in pure electron plasmas*

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(Received 6 December 1989; accepted 21 February 1990)

Magnetically confined columns of electrons are excellent experimental manifestations of two-dimensional (2-D) vortices in an inviscid fluid. Surface charge perturbations on the electron column (diocotron modes) are equivalent to surface ripples on extended vortices; and unstable diocotron modes on hollow electron columns are examples of the Kelvin–Helmholtz instability. Experiments demonstrate that the stable and unstable modes are distinct and may coexist, having different frequencies and radial eigenfunctions. For azimuthal mode number $l = 1$, an exponentially unstable mode is observed on hollow columns, in apparent contradiction to 2-D fluid theory. For $l = 2$, a similar unstable mode is observed, consistent with fluid theory. These diocotron instabilities on hollow columns saturate with the formation of smaller vortex structures, and radial transport is determined by the nonlinear interaction of these secondary vortices. The vortex pairing instability has been observed for isolated, well-controlled vortices, and the instability is found to depend critically on the vortex separation distance.

Phys. Fluids B **2**, 1359 (1990)

The modified plasma dispersion function

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(Received 22 October 1990; accepted 8 April 1991)

In the linear theory of waves in a hot plasma if the zeroth-order velocity distribution function is taken to be Maxwellian, then there arises a special, complex-valued function of a complex variable $\xi = x + iy$, namely $\mathbf{Z}(\xi)$, known as the plasma dispersion function. In space physics many particle distributions possess a high-energy tail that can be well modeled by a generalized Lorentzian (or kappa) distribution function containing the spectral index κ. In this paper, as a natural analog to the definition of $\mathbf{Z}(\xi)$, a new special function $\mathbf{Z}^*_\kappa(\xi)$ is defined based on the kappa distribution function. Here, $\mathbf{Z}^*_\kappa(\xi)$ is called the modified plasma dispersion function. For any positive integral value of κ, $\mathbf{Z}^*_\kappa(\xi)$ is calculated in closed form as a finite series. General properties, including small-argument and large-argument expansions, of $\mathbf{Z}^*_\kappa(\xi)$ are given, and simple explicit forms are given for $\mathbf{Z}^*_1(\xi)$, $\mathbf{Z}^*_2(\xi)$, ..., $\mathbf{Z}^*_6(\xi)$. A comprehensive set of graphs of the real and imaginary parts of $\mathbf{Z}^*_\kappa(\xi)$ is presented. It is demonstrated how the modified plasma dispersion function approaches the plasma dispersion function in the limit as $\kappa \to \infty$, a result to be expected since the (appropriately defined) kappa distribution function formally approaches the Maxwellian as $\kappa \to \infty$. The function $\mathbf{Z}^*_\kappa(\xi)$ is expected to be instrumental in studying microinstabilities in plasmas when the particle distribution function is not only the standard generalized Lorentzian, but also of the Lorentzian type, including *inter alia*, the loss-cone, bi-Lorentzian, and product bi-Lorentzian distributions.

Phys. Fluids B **3**, 1835 (1991)

The radial structure of the ion-temperature-gradient-driven mode

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(Received 16 June 1993; accepted 11 August 1993)

An analysis of the radial structure of the ion-temperature-gradient-driven mode is presented and the dependence of the radial correlation length L_r on parameters such as magnetic shear is discussed. It is found that L_r decreases algebraically with increasing shear for moderate to large shear values, and it decreases exponentially with decreasing shear for low shear values. These results seem in qualitative agreement with several experiments which observe strong reduction of the transport coefficients close to the magnetic axis.

Phys. Fluids B **5**, 4081 (1993)

Creation and uses of positron plasmas*

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(Received 4 November 1993; accepted 14 January 1994)

Advances in positron trapping techniques have led to room-temperature plasmas of 10^7 positrons with lifetimes of 10^3 s. Improvements in plasma manipulation and diagnostic methods make possible a variety of new experiments, including studies just being initiated of electron–positron plasmas. The large numbers of confined positrons have also opened up a new area of positron annihilation research, in which the annihilation cross sections for positrons with a variety of molecules have been measured, as well as the energy spread of the resulting gamma rays. Such measurements are of interest for fundamental physics and for the modeling of astrophysical plasmas.

Phys. Plasmas **1**, 1439 (1994)

Study of driven magnetic reconnection in a laboratory plasma*

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(Received 12 November 1996; accepted 17 January 1997)

The magnetic reconnection experiment has been constructed to investigate the fundamental physics of magnetic reconnection in a well-controlled laboratory setting. This device creates an environment satisfying the criteria for a magnetohydrodynamic plasma ($S \gg 1$, $\rho_i \ll L$). The boundary conditions can be controlled externally, and experiments with fully three-dimensional reconnection are now possible. In the initial experiments, the effects of the third vector component of reconnecting fields have been studied. Two distinctively different shapes of neutral sheet current layers, depending on the third component, are identified during driven magnetic reconnection. Without the third component (antiparallel or null–helicity reconnection), a thin double-Y-shaped diffusion region is identified. A neutral sheet current profile is measured accurately to be as narrow as the order of the ion gyroradius. In the presence of an appreciable third component (co-helicity reconnection), an O-shaped diffusion region appears and grows into a spheromak configuration. © *1997 American Institute of Physics.* [S1070-664X(97)92905-0]

Phys. Plasmas **4**, 1936 (1997)

Nonlinear Phenomena, Turbulence, Transport

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 1 JANUARY-FEBRUARY, 1960

Irreversible Processes in Ionized Gases

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(Received August 28, 1959; revised manuscript received November 2, 1959)

The general theory of irreversible processes, developed by Prigogine and Balescu, is applied to the case of long range interactions in ionized gases. A similar diagram technique permits the systematic selection of all the contributions to the evolution of the distribution function, to an order of approximation equivalent to Debye's equilibrium theory. The infinite series which appear in this way can be summed exactly. The resulting evolution equations have a clear physical significance: they describe interactions of "quasi particles," which are electrons or ions "dressed" by their polarization clouds. These clouds are not a permanent feature, as in equilibrium theory, but have a nonequilibrium, changing shape, distorted by the motions of the particles. From the mathematical point of view, these equations exhibit a new type of nonlinearity, which is very directly related to the collective nature of the interactions.

Phys. Fluids **3**, 52 (1960)

THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 12 DECEMBER 1962

Anomalous Diffusion Arising from Microinstabilities in a Plasma

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(Received June 18, 1962)

A plasma is considered in which a Maxwellian distribution of electrons with thermal velocity v_e and drift velocity v_D is drifting relative to a Maxwellian distribution of ions with thermal velocity v_i. For $v_D \lesssim v_e$ the usual ion acoustic waves are stable, however, electrostatic ion cyclotron waves with $\omega \cong \Omega_i$ are unstable for $v_D \gtrsim 5v_i$. In the case when $5v_i \lesssim v_D \lesssim v_e$, and $T_e/T_i < 2$ the electrostatic ion cyclotron waves grow to a nonlinear equilibrium spectrum. This spectrum of waves leads to a diffusion of electrons across the field lines with a diffusion coefficient $D = \alpha\rho^2_e\Omega_e$, where ρ_e is the electron Larmor radius and Ω_e is the electron Larmor frequency. α, the ratio of the resulting diffusion coefficient to the Bohm diffusion coefficient, is given by a constant $\times\ (v_D/v_e)^5(T_e/T_i)^2$.

Phys. Fluids **5**, 1507 (1962)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 3 MARCH 1963

Effect of Ion Correlations on High-Frequency Plasma Conductivity

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(Received 13 August 1962)

In an earlier work the ac conductivity of a plasma was investigated by means of an elementary model. The validity of this model has been borne out by a rigorous treatment of plasma at thermal equilibrium. The elementary model is now extended to include the effects of ion correlations for arbitrary fixed ion distributions. For thermal equilibrium correlations it is found that the ion shielding reduces the maximum effective impact parameter by the factor $(1 + Z)^{\frac{1}{2}}$ (i.e., both ions and electrons contribute to the shielding) for frequencies low compared to the plasma frequency ω_p. For frequencies high compared to ω_p, the previous results obtain. The resistance due to the excitation of longitudinal waves at frequencies just in excess of ω_p is reduced by the factor $(1 + Z)^{-1}$. However, if large-amplitude (nonthermal) ion fluctuations are present, the longitudinal wave contribution to the resistance may be greatly enhanced.

Phys. Fluids **6**, 394 (1963)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 12 DECEMBER 1965

Collisionless Damping of Nonlinear Plasma Oscillations

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(Received 12 July 1965)

It is well known that the linear theory of collisionless damping breaks down after a time $\tau \equiv (m/e\mathcal{E}k)^{\frac{1}{2}}$, where k is the wavenumber and $\mathcal{E}$ is the amplitude of the electric field. Jacobi elliptic functions are now used to provide an exact solution of the Vlasov equation for the resonant electrons, and the damping coefficient is generalized to be valid for times greater than $t = \tau$. This generalized damping coefficient reduces to Landau's result when $t/\tau \ll 1$; it has an oscillatory behavior when t/τ is of order unity, and it phase mixes to zero as t/τ approaches infinity. The above results are all shown to have simple physical interpretations.

Phys. Fluids **8**, 2255 (1965)

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 9 SEPTEMBER 1966

A Perturbation Theory for Strong Plasma Turbulence

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(Received 29 April 1966)

A new perturbation theory for solving the Vlasov equation is derived. The theory is especially designed to cope with time secularities and nonanalyticity in the expansion parameter (the field strength). The method is based on the use of a statistical set of exact particle orbits instead of the unperturbed orbits conventionally used in perturbation solutions of the Vlasov equation. A principal result of the theory is a modification of the particle–wave interaction and a "broadening" of the associated resonant denominator $(\omega - \mathbf{k}\cdot\mathbf{v})^{-1}$. The nature of the time secularities associated with the streaming modes $\exp i\mathbf{k}\cdot\mathbf{v}t$ is discussed. A simple application to velocity-space diffusion and trapping and its effect on wave growth is described.

Phys. Fluids **9**, 1773 (1966)

THE PHYSICS OF FLUIDS VOLUME 9, NUMBER 12 DECEMBER 1966

Velocity Space Diffusion from Weak Plasma Turbulence in a Magnetic Field

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(Received 14 March 1966; final manuscript received 8 August 1966)

The quasi-linear velocity space diffusion is considered for waves of any oscillation branch propagating at an arbitrary angle to a uniform magnetic field in a spatially uniform plasma. The space-averaged distribution function is assumed to change slowly compared to a gyroperiod and characteristic times of the wave motion. Nonlinear mode coupling is neglected. An H-like theorem shows that both resonant and nonresonant quasi-linear diffusion force the particle distributions towards marginal stablity. Creation of the marginally stable state in the presence of a sufficiently broad wave spectrum in general involves diffusing particles to infinite energies, and so the marginally stable plateau is not accessible physically, except in special cases. Resonant particles with velocities much larger than typical phase velocities in the excited spectrum are scattered primarily in pitch angle about the magnetic field. Only particles with velocities the order of the wave phase velocities or less are scattered in energy at a rate comparable with their pitch angle scattering rate.

Phys. Fluids **9**, 2377 (1966)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 2 FEBRUARY 1967

Transport Coefficients of Partially Ionized Argon

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(Received 25 May 1966; final manuscript received 17 October 1966)

The complete Chapman–Enskog–Burnett expressions for the transport coefficients of multicomponent gas mixtures are applied to the computation of the properties of partially ionized argon. Studies of the rate of convergence of the approximations to the coefficients show that the third approximation to the thermal conductivity and the second to the viscosity are adequate at all degrees of ionization. The ordinary ambipolar diffusion coefficient is given to excellent accuracy by twice the binary ion–atom diffusion coefficient but, at low ionization, apparently not even the fourth approximation to the electrical conductivity has converged to the true value. The computed electrical and thermal conductivities are compared with experimental measurements.

Phys. Fluids **10**, 354 (1967)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 4 APRIL 1967

Anomalous Skin Effect in a Plasma

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(Received 10 August 1966)

The theory of the skin effect in a plasma is developed for the case in which the relation between current and electric field is not local.

Phys. Fluids **10**, 741 (1967)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 5 MAY 1967

Nonlinear Theory of Drift-Wave Turbulence and Enhanced Diffusion

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(Received 13 October 1966)

The turbulent plasma state which develops from unstable, current-driven drift waves is analyzed. In the nonlinear theory, the wave growth predicted by the linear theory is ultimately suppressed by ion damping. Since the phase speeds of the unstable waves are much greater than the ion thermal velocity, the ions cannot absorb wave energy until they become trapped. The amplitude of the turbulent spectrum grows until trapping occurs, and a quasi-steady state is reached in which the directed electron energy is converted into ion thermal energy at a constant rate. In this state the perturbation of the density gradient due to the turbulence is equal to the mean gradient. Nonlinear limitation due to mode coupling does not suppress the unstable wave growth until much larger density perturbations have developed. Therefore, ion trapping is established as the controlling nonlinear mechanism. In the steady state, the ions diffuse across the magnetic field with a diffusion coefficient $D_\perp \approx (k_\perp^{-2}\gamma)_{\max}$, where γ is the growth rate predicted by the linear theory and $k_\perp$ is a perpendicular wavenumber. Although the detailed treatment is for a specific instability, the general conclusions appear to apply to a variety of drift waves.

Phys. Fluids **10**, 1049 (1967)

THE PHYSICS OF FLUIDS VOLUME 11, NUMBER 8 AUGUST 1968

Nonlinear Effects of Large-Amplitude Plasma Waves

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(Received 5 February 1968)

The oscillations of resonant electrons in the potential of a large-amplitude, spatially propagating plasma wave result in: (1) periodic maxima in space of wave amplitude, (2) growth of sidebands on the transmitted frequency, and (3) periodic enhancement of the energy of the trapped electrons. Measurement of these effects is reported.

Phys. Fluids **11**, 1761 (1968)

THE PHYSICS OF FLUIDS VOLUME 11, NUMBER 11 NOVEMBER 1968

Collisional Drift Waves—Identification, Stabilization, and Enhanced Plasma Transport

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(Received 24 January 1967; final manuscript received 3 July 1968)

Density-gradient-driven collisional drift waves are identified by the dependences of ω and $\mathbf{k}$ on density, temperature, magnetic field, and ion mass, and by comparisons with a linear theory which includes resistivity and viscosity. Abrupt stabilization of azimuthal modes is observed when the stabilizing ion diffusion over the transverse wavelength due to the combined effects of ion Larmor radius and ion–ion collisions (viscosity) balances the destabilizing electron-fluid expansion over the parallel wavelength, determined by electron–ion collisions (resistivity). The finite-amplitude ($\tilde{n}/n_0 \simeq 10\%$) coherent oscillation, involving the entire plasma body, shows a phase difference between density and potential waves (which is predicted by linear theory for growing perturbations). The wave-induced radial transport exceeds classical diffusion, but is below the Bohm value by an order of magnitude. Although observations have been extended to magnetic fields three times those for drift-wave onset, turbulence has not been encountered.

Phys. Fluids **11**, 2426 (1968)

THE PHYSICS OF FLUIDS VOLUME 12, NUMBER 5 MAY 1969

Formulation of a Statistical Theory of Strong Plasma Turbulence

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(Received 6 September 1968; final manuscript received 3 February 1969)

A new formulation of methods introduced by Dupree, and Orszag and Kraichnan, for solving the Vlasov equation for turbulent plasmas based on algebraic use of an *averaging operator* is described. Formally exact sets of integrodifferential equations are thereby derived for determining the ensemble average of the one-particle distribution function, and the electric field spectrum of turbulent plasmas. The formal difference between these equations and the approximate equations of Dupree, and Orszag and Kraichnan, is that the average "Vlasov" propagator $U(t,t_0)$ of the latter is replaced by a new propagator $U_A(t,t_0)$ which involves the averaging operator. The potential usefulness of the present equations can be judged by the fact that, in a simple lowest-order limit, they immediately reduce to the turbulence equation of Dupree. These equations are used to develop a modified perturbation theory which avoids certain time secularities. Cumulant expansions are introduced to evaluate average "Vlasov" propagators, and to rigorously treat the variation of the diffusion coefficient with velocity. It is explicitly shown that (diffusive) perturbed trajector corrections are equal to mean square deviations from the mean of "Vlasov" trajectories.

Phys. Fluids **12**, 1045 (1969)

THE PHYSICS OF FLUIDS VOLUME 12, NUMBER 11 NOVEMBER 1969

Numerical Simulation of Warm Two-Beam Plasma

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(Received 14 February 1969; final manuscript received 3 June 1969)

One-dimensional numerical simulation of plasmas consisting of two unequal warm beams has shown flattening of the small beam and, in most cases, a strong single mode structure at about the wavelength of largest linear growth rate, accompanied by an eddylike arrangement of trapped particles in phase space. The total electrostatic field energy first increases at the linear growth rate and then, after saturating abruptly, decreases at about the same rate to an intermediate level where a much slower decay begins.

Phys. Fluids **12**, 2418 (1969)

THE PHYSICS OF FLUIDS VOLUME 12, NUMBER 12 DECEMBER 1969

Laser-Induced Anomalous Heating of a Plasma

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(Received 23 December 1968; final manuscript received 25 June 1969)

It is shown that a sufficiently intense laser beam can drive low-frequency instabilities in a fully ionized plasma; these instabilities may cause considerable enhancement of the high-frequency resistivity of the plasma around certain frequencies and thus lead to an anomalous heating effect.

Phys. Fluids **12**, 2586 (1969)

Nonlinear Development of the Beam–Plasma Instability

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The nonlinear limit of wave growth induced by a low density cold electron beam in a collisionless plasma is calculated from a simple physical model. The bandwidth of the growing "noise" is so small that the beam interacts with a nearly sinusoidal electric field.

Phys. Fluids **13**, 2422 (1970)

THE PHYSICS OF FLUIDS VOLUME 14, NUMBER 6 JUNE 1971

Nonlinear Interaction of a Small Cold Beam and a Plasma

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Recently, a simple model was proposed for the nonlinear interaction of a low-density monoenergetic electron beam and a relatively cold infinite homogeneous one-dimensional plasma. The essential feature of this model is the observation that after several *e*-foldings the bandwidth of the growing waves is so narrow that the electrons interact with a very nearly pure sinusoidal field. In terms of this single wave model, a properly scaled solution of the nonlinear beam–plasma problem which depends analytically on all the basic parameters of the problem (i.e., plasma density, beam density, plasma thermal velocity, and beam drift velocity) is presented. This solution shows that the single wave grows exponentially at the linear growth rate until the beam electrons are trapped. At that time the wave amplitude stops growing and begins to oscillate about a mean value. During the trapping process the beam electrons are bunched in space and a power spectrum of the higher harmonics of the electric field is produced. Both the oscillation in wave amplitude and the power spectrum are given a simple physical interpretation.

Phys. Fluids **14**, 1204 (1971)

THE PHYSICS OF FLUIDS VOLUME 14, NUMBER 7 JULY 1971

Plasma Diffusion in Two Dimensions

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(Received 12 October 1970)

Diffusion of plasma in two dimensions is studied in the guiding center model. It is shown that in this model diffusion always exhibits the anomalous $1/B$ variation with magnetic field. The velocity correlation function and the diffusion coefficient are calculated in detail using functional probabilities. In addition to the $1/B$ field dependence, the diffusion coefficient is unusual in that it depends weakly on the size of the system. These theoretical results are compared with those from computer experiments and their significance for real plasma is discussed.

Phys. Fluids **14**, 1492 (1971)

THE PHYSICS OF FLUIDS VOLUME 14, NUMBER 12 DECEMBER 1971

Parallel Propagation of Nonlinear Low-Frequency Waves in High-β Plasma

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(Received 7 July 1970; final manuscript received 2 August 1971)

A pair of coupled, nonlinear, partial differential equations which describe the evolution of low-frequency, large-scale-length perturbations propagating parallel, or nearly parallel, to the equilibrium magnetic field in high-β plasma have been obtained. The equations account for irreversible resonant particle effects. In the regime of small but finite propagation angles, the pair of equations collapses into a single Korteweg–de Vries equation (neglecting irreversible terms) which agrees with known results.

Phys. Fluids **14**, 2733 (1971)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 1 JANUARY 1972

Plasma Transport in Toroidal Confinement Systems

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The neoclassical theory of plasma transport in axisymmetric, toroidal confinement systems, is developed by means of a variational principle for the rate of irreversible entropy production. The variational principle derived here employs the full Fokker–Planck collision operator, including both like and unlike species collisions. Using the variational principle, all the relevant neoclassical transport coefficients are systematically evaluated in the "banana" regime of small collisional frequency, to lowest order in the inverse aspect ratio. These results include both the "diagonal" and "cross" coefficients for the particle fluxes, ion and electron heat flux, and electric current. By combining the transport coefficients with appropriate moments of the drift equation, a closed set of equations which accurately summarize the predictions of neoclassical theory in the banana regime is obtained. The significance of these equations, in particular with regard to recent tokamak experiments, is discussed briefly.

Phys. Fluids **15**, 116 (1972)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 2 FEBRUARY 1972

Theory of Phase Space Density Granulation in Plasma

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A novel state of turbulent plasma characterized by small scale phase-space granulations called "clumps" is proposed. Clumps are produced when regions of different phase space density are mixed by the fluctuating electric field. They move along ballistic orbits and drive the turbulent field in a manner similar to that in which thermal fluctuations are driven by particle discreteness. In the coherent wave limit the clumps become the familiar trapped particle eddies of a Bernstein–Green–Kruskal mode. The turbulent state can exist in the absence of linear instability although it is more likely to occur in a linearly unstable plasma. The spectrum contains a ballistic portion as well as resonances at the wave (collective) frequencies. The discreteness of the clumps produces collision-like process. For example, the average distribution function satisfies a Fokker–Planck equation instead of a quasilinear diffusion equation.

Phys. Fluids **15**, 334 (1972)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 3 MARCH 1972

Anomalous High-Frequency Resistivity of a Plasma

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(Received 28 June 1971)

In one- and two-dimensional computer simulations an anomalous high-frequency resistivity in a plasma driven by a large electric field oscillating near the electron plasma frequency is investigated. The large field excites the oscillating two-stream and the ion-acoustic decay instabilities in agreement with the linear theory. When the ion and electron fluctuations saturate, a strong anomalous heating of the plasma sets in. This strong heating is due to an efficient coupling of the externally imposed large electric field to the plasma by ion fluctuations. The anomalous collision frequency and the saturation fluctuation amplitudes are determined as a function of the external field amplitude and frequency, and the electron-ion mass ratio. A simple nonlinear theory gives results in reasonable agreement with simulations.

Phys. Fluids **15**, 446 (1972)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 5 MAY 1972

Theory and Computer Experiment on Self-Trapping Instability of Plasma Cyclotron Waves

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(Received 27 August 1971; final manuscript received 17 December 1971)

A theory explaining the self-trapping instability (modulational instability) of plasma cyclotron waves is developed and the results are compared with computer experiments using a sheet current model. The observed growth rate at an initial phase of the instability is in rough agreement with that given by perturbation theory. However, as the level of the modulation increases, the rate of the growth of the modulation increases due to excitation of additional side bands, and finally, the carrier wave is found to collapse suddenly leading to rapid thermalization. The cause of the sudden collapse of the wave is attributed to the crossing of particles which are accelerated in the direction parallel to the ambient magnetic field by a large pressure gradient force, $\nabla(B_\perp^2/2\mu_0)$, developed by the instability, where $B_\perp$ is the transverse magnetic field associated with the wave.

