SECOND EUROPEAN CONFERENCE ON
CONTROLLED FUSION & PLASMA PHYSICS
(Stockholm, August 14-18, 1967)

Abstracts

Plasma Physics, Vol. 10, pp. 421 to 476. Pergamon Press 1968. Printed in Northern Ireland

SECOND EUROPEAN CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS

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Abstract—The *Second European Conference on Controlled Fusion and Plasma Physics* was held at the Royal Institute of Technology in Stockholm, Sweden, from the 14th to the 18th of August 1967. A total number of 249 participants from 21 countries attended. The present report summarizes the conference proceedings and includes the abstracts of papers presented.

1. THE ORGANIZATION OF THE CONFERENCE

1.1 *Supporters*

Financial support from the following organizations is gratefully acknowledged:

Konung Gustaf VI Adolfs 80-årsfond för svensk kultur (King Gustaf VI Adolf's 80th Anniversary Foundation for Swedish Culture)

EURATOM, Brussels

Statens råd för atomforskning (The Swedish Atomic Research Council)

International Atomic Energy Agency, Vienna (part of the administrative costs)

The Organizing Committee also wishes to express its sincere thanks to Professor Yngve Zotterman of Wenner-Gren Center, Stockholm and to the Swedish Atomic Research Council for valuable help during the preparation of the Conference.

1.2 *Organizing Committee*

Chairman of Committee and President of the Conference: Bo Lehnert
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1.4 *Session Chairmen and Secretaries*

The following persons acted as session chairmen: A. Baños, A. B. Berezin, A. S. Bishop, H. G. van Bueren, R. Carruthers, C. T. Chang, T. Consoli, L. Enriques,

I. N. Golovin, P. Hubert, M. Sadowski, R. Z. Sagdeev, A. Schlüter, P. C. Thonemann, S. Tjötta, P. Vandenplas, F. Waelbroeck, E. S. Weibel.

The following persons acted as session secretaries: L. Block, B. Bonnevier, L. Egardt, C.-G. Fälthammar, C. T. Jacobsen, R. Johansson, E. Karlson, L. Lindberg, H. Persson, S. Sandahl, E. Smårs, T. Stefánsson, E. Tennfors, S. Torvén, H. Wilhelmsson, B. Wilner, E. Witalis.

2. THE SCIENTIFIC PROGRAMME

Monday 14 August

Opening of the Conference (B. LEHNERT)

Invited Paper

E. A. FRIEMAN, Toroidal Confinement

Confinement and Stability—Theory

D. A. DUNNETT, E. W. LAING and J. B. TAYLOR, Invariants in the Motion of a Charged Particle in a Spatially Modulated Magnetic Field

C. GOURDON, D. MARTY and M. VUILLEMIN, Stellarator Configurations with Strong Shear and Negative V''

G. D. HOBBS and J. B. TAYLOR, Some Theoretical Aspects of Multipole Devices

C. MERCIER, Motion of Charged Particles in Toroidal Geometry

E. KARLSON, Stationary Equilibrium of a Toroidal Plasma

N. N. FILONENKO, A. V. KOMIN, R. Z. SAGDEEV and G. M. ZASLAVSKI, Destruction of Magnetic Surfaces in Toroidal Systems

B. LEHNERT, Plasma Confinement in Ring-Current Configurations

J. H. HILTON, C. K. HINRICHS and A. A. WARE, Theoretical and Experimental Results on the Electrostatic Plugging of a Cusp Containment System

J. LACINA, Equilibrium of Plasma in Axially Symmetric Magnetic Fields

W. FENEBERG, Toroidal Confinement with Temperature Gradients

Cusped Geometry

H. J. BELITZ and E. KUGLER, Investigations on a Cusp Compression Experiment

H. SCHINDLER, Experiments on Plasma Behaviour in a Stationary Cusp-Field Combined with a Theta-Pinch

Theta Pinches

H. A. B. BODIN and A. A. NEWTON, Diffusion and Stability in an 8-M Theta Pinch

P. BOGEN, K. H. DIPPEL, P. NOLL, D. RUSBÜLDT, K. SUGITA, H. WITULSKI and F. WAELBROECK, Recent Results from the Jülich Theta-Pinch Experiments

R. BONO, I. FACCINI, P. L. MONDINO and G. ROSTAGNI, Breakdown and Compression in Superposed Fields Theta-Pinch

F. HERTWECK and W. SCHNEIDER, A Two-Dimensional Computer-Program for End Losses from a Theta-Pinch

J. G. LINHART and G. SCHENK, Use of Exploding Foils in a Rapid Theta-Pinch

Confinement and Stability—Experiments

A. N. KOZYREV, B. P. PEREGOOD, L. V. HABARIN and A. F. IOFFE, Confinement of Electrons in "Tornado Traps"

R. A. DEMIRKHANOV, A. G. KIROV, M. A. STOTLAND and N. I. MALIKH, Investigations of Plasma Equilibrium in a Torus with High-Frequency and Longitudinal Static Magnetic Fields

A. S. KAUFMAN, Principles of Electrostatic Containment of an Ionized Gas and the Apparatus MAYA

Tuesday 15 August

Invited Paper

B. B. KADOMTSEV, Recent Investigations on Plasma Instabilities

Instabilities—Theory

R. J. HASTIE and J. B. TAYLOR, U.K.A.E.A., Drift Instability in General Magnetic Fields

G. LAVAL, E. K. MASCHKE, R. PELLAT and M. VUILLEMIN, Stabilization of Density Gradient Instabilities by the Dispersion of Curvature Drift Velocity

J. E. MCCUNE and B. D. FRIED, Explicit Solution of Loss-Cone Dispersion Relations

C. O. BEASLEY and J. G. CORDEY, Convective and Absolute Ion–Cyclotron Instabilities in Homogeneous Plasmas

A. A. GALEEV and R. Z. SAGDEEV, Equilibria, Stability and Transport Coefficients of Plasma in a Toroidal Geometry

G. KALMAN, C. MONTES and D. QUEMADA, Thermally Anisotropic Plasma Instabilities

F. R. CROWNFIELD JR. and M. R. FEIX, Fourier–Hermite Expansion of the Non-linear Vlasov Equation

L. S. HALL and W. HECKROTTE, Propagation and Growth of a Pulse Disturbance in an Unstable Medium

F. W. CRAWFORD, J. C. LEE and J. A. TATARONIS, Some Studies of Transverse Plasma Wave Instabilities

T. E. STRINGER, Guiding Centre Plasma Equations

H. MELCHIOR and M. POPOVIC, Finite Larmor Radius Effect on the Kelvin–Helmholtz Instability

F. HERRNEGGER, Stability of Helmholtz Flow in a Discontinous Magnetic Field

D. K. CALLEBAUT, Second-Order Magnetodynamic Stability of Infinite Cylinder

Instabilities—Experiments

V. V. ALIKAEV, V. M. GLAGOLEV and S. A. MOROZOV, Anisotropic Instability of a Hot Electron Plasma Confined in an Adiabatic Trap

L. ENRIQUES, A. LEVINE and G. B. RIGHETTI, Study of Universal Drift Waves in a Large Diameter "*Q*" Machine

P. EVRARD, J. JACQUINOT, C. LELOUP, J. P. POFFÉ, M. DE PRÉTIS and F. WAELBROECK, Properties of a Pulse Heated Plasma in a Magnetic Mirror Geometry

V. P. GORDIENKO, L. V. DUBOVOI and I. M. ROIFE, D. V. EFREMOV, High-Frequency Stabilization and Heating of the Current Carrying Plasma Column in a Longitudinal Magnetic Field

P. C. T. VAN DER LAAN, R. F. DE Vries and C. BOBELDIJK, Toroidal Screw Pinch Experiments

D. C. ROBINSON, B. C. BOLAND, R. E. KING and R. S. PEASE, The Outer Regions During a Period of Improved Stability in ZETA

H. IKEGAMI, H. IKEZI, M. HOSOKAWA, S. TANAKA and K. TAKAYAMA, Instability of Hot-Electron Plasma

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Wednesday 16 August

Invited Paper

D. W. MASON, Methods for the Exploration of Plasma Confinement

Instabilities—Experiments (cont'd)

L. I. ARTEMENKOV, I. V. GALKIN, R. DEI-CAS, V. A. ZHILTZOV, V. KH. LIECHTENSTEIN, D. A. PANOV and V. A. CHUYANOV, Properties of Plasma in OGRA-II

YU. T. BAYBORODOV, M. S. IOFFE, R. I. SOBOLEV and E. E. YUSHMANOV, Plasma Ion–Cyclotron Instability in Adiabatic Trap with Minimum "*B*"

P. BROSSIER, Ion–Cyclotron Instability in DECA II

W. CALVERT, L. G. KUO-Petravic, E. G. MURPHY, M. PETRAVIC, E. THOMPSON and D. R. SWEETMAN, Ion Cyclotron Instabilities in a Plasma Confined in a Magnetic Well

J. G. CORDEY, L. G. KUO-PETRAVIC and M. PETRAVIC, The Ion Cyclotron Drift Loss-Cone Instability in Mirror Magnetic Wells

A. V. BORTNIKOV, N. N. BREVNOV, V. G. ZHUKOVSKII and M. K. ROMANOVSKII, Experimental Study of Ion–Cyclotron Plasma Instability in a Mirror Machine

Information Lecture

P. C. THONEMANN, The Formation of a European Physical Society

Toroidal and Straight Pinches and Arcs

A. P. GORBUNOV, S. V. MIRNOV and V. S. STRELKOV, The Energy Replacement Time in TOKAMAK-3 at Various Discharge Parameters

B. B. KADOMTSEV and O. P. POGUTSE, Resistivity of the Plasma in Strong Magnetic Fields

G. A. BOBROVSKY, K. A. RAZUMOVA and J. A. SCEGLOV, Some Peculiarities of the Plasma Behavior in TOKAMAK TM-3

G. ZANKL, The Influence of the Axial Heat Losses Upon the Temperature of a Stationary Hydrogen Discharge in a Strong Axial Magnetic Field

I. R. JONES, A. LIETTI and J.-M. PEIRY, A Rotating Magnetic Field Pinch

A. Heym, Electron Line Density Measurements in a Magnetic Rotating Field Pinch

E. S. Weibel, Stability of Coupling Between Plasma and r.f. Generator in a Rotating Field Pinch

G. Basque, A. Jolas and J. P. Watteau, Ball-Shaped Plasma Produced by a Non-Cylindrical Linear Discharge

Diagnostics

M. Hashmi, A. J. van der Houven van Oordt, F. Rau and J. G. Wegrowe, On the Use of Langmuir Probes in a *Q*-Device

D. Bize, T. Consoli, L. Slama and M. Zymanski, Two Microwave Cavity Device for the Study of Wave Scattering

H. Röhr, A 90° Laser Scattering Experiment for Measuring Temperature and Density of the Ions and Electrons in a Cold Dense Theta-Pinch Plasma