Phys. Fluids **15**, 870 (1972)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 6 JUNE 1972

Quasilinear Diffusion of an Axisymmetric Toroidal Plasma

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In a toroidal plasma with axial symmetry, the three adiabatically invariant actions of a particle are the magnetic moment, the canonical angular momentum, and the toroidal flux enclosed by the drift surface. Resonant interactions between particles and the normal modes of collective oscillation produce mode growth or decay and random changes in the actions. This random walk is represented by a diffusion equation in action space. Both the diffusion tensor and the growth rate depend upon a coupling coefficient which represents the work done by a normal-mode field eigenfunction on the current density of an unperturbed particle orbit. The diffusion of the plasma causes adiabatic changes in the electric and magnetic self-consistent fields. Accordingly, energy is not conserved, but is exchanged with external currents.

Phys. Fluids **15**, 1063 (1972)

THE PHYSICS OF FLUIDS VOLUME 15, NUMBER 12 DECEMBER 1972

Theory and Simulation of Turbulent Heating by the Modified Two-Stream Instability

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Results of an analytical and numerical study of the nonresonant, modified plasma two-stream instability, which is driven by relative streaming of electrons and ions across a magnetic field $\mathbf{B}_0$ are presented. The instability has characteristic frequency and growth rate comparable to the lower-hybrid frequency. The linear theory is discussed both in the electrostatic and fully electromagnetic cases, and a detailed numerical study of the dependence of the unstable roots of the dispersion relation for a wide range of plasma parameters is presented. The nonlinear theory includes discussions of (1) quasilinear theory, (2) trapping, which is responsible for nonlinear stabilization, (3) a derivation of a fully nonlinear scaling law which shows how results scale with electron–ion mass ratio, and (4) the effect of cross-field vortex-like motion caused by turbulence induced $\mathbf{E}\times\mathbf{B}$ drifts. One-and two-dimensional computer simulations with dense k-space spectra are presented in support of this theory. The simulations show that the instability can be a very important turbulent heating mechanism that heats the ions (perpendicular to $\mathbf{B}_0$) and the electrons (parallel to $\mathbf{B}_0$) comparably. The final state has $(T_{i\perp}/m_i)^{1/2}\approx(T_{e\|}/m_i)^{1/2}\sim\frac{1}{2}U$, where U is the initial relative drift speed. Applications to experimental situations are discussed.

Phys. Fluids **15**, 2367 (1972)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 3 MARCH 1973

Theory and numerical simulation on plasma diffusion across a magnetic field

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(Received 6 March 1972; final manuscript received 25 October 1972)

The diffusion of two and two and a half-dimensional plasmas across magnetic fields have been studied theoretically and by numerical simulation. Only diffusion at thermal equilibrium is studied. It is found that there are three regions: for sufficiently weak magnetic fields the diffusion coefficient is the classical one with $D_\perp$ going like B^{-2}; for moderate magnetic fields ($\omega_{ce}\approx\omega_{pe}$) the diffusion rate is enhanced and $D_\perp$ is almost independent of B; finally, for very large fields ($\omega_{ci}>\omega_{pi}$) the diffusion coefficient goes like B^{-1}. The enhanced diffusion at moderate and high magnetic fields is dominated by collective modes; i.e., by thermally excited convective modes. Theory and simulation are in good agreement. It is also shown that the diffusion coefficient behaves essentially the same way for a three-dimensional plasma when the magnetic field lines are closed.

Phys. Fluids **16**, 408 (1973)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 6 JUNE 1973

Transport properties of a toroidal plasma at low-to-intermediate collision frequencies

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(Received 15 June 1972; final manuscript received 8 January 1973)

The neoclassical plasma transport coefficients for axisymmetric toroidal magnetic confinement systems are calculated in the regime of low-to-intermediate collision frequency. The problem of solving the linearized drift kinetic equations, and calculating the transport coefficients, is formulated as a variational principle. A maximal form of the variational principle, which is valid in the low-to-intermediate collision frequency regime, is used in a numerical solution of the finite dfiference equations, to obtain the distribution function at points on a mesh in phase space. A new analytical result is used to check the accuracy of the numerical calculation for small collision frequencies; this is a correction to the asymptotic banana regime result, obtained from a Wiener–Hopf analysis of the boundary layer in phase space between the trapped and untrapped particle regions. An analytical correction to the plateau regime analtyical result is also obtained. The transport coefficients are found to be monotonic functions of collision frequency, with a gradual transition from the banana regime to the plateau regime. Analytical formulas have been fitted to the numerically computed results.

Phys. Fluids **16**, 836 (1973)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 9 SEPTEMBER 1973

Filamentation and trapping of electromagnetic radiation in plasmas

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(Received 27 December 1972)

It is shown that an electromagnetic wave interacting with a plasma is subject to instabilities leading to light filamentation. Nonlinear solutions for light filaments and light trapping are also investigated.

Phys. Fluids **16**, 1522 (1973)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 10 OCTOBER 1973

Experiments on ion-acoustic solitary waves

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(Received 22 January 1973; final manuscript received 31 May 1973)

Ion-acoustic solitary wave (solitons) have been studied experimentally by employing a double-plasma device. The solitary waves are found to be produced from both a single compressional pulse and a continuous wave. A rarefaction pulse also produces solitons if the pulse width is sufficiently wide. A theory based on the Schrödinger equation accounts for the number of solitons. Recurrence to the original state is observed when a continuous wave is launched. A simple wave–wave coupling analysis for the recurrence of the original state is given.

Phys. Fluids **16**, 1668 (1973)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 11 NOVEMBER 1973

Nonlinear growth of the tearing mode

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(Received 6 April 1973)

The resistive tearing mode is analyzed in the nonlinear regime; nonlinearity is important principally in the singular layer around $\mathbf{k}\cdot\mathbf{B}=0$. In the case where the resistive skin time τ_R is much longer than the hydromagnetic time τ_H, exponential growth of the field perturbation is replaced by algebraic growth like t^2 at an amplitude of order $(\tau_H/\tau_S)^{4/5}$. Application of the theory to the unstable tearing modes of a tokamak with a shrinking current channel yields good agreement with the observed amplitudes of the $m \geq 2$ oscillations. The analysis excludes the very long wavelength mode, and $m = 1$ in the tokamak, for which the "constant-ψ" approximation is invalid.

Phys. Fluids **16**, 1903 (1973)

Parametric instabilities of electromagnetic waves in plasmas

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(Received 23 July 1973)

A simple formalism for the parametric decay of an intense, coherent electromagnetic wave into an electrostatic wave and scattered electromagnetic waves in a homogeneous plasma is developed. Various instabilities including Brillouin and Raman scattering, Compton scattering, filamentational and modulational instabilities are derived and discussed in a systematic manner. Growth rates as a function of the incident pump power are shown.

Phys. Fluids **17**, 778 (1974)

Plasma heating by spatial resonance of Alfvén wave

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(Received 3 January 1974)

Heating of a collisionless plasma by utilizing the spatial resonance of shear Alfvén waves is proposed and application to toroidal plasmas is discussed. The resonance exists due to the nonuniform Alfvén speed. This heating scheme is analyzed in one dimension including the effects of a shear magnetic field and plasma compressibility. For plasmas with smooth nonuniformities ($|k_\perp l| \gg 1$, $k_\perp$ is the wavenumber prependicular to the ambient magnetic field and the nonuniformity direction, and l is the scale length of the nonuniformity), the energy absorbed per unit surface area per driving cycle is $[b_0^2(\mu_0 k_\perp)^{-1}]$. Here, b_0 is the flux density of the driving magnetic field evaluated at the resonant point. With sharp nonuniformities ($|k_\perp l| \ll 1$), absorption is large if the surface eigenmode is excited. The corresponding value is $[b_0^2(\mu_0 k_\perp)^{-1}(k_\perp l)^{-1}]$. Otherwise, it is $[b_0^2(\mu_0 k_\perp)^{-1}(k_\perp l)]$.

Phys. Fluids **17**, 1399 (1974)

Nonlinear stabilization of beam plasma interactions by parametric effects

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The nonlinear stabilization of the kinetic stage of electron beam plasma instabilities by parametric effects is investigated. It is found that within a definite range of plasma parameters parametric instatilities induced by the beam generated waves can stabilize the system at a level of wave energy density substantially lower than expected by quasi-linear theory. This occurs because at a certain level of beam-generated plasma waves, the transfer rate of wave energy outside the spectral region in resonance with the beam exceeds the beam plasma instability growth rate. A model of a quasi-steady state for the case of continuous beam injection is proposed. The possibility of utilizing ultrarelativistic electron beams for achieving ignition temperatures in a tokamak is discussed.

Phys. Fluids **18**, 1769 (1975)

Kinetic processes in plasma heating by resonant mode conversion of Alfvén wave

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(Received 17 May 1976)

An externally applied oscillating magnetic field (at a frequency near 1 MHz for typical tokamak parameters) resonantly mode converts to the kinetic Alfvén wave, the Alfvén wave with the perpendicular wavelength comparable to the ion gyroradius. The kinetic Alfvén wave, while it propagates into the higher density side of the plasma after the mode conversion, dissipates due to both linear and nonlinear processes and heats the plasma. If a magnetic field of 50 G effective amplitude is applied, approximately 10 MJ per cubic meter of energy can be deposited in 1 sec into the plasma. The heating rate here is faster than that in the transit time magnetic pumping by a factor of β^{-1}.

Phys. Fluids **19**, 1924 (1976)

Saturation of the tearing mode

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A quasi-linear analytical model is used to describe the nonlinear growth and saturation of tearing modes with mode number $m \geq 2$. The saturation of the magnetic island growth is the quasi-linear development of a single mode rather than a mode coupling process. The saturation amplitude, which is dependent on the form of the resistivity, is in good agreement with results obtained previously by numerically advancing the full set of nonlinear equations.

Phys. Fluids **20**, 800 (1977)

Pseudo-three-dimensional turbulence in magnetized nonuniform plasma

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(Received 21 June 1977)

A simple nonlinear equation is derived to describe the pseudo-three-dimensional dynamics of a nonuniform magnetized plasma with $T_e \gg T_i$ by taking into account the three-dimensional electron, but two-dimensional ion dynamics in the direction perpendicular to B_0. The equation bears a close resemblance to the two-dimensional Navier–Stokes equation. A stationary spectrum in the frequency range of drift waves is obtained using this equation by assuming a coexisting large amplitude long wavelength mode. The ω-integrated k spectrum is given by $k^{1.8}(1+k^2)^{-2.2}$, while the width of the frequency spectrum is proportional to $k^3(1+k^2)^{-1}$, where k is normalized by c_s/ω_{ci}. The result compares well with the recently observed spectrum in the ATC tokamak.

Phys. Fluids **21**, 87 (1978)

Stochastic ion heating by a lower hybrid wave

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(Received 20 March 1978)

The motion of an ion in a lower hybrid wave in a tokamak type plasma is studied. For ions with $v_\perp \gtrsim \omega/k_\perp$ the motion is stochastic for fields satisfying $E/B_0 > (1/4)(\Omega_i/\omega)^{1/3}(\omega/k_\perp)$. Provided that the perpendicular phase velocity, $\omega/k_\perp$, can be slowed down to a few times the ion thermal speed, this stochastic ion motion may be an important mechanism by which injected rf power near the lower hybrid frequency can directly heat the ions.

Phys. Fluids **21**, 1584 (1978)

Externally driven magnetic reconnection and a powerful magnetic energy converter

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(Received 17 July 1978; final manuscript received 5 February 1979)

Numerical simulation of two-dimensional compressible magnetic reconnection is carried out for more than a dozen cases with different anomalous resistivities and boundary conditions. After a quiescent stage of magnetic energy buildup, anomalous resistivity leads to an abrupt conversion of the stored magnetic energy into the plasma bulk motion and heat. Consequently, plasma jets as high as the local Alfvén speed are generated downstream of the magnetic separatrix. Slow shocks formed just downstream of the separatrix and fast mode expansion in the upstream region play a leading role in the formation of strong plasma jets. Anomalous resistivity is the primary cause of the abrupt onset of reconnection. Once reconnection proceeds, however, its ultimate fate no longer seems to be dependent on the resistivity, but is largely controlled by the boundary conditions.

Phys. Fluids **22**, 1189 (1979)

Nonlinear behavior and turbulence spectra of drift waves and Rossby waves

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Spectrum cascade in drift wave turbulence in a magnetized plasma as well as Rossby wave turbulence in an atmospheric pressure system are studied based on a three-wave decay process derivable from the model equation applicable to both cases. The decay in the three-way interaction occurs to smaller and larger values of $|k|$. In a region of large wavenumbers this leads to the dual cascade; the energy spectrum cascades to smaller $|k|$ and the enstrophy spectrum to larger $|k|$, similar to the case of two-dimensional Navier–Stokes turbulence. In a small wavenumber region a resonant three-wave decay process dominates the cascade process, and an anisotropic spectrum develops. As a consequence of the cascade, zonal flows in the direction perpendicular to the direction of inhomogeneity appear which presents a potential implication for the particle confinement in a turbulent plasma.

Phys. Fluids **22**, 2122 (1979)

Nonlinear gyrokinetic equations for low-frequency electromagnetic waves in general plasma equilibria

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(Received 6 October 1981; accepted 6 January 1982)

A nonlinear gyrokinetic formalism for low-frequency (less than the cyclotron frequency) microscopic electromagnetic perturbations in general magnetic field configurations is developed. The nonlinear equations thus derived are valid in the strong-turbulence regime and contain effects due to finite Larmor radius, plasma inhomogeneities, and magnetic field geometries. The specific case of axisymmetric tokamaks is then considered and a model nonlinear equation is derived for electrostatic drift waves. Also, applying the formalism to the shear Alfvén wave heating scheme, it is found that nonlinear ion Landau damping of kinetic shear-Alfvén waves is modified, both qualitatively and quantitatively, by the diamagnetic drift effects. In particular, wave energy is found to cascade in wavenumber instead of frequency.

Phys. Fluids **25**, 502 (1982)

A collisional drift wave description of plasma edge turbulence

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(Received 25 August 1983; accepted 5 December 1983)

Model mode-coupling equations for the resistive drift wave instability are numerically solved for realistic parameters found in tokamak edge plasmas. The Bohm diffusion is found to result if the parallel wavenumber is chosen to maximize the growth rate for a given value of the perpendicular wavenumber. The saturated turbulence energy has a broad frequency spectrum with a large fluctuation level proportional to $\bar{\kappa}$ ($=\rho_s/L_n$, the normalized inverse scale length of the density gradient) and a wavenumber spectrum of the two-dimensional Kolmogorov–Kraichnan type, $\sim k^{-3}$.

Phys. Fluids **27**, 611 (1984)

An electron conductivity model for dense plasmas

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(Received 5 July 1983; accepted 12 December 1983)

An electron conductivity model for dense plasmas is described which gives a consistent and complete set of transport coefficients including not only electrical conductivity and thermal conductivity, but also thermoelectric power, and Hall, Nernst, Ettinghausen, and Leduc–Righi coefficients. The model is useful for simulating plasma experiments with strong magnetic fields. The coefficients apply over a wide range of plasma temperature and density and are expressed in a computationally simple form. Different formulas are used for the electron relaxation time in plasma, liquid, and solid phases. Comparisons with recent calculations and available experimental measurement show the model gives results which are sufficiently accurate for many practical applications.

Phys. Fluids **27**, 1273 (1984)

Magnetic reconnection via current sheets

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(Received 5 August 1985; accepted 29 January 1986)

A general picture of magnetic reconnection in the framework of 2-D incompressible resistive magnetohydrodynamic theory is presented. Numerical studies of (quasi-) steady-state driven reconnection reveal current sheet formation for Mach numbers $M = u/v_A$ exceeding the Sweet–Parker reconnection rate $M_{SP} = (\eta/Lv_A)^{1/2}$. Since the thickness δ of the current sheet is found to be invariant to a change of the resistivity η, its length Δ increases rapidly with decreasing η or increasing M, which can be written in the form $\Delta \sim (M/M_{SP})^4$, so that Δ reaches the global system size L within a short range of the parameter M/M_{SP}. The results are rather insensitive to the particular choice of boundary conditions. Because of the presence of a current sheet, the overall reconnection process is quite slow. This picture essentially agrees with Syrovatsky's [Sov. Phys. JETP **33**, 933 (1971)] theory and disproves Petschek's [*AAS/NASA Symposium on the Physics of Solar Flares*, (NASA, Washington, DC, 1964) p. 425] mechanism of fast magnetic reconnection. A theory of the solution in the external and in the diffusion region is developed and analytical expressions in agreement with the simulation results are obtained by means of a variational principle. For sufficiently long current sheets the tearing mode becomes unstable in spite of the stabilizing effect of the inhomogeneous flow. The tearing mode contributes to the overall reconnection process, but a general assessment of this effect in the asymptotic regime of almost vanishing η is difficult.

Phys. Fluids **29**, 1520 (1986)

Theory of ion-temperature-gradient-driven turbulence in tokamaks

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An analytic theory of ion-temperature-gradient-driven turbulence in tokamaks is presented. Energy-conserving, renormalized spectrum equations are derived and solved in order to obtain the spectra of stationary ion-temperature-gradient-driven turbulence. Corrections to mixing-length estimates are calculated explicitly. The resulting anomalous ion thermal diffusivity $\chi_i = 0.4[(\pi/2)\ln(1+\eta_i)]^2[(1+\eta_i)/\tau]^2\rho_p^2 c_s/L_s$ is derived and is found to be consistent with experimentally deduced thermal diffusivities. The associated electron thermal and particle diffusivity, and particle and heat-pinch velocities are also calculated. The effect of impurity gradients on saturated ion-temperature-gradient-driven turbulence is discussed and a related explanation of density profile steepening during Z-mode operation is proposed.

Phys. Fluids **29**, 3291 (1986)

Toroidal ion-pressure-gradient-driven drift instabilities and transport revisited

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(Received 14 March 1988; accepted 6 September 1988)

A unified theory of ion-pressure-gradient-driven drift wave instabilities and transport is presented, which ties the long-wavelength trapped-ion mode to the moderate-wavelength hydrodynamic mode in toroidal geometry. An analytic dispersion relation that retains ion drift resonances, and keeps the leading-order contribution from finite Larmor radius effects and parallel compressibility, is derived. Results indicate that the slab and toroidal branches of these instabilities are of comparable importance, and are both strong candidates to explain the observed anomalous ion loss in toroidal fusion devices. However, it is concluded that in the limit of flat-density profiles characteristic of H-mode discharges, the stabilizing influence of perpendicular compressibility is insufficient to corroborate an improvement, if any, in *ion* confinement quality. Mixing-length expressions for the fluctuation amplitudes and both electron and ion transport coefficients are derived. Results also indicate that the heretofore experimentally observed favorable current scaling of the energy confinement time may saturate in low ion-collisionality discharges. Finally, it is shown that a population of energetic trapped particles, such as those that may be produced during radio frequency or perpendicular neutral beam heating, can significantly exacerbate the instability. Several suggestions for experiments are made to help in differentiating among various anomalous transport scenarios.

Phys. Fluids B **1**, 109 (1989)

Dynamics of decaying two-dimensional magnetohydrodynamic turbulence

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(Received 17 April 1989; accepted 6 June 1989)

High-resolution numerical studies of decaying two-dimensional magnetohydrodynamic turbulence were performed with up to 1024^2 collocation points in general periodic systems using various initial states, but restricting consideration to weak velocity-magnetic field correlation ρ. The global evolution is self-similar with constant kinetic to magnetic energy ratio E^V/E^M, macro- and microscale Reynolds numbers, and correlation ρ, while the total energy decays as $E(t) \propto (t + t_0)^{-1}$. As in three dimensions, dissipative small-scale turbulence adjusts in such a way as to make the energy dissipation rate ϵ independent of the collisional dissipation coefficients. Normalized energy spectra are also invariant. The spectral index in the inertial range is, in general, close to 3/2 in agreement with Kraichnan's Alfvén wave argument $E_k = DB^{1/2}\epsilon^{1/2}k^{-3/2}$, $B = (E^M)^{1/2}$, $D \simeq 1.8 \pm 0.2$, but may be close to 5/3 in transient states, in which turbulence is concentrated in regions of weak magnetic field. In the dissipation range, intermittency gives rise to a modified dissipation scale $l_{\text{eff}} = (l^2\lambda)^{1/3}$, with $l =$ Kolmogorov scale and $\lambda =$ Taylor microscale. This reflects the intermittency of the dissipation process, which is consistent with the picture of current microsheets of thickness l and width and spacing λ.

Phys. Fluids B **1**, 1964 (1989)

Influence of sheared poloidal rotation on edge turbulence

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(Received 5 June 1989; accepted 20 October 1989)

The impact of radially sheared poloidal flows on ambient edge turbulence in tokamaks is investigated analytically. In the regime where poloidal shearing exceeds turbulent radial scattering, a hybrid time scale weighted toward the former is found to govern the decorrelation process. The coupling between radial and poloidal decorrelation results in a suppression of the turbulence below its ambient value. The turbulence quench mechanism is found to be insensitive to the sign of either the radial electric field or its shear.

Phys. Fluids B **2**, 1 (1990)

Theory of mean poloidal flow generation by turbulence

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(Received 25 September 1990; accepted 1 March 1991)

The mechanism for generation of mean poloidal flow by turbulence is identified and elucidated. Two methods of calculating poloidal flow acceleration are given and shown to yield predictions which agree. These methods link flow generation to the quasilinear radial current or the Reynolds stress $\langle \tilde{V}_r \tilde{V}_\theta \rangle$. It is shown that poloidal acceleration will occur if the turbulence supports radially propagating waves and if radial gradients in the turbulent Reynolds stress and wave energy density flux are present. In practice, these conditions are met in the tokamak edge region when waves propagate through the outermost closed flux surface or when convection cells with large radial correlation length are situated in steep gradient regions. The possible impact of these results on the theory of the $L \rightarrow H$ transition is discussed.

Phys. Fluids B **3**, 1626 (1991)

A fully nonlinear characteristic method for gyrokinetic simulation

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(Received 17 June 1992; accepted 16 September 1992)

A new scheme that evolves the perturbed part of the distribution function along a set of characteristics that solves the fully nonlinear gyrokinetic equations is presented. This low-noise nonlinear characteristic method for particle simulation is an extension of the partially linear weighting scheme, and may be considered an improvement over existing δf methods. Some of the features of this new method include the ability to keep all nonlinearities, particularly those associated with the velocity space, the use of conventional particle loading techniques, and also the retention of the conservation properties of the original gyrokinetic system in the numerically converged limit. The new method is used to study a one-dimensional drift wave model that isolates the parallel velocity nonlinearity. A mode coupling calculation for the saturation amplitude is given, which is in good agreement with the simulation results. Finally, the method is extended to the electromagnetic gyrokinetic equations in general geometry.

Phys. Fluids B **5**, 77 (1993)

Gyrofluid turbulence models with kinetic effects

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(Received 17 August 1992; accepted 30 October 1992)

Nonlinear gyrofluid equations are derived by taking moments of the nonlinear, electrostatic gyrokinetic equation. The principal model presented includes evolution equations for the guiding center n, $u_{\|}$, $T_{\|}$, and $T_{\perp}$ along with an equation expressing the quasineutrality constraint. Additional evolution equations for higher moments are derived that may be used if greater accuracy is desired. The moment hierarchy is closed with a Landau damping model [G. W. Hammett and F. W. Perkins, Phys. Rev. Lett. **64**, 3019 (1990)], which is equivalent to a multipole approximation to the plasma dispersion function, extended to include finite Larmor radius effects (FLR). In particular, new dissipative, nonlinear terms are found that model the perpendicular phase mixing of the distribution function along contours of constant electrostatic potential. These "FLR phase-mixing" terms introduce a hyperviscositylike damping $\propto k_{\perp}^2 \, |\Phi_{\mathbf{k}}\mathbf{k}\times\mathbf{k}'|$, which should provide a physics-based damping mechanism at high $k_{\perp}\rho$ which is potentially as important as the usual polarization drift nonlinearity. The moments are taken in guiding center space to pick up the correct nonlinear FLR terms and the gyroaveraging of the shear. The equations are solved with a nonlinear, three-dimensional initial value code. Linear results are presented, showing excellent agreement with linear gyrokinetic theory.

Phys. Fluids B **5**, 812 (1993)

Toroidal gyro-Landau fluid model turbulence simulations in a nonlinear ballooning mode representation with radial modes

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(Received 7 February 1994; accepted 7 April 1994)

The method of Hammett and Perkins [Phys. Rev. Lett. **64**, 3019 (1990)] to model Landau damping has been recently applied to the moments of the gyrokinetic equation with curvature drift by Waltz, Dominguez, and Hammett [Phys. Fluids B **4**, 3138 (1992)]. The higher moments are truncated in terms of the lower moments (density, parallel velocity, and parallel and perpendicular pressure) by modeling the deviation from a perturbed Maxwellian to fit the kinetic response function at all values of the kinetic parameters: $k_{\|}v_{\text{th}}/\omega$, $b=(k_{\perp}\rho)^2/2$, and ω_D/ω. Here the resulting gyro-Landau fluid equations are applied to the simulation of ion temperature gradient (ITG) mode turbulence in toroidal geometry using a novel three-dimensional (3-D) nonlinear ballooning mode representation. The representation is a Fourier transform of a field line following basis (k_y', k_x', z') with periodicity in toroidal and poloidal angles. Particular emphasis is given to the role of nonlinearly generated $n=0$ ($k_y'=0$, $k_x' \neq 0$) "radial modes" in stabilizing the transport from the finite-n ITG ballooning modes. Detailing the parametric dependence of toroidal ITG turbulence is a key result.

Phys. Plasmas **1**, 2229 (1994)

Advances in the simulation of toroidal gyro-Landau fluid model turbulence*

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(Received 14 November 1994; accepted 13 February 1995)

The gyro-Landau fluid (GLF) model equations for toroidal geometry [R. E. Waltz, R. R. Dominguez, and G. W. Hammett, Phys. Fluids B **4**, 3138 (1992)] have been recently applied to study ion temperature gradient (ITG) mode turbulence using the three-dimensional (3-D) nonlinear ballooning mode representation (BMR) outlined earlier [R. E. Waltz, G. D. Kerbel, and J. Milovich, Phys. Plasmas **1**, 2229 (1994)]. The present paper extends this work by treating some unresolved issues concerning ITG turbulence with adiabatic electrons. Although eddies are highly elongated in the radial direction, long time radial correlation lengths are short and comparable to poloidal lengths. Although transport at vanishing shear is not particularly large, transport at reverse global shear, is significantly less. Electrostatic transport at moderate shear is not much affected by inclusion of local shear and average favorable curvature. Transport is suppressed when critical $E\times B$ rotational shear is comparable to the maximum linear growth rate with only a weak dependence on magnetic shear. Self-consistent turbulent transport of toroidal momentum can result in a transport bifurcation at sufficiently large $r/(Rq)$. However, the main thrust of the new formulation in the paper deals with advances in the development of finite beta GLF models with trapped electrons and BMR numerical methods for treating the fast parallel field motion of the untrapped electrons. *© 1995 American Institute of Physics.*

Phys. Plasmas **2**, 2408 (1995)

On the dynamics of turbulent transport near marginal stability

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A general methodology for describing the dynamics of transport near marginal stability is formulated. Marginal stability is a special case of the more general phenomenon of self-organized criticality. Simple, one field models of the dynamics of tokamak plasma self-organized criticality have been constructed, and include relevant features such as sheared mean flow and transport bifurcations. In such models, slow mode (i.e., large-scale, low-frequency transport events) correlation times determine the behavior of transport dynamics near marginal stability. To illustrate this, impulse response scaling exponents (z) and turbulent diffusivities (D) have been calculated for the minimal (Burgers') and sheared flow models. For the minimal model, $z=1$ (indicating ballistic propagation) and $D\sim(S_0^2)^{1/3}$, where S_0^2 is the noise strength. With an identically structured noise spectrum and flow with shearing rate exceeding the ambient decorrelation rate for the largest-scale transport events, diffusion is recovered with $z=2$ and $D\sim(S_0^2)^{3/5}$. This indicates a qualitative change in the dynamics, as well as a reduction in losses. These results are consistent with recent findings from dimensionless scaling studies. Several tokamak transport experiments are suggested. *© 1995 American Institute of Physics.*

Phys. Plasmas **2**, 3640 (1995)

The dynamics of marginality and self-organized criticality as a paradigm for turbulent transport*

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A general paradigm, based on the concept of self-organized criticality (SOC), for turbulent transport in magnetically confined plasmas, has been recently suggested as an explanation for some of the apparent discrepancies between most theoretical models of turbulent transport and experimental observations of the transport in magnetically confined plasmas. This model describes the dynamics of the transport without relying on the underlying local fluctuation mechanisms. Computations based on a cellular automata realization of such a model have found that noise-driven SOC systems can maintain average profiles that are linearly stable (submarginal) and yet are able to sustain active transport dynamics. It is also found that the dominant scales in the transport dynamics in the absence of sheared flow are system scales rather than the underlying local fluctuation scales. The addition of sheared flow into the dynamics leads to a large reduction of the system-scale transport events and a commensurate increase in the fluctuation-scale transport events needed to maintain the constant flux. The dynamics of these models and the potential ramifications for transport studies are discussed. © *1996 American Institute of Physics.* [S1070-664X(96)91105-2]

Phys. Plasmas **3**, 1858 (1996)

A model realization of self-organized criticality for plasma confinement

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A model for plasma transport near marginal stability is presented. The model is based on subcritical resistive pressure-gradient-driven turbulence. Three-dimensional nonlinear calculations based on this model show effective transport for subcritical mean profiles. This model exhibits some of the characteristic properties of self-organized criticality. Perturbative transport techniques are used to elucidate the transport properties. Propagation of positive and negative pulses is studied. The observed results suggest a possible explanation of the apparent nonlocal effects observed with perturbative experiments in tokamaks. © *1996 American Institute of Physics.* [S1070-664X(96)03108-4]

Phys. Plasmas **3**, 2903 (1996)

A gyro-Landau-fluid transport model

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A physically comprehensive and theoretically based transport model tuned to three-dimensional (3-D) ballooning mode gyrokinetic instabilities and gyrofluid nonlinear turbulence simulations is formulated with global and local magnetic shear stabilization and $E\times B$ rotational shear stabilization. Taking no fit coefficients from experiment, the model is tested against a large transport profile database with good agreement. This model is capable of describing enhanced core confinement transport barriers in negative central shear discharges based on rotational shear stabilization. The model is used to make ignition projections from relative gyroradius scaling discharges. © *1997 American Institute of Physics.* [S1070-664X(97)01407-9]

Phys. Plasmas **4**, 2482 (1997)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 3 MARCH 1999

Shearing rate of time-dependent E×B flow

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(Received 28 August 1998; accepted 10 December 1998)

Theory of **E**×**B** shear suppression of turbulence in toroidal geometry [Phys. Plasmas **2**, 1648 (1995)] is extended to include fast time variations of the **E**×**B** flows often observed in nonlinear simulations of tokamak turbulence. It is shown that the quickly time varying components of the **E**×**B** flows, while they typically contribute significantly to the instantaneous **E**×**B** shearing rate, are less effective than the slowly time varying components in suppressing turbulence. This is because the shear flow pattern changes before eddies get distorted enough. The effective **E**×**B** shearing rate capturing this important physics is analytically derived and estimated from zonal flow statistics of gyrofluid simulation. This provides new insights into understanding recent gyrofluid and gyrokinetic simulations that yield a reduced, but not completely quenched, level of turbulence in the presence of turbulence-driven zonal flows. © *1999 American Institute of Physics.*
[S1070-664X(99)04603-0]

Phys. Plasmas **6**, 922 (1999)

PHYSICS OF PLASMAS VOLUME 7, NUMBER 5 MAY 2000

Electron temperature gradient driven turbulence*

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(Received 19 November 1999; accepted 4 February 2000)

Collisionless electron-temperature-gradient-driven (ETG) turbulence in toroidal geometry is studied via nonlinear numerical simulations. To this aim, two massively parallel, fully gyrokinetic Vlasov codes are used, both including electromagnetic effects. Somewhat surprisingly, and unlike in the analogous case of ion-temperature-gradient-driven (ITG) turbulence, we find that the turbulent electron heat flux is significantly underpredicted by simple mixing length estimates in a certain parameter regime ($\hat{s}\sim 1$, low α). This observation is directly linked to the presence of radially highly elongated vortices (''streamers'') which lead to very effective cross-field transport. The simulations therefore indicate that ETG turbulence is likely to be relevant to magnetic confinement fusion experiments. © *2000 American Institute of Physics.* [S1070-664X(00)95905-6]

Phys. Plasmas **7**, 1904 (2000)

Magnetically Confined Plasmas, Heating, Confinement

VOLUME 1, NUMBER 4 JULY-AUGUST, 1958

The Stellarator Concept*

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(Received May 27, 1958)

The basic concepts of the controlled thermonuclear program at Project Matterhorn, Princeton University are discussed. In particular, the theory of confinement of a fully ionized gas in the magnetic configuration of the stellarator is given, the theories of heating are outlined, and the bearing of observational results on these theories is described.

Magnetic confinement in the stellarator is based on a strong magnetic field produced by solenoidal coils encircling a toroidal tube. The configuration is characterized by a "rotational transform," such that a single line of magnetic force, followed around the system, intersects a cross-sectional plane in points which successively rotate about the magnetic axis. A theorem by Kruskal is used to prove that each line of force in such a system generates a toroidal surface; ideally the wall is such a surface. A rotational transform may be generated either by a solenoidal field in a twisted, or figure-eight shaped, tube, or by the use of an additional transverse multipolar helical field, with helical symmetry.

Plasma confinement in a stellarator is analyzed from both the macroscopic and the microscopic points of view. The macroscopic equations, derived with certain simplifying assumptions, are used to show the existence of an equilibrium situation, and to discuss the limitations on material pressure in these solutions. The single-particle, or microscopic, picture shows that particles moving along the lines of force remain inside the stellarator tube to the same approximation as do the lines of force. Other particles are presumably confined by the action of the radial electric field that may be anticipated.

Theory predicts and observation confirms that initial breakdown, complete ionization, and heating of a hydrogen or helium gas to about 10^6 degrees K are possible by means of a current parallel to the magnetic field (ohmic heating). Flow of impurities from the tube walls into the heated gas, during the discharge, may be sharply reduced by use of an ultra-high vacuum system; some improvement is also obtained with a divertor, which diverts the outer shell of magnetic flux away from the discharge. Experiments with ohmic heating verify the presence of a hydromagnetic instability predicted by Kruskal for plasma currents greater than a certain critical value and also indicate the presence of other cooperative phenomena. Heating to very much higher temperatures can be achieved by use of a pulsating magnetic field. Heating at the positive-ion cyclotron resonance frequency has been proposed theoretically and confirmed observationally by Stix. In addition, an appreciable energy input to the positive ions should be possible, in principle, if the pulsation period is near the time between ion-ion collisions or the time required for a positive ion to pass through the heating section (magnetic pumping).

Phys. Fluids **1**, 253 (1958)

THE PHYSICS OF FLUIDS VOLUME 1, NUMBER 4 JULY-AUGUST, 1958

Equilibrium of a Magnetically Confined Plasma in a Toroid*

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(Received May 27, 1958)

A variety of properties are derived satisfied by any static equilibrium of a plasma governed by the well-known magnetostatic equations. Some of these are local and quite trivial. Others involve integrals over surfaces of constant pressure, which are shown to be topologically toroidal under fairly general assumptions.

A variational principle for such equilibria is derived. One of its consequences is to provide a characterization of equilibria by their values of certain invariants.

Finally, conditions are obtained additional to the magnetostatic equations appropriate to the steady state of a plasma slowly diffusing across a magnetic field out of a topologically toroidal region.

Phys. Fluids **1**, 265 (1958)

VOLUME 6, NUMBER 11 NOVEMBER 1963

Some Stable Plasma Equilibria in Combined Mirror-Cusp Fields

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(Received 3 June 1963)

The problem of equilibrium and stability of plasma confined in certain magnetic fields of combined mirror-cusp form is discussed. These fields have the properties that they are nowhere zero and everywhere increase toward the periphery. Attention is drawn to the importance of the existence of closed surfaces of constant $|B|$—the magnetic isobars. The conditions for plasma equilibrium are derived and interpreted; then by exploiting the existence of closed magnetic isobars certain low-β confined equilibria are constructed. These equilibria are shown to be stable according to the fluid (double adiabatic) energy principle and according to the small Larmor radius limit theory. A direct proof of stability against motions which preserve the magnetic moment is given. These equilibria have the property that there is no current along lines of force so that they are also immune to several drift instabilities.

Phys. Fluids **6**, 1529 (1963)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 2 FEBRUARY 1965

Formation of a High-Density Deuterium Plasma Focus

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(Received 27 July 1964)

During the early investigation of the high-energy, low-pressure mode of a coaxial hydromagnetic gun, a second mode of action was established for large gas fillings. This particular mode, previously reported was found to lead to a high-density plasma focus situated at a distance ~1–1.5 cm beyond the face of the center electrode. The plasma focus has the following properties; particle density $\rho \sim 2\text{–}3 \times 10^{19}/\text{cm}^3$, temperature $T \sim 1\text{–}3$ keV, time duration $t \sim 0.2\text{–}0.3$ μsec, and volume ~15 mm³. Neutron yields $>10^{10}$/burst and soft x rays are observed. These results are remarkably similar to those reported by Petrov *et al.* and Filippov *et al.* of the USSR using a metal wall pinch tube apparatus. The average velocity v_z of the current sheath in the gun proper is found to depend on the fourth root of the applied voltage squares, divided by the mass density according to the simple "snowplow" "*M*" theory. The current sheath is found to be nonplanar and mass pickup by the advancing sheath is nonlinear with radius. The sudden collapse of the radial current sheath toward the axis at the center electrode end is most likely caused by the rapid conversion of stored magnetic energy into radial sheath motion ($\bar{v}_r \sim 3.5 \times 10^7$ cm/sec) forming in essence a super dense pinch effect.

Phys. Fluids **8**, 366 (1965)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 1 JANUARY 1967

Toroidal Containment of a Plasma

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(Received 5 July 1966; final manuscript received 10 October 1966)

The question of plasma containment in a torus is much more complicated than in an open-ended mirror system. Serious questions arise of the nonexistence of flux surfaces, of noncontained particle drifts, and of nonexistence of self-consistent equilibria at small gyroradius.

Phys. Fluids **10**, 137 (1967)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 7 JULY 1973

Tearing mode in the cylindrical tokamak

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(Received 12 May 1972; final manuscript received 6 March 1973)

Detailed computational results are presented on the stability and radial distribution of linear tearing modes in cylindrical tokamaks of various radial profiles. In the case of a skin-current profile, a "double tearing mode", with two points of discontinuity in the radial magnetic field perturbation is found. An analytical method is also derived for comparison of the stability of different radial profiles. It is further shown that the tearing mode can be driven by finite electron viscosity, as well as by the usual finite resistivity mechanism.

Phys. Fluids **16**, 1054 (1973)

THE PHYSICS OF FLUIDS VOLUME 16, NUMBER 8 AUGUST 1973

Decay of poloidal rotation in a tokamak plasma

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(Received 4 October 1972)

Radial electric fields may be built up in a tokamak by several mechanisms such as nonambipolar particle transport or loss, or the inhomogeneous deposition of electric charge which occurs as a result of the injection of fast neutral atoms. The initial effect of the radial fields is to produce a poloidal rotation of the plasma. Such rotation, however, subjects the moving elements of the plasma to energy dissipation by magnetic pumping, which damps the rotation in a period of the order of the ion–ion collision time. The problem is analyzed for the "plateau" and "banana" regimes by applying the drift kinetic equation, with a simple relaxation collision term, to a slab-model low-β plasma. The calculation may be more generally applied to the problem of momentum dissipation for any low-β long-mean-free-path plasma in a periodic or stochastic magnetic field.

Phys. Fluids **16**, 1260 (1973)

Rotation of a toroidally confined, collisional plasma

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(Received 7 November 1973)

Plasma rotation in the collisional regime is considered from the viewpoint of the drift-kinetic equation, using orderings which have become standard in neoclassical transport theory. Kinetic arguments require a unique relation between the ion parallel flow U and the radial gradients of density, temperature, and electrostatic potential; this relation is derived and compared to similar relations for collisionless regimes. The off-diagonal stress tensor component, which governs the time evolution of U is also calculated. This component does not resemble a viscous stress, and dominates classical viscosity by roughly the usual Pfirsch–Schlüter factor.

Phys. Fluids **17**, 961 (1974)

Nonlinear, three-dimensional magnetohydrodynamics of noncircular tokamaks

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(Received 27 May 1975)

Rosenbluth's nonlinear, approximate tokamak equations of motion are generalized to three dimensions. The equations describe magnetohydrodynamics in the low β, incompressible, large aspect ratio limit. Conservation laws are derived and a well-known form of the energy principle is recovered from the linearized equations. The equations are solved numerically to study kink modes in tokamaks with rectangular cross section. Fixed-boundary kink modes, for which the plasma completely fills the conducting chamber, are considered. These modes, which are marginally stable to lowest order in circular tokamaks, become unstable with large growth rates, comparable to the growth rates of free boundary kink modes. The unstable modes are found using linearized, two-dimensional equations. The linear results are used as initial values in the nonlinear, three-dimensional computations. The nonlinear results show that the magnetic field is perturbed only slightly, while a large amount of plasma convection takes place carrying plasma from the center of the chamber to the walls.

Phys. Fluids **19**, 134 (1976)

Plasma confinement by localized cusps

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Details of the confinement of primary ionizing electrons and plasma by multidipole fields are given. It is shown that primary electrons are very efficiently confined by the cusps, with leakage half-widths given by the electron gyroradii. Plasma is confined much more weakly. Leakage half-widths of helium, argon, and xenon plasmas are found to be twice the hydrid gyroradii. Plasma noise in the neighborhood of the hybrid frequency is observed in the cusp regions.

Phys. Fluids **19**, 1045 (1976)

Numerical studies of nonlinear evolution of kink modes in tokamaks

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(Received 22 December 1975; final manuscript received 22 June 1976)

A set of numerical techniques for investigating the full nonlinear unstable behavior of low-β kink modes of given helical symmetry in tokamaks is presented. Uniform current density plasmas display complicated deformations including the formation of large vacuum bubbles provided that the safety factor q is sufficiently close to integral. Fairly large $m=1$ deformations, but not bubble formation, persist for a plasma with a parabolic current density profile (and hence shear). Deformations for $m \geq 2$ are, however, greatly suppressed.

Phys. Fluids **19**, 1987 (1976)

Dynamics of high β tokamaks

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(Received 5 October 1976; final manuscript received 22 March 1977)

The reduced nonlinear low β tokamak magnetohydrodynamic equations are extended to the case of high β. A large aspect ratio ordering is used. The dynamics can be described using only three variables: the stream functions for the poloidal magnetic field and velocity, and the pressure. The equations are solved numerically to find two-dimensional equilibria. These equilibria can be unstable to ballooning modes, which tend to grow to large amplitude in nonlinear, three-dimensional computations.

Phys. Fluids **20**, 1354 (1977)

Effect of transonic flow in the ablation cloud on the lifetime of a solid hydrogen pellet in a plasma

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A knowledge of solid hydrogen pellet lifetimes in a plasma is critical to the design of devices to refuel tokamak fusion reactors. When the pellet is injected into the plasma, the ablated material from the pellet undergoes a transonic flow since it is heated while it expands. Calculations are done on the behavior of the transonic flow for various plasma conditions and pellet sizes. From these calculations, the ablation rate and lifetimes of the pellet are determined. A scaling law is given which allows pellet lifetimes to be easily calculated for any plasma conditions. The results of these calculations give good agreement when compared with experiments.

Phys. Fluids **21**, 1735 (1978)

Nonlinear interaction of tearing modes in highly resistive tokamaks

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(Received 11 September 1978; final manuscript received 24 January 1979)

A mechanism for the major disruption in tokamaks is proposed involving the nonlinear destabilization of tearing modes by the $m = 2$, $n = 1$ tearing mode. A three-dimensional cylindrical nonlinear code based on a set of equations valid in the limit of low β and large ratio of the toroidal and poloidal magnetic fields has been constructed. The essential result is that for safety factor profiles flat in the plasma core the 2/1 mode significantly destabilizes other modes, particularly odd modes such as the 3/2 mode, before the 2/1 island in the single-pitch limit has expanded to its maximum width. Many magnetic islands of different pitch are produced and the corresponding deformation of the toroidal current density is more severe than in the two-dimensional case. The magnetic islands generated can extend across the plasma cross section; presumably, the corresponding ergodic magnetic fields can result in the escape of particles and heat from the plasma core. An analytic model in agreement with these results is also presented.

Phys. Fluids **22**, 896 (1979)

Current generation with low-frequency waves

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Various types of traveling waves may be injected into a tokamak to continuously sustain the toroidal current. Interest in this problem arises from the possibility of operating tokamak reactors in the steady state. The low-frequency waves most suitable for this task are identified in terms of the power cost for deployment in a reactor. Means of exciting these waves and tradeoffs with design criteria are discussed. A comparison is made with the alternative attractive regime of high-frequency waves. Conclusions are based, in part, on the numerical solution of the two-dimensional Fokker–Planck equation with an added quasi-linear term due to the waves.

Phys. Fluids **24**, 27 (1981)

Plasma equilibrium with rational magnetic surfaces

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The self-consistent classical plasma equilibrium with diffusion is studied in a toroidal geometry having a sheared magnetic field. Near each rational surface it is found that the pressure gradient is zero unless the Fourier component of $1/B^2$, which resonates with that surface, vanishes. Despite the resonances, the overall plasma confinement is, in practice, only slightly modified by the rational surfaces.

Phys. Fluids **24**, 1999 (1981)

Measuring plasma drift velocities in tokamak edge plasmas using probes

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(Received 1 December 1983; accepted 3 July 1984)

Plasma drift or rotation is caused at the edge of tokamaks by various mechanisms including flow to surfaces and neutral injection. These drift velocities can be measured using electrostatic probes and a theory is presented providing a method of probe analysis to deduce drift velocity, plasma density, and temperature. Initial probe experiments using this probe analysis yield credible values of drift velocity, but comparison with an independent technique, e.g., spectroscopic Doppler shifts, is sought.

Phys. Fluids **27**, 2699 (1984)

Turbulent structure in the edge plasma of the TEXT tokamak

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(Received 18 July 1984; accepted 7 September 1984)

A reversal has been observed in the mean phase velocity of the turbulent fluctuations in the edge plasma of the TEXT tokamak. The observations can be described by a model in which the wave velocity in the lab frame is dominated by a nonuniform $E_r \times B$ velocity and a gradient driven drift. The measurements also exhibit a localized instability which occurs in the region of maximum velocity shear.