S. Kuliński, J. Nowikowski and S. Suckewer, Use of a Monochromator for the Velocity and Temperature Measurements in a Coaxial Plasma Accelerator

R. Vanhauwermeiren, A Spectroscopic Method of Density Measurement in an Optically Thick Plasma

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Thursday August 17

Heating and Acceleration of a Plasma

M. Kristiansen and A. A. Dougal, Plasma Heating and Wave Propagation at Harmonics of the Ion Cyclotron Frequency

M. M. Larionov and V. V. Rozhdestvenskii, Investigation of Plasma Turbulence in a High-Current Toroidal Discharge by a Microwave Probing Method

J. Consolino, R. Geller and J. Hosea, Collision Effects on the CIRCE Device

P. Briand, T. Consoli, G. Mourier, L. Slama and P. Vial, The "ICARE" Experiment

A. Buffa, T. Consoli and L. Dupas, Heating of Plasma at the Electron Cyclotron Resonance in Non-Uniform Fields

D. K. Akulina, S. E. Grebenschikov, Yu. I. Nechaev, I. S. Sbitnikova and I. S. Spigel, Investigation of Electron Plasma Heating at the Cyclotron Frequency in the Stellarator L-I

E. Canobbio, High Frequency Electron Acceleration in a Mirror Region

A. B. Berezin, V. A. Ipatov, M. G. Kagansky, S. G. Kalmikov, A. I. Kislyakov, G. M. Malishev, V. A. Ovsyannikov, L. V. Sokolova and S. S. Tulpanov, Plasma Investigation in "TUMAN" Machine

S. M. Hamberger, J. H. Adlam, M. Frieman and A. Malein, Rapid Plasma Heating by Current Induced Turbulence in a Torus

M. V. Babykin, P. P. Gavrin, B. A. Demidov, N. I. Elagin, E. K. Zavoisky, D. N. Lin, S. L. Nedoseiev, N. F. Perepelkin, L. I. Rudakov, D. D. Ryutov, V. A. Skoryupin and S. D. Fanchenko, Study of Current-Produced Turbulent-Heating Mechanism

A. SCHLÜTER, Ponderomotive Action of Light

H. ISHIZUKA, G. MIYAMOTO, M. OKABAYASHI and H. TOYAMA, Plasma Acceleration Using a High Power Microwave and a Static Magnetic Field

M. HAEGI, Ionization and Heating of a Hypersonic Deuterium Jet

Diffusion

M. BERNARD, G. BRIFFOD, M. GREGOIRE and J. WEISSE, Diffusion and Space and Time Correlation Measurements in DAPHNIS II

P. F. LITTLE, P. E. STOTT and J. BURT, Fluctuations and Diffusion in a Lithium Plasma

J. POLMAN, Instability and Anomalous Diffusion of a Weakly Ionized Magnetized Radio-Frequency Plasma

Oscillations and Waves

G. VOJTA and M. MOCKER, Singular Normal Modes of the Vlasov Equation with BGK Collision Damping

P. G. SCHÜLLER, G. MÜLLER, W. ALDRINGER, E. RÄUCHLE and H. J. KAEPPELER, Study of Torsional Alfvén Waves in Inhomogeneous Plasmas

D. KAHN, Electron and Ion Waves in Fully Ionized Plasmas

Large Amplitude Waves and Shocks

E. CANOBBIO and R. COLLET, Ion Acceleration and Shock Waves in a High Frequency Plasma Structure

A. M. MESSIAEN and P. E. VANDENPLAS, Non-Linear Resonance Effects at High Power in a Cylindrical Plasma

H. TASSO, Shock-Like Drift Waves

H. HARTWIG and E. HINTZ, Application of Microwave Diagnostics to a Collision Free Shock Wave Experiment

M. ALIDIÈRES, R. AYMAR, P. JOURDAN, F. KOECHLIN and A. SAMAIN, Experimental Study of a Hydromagnetic Shock-Wave

J. H. MALMBERG and C. B. WHARTON, Collisionless Damping of Large Amplitude Plasma Waves

V. G. ESELEVITCH, R. H. KURTMULLAEV, K. I. MEKLER and V. I. PILSCY, Investigation of "Overturning" of the Strong Shock Wave in a Plasma

Injection Mechanisms and Devices

M. FUMELLI, J. P. GIRARD and C. GOURDON, Kinetics of the Formation of a Plasma by Injection of Fast Atoms into a Closed Magnetic Configuration

M. GRYZIŃSKI, J. NOWIKOWSKI, M. SADOWSKI, E. SKŁADNIK-SADOWSKA and S. SUCKEWER, Research on a New Type of Plasma Injector

M. SADOWSKI and E. SKŁADNIK-SADOWSKA, Research on Magnetic Fields and Integral Visible Radiation of a Plasma Generated by a New Type of Injector

E. W. BECKER, H. BURGHOFF and R. KLINGELHÖFER, Hollow Pinch Discharges in Condensed Molecular Beams

E. W. Becker, K. Bucheit and W. Henkes, Experiments Relating to High Energy Injection of Charged Hydrogen Clusters

E. D. Andrukhina, I. A. Kossyi and I. S. Shpigel, The Influence of External Steady Magnetic Fields on the Operating Regime and the Properties of the Plasma Generated by a Hydrogen Loaded Titanium Washer Source and an Electrodeless Source