Phys. Fluids **27**, 2956 (1984)

Low-*n* shear Alfvén spectra in axisymmetric toroidal plasmas

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(Received 31 October 1985; accepted 4 August 1986)

In toroidal plasmas, the toroidal magnetic field is nonuniform over a magnetic surface and causes coupling of different poloidal harmonics. It is shown both analytically and numerically that the toroidicity not only breaks up the shear Alfvén continuous spectrum, but also creates new, discrete, toroidicity-induced shear Alfvén eigenmodes with frequencies inside the continuum gaps. Potential applications of the low-*n* toroidicity-induced shear Alfvén eigenmodes on plasma heating and instabilities are addressed.

Phys. Fluids **29**, 3695 (1986)

Marfes: Radiative condensation in tokamak edge plasma

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(Received 21 January 1987; accepted 11 May 1987)

Marfes are toroidally symmetric bands of high density radiating plasma that form at the edge of tokamak plasmas. The marfe results from a process of radiative condensation: A local increase in the plasma density increases the radiation rate and lowers the temperature, allowing the density to rise further to maintain pressure balance. It is demonstrated that the marfe onsets when the plasma density exceeds a critical threshold that is just below the density limit, in agreement with observations. This threshold results from a balance between condensation and cross-field thermal flux from the central hot plasma. Finally, it is noted that radiative condensation is also the driving mechanism of solar prominences and other astrophysical objects.

Phys. Fluids **30**, 2429 (1987)

Ion temperature-gradient-driven modes and anomalous ion transport in tokamaks

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(Received 18 February 1988; accepted 20 December 1988)

The stability of the ion temperature gradient modes is investigated using the kinetic ion response without expansions in ω_D/ω. A systematic parameter study is carried out using a low-beta circular flux surface equilibrium in order to determine the stability boundaries in η_i vs ϵ_n space ($\eta_i = d \ln T_i/d \ln n$, $\epsilon_n = L_n/R$). Particular attention is devoted to the consequences of the presence of these modes for anomalous ion transport.

Phys. Fluids B **1**, 1018 (1989)

Excitation of the toroidicity-induced shear Alfvén eigenmode by fusion alpha particles in an ignited tokamak

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(Received 18 April 1989; accepted 6 July 1989)

The toroidicity-induced shear Alfvén eigenmode is found to be destabilized by fusion alpha particles in an ignited tokamak plasma.

Phys. Fluids B **1**, 1949 (1989)

Bifurcation of poloidal rotation and suppression of turbulent fluctuations: A model for the L–H transition in tokamaks*

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(Received 4 December 1989; accepted 21 February 1990)

The poloidal momentum balance equation in tokamaks is shown to have bifurcated solutions; the poloidal flow velocity U_p can suddenly become more positive when the ion collisionality decreases. The corresponding radial electric field E_r becomes more negative, suppresses turbulent fluctuations, and improves plasma confinement. A heuristic argument is employed to illustrate the effects of E_r on turbulent fluctuations. A more negative value of E_r and/or a more positive value of dE_r/dr can suppress the fluctuation amplitudes, if $dP/dr < 0$ (with r the local minor radius and P the plasma pressure). The theory is employed to explain the L–H transition observed in tokamaks.

Phys. Fluids B **2**, 1492 (1990)

Fluctuations and anomalous transport in tokamaks

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This is a review of what is known about fluctuations and anomalous transport processes in tokamaks. It mostly considers experimental results obtained after, and not included in, the reviews of Liewer [Nucl. Fusion **25**, 543 (1985)], Robinson [in *Turbulence and Anomalous Transport in Magnetized Plasmas* (Ecole Polytechnique, Palaiseau, France, 1986), p. 21], and Surko [in *Turbulence and Anomalous Transport in Magnetized Plasmas* (Ecole Polytechnique, Palaiseau, France, 1986), p. 93]. Therefore much of the pioneering work in the field is not covered. Emphasis is placed on results where comparisons between fluctuations and transport properties have been attempted, particularly from the tokamak TEXT [Nucl. Technol./Fusion **1**, 479 (1981)]. A brief comparison of experimentally measured total fluxes with the predictions of neoclassical theory demonstrates that transport is often anomalous; fluctuations are thought to be the cause. The measurements necessary to determine any such fluctuation-driven fluxes are described. The diagnostics used to measure these quantities, together with some of the statistical techniques employed to analyze the data, are outlined. In the plasma edge detailed measurements of the quantities required to directly determine the fluctuation-driven fluxes are available. The total and fluctuation-driven fluxes are compared: the result emphasizes the importance of edge turbulence. No model adequately describes all the measured properties. In the confinement region experimental observations are presently restricted to measurements of density and potential fluctuations and their correlations. Various distinct turbulence features that have been observed are described, and their characteristics compared with the predictions of various models. Correlations observed between these fluctuations and plasma transport properties are summarized. A separate section on magnetic fluctuations shows there is very little information available inside the plasma, generally prohibiting quantified comparisons between fluctuation levels and transport. Both coherent and turbulent magnetic fluctuations are addressed, and the differences between low and high plasma pressure (low and high beta) are noted. The contributions of alternate confinement devices, such as stellarators and reversed field pinches, to understanding tokamak anomalous transport are discussed. Finally, future directions are proposed.

Phys. Fluids B **2**, 2879 (1990)

The interaction of resonant magnetic perturbations with rotating plasmas

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(Received 15 August 1990; accepted 22 October 1990)

The penetration of a helical magnetic perturbation into a rotating tokamak plasma is investigated. In the linear regime, it is found that unless the frequency of the imposed perturbation matches closely to one of the natural mode frequencies, reconnection at the rational surface is suppressed by a large factor. In order to deal with the problem in the nonlinear regime a theory of propagating, constant-ψ magnetic islands is developed. This theory is valid provided the island width greatly exceeds any microscopic scale length (but still remains small compared with the minor radius), and the magnetic Reynolds number of the plasma is sufficiently large. An island width evolution equation is obtained which, in addition to the usual Rutherford term, contains a *stabilizing* term due ultimately to the inertia of the plasma flow pattern set up around the propagating island. A complete solution is presented for the case where the island and its associated flow pattern are steady. In the nonlinear regime, a fairly sharp threshold is predicted for the magnitude of the applied perturbation. Below this threshold, the induced islands are rotationally suppressed and partially dragged along by the rotating plasma, and above it the islands are virtually fully reconnected and "locked" at the applied frequency of the perturbation. Numerical results from an initial value code are presented, which show good agreement with the analytic predictions. Finally, it is demonstrated that these theories can be used to interpret data recently obtained from the COMPASS-C device [*Controlled Fusion and Plasma Heating 1990* (EPS, Geneva, 1990), Vol. 1, p. 379]. In particular, a possible explanation is given of why in some cases an applied quasistatic resonant magnetic perturbation can stabilize magnetohydrodynamic modes, but in others leads to a disruption.

Phys. Fluids B **3**, 644 (1991)

Thermal confinement bifurcation and the L- to H-mode transition in tokamaks

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A bifurcation in the thermal confinement of tokamaks, which resembles the L- to H-mode transition, is shown to follow from properties of edge turbulence recently derived by Biglari *et al.* [Phys. Fluids B **2**, 1 (1990)], and the standard neoclassical theory of poloidal rotation. The temperature profiles develop a pedestal at the plasma edge, and the poloidal rotation near the edge is considerably increased, when the heating power exceeds a critical value. The energy confinement time is a discontinuous function of increasing heating power, but is continuous for decreasing power (power hysteresis). Critical values of density and magnetic field are found, which must be exceeded in order for the bifurcation to occur. The scaling of the power threshold with density, magnetic field, and ion mass is similar to what is found experimentally.

Phys. Fluids B **3**, 696 (1991)

Neoclassical poloidal and toroidal rotation in tokamaks

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Explicit expressions for the neoclassical poloidal and toroidal rotation speeds of primary ion and impurity species are derived via the Hirshman and Sigmar moment approach. The rotation speeds of the primary ion can be significantly different from those of impurities in various interesting cases. The rapid increase of impurity poloidal rotation in the edge region of H-mode discharges in tokamaks can be explained by a rapid steepening of the primary ion pressure gradient. Depending on ion collisionality, the poloidal rotation speed of the primary ions at the edge can be quite small and the flow direction may be opposite to that of the impurities. This may cast considerable doubts on current L to H bifurcation models based on primary ion poloidal rotation only. Also, the difference between the toroidal rotation velocities of primary ions and impurities is not negligible in various cases. In Ohmic plasmas, the parallel electric field induces a large impurity toroidal rotation close to the magnetic axis, which seems to agree with experimental observations. In the ion banana and plateau regime, there can be non-negligible disparities between primary ion and impurity toroidal rotation velocities due to the ion density and temperature gradients. Detailed analytic expressions for the primary ion and impurity rotation speeds are presented, and the methodology for generalization to the case of several impurity species is also presented for future numerical evaluation.

Phys. Fluids B **3**, 2050 (1991)

Modifications in turbulence and edge electric fields at the L–H transition in the DIII-D tokamak*

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The L to H transition in the DIII-D tokamak [*Plasma Physics and Controlled Nuclear Fusion Research 1986* (IAEA, Vienna, 1987), Vol. I, p. 159] is associated with two clear signatures: edge density fluctuations are abruptly suppressed (in $\approx 100\,\mu$sec), while the edge poloidal rotation velocity v_θ increases, implying that the radial electric field E_r becomes more negative. Detailed new spectroscopic profile measurements show that the changes in v_θ and E_r generate a region of sheared electric field and poloidal flow of width $\approx$3–5 cm. This region develops simultaneously with, and has the same spatial extent as, the edge fluctuation suppression zone as measured using a reflectometer system. Furthermore, the radial extent of the shear and fluctuation suppression zones encompass the location of the H-mode edge transport barrier. These observations are consistent with recent theoretical models of the L–H transition, and a comparison with these theories is presented. Data are also presented on the evolution of edge parameters and density fluctuations after the transition: the shear and fluctuation suppression layers are maintained for the duration of the quiescent H-mode phase, while relative density fluctuation levels decrease and interior plasma confinement gradually improves. Precursors to several different types of edge localized mode (ELM's) are also discussed.

Phys. Fluids B **3**, 2300 (1991)

Physics optimization of stellarators*

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The theoretical and experimental development of stellarators has removed some of the specific deficiencies of this configuration, viz., the limitations in β, the high neoclassical transport, and the low collisionless confinement of α particles. These optimized stellarators can best be realized with a modular coil system. The W7-AS experiment [Plasma Phys. Controlled Fusion **31**, 1579 (1989)] has successfully demonstrated two aspects of advanced stellarators, the improved equilibrium and the modular coil concept. Stellarator optimization will much more viably be demonstrated by W7-X [*Plasma Physics and Controlled Fusion Research*, Proceedings of the 12th International Conference, Nice, 1988 (IAEA, Vienna, 1989), Vol. 2, p. 369], the successor experiment presently under design. Optimized stellarators seem to offer an independent reactor option. In addition, they supplement, in a unique form, the toroidal confinement fusion program, e.g., energy transport is anomalous in stellarators too, but possibly more easily understandable in the frame of existing theoretical concepts than in tokamaks.

Phys. Fluids B **4**, 2081 (1992)

Kinetic theory of toroidicity-induced Alfvén eigenmodes

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An analytic kinetic description of the toroidicity-induced Alfvén eigenmode (TAE) is presented. The theory includes electron parallel dynamics nonperturbatively, an effect that is found to strongly influence the character, and damping of the TAE—contrary to previous theoretical predictions. A parallel conductivity model that includes collisionless (Landau) damping on the passing electrons and collisional damping on both trapped and passing electrons is used. Together, these mechanisms damp the TAE more strongly than previously expected. This is because the TAE couples (or merges) with the kinetic Alfvén wave (KAW) within the gap region under conditions that depend on the gap size, the shear, the magnitude of the conductivity, and the mode numbers. The high damping could be relevant to recent experimental measurements of the TAE damping coefficient. In addition, the theory predicts a "kinetic" TAE, whose eigenfreqeuency lies just above the gap, whose existence depends on finite conductivity, and that is formed by the coupling of two KAW's

Phys. Fluids B **4**, 2885 (1992)

Nondimensional transport scaling in the Tokamak Fusion Test Reactor: Is tokamak transport Bohm or gyro-Bohm?

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General plasma physics principles state that power flow $Q(r)$ through a magnetic surface in a tokamak should scale as $Q(r)=\{32\pi^2Rr^3T_e^2c\, n_ea/[eB(a^2-r^2)^2]\}\ F(\rho^*,\beta,\nu^*,r/a,q,s,r/R,...)$ where the arguments of F are local, nondimensional plasma parameters and nondimensional gradients. This paper reports an experimental determination of how F varies with normalized gyroradius $\rho^*\equiv(2T_eM_i)^{1/2}c/eBa$ and collisionality $\nu^*\equiv(R/r)^{3/2}qR\nu_e(m_e/2T_e)^{1/2}$ for discharges prepared so that other nondimensional parameters remain close to constant. Tokamak Fusion Test Reactor (TFTR) [D. M. Meade *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research, 1990*, Proceedings of the 13th International Conference, Washington (International Atomic Energy Agency, Vienna, 1991), Vol. 1, p. 9] L-mode data show F to be independent of ρ^* and numerically small, corresponding to Bohm scaling with a small multiplicative constant. By contrast, most theories predict gyro-Bohm scaling: $F\propto\rho^*$. Bohm scaling implies that the largest scale size for microinstability turbulence depends on machine size. Analysis of a collisionality scan finds Bohm-normalized power flow to be independent of collisionality. Implications for future theory, experiment, and reactor extrapolations are discussed.

Phys. Fluids B **5**, 477 (1993)

An emerging understanding of H-mode discharges in tokamaks*

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A remarkable degree of consistency of experimental results from tokamaks throughout the world has developed with regard to the phenomenology of the transition from L-mode to H-mode confinement in tokamaks. The transition is initiated in a narrow layer at the plasma periphery where density fluctuations are suppressed and steep gradients of temperature and density form in a region with large first and second radial derivatives in the $v_E=(\mathbf{E}\times\mathbf{B})/B^2$ flow velocity. These results are qualitatively consistent with theories which predict suppression of fluctuations by shear or curvature in v_E. The required v_E flow is generated very rapidly when the magnitude of the heating power or of an externally imposed radial current exceed threshold values and several theoretical models have been developed to explain the observed changes in the v_E flow. After the transition occurs, the altered boundary conditions enable the development of improved confinement in the plasma interior on a confinement time scale. The resulting H-mode discharge has typically twice the confinement of L-mode discharges and regimes of further improved confinement have been obtained in some H-mode scenarios.

Phys. Fluids B **5**, 2343 (1993)

Three-dimensional fluid simulations of the nonlinear drift-resistive ballooning modes in tokamak edge plasmas

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A three-dimensional study of the turbulence and sheared flow generated by the drift-resistive ballooning modes in tokamak edge plasmas has been completed. The fluid simulations show that 10%–15% percent density fluctuations can develop in the nonlinear state when the self-consistently generated shear flow is suppressed. These modes are also found to give rise to poloidally asymmetric particle transport. Characteristic scale lengths of these fluctuations are isotropic in the plane transverse to **B** and smaller than the connection length along the field line. Sheared poloidal flow is self-consistently driven by both the Reynolds stress and the Stringer mechanisms. In the presence of self-consistent shear flow, the transverse spectrum is no longer isotropic transverse to **B**. The vortices become elongated in the poloidal direction. Also, there is a substantial reduction in both the level of fluctuations of the density and potential and the associated particle transport. These features are in qualitative agreement with L–H transitions observed in tokamaks.

Phys. Fluids B **5**, 3712 (1993)

First results from Alcator-C-MOD*

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Early operation of the Alcator-C-MOD tokamak [I.H. Hutchinson, *Proceedings of IEEE 13th Symposium on Fusion Engineering*, Knoxville, TN, edited by M. Lubell, M. Nestor, and S. Vaughan (Institute of Electrical and Electronic Engineers, New York, 1990), Vol. 1, p. 13] is surveyed. Reliable operation, with plasma current up to 1 MA, has been obtained, despite the massive conducting superstructure and the associated error fields. However, vertical disruptions are not slowed by the long vessel time constant. With pellet fueling, peak densities up to 9×10^{20} m^{-3} have been attained and "snakes" are often seen. Initial characterization of divertor and scrape-off layer is presented and indicates approximately Bohm diffusion. The edge plasma shows a wealth of marfe-like phenomena, including a transition to detachment from the divertor plates with accompanying radiative divertor regions. Energy confinement generally appears to exceed the expectations of neo-Alcator scaling. A transition to Ohmic H mode has been observed. Ion cyclotron heating experiments have demonstrated good power coupling, in agreement with theory.

Phys. Plasmas **1**, 1511 (1994)

Helical temperature perturbations associated with tearing modes in tokamak plasmas

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An investigation is made into the electron temperature perturbations associated with tearing modes in tokamak plasmas. It is found that there is a critical magnetic island width below which the conventional picture where the temperature is flattened inside the separatrix is invalid. This effect comes about because of the *stagnation* of magnetic field lines in the vicinity of the rational surface and the *finite* parallel thermal conductivity of the plasma. Islands whose widths lie below the critical value are not destabilized by the perturbed bootstrap current, unlike conventional magnetic islands. This effect may provide an explanation for some puzzling experimental results regarding error field-induced magnetic reconnection. The critical island width is found to be fairly substantial in conventional tokamak plasmas, provided that the long mean-free path nature of parallel heat transport and the anomalous nature of perpendicular heat transport are taken into account in the calculation. © *1995 American Institute of Physics.*

Phys. Plasmas **2**, 825 (1995)

Flow shear induced fluctuation suppression in finite aspect ratio shaped tokamak plasma

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The suppression of turbulence by the $\mathbf{E}\times\mathbf{B}$ flow shear and parallel flow shear is studied in an arbitrary shape finite aspect ratio tokamak plasma using the two point nonlinear analysis previously utilized in a high aspect ratio tokamak plasma [Phys. Plasmas **1**, 2940 (1994)]. The result shows that only the $\mathbf{E}\times\mathbf{B}$ flow shear is responsible for the suppression of flute-like fluctuations. This suppression occurs regardless of the plasma rotation direction and is, therefore, relevant for the very high (VH) mode plasma core as well as for the high (H) mode plasma edge. Experimentally observed in–out asymmetry of fluctuation reduction behavior can be addressed in the context of flux expansion and magnetic field pitch variation on a given flux surface. The adverse effect of neutral particles on confinement improvement is also discussed in the context of the charge exchange induced parallel momentum damping. © *1995 American Institute of Physics.*

Phys. Plasmas **2**, 1648 (1995)

Quantitative predictions of tokamak energy confinement from first-principles simulations with kinetic effects*

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A first-principles model of anomalous thermal transport based on numerical simulations is presented, with stringent comparisons to experimental data from the Tokamak Fusion Test Reactor (TFTR) [Fusion Technol. **21**, 1324 (1992)]. This model is based on nonlinear gyrofluid simulations, which predict the fluctuation and thermal transport characteristics of toroidal ion-temperature-gradient-driven (ITG) turbulence, and on comprehensive linear gyrokinetic ballooning calculations, which provide very accurate growth rates, critical temperature gradients, and a quasilinear estimate of χ_e/χ_i. The model is derived solely from the simulation results. More than 70 TFTR low confinement (L-mode) discharges have been simulated with quantitative success. Typically, the ion and electron temperature profiles are predicted within the error bars, and the global energy confinement time within $\pm 10\%$. The measured temperatures at $r/a \simeq 0.8$ are used as a boundary condition to predict the temperature profiles in the main confinement zone. The dramatic transition to the improved confinement in the supershot regime is also qualitatively explained. Further work is needed to extend this model of core heat transport to include particle and momentum transport, the edge region, and other operating regimes besides the ITG-dominated L mode. Nevertheless, the present model is very successful in predicting thermal transport in the main plasma over a wide range of parameters. © *1995 American Institute of Physics.*

Phys. Plasmas **2**, 2381 (1995)

Beyond paradigm: Turbulence, transport, and the origin of the radial electric field in low to high confinement mode transitions in the DIII-D tokamak*

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The paradigm of shear suppression of turbulence as the mechanism for the low to high confinement mode (L to H) transition is examined by quantitative comparison of the predictions of the paradigm with experimental results from the DIII-D tokamak [*Plasma Physics and Controlled Fusion Research* (International Atomic Energy Agency, Vienna, 1986), p. 159]. The L to H transition trigger is $\mathbf{V}\times\mathbf{B}$ rotation, not the main ion pressure gradient. The radial electric field E_r shear increases before the fluctuation suppression, consistent with increasing E_r shear as the cause of the turbulence suppression. The spatial dependence of the turbulence reduction is consistent with shear suppression for negative E_r shear. For positive E_r shear, the turbulence suppression is consistent with the effect of E_r curvature for modes for which an E_r well is destabilizing. Finally, the transport barrier depends on the phase angle between the density and potential fluctuations inside the E_r well, an effect not included in existing L to H transition models. © *1995 American Institute of Physics.*

Phys. Plasmas **2**, 2397 (1995)

Threshold for neoclassical magnetic islands in a low collision frequency tokamak

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A kinetic theory for magnetic islands in a low collision frequency tokamak plasma is presented. Self-consistent equations for the islands' width, w, and propagation frequency, ω, are derived. These include contributions from the perturbed bootstrap current and the toroidally enhanced ion polarization drift. The bootstrap current is independent of the island propagation frequency and provides a drive for the island in tokamak plasmas when the pressure decreases with an increasing safety factor. The polarization drift is frequency dependent, and therefore its effect on the island stability cannot be deduced unless ω is known. This frequency is determined by the dominant dissipation mechanism, which for low effective collision frequency, $\nu_{\text{eff}}=\nu/\epsilon<\omega$, is governed by the electrons close to the trapped/passing boundary. The islands are found to propagate in the electron diamagnetic direction in which case the polarization drift is stabilizing and results in a threshold width for island growth, which is of the order of the ion banana width. At larger island widths the polarization current term becomes small and the island evolution is determined by the bootstrap current drive and Δ' alone, where Δ' is a measure of the magnetic free energy. [S1070-664X(96)02601-7]

Phys. Plasmas **3**, 248 (1996)

Rotational and magnetic shear stabilization of magnetohydrodynamic modes and turbulence in DIII-D high performance discharges*

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The confinement and the stability properties of the DIII-D tokamak [*Plasma Physics and Controlled Nuclear Fusion Research 1986* (International Atomic Energy Agency, Vienna, 1987), Vol. 1, p. 159] high-performance discharges are evaluated in terms of rotational and magnetic shear, with an emphasis on the recent experimental results obtained from the negative central magnetic shear (NCS) experiments. In NCS discharges, a core transport barrier is often observed to form inside the NCS region accompanied by a reduction in core fluctuation amplitudes. Increasing negative magnetic shear contributes to the formation of this core transport barrier, but by itself is not sufficient to fully stabilize the toroidal drift mode (trapped-electron-η_i mode) to explain this formation. Comparison of the Doppler shift shear rate to the growth rate of the η_i mode suggests that the large core $E\times B$ flow shear can stabilize this mode and broaden the region of reduced core transport. Ideal and resistive stability analysis indicates the performance of NCS discharges with strongly peaked pressure profiles is limited by the resistive interchange mode to low $\beta_N\leqslant 2.3$. This mode is insensitive to the details of the rotational and the magnetic shear profiles. A new class of discharges, which has a broad region of weak or slightly negative magnetic shear (WNS), is described. The WNS discharges have broader pressure profiles and higher β values than the NCS discharges, together with high confinement and high fusion reactivity. © *1996 American Institute of Physics.* [S1070-664X(96)92505-4]

Phys. Plasmas **3**, 1951 (1996)

Effects of $E\times B$ velocity shear and magnetic shear on turbulence and transport in magnetic confinement devices*

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One of the scientific success stories of fusion research over the past decade is the development of the $E\times B$ shear stabilization model to explain the formation of transport barriers in magnetic confinement devices. This model was originally developed to explain the transport barrier formed at the plasma edge in tokamaks after the L (low) to H (high) transition. This concept has the universality needed to explain the edge transport barriers seen in limiter and divertor tokamaks, stellarators, and mirror machines. More recently, this model has been applied to explain the further confinement improvement from H (high) mode to VH (very high) mode seen in some tokamaks, where the edge transport barrier becomes wider. Most recently, this paradigm has been applied to the core transport barriers formed in plasmas with negative or low magnetic shear in the plasma core. These examples of confinement improvement are of considerable physical interest; it is not often that a system self-organizes to a higher energy state with reduced turbulence and transport when an additional source of free energy is applied to it. The transport decrease that is associated with $E\times B$ velocity shear effects also has significant practical consequences for fusion research. The fundamental physics involved in transport reduction is the effect of $E\times B$ shear on the growth, radial extent, and phase correlation of turbulent eddies in the plasma. The same fundamental transport reduction process can be operational in various portions of the plasma because there are a number of ways to change the radial electric field E_r. An important theme in this area is the synergistic effect of $E\times B$ velocity shear and magnetic shear. Although the $E\times B$ velocity shear appears to have an effect on broader classes of microturbulence, magnetic shear can mitigate some potentially harmful effects of $E\times B$ velocity shear and facilitate turbulence stabilization. Considerable experimental work has been done to test this picture of $E\times B$ velocity shear effects on turbulence; the experimental results are generally consistent with the basic theoretical models. © *1997 American Institute of Physics.* [S1070-664X(97)93605-3]

Phys. Plasmas **4**, 1499 (1997)

Local transport barrier formation and relaxation in reverse-shear plasmas on the Tokamak Fusion Test Reactor*

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(Received 14 November 1996; accepted 11 February 1997)

The roles of turbulence stabilization by sheared $E\times B$ flow and Shafranov shift gradients are examined for Tokamak Fusion Test Reactor [D. J. Grove and D. M. Meade, Nucl. Fusion **25**, 1167 (1985)] enhanced reverse-shear (ERS) plasmas. Both effects in combination provide the basis of a positive-feedback model that predicts reinforced turbulence suppression with increasing pressure gradient. Local fluctuation behavior at the onset of ERS confinement is consistent with this framework. The power required for transitions into the ERS regime are lower when high power neutral beams are applied earlier in the current profile evolution, consistent with the suggestion that both effects play a role. Separation of the roles of $E\times B$ and Shafranov shift effects was performed by varying the $E\times B$ shear through changes in the toroidal velocity with nearly steady-state pressure profiles. Transport and fluctuation levels increase only when $E\times B$ shearing rates are driven below a critical value that is comparable to the fastest linear growth rates of the dominant instabilities. While a turbulence suppression criterion that involves the ratio of shearing to linear growth rates is in accord with many of these results, the existence of hidden dependencies of the criterion is suggested in experiments where the toroidal field was varied. The forward transition into the ERS regime has also been examined in strongly rotating plasmas. The power threshold is higher with unidirectional injection than with balance injection. [S1070-664X(97)95405-7]

Phys. Plasmas **4**, 1736 (1997)

Beta limits in long-pulse tokamak discharges*

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The maximum normalized beta achieved in long-pulse tokamak discharges at low collisionality falls significantly below both that observed in short pulse discharges and that predicted by the ideal MHD theory. Recent long-pulse experiments, in particular those simulating the International Thermonuclear Experimental Reactor (ITER) [M. Rosenbluth *et al.*, *Plasma Physics and Controlled Nuclear Fusion* (International Atomic Energy Agency, Vienna, 1995), Vol. 2, p. 517] scenarios with low collisionality ν_{e*}, are often limited by low-m/n nonideal magnetohydrodynamic (MHD) modes. The effect of saturated MHD modes is a reduction of the confinement time by 10%–20%, depending on the island size and location, and can lead to a disruption. Recent theories on neoclassical destabilization of tearing modes, including the effects of a perturbed helical bootstrap current, are successful in explaining the qualitative behavior of the resistive modes and recent results are consistent with the size of the saturated islands. Also, a strong correlation is observed between the onset of these low-m/n modes with sawteeth, edge localized modes (ELM), or fishbone events, consistent with the seed island required by the theory. We will focus on a quantitative comparison between both the conventional resistive and neoclassical theories, and the experimental results of several machines, which have all observed these low-m/n nonideal modes. This enables us to single out the key issues in projecting the long-pulse beta limits of ITER-size tokamaks and also to discuss possible plasma control methods that can increase the soft β limit, decrease the seed perturbations, and/or diminish the effects on confinement.
[S1070-664X(97)94005-2]

Phys. Plasmas **4**, 1654 (1997)

Bootstrap current and neoclassical transport in tokamaks of arbitrary collisionality and aspect ratio

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A multi-species fluid model is described for the steady state parallel and radial force balance equations in axisymmetric tokamak plasmas. The bootstrap current, electrical resistivity, and particle and heat fluxes are evaluated in terms of the rotation velocities and friction and viscosity coefficients. A recent formulation of the neoclassical plasma viscosity for arbitrary shape and aspect ratio (including the unity aspect ratio limit), arbitrary collisionality, and orbit squeezing from strong radial electric fields is used to illustrate features of the model. The bootstrap current for the very low aspect ratio National Spherical Torus Experiment [J. Spitzer *et al.*, Fusion Technol. **30**, 1337 (1996)] is compared with other models; the largest differences occur near the plasma edge from treatment of the collisional contributions. The effects of orbit squeezing on bootstrap current, thermal and particle transport, and poloidal rotation are illustrated for an enhanced reverse shear plasma in the Tokamak Fusion Test Reactor [D. Meade and the TFTR Group, *Plasma Physics and Controlled Nuclear Fusion Research*, 1990 (International Atomic Energy Agency, Vienna, 1991), Vol. I, p. 9]. Multiple charge states of impurities are incorporated using the reduced ion charge state formalism for computational efficiency. Because the force balance equations allow for inclusion of external momentum and heat sources and sinks they can be used for general plasma rotation studies while retaining the multi-species neoclassical effects.
[S1070-664X(97)04009-3]

Phys. Plasmas **4**, 3230 (1997)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

Initial physics achievements of large helical device experiments*

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(Received 16 November 1998; accepted 8 December 1998)

The Large Helical Device (LHD) experiments [O. Motojima, *et al.*, Proceedings, 16th Conference on Fusion Energy, Montreal, 1996 (International Atomic Energy Agency, Vienna, 1997), Vol. 3, p. 437] have started this year after a successful eight-year construction and test period of the fully superconducting facility. LHD investigates a variety of physics issues on large scale heliotron plasmas ($R=3.9\,\mathrm{m}$, $a=0.6\,\mathrm{m}$), which stimulates efforts to explore currentless and disruption-free steady plasmas under an optimized configuration. A magnetic field mapping has demonstrated the nested and healthy structure of magnetic surfaces, which indicates the successful completion of the physical design and the effectiveness of engineering quality control during the fabrication. Heating by 3 MW of neutral beam injection (NBI) has produced plasmas with a fusion triple product of $8\times10^{18}\,\mathrm{keV\,m^{-3}\,s}$ at a magnetic field of 1.5 T. An electron temperature of 1.5 keV and an ion temperature of 1.4 keV have been achieved. The maximum stored energy has reached 0.22 MJ, which corresponds to $\langle\beta\rangle=0.7\%$, with neither unexpected confinement deterioration nor visible magnetohydrodynamics (MHD) instabilities. Energy confinement times, reaching 0.17 s at the maximum, have shown a trend similar to the present scaling law derived from the existing medium sized helical devices, but enhanced by 50%. The knowledge on transport, MHD, divertor, and long pulse operation, etc., are now rapidly increasing, which implies the successful progress of physics experiments on helical currentless-toroidal plasmas.
[S1070-664X(99)90605-5]

Phys. Plasmas **6**, 1843 (1999)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 7 JULY 1999

Neoclassical conductivity and bootstrap current formulas for general axisymmetric equilibria and arbitrary collisionality regime

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Expressions for the neoclassical resistivity and the bootstrap current coefficients in terms of aspect ratio and collisionality are widely used in simulating toroidal axisymmetric equilibria and transport evolution. The formulas used are in most cases based on works done 15–20 years ago, where the results have been obtained for large aspect ratio, small or very large collisionality, or with a reduced collision operator. The best expressions to date and to our knowledge are due to Hirshman [S. P. Hirshman, Phys. Fluids **31**, 3150 (1988)] for arbitrary aspect ratio in the banana regime and Hinton–Hazeltine [F. L. Hinton and R. D. Hazeltine, Rev. Mod. Phys. **48**, 239 (1976)] for large aspect ratio and arbitrary collisionality regime. A code solving the Fokker–Planck equation with the full collision operator and including the variation along the magnetic field line, coupled with the adjoint function formalism, has been used to calculate these coefficients in arbitrary equilibrium and collisionality regimes. The coefficients have been obtained for a wide variety of plasma and equilibrium parameters and a comprehensive set of formulas, which have been fitted to the code results within 5%, is proposed for evaluating the neoclassical conductivity and the bootstrap current coefficients. This extends previous works and also highlights inaccuracies in the previous formulas in this wide plasma parameter space.
[S1070-664X(99)03907-5]

Phys. Plasmas **6**, 2834 (1999)

PHYSICS OF PLASMAS VOLUME 7, NUMBER 3 MARCH 2000

Comparisons and physics basis of tokamak transport models and turbulence simulations

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The predictions of gyrokinetic and gyrofluid simulations of ion-temperature-gradient (ITG) instability and turbulence in tokamak plasmas as well as some tokamak plasma thermal transport models, which have been widely used for predicting the performance of the proposed International Thermonuclear Experimental Reactor (ITER) tokamak [*Plasma Physics and Controlled Nuclear Fusion Research, 1996* (International Atomic Energy Agency, Vienna, 1997), Vol. 1, p. 3], are compared. These comparisons provide information on effects of differences in the physics content of the various models and on the fusion-relevant figures of merit of plasma performance predicted by the models. Many of the comparisons are undertaken for a simplified plasma model and geometry which is an idealization of the plasma conditions and geometry in a Doublet III-D [*Plasma Physics and Controlled Nuclear Fusion Research, 1986* (International Atomic Energy Agency, Vienna, 1987), Vol. 1, p. 159] high confinement (H-mode) experiment. Most of the models show good agreements in their predictions and assumptions for the linear growth rates and frequencies. There are some differences associated with different equilibria. However, there are significant differences in the transport levels between the models. The causes of some of the differences are examined in some detail, with particular attention to numerical convergence in the turbulence simulations (with respect to simulation mesh size, system size and, for particle-based simulations, the particle number). The implications for predictions of fusion plasma performance are also discussed. [S1070-664X(00)03703-4]

Phys. Plasmas **7**, 969 (2000)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 11 NOVEMBER 2001

Transport by intermittent convection in the boundary of the DIII-D tokamak

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Intermittent plasma objects (IPOs) featuring higher pressure than the surrounding plasma, and responsible for ~50% of the $E \times B_T$ radial transport, are observed in the scrape off layer (SOL) and edge of the DIII-D tokamak [J. Watkins *et al.*, Rev. Sci. Instrum. **63**, 4728 (1992)]. Conditional averaging reveals that the IPOs, produced at a rate of $\sim 3 \times 10^3\ s^{-1}$, are positively charged and also polarized, featuring poloidal electric fields of up to 4000 V/m. The IPOs move poloidally at speeds of up to 5000 m/s and radially with $\mathbf{E} \times \mathbf{B}_T / B^2$ velocities of ~2600 m/s near the last closed flux surface (LCFS), and ~330 m/s near the wall. The IPOs slow down as they shrink in radial size from 4 cm at the LCFS to 0.5 cm near the wall. The IPOs appear in the SOL of both L and H mode discharges and are responsible for nearly 50% of the SOL radial $E \times B$ transport at all radii; however, they are highly reduced in absolute amplitude in H-mode conditions. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1406940]

Phys. Plasmas **8**, 4826 (2001)

PHYSICS OF PLASMAS VOLUME 9, NUMBER 5 MAY 2002

Edge localized modes and the pedestal: A model based on coupled peeling–ballooning modes[a]

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A model based on magnetohydrodynamic (MHD) stability of the tokamak plasma edge region is presented, which describes characteristics of edge localized modes (ELMs) and the pedestal. The model emphasizes the dual role played by large bootstrap currents driven by the sharp pressure gradients in the pedestal region. Pedestal currents reduce the edge magnetic shear, stabilizing high toroidal mode number (n) ballooning modes, while at the same time providing drive for intermediate to low n peeling modes. The result is that coupled peeling–ballooning modes at intermediate n ($3 < n < 20$) are often the limiting instability which constrains the pedestal and triggers ELMs. These modes are characterized in shaped tokamak equilibria using an efficient new numerical code, and simplified models are developed for pedestal limits and the ELM cycle. Results are compared to several experiments, and nonideal MHD effects are briefly discussed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1449463]

Phys. Plasmas **9**, 2037 (2002)

Inertially Confined Plasmas, High Energy Density Plasma Science, Warm Dense Matter

Plasma simulation studies of stimulated scattering processes in laser-irradiated plasmas

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(Received 26 November 1973; final manuscript received 24 March 1975)

The behavior of stimulated Brillouin and Raman scattering is studied by a number of periodic and aperiodic plasma simulations. The one-dimensional studies at low power, roughly defined by the oscillating velocity of an electron being less than its thermal velocity, tend to support the spatial theory. Typically, in the aperiodic simulations trapping nonlinearities of the electrostatic wave and electron heating can saturate the amount of backscatter at a reasonable level. At high powers in both periodic and aperiodic simulations an x-type breaking or wave collapse phenomenon occurs after saturation which leads to an equilibration between pondermotive force, electron pressure, and ion pressure. Simulations of a random frequency modulated laser are discussed. Two-dimensional simulations and their relationship to the one-dimensional results are briefly mentioned.

Phys. Fluids **18**, 1017 (1975)

Existence of rarefaction shocks in a laser-plasma corona

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(Received 27 January 1978)

General conditions under which rarefaction shocks can exist in the expanding corona of a plasma heated by a laser are derived. In particular, for the case of a two-electron temperature isothermal plasma with temperatures T_h and T_c, such a shock is shown to occur if $T_h/T_c > 5+\sqrt{24}$. The case of rarefaction shocks induced by the ponderomotive force is also briefly discussed.

Phys. Fluids **21**, 2179 (1978)

Laser-plasma interaction and ablative acceleration of thin foils at 10^{12}–10^{15} W/cm^2

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The interaction physics and hydrodynamic motion of thin-foil targets irradiated by long, low-flux Nd-laser pulses (3 nsec, 10^{12}–10^{15} W/cm^2) are studied experimentally and compared with theoretical models. Laser light absorption is high (80%–90%) and thin-foil targets are accelerated up to 10^7 cm/sec with good (20%) hydrodynamic efficiency in the 10^{12}–10^{13} W/cm^2 range. These results agree with a simple rocket ablation model. Details of thermal heat flow, both axially (related to ablation depth) and laterally (related to beam uniformity requirements), are also presented.

Phys. Fluids **23**, 1012 (1980)

Self-consistent eigenvalue analysis of Rayleigh–Taylor instability in an ablating plasma

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(Received 13 September 1982; accepted 8 April 1983)

A mathematical method for a fully self-consistent treatment of the Rayleigh–Taylor instability is developed by solving the linearized fluid equations as an eigenvalue problem. The method is applied to analyze the instability in stationary ablating plasmas with strong inhomogeneity. A reduction of growth rate compared to the classical value is found. The importance of a self-consistent treatment of the Rayleigh–Taylor instability is shown by comparing the result with the growth rate estimated by approximate theoretical arguments.

Phys. Fluids **26**, 2299 (1983)

Self-consistent growth rate of the Rayleigh–Taylor instability in an ablatively accelerating plasma

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The linear stability of an ablating plasma is investigated as an eigenvalue problem by assuming the plasma to be at the stationary state. For various structures of the ablating plasma, the growth rate is found to be expressed well in the form $\gamma = \alpha\sqrt{kg} - \beta k v_a$, where $\alpha = 0.9$, $\beta \simeq 3$–4, and v_a is the flow velocity across the ablation front, and is found to agree well with recent two-dimensional simulations in a classical transport regime. Short-wavelength lasers inducing enhanced mass ablation are suggested to be advantageous to stable implosion because of the ablative stabilization.

Phys. Fluids **28**, 3676 (1985)

Beam optics of exploding foil plasma x-ray lasers

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(Received 4 August 1987; accepted 24 September 1987)

In soft x-ray lasers, amplification is achieved as the x rays propagate down a long narrow plasma column. Refraction, due to electron density gradients, tends to direct the x rays out of high density regions. This can have the undesirable effect of shortening the distance that the x rays stay within the plasma, thereby limiting the amount of amplification. The exploding foil design lessens refraction, but does not eliminate it. In this paper, a quantitative analysis of propagation and amplification in an exploding foil x-ray laser is presented. The density and gain profiles within the plasma are modeled in an approximate manner, which enables considerable analytic progress. It is found that refraction introduces a loss term to the laser amplification. The beam pattern from a parabolic gain profile laser has a dominant peak on the x-ray laser axis. The pattern from a quartic gain profile having a dip on-axis can produce a profile with off-axis peaks, in better agreement with recent experimental data.

Phys. Fluids **31**, 184 (1988)

Weakly nonlinear hydrodynamic instabilities in inertial fusion*

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(Received 11 December 1990; accepted 1 April 1991)

For many cases of interest to inertial fusion, growth of Rayleigh–Taylor and other hydrodynamic instabilities is such that the perturbations remain linear or weakly nonlinear. The transition to nonlinearity is studied via a second-order solution for multimode classical Rayleigh–Taylor growth. The second-order solution shows how classical Rayleigh–Taylor systems forget initial amplitude information in the weakly nonlinear phase. Stabilized growth relevant to inertial fusion is qualitatively different, and initial amplitudes are not dominated by nonlinear effects. In all systems with a full spectrum of modes, nonlinear effects begin when mode amplitudes reach about $1/Lk^2$, for modes of wave number k and system size L.

Phys. Fluids B **3**, 2349 (1991)

Interaction of an ultrashort, relativistically strong laser pulse with an overdense plasma

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The results of an analytical description and of a particle-in-cell simulation of the interaction of an ultrashort, relativistically intense laser pulse, obliquely incident on a nonuniform overdense plasma, are presented and several novel features are identified. The absorption and reflection of the ultraintense electromagnetic laser radiation from a sharp-boundary plasma, high harmonic generation, and the transformation into low-frequency radiation are discussed. In the case of weak plasma nonuniformity the excitation of nonlinear Langmuir oscillations in the plasma resonance region and the resulting electron acceleration are investigated. The vacuum heating of the electrons and the self-intersection of the electron trajectories are also studied. In the case of a sharp-boundary plasma, part of the energy of the laser pulse is found to be converted into a localized, relativistically strong, nonlinear electromagnetic pulse propagating into the plasma. The expansion of the hot electron cloud into the vacuum region and the action of the ponderomotive force of the laser pulse in the localized longitudinal electric field of the Langmuir oscillations lead to ion acceleration. The energy increase of a minority population of multicharged ions is found to be much greater than that of the ambient ions.

Phys. Plasmas **1**, 745 (1994)

A review of the ablative stabilization of the Rayleigh–Taylor instability in regimes relevant to inertial confinement fusion*

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It has been recognized for many years that the most significant limitation of inertial confinement fusion (ICF) is the Rayleigh–Taylor (RT) instability. It limits the distance an ablatively driven shell can be moved to several times its initial thickness. Fortunately material flow through the unstable region at velocity v_A reduces the growth rate to $\sqrt{kg/1+kL}-\beta kv_A$ with β from 2–3. In recent years experiments using both x-ray drive and smoothed laser drive to accelerate foils have confirmed the community's understanding of the ablative RT instability in planar geometry. The growth of small initial modulations on the foils is measured for growth factors up to 60 for direct drive and 80 for indirect drive. For x-ray drive large stabilization is evident. After some growth, the instability enters the nonlinear phase when mode coupling and saturation are also seen and compare well with modeling. Normalized growth rates for direct drive are measured to be higher, but strategies for reduction by raising the isentrope are being investigated. For direct drive, high spatial frequencies are imprinted from the laser beam and amplified by the RT instability. Modeling shows an understanding of this "laser imprinting."

Phys. Plasmas **1**, 1379 (1994)

Ignition and high gain with ultrapowerful lasers*

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(Received 5 November 1993; accepted 12 January 1994)

Ultrahigh intensity lasers can potentially be used in conjunction with conventional fusion lasers to ignite inertial confinement fusion (ICF) capsules with a total energy of a few tens of kilojoules of laser light, and can possibly lead to high gain with as little as 100 kJ. A scheme is proposed with three phases. First, a capsule is imploded as in the conventional approach to inertial fusion to assemble a high-density fuel configuration. Second, a hole is bored through the capsule corona composed of ablated material, as the critical density is pushed close to the high-density core of the capsule by the ponderomotive force associated with high-intensity laser light. Finally, the fuel is ignited by suprathermal electrons, produced in the high-intensity laser–plasma interactions, which then propagate from critical density to this high-density core. This new scheme also drastically reduces the difficulty of the implosion, and thereby allows lower quality fabrication and less stringent beam quality and symmetry requirements from the implosion driver. The difficulty of the fusion scheme is transferred to the technological difficulty of producing the ultrahigh-intensity laser and of transporting this energy to the fuel.

Phys. Plasmas **1**, 1626 (1994)

Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain

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(Received 14 November 1994; accepted 14 June 1995)

Inertial confinement fusion (ICF) is an approach to fusion that relies on the inertia of the fuel mass to provide confinement. To achieve conditions under which inertial confinement is sufficient for efficient thermonuclear burn, a capsule (generally a spherical shell) containing thermonuclear fuel is compressed in an implosion process to conditions of high density and temperature. ICF capsules rely on either electron conduction (direct drive) or x rays (indirect drive) for energy transport to drive an implosion. In direct drive, the laser beams (or charged particle beams) are aimed directly at a target. The laser energy is transferred to electrons by means of inverse bremsstrahlung or a variety of plasma collective processes. In indirect drive, the driver energy (from laser beams or ion beams) is first absorbed in a high-Z enclosure (a hohlraum), which surrounds the capsule. The material heated by the driver emits x rays, which drive the capsule implosion. For optimally designed targets, 70%–80% of the driver energy can be converted to x rays. The optimal hohlraum geometry depends on the driver. Because of relaxed requirements on laser beam uniformity, and reduced sensitivity to hydrodynamic instabilities, the U.S. ICF Program has concentrated most of its effort since 1976 on the x-ray or indirect-drive approach to ICF. As a result of years of experiments and modeling, we are building an increasingly strong case for achieving ignition by indirect drive on the proposed National Ignition Facility (NIF). The ignition target requirements for hohlraum energetics, radiation symmetry, hydrodynamic instabilities and mix, laser plasma interaction, pulse shaping, and ignition requirements are all consistent with experiments. The NIF laser design, at 1.8 MJ and 500 TW, has the margin to cover uncertainties in the baseline ignition targets. In addition, data from the NIF will provide a solid database for ion-beam-driven hohlraums being considered for future energy applications. In this paper we analyze the requirements for indirect drive ICF and review the theoretical and experimental basis for these requirements. Although significant parts of the discussion apply to both direct and indirect drive, the principal focus is on indirect drive.