Radiation

J. W. Long, N. J. Peacock, R. J. Speer and P. D. Wilcock, Electro-Magnetic Emission from Plasma Focus.

V. A. Abramov, N. D. Vinogradova, V. I. Kogan, E. I. Kusnetsov and D. A. Sceglov, Measurements of Fluxes of Neutral H-Atoms and Impurities by Spectroscopic Methods in TOKAMAK TM-3

Friday 18 August

Turbulence

D. Pfirsch, K. Elsässer and D. Biskamp, Kinetic Equations for Microscopic Turbulence

J. L. Wyatt, A Kinetic Theory for Quiescent and Weakly Turbulent Plasma in Nearly-Adiabatic Fields

Technical and Economical Aspects of Fusion Devices

R. Carruthers, A Study of Some Technological Aspects and Economic Problems Associated with a Possible Fusion Reactor

M. L. Pool, J. W. Snyder, P. E. Weiler and P. Polishuk, Fusion Efficiency for Revolving Fields

J. G. Linhart, Ch. Maisonnier and J. P. Somon, Theory of Internal Confinement of Dense Plasmas

Visits

To the Division of Plasma Physics, Royal Institute of Technology, Stockholm and to Stockholm Observatory, Saltsjöbaden.

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3. OPENING ADDRESS

B. Lehnert
Royal Institute of Technology, Stockholm, Sweden

Ladies and Gentlemen,

During the last ten years a number of informal study groups have been organized on controlled fusion and plasma physics at several places in Europe. Every year these groups have increased in magnitude, and during last autumn they were converted into the *First European Conference on Controlled Fusion and Plasma Physics* which was held in Munich. It is a great honour to Sweden, and also a difficult task for the present Organizing Committee, to become the host of a conference which is the successor to the excellent Munich meeting.

It should perhaps be stressed that these meetings have never been organized with any intention to interfere with the large conferences arranged by the International Atomic Energy Agency at intervals of four years. It is also obvious that there should be no European meeting during a year when there is a conference by the Agency. Nevertheless it must be admitted that the very large interest shown in this Stockholm conference is both surprising, encouraging and somewhat frightening.

Far more papers have been submitted for presentation than could possibly be included in the programme. Unfortunately, it therefore became necessary for a Paper Selection Committee to cut down the number of presented contributions. During the preselection of papers valuable help has been offered by several institutes in- and outside of Europe and also by the Soviet Embassy in Stockholm. This help is gratefully acknowledged. Attempts have been made to exclude only such papers which deal with subjects which are largely aside from the main line of the conference. The selection has not been based on any judgement about the quality of the submitted abstracts. Even with the large reduction of papers which has taken place, the programme includes both double and triple sessions. It is still the hope that every participant will be able to attend the lectures of his main interest.

At this occasion I wish to express the sincere gratitude of the Organizing Committee to EURATOM in Brussels, the International Atomic Agency in Vienna, King Gustaf Adolf's 80th Anniversary Foundation for Swedish Culture and to the Swedish Atomic Research Council without the support of which this conference would not have been possible to realize.

It is a great pleasure to see so many colleagues and friends being fused together here from all corners in- and outside of the geographical boundaries of Europe and I wish you a hearty welcome in Sweden. Last but not least it is also a pleasure to announce that our dear "Father of Magnetohydrodynamics", Hannes Alfvén, is among us during this conference.

With the sincere hope that this will become a profitable meeting with plenty of interesting discussions, I hereby declare the conference open for its first session to begin.

4. ABSTRACTS OF PAPERS PRESENTED

Measurements of fluxes of neutral H-atoms and impurities by spectroscopic methods in Tokamak TM-3*

V. A. ABRAMOV, N. D. VINOGRADOVA, V. I. KOGAN, E. I. KUSNETSOV
and D. A. ŠČEGLOV
I. V. Kurchatov Institute of Atomic Energy, Moscow, USSR

ONE of the effects of the distruction of plasma thermal insulation in quasistationary discharges in toroidal Tokamak-type installations is the interaction of plasma particles with the diaphragm and chamber walls causing an influx of neutral gas desorbed from the walls into the plasma.

The experimental study of interaction processes between the plasma and the neutral particle flux entering the plasma column from outside enables us to understand the dynamics of charged particle losses from the plasma, the energy balance and also helps us to interpret the energy distribution of charge-exchange H-atoms emitted from the plasma column.

* Presented by K. A. RAZUMOVA.

We present here the results of measurements of spectral line intensities of the H-atom ($\lambda = 6563$ Å, 4861 Å) and impurities as ion CV ($\lambda = 2271$ Å) across the small diameter of the plasma column. From the measured distribution of light intensity the radial distribution of photon emitters was calculated with the use of Abel's transformation, assuming the plasma column cross section to be of cylindrical symmetry. With certain assumptions concerning the radial variation of electron density and temperature one can determine the profile of the neutral atom concentration from the distribution of the photon emitters.

The measurements of absolute values of the above-mentioned line intensities together with the measurements of the photon emitter distribution as well as the measurements of the electron density by means of a microwave interferometer allow us to estimate the concentration of radiating atoms (ions) for the central region of the discharge column. In these calculations, besides the processes of ionization and excitation from the ground level of the H-atom, the processes of step ionization and cascade transition were taken into account. The necessity for such a procedure arises from the measurements of the ratios of the hydrogen line intensities.