Phys. Plasmas **2**, 3933 (1995)

A study of picosecond laser–solid interactions up to 10^{19} W cm^{-2}

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(Received 16 August 1996; accepted 2 October 1996)

The interaction of a 1053 nm picosecond laser pulse with a solid target has been studied for focused intensities of up to 10^{19} W cm^{-2}. The maximum ion energy cutoff $E_{\rm max}$ (which is related to the hot electron temperature) is in the range 1.0–12.0 MeV and is shown to scale as $E_{\rm max} \approx I^{1/3}$. The hot electron temperatures were in the range 70–400 keV for intensities up to 5×10^{18} W cm^{-2} with an indication of a high absorption of laser energy. Measurements of x-ray/γ-ray bremsstrahlung emission suggest the existence of at least two electron temperatures. Collimation of the plasma flow has been observed by optical probing techniques. [S1070-664X(97)01701-1]

Phys. Plasmas **4**, 447 (1997)

Z pinches as intense x-ray sources for high-energy density physics applications*

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(Received 14 November 1996; accepted 7 February 1997)

Fast Z-pinch implosions can efficiently convert the stored electrical energy in a pulsed-power accelerator into x rays. These x rays are produced when an imploding cylindrical plasma, driven by the magnetic field pressure associated with very large axial currents, stagnates upon the cylindrical axis of symmetry. On the Saturn pulsed-power accelerator [R. B. Spielman *et al.*, in *Proceedings of the 2nd International Conference on Dense Z Pinches*, Laguna Beach, CA, 1989, edited by N. R. Pereira, J. Davis, and N. Rostoker (American Institute of Physics, New York, 1989), p. 3] at Sandia National Laboratories, for example, currents of 6–8 MA with a rise time of less than 50 ns are driven through cylindrically symmetric loads, producing implosion velocities as high as 10^8 cm/s and x-ray energies exceeding 400 kJ. Hydromagnetic Rayleigh–Taylor instabilities and cylindrical load symmetry are critical, limiting factors in determining the assembled plasma densities and temperatures, and thus in the x-ray energies and pulse widths that can be produced on these accelerators. In recent experiments on the Saturn accelerator, these implosion nonuniformities have been minimized by using wire arrays with as many as 192 wires. Increasing the wire number produced significant improvements in the pinched plasma quality, reproducibility, and x-ray output power. X-ray pulse widths of less than 5 ns and peak powers of 75 ± 10 TW have been achieved with arrays of 120 tungsten wires. Similar loads have recently been fielded on the Particle Beam Fusion Accelerator (PBFA II), producing x-ray energies in excess of 1.8 MJ at powers in excess of 160 TW. These intense x-ray sources offer the potential for performing many new basic physics and fusion-relevant experiments. [S1070-664X(97)95205-8]

Phys. Plasmas **4**, 1519 (1997)

PHYSICS OF PLASMAS VOLUME 5, NUMBER 5 MAY 1998

Direct-drive laser fusion: Status and prospects*

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Techniques have been developed to improve the uniformity of the laser focal profile, to reduce the ablative Rayleigh–Taylor instability, and to suppress the various laser–plasma instabilities. There are now three direct-drive ignition target designs that utilize these techniques. An evaluation of these designs is still ongoing. Some of them may achieve the gains above 100 that are necessary for a fusion reactor. Two laser systems have been proposed that may meet all of the requirements for a fusion reactor. [S1070-664X(98)96205-X]

Phys. Plasmas **5**, 1901 (1998)

PHYSICS OF PLASMAS VOLUME 5, NUMBER 5 MAY 1998

Hot electron production and heating by hot electrons in fast ignitor research*

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(Received 26 November 1997; accepted 23 January 1998)

In an experimental study of the physics of fast ignition, the characteristics of the hot electron source at laser intensities up to 10^{20} W cm^{-2} have been measured and a diagnosis of the heating at depth by hot electrons has been initiated. Generation of hot electrons with more than 30% efficiency has been observed. Preliminary heating data suggest temperatures kT in the range 300–800 eV. [S1070-664X(98)93805-8]

Phys. Plasmas **5**, 1966 (1998)

PHYSICS OF PLASMAS VOLUME 5, NUMBER 5 MAY 1998

Tungsten wire-array Z-pinch experiments at 200 TW and 2 MJ*

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(Received 19 November 1997; accepted 3 February 1998)

Here Z, a 60 TW/5 MJ electrical accelerator located at Sandia National Laboratories, has been used to implode tungsten wire-array Z pinches. These arrays consisted of large numbers of tungsten wires (120–300) with wire diameters of 7.5 to 15 μm placed in a symmetric cylindrical array. The experiments used array diameters ranging from 1.75 to 4 cm and lengths from 1 to 2 cm. A 2 cm long, 4 cm diam tungsten array consisting of 240, 7.5 μm diam wires (4.1 mg mass) achieved an x-ray power of ~200 TW and an x-ray energy of nearly 2 MJ. Spectral data suggest an optically thick, Planckian-like radiator below 1000 eV. One surprising experimental result was the observation that the total radiated x-ray energies and x-ray powers were nearly independent of pinch length. These data are compared with two-dimensional radiation magnetohydrodynamic code calculations. © *1998 American Institute of Physics.* [S1070-664X(98)95005-4]

Phys. Plasmas **5**, 2105 (1998)

PHYSICS OF PLASMAS VOLUME 7, NUMBER 5 MAY 2000

Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets*

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In recent Petawatt laser experiments at Lawrence Livermore National Laboratory, several hundred joules of 1 μm laser light in 0.5–5.0-ps pulses with intensities up to 3×10^{20} W cm^{-2} were incident on solid targets and produced a strongly relativistic interaction. The energy content, spectra, and angular patterns of the photon, electron, and ion radiations have all been diagnosed in a number of ways, including several novel (to laser physics) nuclear activation techniques. About 40%–50% of the laser energy is converted to broadly beamed hot electrons. Their beam centroid direction varies from shot to shot, but the resulting bremsstrahlung beam has a consistent width. Extraordinarily luminous ion beams (primarily protons) almost precisely normal to the rear of various targets are seen—up to 3×10^{13} protons with $kT_{\text{ion}}\sim$several MeV representing $\sim$6% of the laser energy. Ion energies up to at least 55 MeV are observed. The ions appear to originate from the rear target surfaces. The edge of the ion beam is very sharp, and collimation increases with ion energy. At the highest energies, a narrow feature appears in the ion spectra, and the apparent size of the emitting spot is smaller than the full back surface area. Any ion emission from the front of the targets is much less than from the rear and is not sharply beamed. The hot electrons generate a Debye sheath with electrostatic fields of order MV per micron, which apparently accelerate the ions. © *2000 American Institute of Physics.* [S1070-664X(00)93905-3]

Phys. Plasmas **7**, 2076 (2000)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 2 FEBRUARY 2001

Energetic proton generation in ultra-intense laser–solid interactions

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An explanation for the energetic ions observed in the PetaWatt experiments is presented. In solid target experiments with focused intensities exceeding 10^{20} W/cm^2, high-energy electron generation, hard bremsstrahlung, and energetic protons have been observed on the backside of the target. In this report, an attempt is made to explain the physical process present that will explain the presence of these energetic protons, as well as explain the number, energy, and angular spread of the protons observed in experiment. In particular, we hypothesize that hot electrons produced on the front of the target are sent through to the back off the target, where they ionize the hydrogen layer there. These ions are then accelerated by the hot electron cloud, to tens of MeV energies in distances of order tens of μm, whereupon they end up being detected in the radiographic and spectrographic detectors. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1333697]

Phys. Plasmas **8**, 542 (2001)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 8 AUGUST 2001

Effect of discrete wires on the implosion dynamics of wire array Z pinches

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(Received 22 March 2001; accepted 24 April 2001)

A phenomenological model of wire array Z-pinch implosions, based on the analysis of experimental data obtained on the mega-ampere generator for plasma implosion experiments (MAGPIE) generator [I. H. Mitchell *et al.*, Rev. Sci. Instrum. **67**, 1533 (1996)], is described. The data show that during the first ~80% of the implosion the wire cores remain stationary in their initial positions, while the coronal plasma is continuously jetting from the wire cores to the array axis. This phase ends by the formation of gaps in the wire cores, which occurs due to the nonuniformity of the ablation rate along the wires. The final phase of the implosion starting at this time occurs as a rapid snowplow-like implosion of the radially distributed precursor plasma, previously injected in the interior of the array. The density distribution of the precursor plasma, being peaked on the array axis, could be a key factor providing stability of the wire array implosions operating in the regime of discrete wires. The modified "initial" conditions for simulations of wire array Z-pinch implosions with one-dimension (1D) and two-dimensions (2D) in the $r-z$ plane, radiation-magnetohydrodynamic (MHD) codes, and a possible scaling to a larger drive current are discussed. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1385373]

Phys. Plasmas **8**, 3734 (2001)

The physics basis for ignition using indirect-drive targets on the National Ignition Facility

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The 1990 National Academy of Science final report of its review of the Inertial Confinement Fusion Program recommended completion of a series of target physics objectives on the 10-beam Nova laser at the Lawrence Livermore National Laboratory as the highest-priority prerequisite for proceeding with construction of an ignition-scale laser facility, now called the National Ignition Facility (NIF). These objectives were chosen to demonstrate that there was sufficient understanding of the physics of ignition targets that the laser requirements for laboratory ignition could be accurately specified. This research on Nova, as well as additional research on the Omega laser at the University of Rochester, is the subject of this review. The objectives of the U.S. indirect-drive target physics program have been to experimentally demonstrate and predictively model hohlraum characteristics, as well as capsule performance in targets that have been scaled in key physics variables from NIF targets. To address the hohlraum and hydrodynamic constraints on indirect-drive ignition, the target physics program was divided into the Hohlraum and Laser–Plasma Physics (HLP) program and the Hydrodynamically Equivalent Physics (HEP) program. The HLP program addresses laser–plasma coupling, x-ray generation and transport, and the development of energy-efficient hohlraums that provide the appropriate spectral, temporal, and spatial x-ray drive. The HEP experiments address the issues of hydrodynamic instability and mix, as well as the effects of flux asymmetry on capsules that are scaled as closely as possible to ignition capsules (hydrodynamic equivalence). The HEP program also addresses other capsule physics issues associated with ignition, such as energy gain and energy loss to the fuel during implosion in the absence of alpha-particle deposition. The results from the Nova and Omega experiments approach the NIF requirements for most of the important ignition capsule parameters, including drive temperature, drive symmetry, and hydrodynamic instability. This paper starts with a review of the NIF target designs that have formed the motivation for the goals of the target physics program. Following that are theoretical and experimental results from Nova and Omega relevant to the requirements of those targets. Some elements of this work were covered in a 1995 review of indirect-drive [J. D. Lindl, "Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain," Phys. Plasmas **2**, 3933 (1995)]. In order to present as complete a picture as possible of the research that has been carried out on indirect drive, key elements of that earlier review are also covered here, along with a review of work carried out since 1995. [DOI: 10.1063/1.1578638]

Phys. Plasmas **11**, 339 (2004)

Ionospheric, Solar-System, and Astrophysical Plasmas

THE PHYSICS OF FLUIDS VOLUME 1, NUMBER 3 MAY-JUNE, 1958

Interaction of the Solar Wind with the Geomagnetic Field*

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(Received April 25, 1958; revised manuscript received May 16, 1958)

The dynamical properties of the solar wind blowing past the geomagnetic field are investigated by considering the effective viscosity and the resulting transition layer thickness. The collision of ions in the solar wind produces a negligible viscosity in the flow past the geomagnetic field, but such an inviscid flow is shown to be unstable. The resulting disordered interface between the field and the wind yields Fermi acceleration of ions and consequently a not insignificant effective viscosity. The Fermi acceleration results in suprathermal ions which may have an energy spectrum like that observed for primary auroral protons.

The auroral zones and the agitated nature of the polar geomagnetic field are shown to follow from the depth of penetration of the solar wind into the geomagnetic field. The injection of gas into the geomagnetic field is studied. The effect at Earth of the distortion of the outer boundary of the geomagnetic field is computed; no matter how unevenly and anisotropically the outer field is distorted, the effect at Earth is a nearly uniform perturbation field which is closely parallel to the geomagnetic axis. Pushing in on the outer field increases the horizontal component at Earth, and pulling out decreases it; the total increase of the horizontal component is the algebraic sum of all the pushing and pulling. The simultaneous world-wide onset and the main phase of a geomagnetic storm follow.

The common tendency of large and/or violent bodies of plasma to produce suprathermal particles is noted and suggested to be a general dynamical property.

Phys. Fluids **1**, 171 (1958)

THE PHYSICS OF FLUIDS VOLUME 11, NUMBER 3 MARCH 1968

Alfvén Waves in the Solar Wind

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(Received 14 August 1967)

Mariner II plasma and magnetic-field data are examined for explicit examples of low-frequency hydromagnetic waves. From the magnetic-field data, several sinusoidal waveforms are isolated. One of these clearly satisfies the hydromagnetic equations relating the magnetic-field variation to the ion-velocity perturbation for an Alfvén wave. This result is consistent with Barnes' theoretical prediction that only the Alfvén mode is not strongly damped in a plasma of moderate or high β.

Phys. Fluids **11**, 563 (1968)

THE PHYSICS OF FLUIDS VOLUME 12, NUMBER 12 DECEMBER 1969

Drift Mirror Instability in the Magnetosphere

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(Received 27 February 1969; final manuscript received 3 July 1969)

A new theory of the mirror instability is developed which includes the effects of ∇B and ∇n, finite Larmor radius, and a coexisting cold plasma. It is shown that the instability becomes overstable with a frequency equal to the drift wave frequency, which may be determined by the wavenumber that gives the maximum growth rate. The theory is applied to explain the sudden kink in the increase (decrease) of proton flux (magnetic field) and the subsequent oscillations observed during a storm time on 18 April 1965 by detectors on the Explorer 26 satellite.

Phys. Fluids **12**, 2642 (1969)

Radiation from a strongly turbulent plasma: Application to electron beam-excited solar emissions

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The emission of radiation at the plasma frequency and at twice the plasma frequency from beam-excited strong Langmuir turbulence, for the case of low-density high-velocity warm beams, is considered. Under these conditions, Langmuir wave packets undergo (direct) collapse in a time short compared with one e folding of a beam mode. The wave packet energy density threshold for collapse depends only on the beam temperature and velocity, not on the beam density. Upper and lower limits on the volume emissivity for harmonic emission from these collapsing wave packets are found. Within most of this range, the emissivity is large enough to account for observations of second harmonic radiation during type III solar radio wave bursts. The radiation at the fundamental is many orders of magnitude larger than predicted by weak turbulence theory.

Phys. Fluids **23**, 388 (1980)

An electron cyclotron maser instability for astrophysical plasmas

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The electron cyclotron maser instability is analyzed for a plasma which consists of a suprathermal electron component characterized by velocity-space anisotropies in directions both parallel and perpendicular to the ambient magnetic field, as well as a high-density thermal plasma in which $\omega_e \sim \Omega_e$ (where ω_e and Ω_e are the electron plasma and cyclotron frequencies). The complete relativistic resonance condition is used and shown to result in a "resonance ellipse" in momentum space. The instability is considered for both cold and warm suprathermal electron distributions, and for frequencies $\omega \sim \Omega_e$ in the ordinary mode and $\omega \sim 2\Omega_e$ in the fast extraordinary mode. It is shown that the growth rates are comparable for these harmonics over a wide range of parameters which, since they are escape modes of the plasma, can lead to comparable radiation intensities.

Phys. Fluids **26**, 2263 (1983)

Magnetohydrodynamic processes in the solar corona: Flares, coronal mass ejections, and magnetic helicity*

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(Received 4 November 1993; accepted 22 December 1993)

The magnetized, million-degree solar corona evolves in cycles of about 11 years, in dynamical response to newly generated magnetic fluxes emerging from below to eventually reverse the global magnetic polarity. Over the larger scales, the corona does not erupt violently all the time. Violent events like the flares and episodic ejections of material into interplanetary space occur frequently, several times a day, but they often originate in long-lived magnetic structures that form continually throughout the solar cycle. In this paper, the creation, stability, and eventual eruption of these structures are discussed from basic principles, drawing on recent advances in observation and theory. A global view is offered in which different pieces of observation relate physically, with distinct roles for the conservation of magnetic helicity and the release of magnetic energy in dissipated and ordered forms.

Phys. Plasmas **1**, 1684 (1994)

Phenomenology for the decay of energy-containing eddies in homogeneous MHD turbulence

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(Received 28 April 1995; accepted 25 July 1995)

We evaluate a number of simple, one-point phenomenological models for the decay of energy-containing eddies in magnetohydrodynamic (MHD) and hydrodynamic turbulence. The MHD models include effects of cross helicity and Alfvénic couplings associated with a constant mean magnetic field, based on physical effects well-described in the literature. The analytic structure of three separate MHD models is discussed. The single hydrodynamic model and several MHD models are compared against results from spectral-method simulations. The hydrodynamic model phenomenology has been previously verified against experiments in wind tunnels, and certain experimentally determined parameters in the model are satisfactorily reproduced by the present simulation. This agreement supports the suitability of our numerical calculations for examining MHD turbulence, where practical difficulties make it more difficult to study physical examples. When the triple-decorrelation time and effects of spectral anisotropy are properly taken into account, particular MHD models give decay rates that remain correct to within a factor of 2 for several energy-halving times. A simple model of this type is likely to be useful in a number of applications in space physics, astrophysics, and laboratory plasma physics where the approximate effects of turbulence need to be included.

Phys. Plasmas **7**, 2886 (1995)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

A new view of the solar corona from the transition region and coronal explorer (TRACE)*

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The TRACE Observatory is the first solar-observing satellite in the National Aeronautics and Space Administration's (NASA) Small Explorer series. Launched April 2, 1998, it is providing views of the solar transition region and low corona with unprecedented spatial and temporal resolution. The corona is now seen to be highly filamented, and filled with flows and other dynamic processes. Structure is seen down to the resolution limit of the instrument, while variability and motions are observed at all spatial locations in the solar atmosphere, and on very short time scales. Flares and shock waves are observed, and the formation of long-lived coronal structures, with consequent implications for coronal heating models, has been seen. This overview describes the instrument and presents some preliminary results from the first six months of operation. [S1070-664X(99)91805-0]

Phys. Plasmas **6**, 2205 (1999)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

Magnetohydrodynamic modeling of the global solar corona*

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(Received 19 November 1998; accepted 21 January 1999)

A three-dimensional magnetohydrodynamic model of the global solar corona is described. The model uses observed photospheric magnetic fields as a boundary condition. A version of the model with a polytropic energy equation is used to interpret solar observations, including eclipse images of the corona, Ulysses spacecraft measurements of the interplanetary magnetic field, and coronal hole boundaries from Kitt Peak He 10 830 Å maps and extreme ultraviolet images from the Solar Heliospheric Observatory. Observed magnetic fields are used as a boundary condition to model the evolution of the solar corona during the period February 1997–March 1998. A model with an improved energy equation and Alfvén waves that is better able to model the solar wind is also presented. [S1070-664X(99)94805-X]

Phys. Plasmas **6**, 2217 (1999)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 11 NOVEMBER 1999

Magnetohydrodynamic turbulence in the solar wind

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(Received 4 June 1999; accepted 2 July 1999)

Low frequency fluctuations in the solar wind magnetic field and plasma velocity are often highly correlated, so much so that the fluctuations may be thought of as originating near the Sun as nearly perfect Alfvén waves. Power spectra of these fluctuations from 10^{-7} Hz to several Hz to suggest that the medium is turbulent. Near 1 AU, fluctuations below 10^{-5} Hz have a relatively flat slope (~ -1) and contain most of the energy in the fluctuating fields. From 10^{-5} Hz to ~ 0.1 Hz, the spectra exhibit a power law inertial range similar to that seen in ordinary fluid turbulence. At the highest frequencies, the rapid fall-off of the power suggests that strong dissipation is occurring. From *in situ* measurements, it is clear that the fluctuations emanate from the solar corona. The turbulent cascade appears to evolve most rapidly in the vicinity of velocity shears and current sheets. Numerical solutions of both the compressible and incompressible equations of magnetohydrodynamics in both Cartesian and spherical geometry corroborate this interpretation. There are conflicting interpretations of observations suggesting that much of the power in magnetic field fluctuations resides in quasi-two-dimensional structures and simulations have helped to elucidate some of these issues. [S1070-664X(99)02811-6]

Phys. Plasmas **6**, 4154 (1999)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 11 NOVEMBER 1999

Evidence for intermittency in Earth's plasma sheet and implications for self-organized criticality

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(Received 10 June 1999; accepted 1 July 1999)

It has been proposed recently that a description of the magnetosphere as a system in a state of self-organized criticality would be fruitful for understanding (and predicting) the global response to solar wind input. In this paper it is shown that the proposed description fits the characteristics of magnetotail plasma flows and their variability. According to observations, the magnetotail is in a bi-modal state: nearly stagnant, except when driven turbulent by transport-efficient fast flows. The distributions of flows are in agreement with sporadic (intermittent) variability in the magnetotail. The variability may resemble hydrodynamic turbulence around a jet. The presence of turbulence alters the conductivity and the mass/momentum diffusion properties across the plasma sheet and may permit cross-scale coupling of localized jets into a global perturbation. Bursty-flow-driven turbulence is a physical process that may have an important role to play in the establishment of a state of self-organized criticality.
[S1070-664X(99)02911-0]

Phys. Plasmas **6**, 4161 (1999)

Lasers, Particle Beams, Accelerators, Radiation Generation

THE PHYSICS OF FLUIDS VOLUME 12, NUMBER 1 JANUARY 1969

Nonlinear Confining and Deconfining Forces Associated with the Interaction of Laser Radiation with Plasma

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(Received 31 May 1968)

The nonlinear interaction of an intense light wave with an inhomogeneous plasma produces a macroscopic motion. A rigorous treatment of this interaction based on the ponderomotive force description leads to a general equation of motion. In a plasma with collisions and high electron density, the resulting force density can be interpreted as an expression of the radiation pressure. Below special densities there results a nonlinear collisionless force whose direction is toward decreasing density, and which produces a deconfinement. The magnitude of this force has a polarization dependence only in the third-order terms of the spatial dependence of the density. The total deconfining recoil momentum transferred to the inhomogeneous transition layer is evaluated. The theory of the nonlinear collisionless acceleration is used to explain the experimentally observed properties of the fast part of plasmas produced by lasers from isolated single small aluminum balls and thick solid targets.

Phys. Fluids **12**, 182 (1969)

THE PHYSICS OF FLUIDS VOLUME 13, NUMBER 7 JULY 1970

Propagation of High Current Relativistic Electron Beams*

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(Received 25 August 1969; final manuscript received 4 February 1970)

Theoretical self-consistent relativistic electron beam models are developed which allow the propagation of relativistic electron fluxes in excess of the Alfvén–Lawson critical-current limit for a fully neutralized beam. Development of a simple, fully relativistic, self-consistent equilibrium is described which can carry arbitrarily large currents at or near complete electrostatic neutralization. A discussion of a model for magnetic neutralization is presented wherein it is shown that large numbers of electrons from a background plasma are counterstreaming slowly within the beam so that the net current density in the system, and therefore, the magnetic field, is nearly zero. A solution of an initial-value problem for a beam–plasma system is given which indicates that magnetic neutralization can be expected to occur for plasma densities that are large compared with beam densities. It is found that the application of a strong axial magnetic field to a uniform beam allows propagation regardless of the magnitude of the beam current. Some comparisons are made with recent experimental data.

Phys. Fluids **13**, 1831 (1970)

Raman and Brillouin scattering of electromagnetic waves in inhomogeneous plasmas

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(Received 25 June 1973; final manuscript received 15 February 1974)

Raman and Brillouin scattering of an electromagnetic wave in an inhomogeneous, expanding plasma are studied. Application to laser-pellet irradiation is considered.

Phys. Fluids **17**, 1211 (1974)

Theory of stimulated scattering processes in laser-irradiated plasmas

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(Received 26 November 1973; final manuscript received 24 March 1975)

Analytic theory of the linear and nonlinear behavior of the one-dimensional Brillouin and Raman scattering instabilities is given. Results are presented for the problems of an infinite homogeneous plasma and of a finite inhomogeneous plasma. Nonlinear fluid equations can predict backscatter energies the order of the incident laser energy; however, the size of the interaction region and nonlinear effects on the excited electrostatic wave are very important in determining the amount of backscatter. In many cases of contemporary interest for a high power laser incident on a target plasma, the latter effects can play a crucial role in reducing backscatter to a tolerable level.

Phys. Fluids **18**, 1002 (1975)

Two-dimensional relativistic simulations of resonance absorption

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(Received 12 June 1974; final manuscript received 23 April 1975)

Resonant absorption has been simulated for radiation of energy density $E_0^2/4\pi nT$ ranging from much less than to somewhat greater than unity. Characteristic features of the absorption process are an absorption efficiency of approximately 50%, generation of suprathermal particles, and strong modification of the density profile in the vicinity of the critical density. The latter effect, the appearance of a finite density variation over the distance of a few Debye lengths, is forced by strong gradients in the plasma wave intensity and electron temperature. Such a density discontinuity enhances the range of incidence angles for which resonance absorption is effective and decreases the effects of the oscillating two-stream and ion-acoustic decay instabilities.

Phys. Fluids **18**, 1151 (1975)

Theoretical model of absorption of laser light by a plasma

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(Received 11 June 1981; accepted 24 February 1982)

A simple model of laser light absorption is described. The absorption mechanism is mainly inverse bremsstrahlung, but a crude description of resonance absorption is also included. The intensity and the wavelength dependence are emphasized, but the model takes into account the target material composition, the laser pulse length, and the focal spot radius. Plane and spherical expansion are treated. Results range from short-wavelength, low-intensity regime, where inverse bremsstrahlung absorption is total, to long-wavelength high-intensity regime, where inverse bremsstrahlung absorption is negligible. Scaling laws concerning absorption, electron temperature, and electron kinetic pressure are given in the two limiting regimes. A characteristic flux Φ^*, or, alternatively, a characteristic wavelength λ^* is defined which separates the two regimes, the other parameters being held constant.

Phys. Fluids **25**, 1051 (1982)

Fast ions and hot electrons in the laser–plasma interaction

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(Received 17 January 1986; accepted 25 April 1986)

Data on the emission of energetic ions produced in laser–matter interactions have been analyzed for a wide variety of laser wavelengths, energies, and pulse lengths. Strong correlation has been found between the bulk energy per AMU for fast ions measured by charge cups and the x-ray-determined hot electron temperature. Five theoretical models have been used to explain this correlation. The models include (1) a steady-state spherically symmetric fluid model with classical electron heat conduction, (2) a steady-state spherically symmetric fluid model with flux limited electron heat conduction, (3) a simple analytic model of an isothermal rarefaction followed by a free expansion, (4) the LASNEX hydrodynamics code [Comments Plasma Phys. Controlled Fusion **2**, 85 (1975)], calculations employing a spherical expansion and simple initial conditions, and (5) the LASNEX code with its full array of absorption, transport, and emission physics. The results obtained with these models are in good agreement with the experiments and indicate that the detailed shape of the correlation curve between mean fast ion energy and hot electron temperature is due to target surface impurities at the higher temperatures (higher laser intensities) and to the expansion of bulk target material at the lower temperatures (lower laser intensities).

Phys. Fluids **29**, 2679 (1986)

A review of free-electron lasers

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(Received 21 November 1984; accepted 14 October 1988)

Free-electron laser (FEL) theory and experiments are reviewed. The physical mechanism responsible for the generation of coherent radiation in the FEL is described and the fundamental role of the ponderomotive wave in bunching and trapping the beam is emphasized. The relationship of the FEL interaction to the beam–plasma interaction is pointed out. Various FEL operating regimes are discussed; these include the high-gain Compton and Raman regimes, both with and without an axial guiding magnetic field. The linear and nonlinear regimes are examined in detail, with particular emphasis on techniques for achieving efficiency enhancement. The quality of the electron beam used to drive FEL's is a critical factor in determining the gain and efficiency. The subject of electron beam quality, for different accelerators, is discussed. Key proof-of-principle experiments for FEL's in an axial guiding magnetic field as well as those driven by induction linacs, rf linacs, electrostatic accelerators, and storage rings, are reviewed. Finally, the requirements on wigglers and resonators are discussed.

Phys. Fluids B **1**, 3 (1989)

Nonlinear depletion of ultrashort and relativistically strong laser pulses in an underdense plasma

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(Received 5 August 1991; accepted 8 January 1992)

The depletion of a relativistically strong laser pulse in the course of interaction with underdense plasmas is considered. The driving mechanisms of distortion and fast depletion of the pulse due to the nonlinear plasma wake excitation are discussed. The role of the backward stimulated Raman scattering in the process of the leading front steepening is traced. Electron acceleration and heating due to plasma wave breaking are demonstrated. The evidence that the final stage of the pulse depletion can be accompanied by the formation of relativistically strong solitonlike electromagnetic modes is presented.

Phys. Fluids B **4**, 1935 (1992)

Interaction of ultrahigh laser fields with beams and plasmas*

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(Received 18 December 1991; accepted 5 February 1992)

The nonlinear interaction of ultraintense laser pulses with electron beams and plasmas is rich in a wide variety of new phenomena. Advances in laser science have made possible compact terawatt lasers capable of generating subpicosecond pulses at ultrahigh powers ($\geqslant 1$ TW) and intensities ($\geqslant 10^{18}$ W/cm^2). These ultrahigh intensities result in highly relativistic nonlinear electron dynamics. This paper briefly addresses a number of phenomena including (i) laser excitation of large-amplitude plasma waves (wake fields), (ii) relativistic optical guiding of laser pulses in plasmas, (iii) optical guiding by preformed plasma channels, (iv) laser frequency amplification by ionization fronts and plasma waves, (v) relativistic harmonic generation, (vi) stimulated backscattering from plasmas and electron beams, (vii) nonlinear Thomson scattering from plasmas and electron beams, and (viii) cooling of electron beams by intense lasers. Potential applications of these effects are also discussed.

Phys. Fluids B **4**, 2241 (1992)

Development and applications of compact high-intensity lasers*

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(Received 18 December 1991; accepted 12 March 1992)

The development of compact high-intensity lasers, made possible by the technique of chirped pulse amplification, is reviewed. This includes the complexities of high-power laser implementation, such as the generation of short pulses, pulse cleaning, wide-bandwidth amplification, temporal stretching and compression, and the requirements for high-average powers. Details of specific solid-state laser systems are given. Some applications of these lasers to short-pulse coherent short-wavelength [x-ray ultraviolet (XUV)] sources are also reviewed. This includes several nonlinear effects observed by focusing a subpicosecond laser into a gas; namely, an anomalous scaling of harmonic generation in atomic media, an upper limit on the conversion efficiency of relativistic harmonics in a plasma, and the observation of short-pulse self-focusing and multifoci formation. Finally, the effects of large ponderomotive pressures (100 Mbars) in short-pulse high-intensity laser–plasma interactions are discussed, with relevance both to recombination x-ray lasers and a novel method of igniting thermonuclear fusion.

Phys. Fluids B **4**, 2315 (1992)

Short wavelength x-ray laser research at the Lawrence Livermore National Laboratory*

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Laboratory x-ray lasers are currently being studied by researchers worldwide. This paper reviews some of the recent work carried out at Lawrence Livermore National Laboratory. Laser action has been demonstrated at wavelengths as short as 35.6 Å while saturation of the small signal gain has been observed with longer wavelength schemes. Some of the most successful schemes to date have been collisionally pumped x-ray lasers that use the thermal electron distribution within a laser-produced plasma to excite electrons from closed shells in neon- and nickel-like ions to metastable levels in the next shell. Attempts to quantify and improve the longitudinal and transverse coherence of collisionally pumped x-ray lasers are motivated by the desire to produce sources for specific applications. Toward this goal there is a large effort underway to enhance the power output of the Ni-like Ta x-ray laser at 44.83 Å as a source for x-ray imaging of live cells. Improving the efficiency of x-ray lasers in order to produce saturated output with smaller pump lasers is also a goal of this work.

Phys. Fluids B **4**, 2326 (1992)

Self-focusing and Raman scattering of laser pulses in tenuous plasmas

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(Received 27 May 1992; accepted 22 January 1993)

The propagation and self-focusing of short, intense laser pulses in a tenuous plasma is studied both analytically and numerically. Specifically, pulses of length of the order of a few plasma wavelengths and of intensity, which is large enough for relativistic self-focusing to occur, are considered. Such pulses are of interest in various laser plasma acceleration schemes. It is found that these pulses are likely to be strongly affected by Raman instabilities. Two different regimes of instability, corresponding to large and small scattering angles, are found to be important. Small-angle scattering is perhaps the most severe since it couples strongly with relativistic self-focusing, leading the pulses to acquire significant axial and transverse structure in a time of the order of the self-focusing time. Thus it will be difficult to propagate smooth self-focused pulses through tenuous plasmas for distances longer than the Rayleigh length, except for pulse duration of the order of the plasma period.

Phys. Fluids B **5**, 1440 (1993)

Ultrafast x-ray sources*

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(Received 18 November 1992; accepted 20 January 1993)

Time-resolved spectroscopy (with a 2 psec temporal resolution) of plasmas produced by the interaction between solid targets and a high contrast subpicosecond table top terawatt (T^3) laser at 10^{16} W/cm^2, is used to study the basic processes which control the x-ray pulse duration. Short x-ray pulses have been obtained by spectral selection or by plasma gradient scalelength control. Time-dependent calculations of the atomic physics [Phys. Fluids B 4, 2007, 1992] coupled to a Fokker–Planck code [Phys. Rev. Lett. 53, 1461, 1984] indicate that it is essential to take into account the non-Maxwellian character of the electron distribution for a quantitative analysis of the experimental results.

Phys. Fluids B **5**, 2676 (1993)

Short-pulse laser harmonics from oscillating plasma surfaces driven at relativistic intensity

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(Received 6 March 1996; accepted 14 June 1996)

The generation of harmonics by interaction of an ultrashort laser pulse with a step boundary of a plane overdense plasma layer is studied at intensities $I\lambda^2 = 10^{17} - 10^{19}$ W cm^{-2} μm^2 for normal and oblique incidence and different polarizations. Fully relativistic one-dimensional particle-in-cell (PIC) simulations are performed with high spectral resolution. Harmonic emission increases with intensity and also when lowering the plasma density. The simulations reveal strong oscillations of the critical surface driven by the normal component of the laser field and by the ponderomotive force. It is shown that the generation of harmonics can be understood as reflection from the oscillating surface, taking full account of retardation. Describing the oscillations by one or more Fourier components with adjustable amplitudes, model spectra are obtained that well reproduce the PIC spectra. The model is based on relativistic cold plasma equations for oblique incidence. General selection rules concerning polarization of odd and even harmonics depending on incident polarization are derived. [S1070-664X(96)04009-8]

Phys. Plasmas **3**, 3425 (1996)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 5 MAY 1999

Filamentation of ultrashort pulse laser beams resulting from their propagation over long distances in air

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(Received 10 September 1998; accepted 19 January 1999)

The propagation of high-power short-pulse laser beams over considerable distances in air is studied both experimentally and via numerical simulations. Filaments are formed after 5–10 m and their propagation over distances in excess of 200 m is reported for the first time. The lateral dimensions of the filaments are found to range from about 100 μm to a few millimeters in diameter. The early values of plasma electron density have been inferred to be a few times $10^{16}\ cm^{-3}$ using longitudinal spectral interferometry. For 500 fs pulses and a wavelength of 1053 nm, the energy in the filament can be quite high initially ($\sim$8 mJ) and is found to stabilize at about 1.5–2 mJ, after about 35 m. A simple model based on the nonlinear Schrödinger equation coupled to a multiphoton ionization law appears to describe several experimental results quite well. © *1999 American Institute of Physics.* [S1070-664X(99)00705-3]

Phys. Plasmas **6**, 1615 (1999)

PHYSICS OF PLASMAS VOLUME 6, NUMBER 7 JULY 1999

Particle acceleration in relativistic laser channels

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(Received 4 January 1999; accepted 1 April 1999)

Energy spectra of ions and fast electrons accelerated by a channeling laser pulse in near-critical plasma are studied using three-dimensional (3D) Particle-In-Cell simulations. The realistic 3D geometry of the simulations allows us to obtain not only the shape of the spectra, but also the absolute numbers of accelerated particles. It is shown that ions are accelerated by a collisionless radial expansion of the channel and have nonthermal energy spectra. The electron energy spectra instead are Boltzmann-like. The effective temperature $T_{\rm eff}$ scales as $I^{1/2}$. The form of electron spectra and $T_{\rm eff}$ depends also on the length of the plasma channel. The major mechanism of electron acceleration in relativistic channels is identified. Electrons make transverse betatron oscillations in the self-generated static electric and magnetic fields. When the betatron frequency coincides with the laser frequency as witnessed by the relativistic electron, a resonance occurs, leading to an effective energy exchange between the laser and electron. This is the inverse free-electron laser mechanism. Electrons are accelerated at the betatron resonance when the laser power overcomes significantly the critical power for self-focusing. © *1999 American Institute of Physics.* [S1070-664X(99)02207-7]

Phys. Plasmas **6**, 2847 (1999)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 5 MAY 2001

Review of physics and applications of relativistic plasmas driven by ultra-intense lasers*

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(Received 26 October 2000; accepted 20 February 2001)

As tabletop lasers continue to reach record levels of peak power, the interaction of light with matter has crossed a new threshold, in which plasma electrons at the laser focus oscillate at relativistic velocities. The highest forces ever exerted by light have been used to accelerate beams of electrons and protons to energies of a million volts in distances of only microns. Not only is this acceleration gradient up to a thousand times greater than in radio-frequency-based sources, but the transverse emittance of the particle beams is comparable or lower. Additionally, laser-based accelerators have been demonstrated to work at a repetition rate of 10 Hz, an improvement of a factor of 1000 over their best performance of just a couple of years ago. Anticipated improvements in energy spread may allow these novel compact laser-based radiation sources to be useful someday for cancer radiotherapy and as injectors into conventional accelerators, which are critical tools for x-ray and nuclear physics research. They might also be used as a spark to ignite controlled thermonuclear fusion. The ultrashort pulse duration of these particle bursts and the x rays they can produce, hold great promise as well to resolve chemical, biological or physical reactions on ultrafast (femtosecond) time scales and on the spatial scale of atoms. Even laser-accelerated protons are soon expected to become relativistic. The dense electron–positron plasmas and vast array of nuclear reactions predicted to occur in this case might even help bring astrophysical phenomena down to Earth, into university laboratories. This paper reviews the many recent advances in this emerging discipline, called high-field science.
[DOI: 10.1063/1.1364515]

Phys. Plasmas **8**, 1774 (2001)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 5 MAY 2001

The Prague Asterix Laser System*

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(Received 19 October 2000; accepted 30 November 2000)

The Prague Asterix Laser System (PALS) is a new international laboratory where research teams are invited to compete for the beam time. The PALS Center runs an iodine photodissociation high-power laser system delivering up to 1.2 kJ of energy in ~400 ps pulses at the wavelength of 1.315 μm. Optional doubling and tripling of the frequency is assured by large-diameter nonlinear crystals. The ASTERIX IV laser [H. Baumhacker *et al.*, Appl. Phys. B **61**, 325 (1995)], transferred from Garching into a new laser hall in Prague, was updated and put into operation on 8 June 2000. These upgrades include new beam delivery options and a twin interaction chamber, which is designed flexibly for a broad spectrum of applications. Results of the first series of experiments are presented and some planned upgrades are briefly described. These include implementation of adaptive optics, replacement of the iodine master oscillator by a more flexible solid state oscillator based on fiber optics, and a femtosecond extension of the laser output to reach the petawatt pulse power region. [DOI: 10.1063/1.1350569]

Phys. Plasmas **8**, 2495 (2001)

Radiation: Emission, Absorption, Transport

THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 5 MAY, 1962

High-Frequency Conductivity and the Emission and Absorption Coefficients of a Fully Ionized Plasma

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(Received January 22, 1962)

The problem of the ac conductivity of a fully ionized plasma is investigated for frequencies embracing the plasma frequency. The finite duration of encounters is taken into account in a self-consistent fashion which includes collective effects. The concomitant processes of absorption and emission of electromagnetic radiation are investigated and in particular the bremsstrahlung emission and absorption coefficients near the plasma frequency are given. The conversion of longitudinal to transverse waves by scattering from ions is discussed.

Phys. Fluids **5**, 517 (1962)

THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 7 JULY 1962

Scattering of Electromagnetic Waves by a Nonequilibrium Plasma*

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(Received March 12, 1961)

Incoherent scattering is determined by the spectral density of electron-density fluctuations. This quantity has previously been calculated for a plasma in thermal equilibrium. We have extended the theory to include spatially homogeneous nonequilibrium states of a hot plasma. An elementary derivation of the previous results and the new results is given in terms of dressed test particles. Numerical calculations have been carried out for a plasma with hot electrons and cold ions, and for a plasma in which the electrons have a net drift relative to the ions.

Phys. Fluids **5**, 776 (1962)

THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 9 SEPTEMBER 1962

Electromagnetic Radiation from an Electric Dipole in a Cold Anisotropic Plasma

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(Received May 14, 1962)

The general solution to the problem of monochromatic radiation from an electric dipole in a magnetically biased, cold, tenuous plasma is presented. It is found that, generally, several waves exist in the radiation zone, traveling in different directions with different indices of refraction. For certain ranges of the plasma, gyro, and operating frequencies, the field becomes very large in certain directions compared with that in other directions, producing highly directive radiation characteristics. In general, the expression for the field is quite complicated although several special cases are treated which yield simple solutions. For high operating frequency it is found that the radiation pattern is identical to the isotropic case although a Faraday rotation takes place. Solutions are given for low and very low frequencies which place in evidence the guiding nature of the magnetostatic field. For the case of a large magnetostatic field it is shown that only two waves exist and that the time-average power flow is purely radial.

Phys. Fluids **5**, 1095 (1962)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 1 JANUARY 1963

Lowering of the Ionization Energy for a Plasma in Thermodynamic Equilibrium

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(Received 6 July 1962)

In a plasma the ionization energy is decreased due to the presence of the microfield. In the past several attempts have been made to calculate this effect. These calculations, which use statistical and thermodynamical procedures, give different results. They produce either a "polarization term" or a "lattice term" or both of them. Moreover there are quantitative discrepancies. The lowering of the ionization energy is here derived by a statistical method, which is physically conceivable. The results cover a wide density range below and above the so-called critical density. The new results are compared with the results of all earlier calculations and reveal the cause of their discrepancies.

Phys. Fluids **6**, 62 (1963)

Diffusion Approximation for a Photon Gas Interacting with a Plasma via the Compton Effect

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(Received 6 July 1965; final manuscript received 31 August 1965)

RECENTLY, Dreicer[1] discussed the relevant kinetic equations for a photon gas interacting with a plasma by means of spontaneous and induced emission, absorption, Compton scattering, and cyclotron radiation.

The purposes of this note are (a) to give a simple, explicit expression for the following problem: the time development of the energy spectrum of a low-energy homogeneous, isotropic photon gas interacting solely through the Compton effect with a low-density, low-temperature electron gas with a Maxwellian distribution, and (b) to point out that under these idealized conditions the equilibrium distribution of the photons will not, in general, be the Planck function because the photon number is conserved.

Phys. Fluids **8**, 2112 (1965)

THE PHYSICS OF FLUIDS VOLUME 10, NUMBER 6 JUNE 1967

Measurement of Emission and Absorption of Radiation by an Argon Plasma

D. L. EVANS* AND R. S. TANKIN
Gas Dynamics Laboratory, Northwestern University, Evanston, Illinois
(Received 12 September 1966; final manuscript received 20 February 1967)

Volumetric radiative loss measurements, correlated with temperature in the range of 10 000 to 26 000°K, have been made on an argon plasma. Pressures of 0.5, 1.0, and 2.0 atm have been used. The 1.0-atm measurements have been corrected for both absorption and ultraviolet emission and the results agree with those of Emmons in the common temperature range. The 6965 Ar I line has also been studied yielding lineshifts, halfwidths, absorption and emission coefficients. The line shift and halfwidth results are below theoretical predictions. Transition probabilities determined from both emission and absorption studies are found to be in reasonable agreement.

Phys. Fluids **10**, 1137 (1967)

Low-Temperature Plasmas, Plasma Applications, Plasma Sources, Sheaths

THE PHYSICS OF FLUIDS VOLUME 2, NUMBER 2 MARCH-APRIL, 1959

Theory of Electrostatic Probes in a Low-Density Plasma

IRA B. BERNSTEIN AND IRVING N. RABINOWITZ
Project Matterhorn, Princeton University, Princeton, New Jersey
(Received November 12, 1958)

The theory of sperical and cylindrical probes immersed in plasmas of such low density that collisions can be neglected is formulated. The appropriate Boltzmann equation is solved, yielding the particle density and flux as functionals of the electrostatic potential, the situation in the body of the plasma, and the properties of the probe. This information when inserted in Poisson's equation serves to determine the potential, and hence the probe characteristic. No *a priori* separation into sheath and plasma regions is required. Though amenable to a determination of the full probe characteristic, the method is applied in detail and numerical results are presented only for the collection of monoenergetic ions, for the case of negligible electron current. These results indicate that the potential is not so insensitive to ion energy as has been believed, and that if the probe radius is sufficiently small, there enters the possibility of a class of ions which are trapped near the probe in troughs of the effective radial potential energy. The population of these trapped ions is determined by collisions, however infrequent. It is difficult to calculate, and conceivably can have a marked effect on the local potential.

Phys. Fluids **2**, 112 (1959)

THE PHYSICS OF FLUIDS VOLUME 2, NUMBER 6 NOVEMBER-DECEMBER, 1959

Thermal and Electrical Properties of an Argon Plasma

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(Received May 1, 1959; revised manuscript received September 8, 1959)

Temperatures ranging from 10 000 to 25 000°K have been measured spectroscopically in thermal plasmas of atmospheric pressure argon arcs at currents in the range of 200 to 800 amp. Electrical properties of the plasmas have been derived from measured radial temperature distributions using Spitzer's theory for the temperature dependence of electrical conductivity of a completely ionized gas. Existence of local thermal equilibrium has been demonstrated by the agreement between excitation temperatures determined from both atomic and ionic spectral line intensities. Agreement between values of electrical quantities obtained by direct measurement and those derived from measured temperatures based on the assumption of thermal equilibrium demonstrates the internal consistency of the experimental and analytical methods.