The following calculation method is used. In calculating the population at each of the excited levels it is assumed, at the first stage, that this level is (apart from the ground level and the continuum) the only one ('binary' scheme). The population of this level is calculated with a high accuracy. At the second stage a certain correction factor, taking account of the presence of a number of excited levels, is introduced. The magnitude of this correction factor is obtained from additional theoretical arguments including a high-temperature ($T_e > 25$ eV) extrapolation of the corresponding factor extracted from a comparison of the results presented in [1] with the ones obtained by the above 'binary' scheme for $T_e < 25$ eV.

The values obtained for the neutral atom concentration were used in the calculations of energy losses due to the charge-exchange process. The impurity ion concentration was taken into consideration when calculating the plasma conductivity and interpreting the results of measurements of soft X-ray radiation.

The measurements of the absolute number of photons emitted by neutral H-atoms enables us to determine the number of ionizations and hence to estimate indirectly the life-time of plasma electrons in the case when the electron density during the time interval being studied changes only slightly and the density balance results mainly from H-atom ionizations.

[1] R. W. P. McWhirter and A. G. Hearn, *Proc. Phys. Soc.* **82**, 641 (1963).

Investigation of electron plasma heating at the cyclotron frequency in the stellarator L-I*

D. K. Akulina, S. E. Grebenschikov, Yu. I. Nechaev, I. S. Sbitnikova and I. S. Spigel
Lebedev Institute of Physics, Moscow, USSR

The results of experiments on electron cyclotron plasma heating in the stellarator LIVEN-1 with $l = 2$ are presented. The life-time of a plasma obtained by external injection into the stellarator was investigated earlier [1, 2].

The aim of this work was to study the electron plasma heating and plasma confinement versus absorbed h.f. energy. The plasma with an initial density of the order of 10^{10} cm^{-3} was obtained by a spark plasma source. The electron cyclotron heating was produced by a h.f. wave excited in the vacuum chamber of the stellarator. The magnetic field intensity in the centre of the vacuum chamber corresponding to the electron cyclotron frequency was $\sim$2·5 kG. The h.f. impulse duration was from 2 up to 100 μsec and the power up to 10 kW. The h.f. power was fed into the stellarator after plasma filling. The main results were obtained with electron heating by a single h.f. impulse with 2–20 μsec duration and with an energy of (3–15) 10^{-3} J supplied.

The resonance absorption of the h.f. power versus the intensity of the magnetic field was studied. The half-width of the resonance absorption curve was in close agreement with the inhomogeneity of the magnetic field along the cross section of the chamber and was of the order of 15 per cent. The absorption length was approximately 17 cm at the magnetic field intensity $\approx$2·4 kG (5 per cent out of resonance). The energy absorbed in the plasma and correspondingly the electron temperature could be changed by varying the duration and intensity of the h.f. impulse and/or the magnetic field intensity. The life-time of the plasma was shown to be inversely proportional to the absorbed h.f. energy. It was found that the electron heating occurred on lines $H =$ const. Then the hot electrons

* Presented by I. S. Spigel.

filled the magnetic surfaces due to the rotational transform. The radial dimension of the heating region was 1·5–2 cm.

[1] M. S. BERESHETSKII, S. E. GREBENSCHIKOV, N. M. ZVEREV and I. S. SPIGEL *Trudy P. N. Lebedev Phys. Inst.* 32, 20 (1965).
[2] D. K. AKULINA, G. M. BATANOV, M. S. BERESHETSKII, S. E. GREBENSCHIKOV, M. S. RABINOVICH, I. S. SBITNIKOVA and I. S. SPIGEL, *Culham Conference*, Report No. 21/244.

Experimental study of a hydromagnetic shock-wave*

M. ALIDIÈRES, R. AYMAR, P. JOURDAN, F. KOECHLIN and A. SAMAIN
Groupe de Recherches de l'Association EURATOM–CEA sur la Fusion
Fontenay-aux-Roses (Hauts-de-Seine), France

WE HAVE carried out a detailed study of a hydromagnetic shock-wave controlled by resistivity in a radiating argon plasma.

The shock-wave appears during the implosion phase of the compression of a plasma in a theta-pinch type magnetic configuration. The preionized gas was enclosed in a spherical vessel ($\phi = 30$ cm) around which was fitted a single turn coil, 24 cm long.

We carried out the following measurements:

(i) magnetic field profiles, by microprobes;
(ii) electronic temperature and relative density by study of the light radiated in the visible region;
(iii) absolute electronic density by a Jamin interferometer;
(iv) ionic radial velocity field and temperature by spectroscopic study of the Doppler effect.

A magnetic field was observed to appear behind the sheath which propagated towards the axis at a velocity increasing from ≈ 3 to 7 cm/μsec. This sheath, in which the electric current is localized, is cylindrically symmetrical, its thickness being nearly constant during the implosion (≈ 1 cm). It divides the inside, containing the axis, where the field assumes its zero initial value from the outside where it reaches a constant value. We observed that the plasma, after being swept up by the sheath, gained the radial velocity of the sheath itself. On the other hand, energy supplied to the electrons by a dissipative process during acceleration was almost completely lost by radiation owing to the nature of the gas. This results in a low final temperature (≈ 5 eV) and in plasma accumulation immediately behind the sheath.

We explain the observed phenomenon by the existence of a stationary shock-wave, for which the Rankine–Hugoniot relations are verified when radiation is taken into account. On the other hand, the only dissipative process at work is the electrical resistivity associated with magnetic field diffusion. Theoretical profiles are given, taking into account, in a collision dominated plasma, only the Lorentz force and not viscosity or pressure gradients. Very good agreement with experimental shock thickness was obtained.

* Presented by P. JOURDAN. Paper to be published in *Plasma Physics*.

Anisotropic instability of a hot electron plasma confined in an adiabatic trap*

V. V. ALIKAEV, V. M. GLAGOLEV and S. A. MOROZOV
I. V. Kurchatov Institute of Atomic Energy, Moscow, U.S.S.R.

THE behaviour of hot electron plasma ($T_e = 20$–30 keV) confined in an adiabatic trap is investigated. Plasma heating was carried out by means of pulsed fields of *S*-band range in a vacuum resonator. The static magnetic field in the trap was changed from the value corresponding to the electron–cyclotron frequency to the second harmonic of this frequency in the centre of the trap. The pressure of the neutral gas was changed from $(1{\cdot}5\text{–}2) \times 10^{-4}$ mm Hg to 6×10^{-4} mm Hg. The plasma obtained with its hot component density $n_e \approx 3 \times 10^{10}$ cm^{-3} and $T_e = 20$–30 keV, was stable with a life-time of 1 msec at a neutral gas pressure from 4×10^{-4} mm Hg to 6×10^{-4} mm Hg. At a lower pressure $[(1{\cdot}5\text{–}2) \times 10^{-4}$ mm Hg$]$ an instability was observed during the afterglow resulting in a rapid loss of transverse plasma energy for $\leqslant 1$ μsec. Simultaneously there was observed an intensive monochromatic

* Presented by M. S. IOFFE. To be published in *Plasma Physics*.

radiation with a frequency close to the electron–cyclotron frequency or to its second harmonic corresponding to the magnetic field at the centre axis of the trap. The instability which is accompanied by radiation at the frequency $\omega = 0{\cdot}75\ \omega_H$ (ω_H is the electron–cyclotron frequency at the centre axis) results in a loss of transverse plasma energy of up to 80 per cent. Simultaneously, during the high frequency radiation (0·25–0·5 μsec), an intense Roentgen radiation was observed from the end side surfaces of the resonator as well as a burst in the visible range from the plasma. The instability with the frequency $\omega = 1{\cdot}8\ \omega_H$ was accompanied by a lower loss of transverse energy (on the average $\approx 10\%$) and by a lower level of the high frequency radiation. There was also observed weak monochromatic radiation at the frequency $\omega = 0{\cdot}6\ \omega_H$ without any noticeable loss of plasma transverse energy and particles. The most probable time at which the instability starts was determined experimentally. It was shown that at first the instability with the frequency $\omega = 1{\cdot}8\ \omega_H$ took place, then with $\omega = 0{\cdot}75\ \omega_H$ and with $\omega = 0{\cdot}6\ \omega_H$. The experimental results are in agreement with the theory of the electron–cyclotron instability of a plasma confined in an adiabatic trap. This instability is connected with the anisotropy of the electron velocity distribution.

The influence of external steady magnetic fields on the operating regime and the properties of the plasma generated by a hydrogen-loaded titanium washer source and an electrodeless source*

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In this paper it is shown that the application of steady magnetic fields to pulsed plasma sources of different types (hydrogen-loaded titanium washer source and electrodeless source) causes considerable changes in the properties of the plasma.

At a given polarity of the voltage on the titanium source there exists a certain threshold value of the outer longitudinal magnetic field, at which the speed of the hydrogen component of the plasma increases by 5–7 or more times. The threshold value of this magnetic field grows with increasing voltage applied to the plasma source. When the source operates at a magnetic field larger than the threshold value, the amount of impurity decreases, the number of atomic hydrogen ions increases and the energy of the hydrogen ions varies approximately as the square of the applied voltage. The observed phenomena testify to a strongly turbulent state of the plasma inside the source during the initial stage of the flow of discharge current.

In the conical electrodeless plasma source a magnetic field which varies slowly with time is used to isolate the plasma and the current induced in the plasma from the walls of the discharge tube. To achieve this, a magnetic field transverse to the induced electric field is applied to the discharge area. A certain value and shape of the transverse magnetic field (a rapid decrease of the field towards the axis of the discharge tube) leads to plasma isolation from the walls of the vacuum chamber. This results in a decrease in the quantity of the impurities in the accelerated plasma by more than one order of magnitude. The experimental values of the critical magnetic fields leading to plasma isolation, are close to the calculated ones. The calculation is based on a study of the motion of an electron in induced and quasi-static transverse fields.

* Presented by I. S. Spigel.

Properties of plasma in OGRA-II*

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Results of studying the properties of low density plasma produced by fast H^0 atoms injected into OGRA-II are reported in this paper. Since the 1965 Culham Conference, improvements of the vacuum system have increased the charge exchange life-time of trapped particles five times and a different

* Presented by I. N. Golovin. Paper submitted to *Plasma Physics*.

connexion of the stabilizing coils has made studies possible with 6-pole and 4-pole magnetic well geometries. An electrostatic feed-back method of stabilizing the flute instability has been proposed and tested. This technique varies the local wall potential in the vicinity of the plasma in response to probe measurements of the local plasma potential. As in OGRA-I an attempt has been made to stabilize the flute instability by maintaining a positive potential on the end plates.

The main results of our experiments are as follows:

1. There are two instabilities in the simple mirror field: low frequency (flute) and high frequency (at the ion–cyclotron frequency and its harmonics).