Phys. Fluids **2**, 614 (1959)

Performance of a Hydromagnetic Plasma Gun

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(Received September 21, 1959)

THE gun discussed here accelerates several liters of hydrogen plasma, containing altogether about 5×10^{19} protons, to a velocity of approximately 1.5×10^{7} cm/sec, and deposits more than 40% of the electrical input energy at its terminals into kinetic energy of the jet. The familiar coaxial tube geometry[1-5] is used, but with the difference that, (1) the tubes or electrodes are longer (30 to 100 cm) than usual, (2) no auxiliary magnetic field is employed, and, (3) the gas to be accelerated is admitted as a puff into the previously evacuated space between the tubes.

Phys. Fluids **3**, 134 (1960)

THE PHYSICS OF FLUIDS VOLUME 3, NUMBER 4 JULY-AUGUST, 1960

Diffusion Processes in a Plasma Column in a Longitudinal Magnetic Field

F. C. HOH AND B. LEHNERT
Royal Institute of Technology, Stockholm, Sweden
(Received March 18, 1960)

Earlier results, by Lehnert, on the diffusion processes in the positive column in a longitudinal magnetic field have been confirmed in a new series of measurements over a wide range of data. Experiments with helium, argon, krypton, nitrogen, and hydrogen are described. In the case of helium good agreement is obtained between the collision diffusion theory and the experiment up to a certain critical magnetic field. For stronger fields the potential drop along the column indicates a much higher diffusion rate across the magnetic field than that expected from the binary collision theory. Account is taken, in the theory, of the presence of molecular ions and of charge exchange collisions. Abnormal voltage characteristics indicating an increased diffusion rate above a certain magnetic field strength have also been investigated in argon, krypton, nitrogen, and hydrogen. The transition from the normal to the abnormal branch of the characteristics seems to depend neither on the length of the discharge tube nor on the length of the magnetic field, provided that these lengths exceed some fifty tube diameters. On the other hand, the transition depends upon the gas density, the nature of the gas, the tube radius, and, also slightly, upon the discharge current. The transition is also indicated by an increasing noise level above the transition point. Finally, the product of the magnetic field strength and the tube radius seems to be constant at this point.

Phys. Fluids **3**, 600 (1960)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 9 SEPTEMBER 1963

Plasma Sheath Formation by Radio-Frequency Fields

H. S. Butler and G. S. Kino
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(Received 19 June 1962; revised manuscript received 3 April 1963)

It has been observed experimentally that the application of a radio-frequency voltage (10 kc/sec–50 Mc/sec) to any one of several electrode configurations around the outside of a plasma discharge tube results in a constriction of the luminous portion of the plasma away from the inner walls of the glass tube. This investigation has established that the phenomenon is basically a radio-frequency rectification effect, leading to the formation of thick ion sheath. The interaction is described mathematically in terms of a differential equation which has an approximate solution that fits qualitatively all the observed characteristics of the phenomenon. The differential equation, in its most general form, has also been solved numerically and the solution is shown to quantitatively fit our experimental observations for both radio-frequency sine and square wave signals. An application of this phenomenon as a possible external diagnostic probe technique is proposed.

Phys. Fluids **6**, 1346 (1963)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 10 OCTOBER 1963

Continuum Theory of Spherical Electrostatic Probes

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AND
S. H. Lam
Gas Dynamics Laboratory, Princeton University, Princeton, New Jersey
(Received 2 January 1963)

A continuum theory for spherical electrostatic probes in a slightly ionized plasma is developed. The density of the plasma is taken to be sufficiently high such that both ions and electrons suffer numerous collisions with the neutrals before being collected by an absorbing probe. A general discussion of probes at an arbitrary potential is given. It is found that for very negative probe potentials the sheath thickness can be comparable to the probe radius. Two explicit forms of current–voltage characteristics are given; one for very negative probes, the other for probes at nearly plasma potential. Both of these are based on the assumption that the probe radius is large compared with the Debye length. Numerical computation is also given for negative probes of a wider range of probe sizes.

Phys. Fluids **6**, 1479 (1963)

THE PHYSICS OF FLUIDS VOLUME 6, NUMBER 12 DECEMBER 1963

Exact Solution of the Collisionless Plasma-Sheath Equation

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(Received 4 March 1963; revised manuscript received 22 July 1963)

The plasma-sheath problem for the low-pressure discharge in plane geometry is treated exactly, that is, with no arbitrary division into plasma and sheath regions. Numerical solutions are presented for various values of the parameter α, which is of the order of the ratio of the Debye length to the discharge width for $10^{-3} \leq \alpha \leq 10^{-1}$; and for three assumptions regarding the ion generation rate, namely generation uniform, proportional to electron density, and proportional to the square of electron density.

For the higher values of α, corresponding to weak laboratory discharges, there is a smooth transition from a quasi-neutral plasma region to a thick sheath. At the smaller values of α, the conventional model of a quasi-neutral plasma region passing rather abruptly into a narrow sheath region is substantiated. In all cases, accurate values for the potential profile throughout the plasma and sheath regions are given and compared with the separate asymptotic plasma and sheath solutions for $\alpha = 0$. The ion current density, wall potential, space-charge density, mean ion energy, and sheath thickness are discussed.

Phys. Fluids **6**, 1762 (1963)

THE PHYSICS OF FLUIDS VOLUME 8, NUMBER 1 JANUARY 1965

Unified Theory for the Langmuir Probe in a Collisionless Plasma

S. H. Lam
Gas Dynamics Laboratory, Princeton University, Princeton, New Jersey
(Received 2 June 1964; final manuscript received 3 September 1964)

An asymptotic analysis is presented of the Langmuir-probe problem in a quiescent, collisionless plasma in the limit of large body dimension to Debye length ratio. The structures of the electric potential distribution about spheres and cylinders are analyzed and discussed in detail. It is shown that when the probe potential is smaller than a certain well defined value, there exists no sheath adjacent to the solid surface. At large body potentials, for which a sheath is present, the electric potential distribution is given in terms of several universal functions. Master current-voltage characteristic diagrams are given which exhibit clearly the effects of all the pertinent parameters in the problem. An explicit trapped-ion criterion is presented. The general problem with an arbitrary body dimension to Debye length ratio is qualitatively discussed.

Phys. Fluids **8**, 73 (1965)

THE PHYSICS OF FLUIDS VOLUME 11, NUMBER 4 APRIL 1968

Measurement of Low Plasma Densities in a Magnetic Field

Francis F. Chen, Claude Etievant,* and David Mosher
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 19 September 1967)

Absolute measurements of plasma density in the range 8×10^8 to 3×10^{11} cm^{-3} were made in a potassium plasma by four methods: (1) Langmuir probes, (2) microwave cavity, (3) microwave interferometry, and (4) propagation of electrostatic waves. Agreement to $\approx 25\%$ between the probe and microwave measurements was achieved by careful application of probe theory. By contrast, indiscriminate use of probe theory would lead to an error of 600% at low densities. The fourth method, though less accurate, was found to be a useful independent check.

Phys. Fluids **11**, 811 (1968)

Electric sheath and presheath in a collisionless, finite ion temperature plasma

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(Received 4 June 1979; accepted 10 January 1980)

The plasma-sheath equation for a collisionless plasma with arbitrary ion temperature in plane geometry is formulated. Outside the sheath, this equation is approximated by the plasma equation, for which an analytic solution for the electrostatic potential is obtained. In addition, the ion distribution function, the wall potential, and the ion energy and particle flux into the sheath are explicitly calculated. The plasma-sheath equation is also solved numerically with no approximation of the Debye length. The numerical results compare well with the analytical results when the Debye length is small.

Phys. Fluids **23**, 803 (1980)

Plasma–wall transition in an oblique magnetic field

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(Received 16 October 1981; accepted 6 May 1982)

The effect of a magnetic field on the transition layer between a plasma and an absorbing wall is studied. A numerical model is used which simulates the motion of plasma particles in the electric and magnetic fields for a prescribed particle influx at the plasma boundary. Bohm's condition for the existence of a monotonic profile of the layer is generalized. The transition layer proves to have a double structure comprising a quasineutral magnetic presheath preceding the electrostatic Debye sheath. The magnetic presheath scales with the ion gyroradius at the sound speed and with the angle of the magnetic field. The total electric potential drop between plasma and wall proves to be fairly insensitive to the magnitude and angle of the magnetic field.

Phys. Fluids **25**, 1628 (1982)

A fluid theory of ion collection by probes in strong magnetic fields with plasma flow

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(Received 24 November 1986; accepted 3 September 1987)

A one-dimensional fluid theory of Langmuir probe operation in strong magnetic fields is presented. Cross-field diffusion of ions both into and out of the the collection region is consistently accounted for, in effect taking momentum and particle diffusivity to be equal. The results differ by significant factors from previous analyses, which did not account for outward diffusion but in effect set momentum diffusivity to zero. The differences are especially large when parallel flow of the external plasma is present. It is thus clear that the value assumed for the momentum diffusivity strongly affects the interpretation of recent probe measurements. It is argued that the present results offer a more reliable basis for this interpretation.

Phys. Fluids **30**, 3777 (1987)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 12 DECEMBER 2001

Plasma flow and plasma–wall transition in Hall thruster channel

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(Received 27 August 2001; accepted 2 October 2001)

In this paper a model of the quasineutral plasma and the transition between the plasma and the dielectric wall in a Hall thruster channel is developed. The plasma is considered using a two-dimensional hydrodynamic approximation while the sheath in front of the dielectric surface is considered to be one dimensional and collisionless. The dielectric wall effect is taken into account by introducing an effective coefficient of the secondary electron emission (SEE), s. In order to develop a self-consistent model, the boundary parameters at the sheath edge (ion velocity and electric field) are obtained from the two-dimensional plasma bulk model. In the considered condition, i.e., ion temperature much smaller than that of electrons and significant ion acceleration in the axial direction, the presheath scale length becomes comparable to the channel width so that the plasma channel becomes an effective presheath. It is found that the radial ion velocity component at the plasma–sheath interface varies along the thruster channel from about $0.5C_s$ (C_s is the Bohm velocity) near the anode up to the Bohm velocity near the exit plane dependent on the SEE coefficient. In addition, the secondary electron emission significantly affects the electron temperature distribution along the channel. For instance in the case of $s=0.95$, the electron temperature peaks at about 16 eV, while in the case of $s=0.8$ it peaks at about 30 eV. The predicted electron temperature is close to that measured experimentally. The model predictions of the dependence of the current–voltage characteristic of the $E\times B$ discharge on the SEE coefficient are found to be consistent with experiment.
[DOI: 10.1063/1.1421370]

Phys. Plasmas **8**, 5315 (2001)

Dusty Plasmas

Coulomb solid of small particles in plasmas

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(Received 11 December 1985; accepted 11 March 1986)

Small particles in plasmas can form a coulomb lattice. The conditions for solidification in a laboratory plasma are discussed.

Phys. Fluids **29**, 1764 (1986)

Laboratory observation of the dust-acoustic wave mode

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(Received 26 May 1995; accepted 30 June 1995)

A laboratory observation of the dust-acoustic instability is reported. The results are compared with available theories.

Phys. Plasmas **2**, 3563 (1995)

Solitary potentials in dusty plasmas

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(Received 11 September 1995; accepted 16 October 1995)

It is found that a dusty plasma with inertial dust fluid and Boltzmann distributed ions admits only negative solitary potentials associated with nonlinear dust-acoustic waves. The dynamics of small-amplitude disturbances is governed by the Korteweg–de Vries (KdV) equation, the stationary solution of which assumes the inverted bell-shaped secant hyperbolic squared profile. The associated dust and ion density perturbations are, on the other hand, positive. The solitary potentials can be identified as nonlinear structures in low-temperature dusty plasmas such as those in laboratory and astrophysical environments. [S1070-664X(96)00302-4]

Phys. Plasmas **3**, 702 (1996)

Experimental observation of very low-frequency macroscopic modes in a dusty plasma

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(Received 28 July 1995; accepted 16 January 1996)

Images of a cloud of grains in a dusty plasma reveal a pair of very low-frequency modes, termed here the filamentary and great void modes. The plasma was a radio-frequency discharge formed between parallel-plate graphite electrodes. A cloud of 100 nm carbon particles was produced by accretion of carbon atoms produced by sputtering the graphite. The cloud was illuminated with a laser sheet and imaged with a video camera. The great void mode was a spoke-shaped region of the cloud that was free of dust and rotated azimuthally in the discharge. The filamentary mode had the appearance of turbulent striations, with a smaller amplitude than the great void. The filamentary mode sometimes appeared as a distinctive vortex, curling in the poloidal direction. Both modes had a very low frequency, on the order of 10 Hz. Two possible causes of the modes are discussed. The low phase velocity of the modes may be consistent with a dust-acoustic wave. Alternatively, the great void may be an ionization wave that moved the dust about, since a modulation in the glow was seen moving at the same speed as the void. It is argued that existing theories of waves in dusty plasmas assume weakly collisional plasmas, which may be unsuitable for explaining experimental results in laboratory dusty plasmas, since they are often strongly coupled. © *1996 American Institute of Physics.* [S1070-664X(96)02204-5]

Phys. Plasmas **3**, 1212 (1996)

Lattice waves in dust plasma crystals

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(Received 19 April 1996; accepted 12 August 1996)

Techniques previously known from solid state physics are used to look at linear and weak non-linear wave propagation in dust lattices. These expansion techniques include only electrostatic interactions between neighbor particles in addition to assuming small vibrations in the dust lattice. As a simple model for the dust lattice, a one-dimensional Bravais lattice is considered. For this particular lattice, expressions for the linear phase velocity are compared to a quasi-particle simulation. The word quasi here means that only the dust particles are represented as diffuse objects, while the plasma is treated as a fluid. The simulation is also used to study the breakdown of the analytical theory and to investigate non-linear dust lattice waves. A very good agreement is found between the analytical expressions and the particle simulations, for cases where the average dust separation a is of the order of or larger than the plasma Debye length λ_D. This is a condition which very often applies to dust crystal in laboratory experiments. Application of this wave theory is therefore discussed with respect to recent laboratory experiments where dust lattice waves are excited. © *1996 American Institute of Physics.* [S1070-664X(96)03311-3]

Phys. Plasmas **3**, 3890 (1996)

Dust-acoustic soliton in a dusty plasma

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(Received 19 July 1996; accepted 21 October 1996)

It is shown that a dusty plasma can admit dust-acoustic solitons on a very slow time scale involving the motion of dust grains, whose charge is self-consistently determined by local electron and ion currents. The solitons exist for a range of velocities and the peak amplitude increases almost linearly with the velocity. © *1997 American Institute of Physics.* [S1070-664X(97)00202-4]

Phys. Plasmas **4**, 253 (1998)

Dust acoustic waves in a direct current glow discharge

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(Received 25 February 1997; accepted 21 April 1997)

An experimental investigation of dust acoustic (DA) waves in a dc glow discharge plasma is described. The glow discharge is formed between a 3 cm anode disk and the grounded walls of a 60 cm diameter vacuum chamber which is filled with nitrogen gas at a pressure of about 100 mTorr. Dust located on a tray in the chamber is attracted into the plasma where it is trapped electrostatically. The dust acoustic waves were produced by applying a modulation signal (5–40 Hz) to the anode. The wavelength of the DA waves was measured from single frame video images of scattered light from the dust grains. The measured dispersion relation is compared with theoretical predictions. © *1997 American Institute of Physics.* [S1070-664X(97)04907-0]

Phys. Plasmas **4**, 2331 (1997)

PHYSICS OF PLASMAS VOLUME 5, NUMBER 5 MAY 1998

Laboratory studies of waves and instabilities in dusty plasmas*

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(Received 17 November 1997; accepted 29 December 1997)

Theoretical and experimental studies of low-frequency electrostatic waves in plasmas containing negatively charged dust grains are described. The presence of charged dust is shown to modify the properties of ion-acoustic waves and electrostatic ion-cyclotron waves through the quasineutrality condition even though the dust grains do not participate in the wave dynamics. If the dust dynamics is included in the analysis, new "dust modes" appear—dust acoustic and dust cyclotron modes. The results of laboratory experiments dealing with dust ion acoustic (DIA) waves and electrostatic dust ion cyclotron (EDIC) waves are shown. These modes are more easily excited in a plasma containing negatively charged dust. Finally, observations of dust acoustic (DA) waves are presented and measurements of the dispersion relation are compared with one obtained from fluid theory. © *1998 American Institute of Physics.* [S1070-664X(98)90505-5]

Phys. Plasmas **5**, 1607 (1998)

PHYSICS OF PLASMAS VOLUME 8, NUMBER 5 MAY 2001

A survey of dusty plasma physics*

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(Received 16 October 2000; accepted 7 November 2000)

Two omnipresent ingredients of the Universe are plasmas and charged dust. The interplay between these two has opened up a new and fascinating research area, that of dusty plasmas, which are ubiquitous in different parts of our solar system, namely planetary rings, circumsolar dust rings, the interplanetary medium, cometary comae and tails, as well as in interstellar molecular clouds, etc. Dusty plasmas also occur in noctilucent clouds in the arctic troposphere and mesosphere, cloud-to-ground lightening in thunderstorms containing smoke-contaminated air over the United States, in the flame of a humble candle, as well as in microelectronic processing devices, in low-temperature laboratory discharges, and in tokamaks. Dusty plasma physics has appeared as one of the most rapidly growing fields of science, besides the field of the Bose–Einstein condensate, as demonstrated by the number of published papers in scientific journals and conference proceedings. In fact, it is a truly interdisciplinary science because it has many potential applications in astrophysics (viz. in understanding the formation of dust clusters and structures, instabilities of interstellar molecular clouds and star formation, decoupling of magnetic fields from plasmas, etc.) as well as in the planetary magnetospheres of our solar system [viz. Saturn (particularly, the physics of spokes and braids in the B and F rings), Jupiter, Uranus, Neptune, and Mars] and in strongly coupled laboratory dusty plasmas. Since a dusty plasma system involves the charging and dynamics of massive charged dust grains, it can be characterized as a complex plasma system providing new physics insights. In this paper, the basic physics of dusty plasmas as well as numerous collective processes are discussed. The focus will be on theoretical and experimental observations of charging processes, waves and instabilities, associated forces, the dynamics of rotating and elongated dust grains, and some nonlinear structures (such as dust ion-acoustic shocks, Mach cones, dust voids, vortices, etc). The latter are typical in astrophysical settings and in several laboratory experiments. It appears that collective processes in a complex dusty plasma would have excellent future perspectives in the twenty-first century, because they have not only potential applications in interplanetary space environments, or in understanding the physics of our universe, but also in advancing our scientific knowledge in multidisciplinary areas of science. [DOI: 10.1063/1.1343087]

Phys. Plasmas **8**, 1791 (2001)

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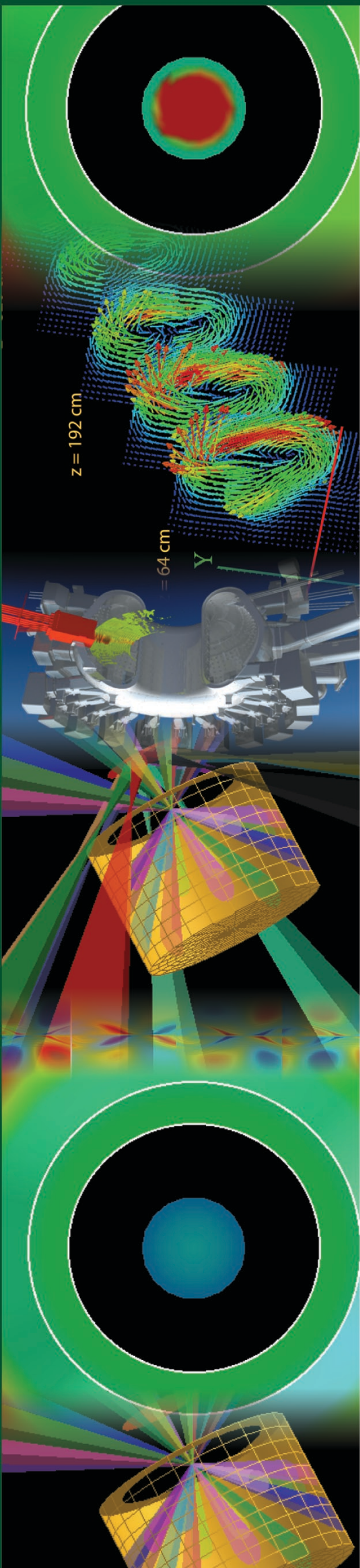

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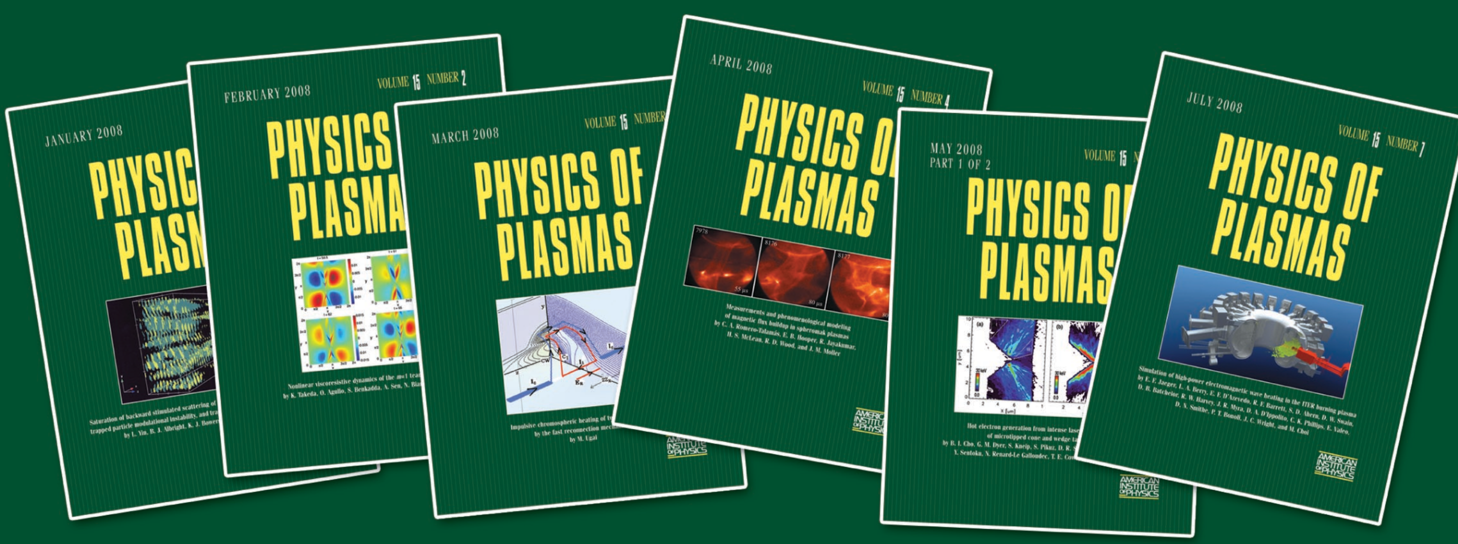

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