2. In simple mirror fields two regions of ion–cyclotron oscillations are observed. These regions appear at different levels of the magnetic field strength and differ in polarization and in the axial distribution of the high frequency field.

3. In a simple mirror field the particle losses are more than 20–30 times larger than the charge exchange loss. The flute instability is the main cause of these losses.

4. In the minimum-B configuration the non-charge exchange losses are much less than in the simple mirror and are caused by ion–cyclotron instabilities. These losses are more prominent in the 6-pole geometry than in the 4-pole.

5. The transition from a simple mirror field to a magnetic well is described satisfactorily by the numerical calculations of the flute instability of Dnestrovsky *et al.*

6. The feedback stabilization effectively suppresses the flute instability in the simple mirror field.

7. The potential of the end plates has little influence on the flute instability.

Study of current-produced turbulent-heating mechanism*

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THE first part of the paper presents experimental data concerning the mechanism of plasma turbulent heating produced by a high-density current passing along the axis of a magnetic mirror machine. Heating-efficiency-ratio vs. time curves were measured for several values of the voltage across the plasma. The energy accumulated in the plasma as a result of heating was shown to increase with the magnetic field. The electromagnetic radiation emitted during the current flow was studied in the 3×10^8–3×10^{10} c/s frequency range for various initial conditions represented by the magnetic field, the longitudinal electric field and the plasma density. The radiation intensity was found to depend on both the electric field strength and its distribution over the plasma column length. The degree of plasma turbulence was deduced from the anomalous resistance value and a $\lambda = 3$ cm electromagnetic signal scattering. The results obtained demonstrate that the heating is indeed connected with plasma turbulence. The turbulent heating of ions in the mirror machine was studied by measuring both the energy and momentum of escaping charge-exchange neutrals. These neutrals bombarded a special external probe protected from the plasma by a triple metal grid. The probe was of the condenser microphone type with an aluminium membrane, one side of which was coated with aluminium oxide. The momentum of charge-exchange neutral flux was transferred to the membrane, causing the latter to oscillate. As the thermal expansion coefficients of aluminium and aluminium oxide do not coincide, the membrane heating due to absorption of neutrals resulted in its mechanical deformation. Measurements with the probe described above have shown that, from current-produced turbulent heating, the ions reach temperatures of several keV.

The second part of the paper treats theoretically the problem of a longitudinal electric-field-induced current in a corrugated magnetic field. Corrugation effects upon plasma conductivity are considered.

The third part of the paper reports experimental results of turbulent plasma heating in the toroidal device V-2. The confining magnetic field ($H = 15$ kOe) was 'bumpy-torus' shaped in the vicinity of the magnetic axis with a 'picket-fence' configuration near the walls. An electric field much above the Dreicer limit for $n = 10^{11}$–10^{12} particles/cm^{-3} was applied around the torus by means of a 1 Mc/s circuit. Plasma heating was studied under different operation conditions. The plasma confinement was found to be much in excess of the toroidal drift period.

* Presented by V. T. TOLOK. Full text of paper not available.

Ball-shaped plasma produced by a non-cylindrical linear discharge*

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THE discharge chamber is symmetrical about its axis, has a bulging central region, two symmetrical necks and cylindrical ends. The peak current of 200 kA has an initial rise time of $3 \cdot 10^{11}$ A . sec^{-1} and the chamber is filled with deuterium at a pressure of 1 torr.

The pinch effect develops more rapidly in the necks producing an axial pressure gradient and plasma jets. In the plane of these necks the compression ratio (initial to minimum radius) is about 30, and the temperature and density reach 130 eV and 5×10^{19} cm^{-3}. The interaction of the plasma jets with the radially compressed plasma in the bulge part of the chamber results in a ball-shaped plasma. This plasma splits off from the two ends of the column by instabilities that appear in the small diameter region.

With other electrical conditions a pulse of 10^7 neutrons is observed when the plasma column collapsing in the necks becomes unstable.

In order to explain the discharge dynamics a two-dimensional snowplough model was used with calculations performed on a computer. To check the validity of the model the momentum equations were first solved, the discharge current being set to its experimental value. The shape of the plasma column determined by a framing camera and the one calculated from the model are in good agreement. Other calculations were then performed in which the current was deduced by simultaneously solving electrical and momentum equations. It was compared with the experimental current. The stored energy is mainly transferred to the plasma located in the small diameter region of the tube.

* Presented by J. P. WATTEAU. Paper submitted to *The Physics of Fluids*.

Plasma ion–cyclotron instability in an adiabatic trap with minimum-B*

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IT HAS been reported previously that in the experiment on the PR-5 machine plasma instability arises spontaneously as several short-bursts during the period of the quiet charge exchange plasma decay. The instability is accompanied by the excitation of h.f. ion–cyclotron oscillations, by the acceleration of a small group of ions up to the energies of tens of keV, and by a sharp decrease of plasma density [1, 2].

Experimental conditions and plasma parameters are as follows: magnetic field in the centre of the trap is 3000 Oe, longitudinal and radial mirror ratios are 1·7 and 1·2 respectively, plasma density at the instant preceding the instability burst is $(3\text{–}5) \times 10^9$ cm^{-3}, proton average energy is 1 keV, electron temperature is 20–50 eV, plasma radius is 5–7 cm, and plasma length is 25–30 cm.

During one decay cycle one burst of instability is usually observed, and occasionally two or three bursts; the duration of each burst is 30–40 μsec.

Plasma losses during a burst may reach 50–80% of the initial amount of plasma in the trap. The plasma loss distribution on the vacuum chamber walls is non-uniform. Maximum losses are localized in the gaps between the stabilizing bars in the positions where magnetic field lines pass through the central region of the trap and intersect the wall. Noticable losses are also observed in the region opposite to the middle of the stabilizing bars, where magnetic lines are tangential to the walls. The analysis of the distribution obtained results in the conclusion that the losses across the magnetic field and along the field are of the same order of magnitude.

The frequency spectrum of the oscillations arising during instability consist of discrete narrow bands around the ion–cyclotron frequency and its harmonics. The ion–cyclotron frequency corresponds to the magnetic field strength in the centre of the trap. The first harmonic is the largest one. The amplitude of the h.f. magnetic field measured close to the walls of the chamber (in the central cross section) is $\approx 10^{-3}$ Oe, and the electric field amplitude amounts to 50–70 V/cm.

From the value of the electric field near the wall one can roughly estimate the transverse wavelength of the oscillations in the plasma $\lambda_\perp$; this proves to be of the order of 30 cm. Such a large value of $\lambda_\perp$ does not correspond to the theoretical values of $\lambda_\perp$ for unstable ion–cyclotron oscillations of a homogeneous plasma ($k_\perp \rho_i \approx 1$).

* Presented by M. S. IOFFE.

[1] YU. V. GOTT, M. S. IOFFE and E. E. YUSHMANOV, *Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham*, CN 21/143 (1965).
[2] YU. T. BAYBORODOV *et al.*, *JETP Lett.* **3**, 92 (1965).

Convective and absolute ion–cyclotron instabilities in homogeneous plasmas*

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ELECTROSTATIC ion–cyclotron instabilities, caused by a combination of the loss-cone effect and temperature anisotropy inherent in mirror confinement machines, are considered in an infinite plasma. For a loss-cone plasma of the type discussed by Guest and Dory, the modes become absolutely unstable at sufficiently high plasma densities for any anisotropy. Moreover, they should be expected in present-generation high-anisotropy mirror machines at currently available densities. Attempting to prevent the occurrence of these modes under reactor conditions would impose severe restrictions on plasma parameters such as electron temperature and length.

* Presented by C. O. BEASLEY. *Plasma Phys.* **10,** 411 (1968).

Experiments relating to high energy injection of charged hydrogen clusters*

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IT HAS been proposed that charged hydrogen clusters be used instead of molecular ions or neutral atoms for high energy injection into magnetic traps [1]. This paper describes experiments performed with hydrogen cluster ions accelerated to energies ranging from 25 to 150 keV cluster ion.

Mass spectrometric observations covering the range $0 \leqslant M/Z \leqslant 150$ (M = mass number, Z = charge number) reveal that the mass numbers of hydrogen cluster ions are predominantly odd, ions with even mass numbers contributing only a few per cent to the observed ion current. It is concluded that in solid or liquid phase the reaction $H_2^+ + H_2^0 = H_3^+ + H^0$ occurs with high probability.

The interaction of clusters with a gas target (water vapor) is investigated. Energy spectra of charged fragments are presented. The fractional mass loss of ions is studied as a function of beam parameter and of target thickness. Neutral fragments are observed by means of a magnetic electron multiplier.

* Presented by W. HENKES. Full text of paper not available.

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W. HENKES, *Phys. Lett.* **12,** 322 (1964).

Hollow pinch discharges in condensed molecular beams*

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HOLLOW beams of hydrogen or nitrogen clusters are produced by expanding the gases through a precooled annular nozzle into a high vacuum. At a distance of 12 cm from the nozzle the outer diameter of the beam was found to be about 30 mm, the inner diameter about 20 mm and the number density about (3–4) $\times 10^{16}$ molecules/cm^3 in the case of hydrogen and (3–4) $\times 10^{15}$ molecules/cm^3 in the case of nitrogen. The beam is passed through two ring-shaped electrodes. The discharge of a capacitor bank of 1·5 μF, 16 kV, along the beam converts the cluster beam into a plasma. As shown by image converter pictures the hollow plasma cylinder collapses within about 1 μsec forming a plasma column having a diameter comparable with the thickness of the initial plasma layer. No instabilities could be detected.

* Presented by R. KLINGELHÖFER. Parts of paper published in *Z. Naturforsch.* **22a,** 4 (1967).

Investigation on a cusp compression experiment*

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THE evolution of a plasma, produced by a fast crowbarred 11 kJ cusp compression experiment has been studied. Two different conical coil pairs were used, producing maximum magnetic field intensities $B \approx 70$ kG in the line- and point-cusps, with quarter periods of 1·7 and 1·1 μsec, respectively. The e-folding time of B after crowbar is 30 μsec. At maximum compression $T_e \approx 120$ eV, $T_i \approx 180$ eV, $n_e \approx 1 \times 10^{17}$ cm^{-3} (determined from soft X-ray emission [1], from Doppler-broadening of the CV spectral line [2], and from H-continuum radiation [3], respectively) for the fastest rising coil.

After crowbar the plasma diameter, obtained photometrically using a modified television camera [4], is about 4 cm and varies only slowly with time. Within the first 5 μsec, n_e decreases by a factor of 3; at later times the decay is slower ($n_e \approx 1 \times 10^{16}$ cm^{-3} at 12th μsec). A decrease of T_e is probable, since the CV and CIV lines reappear after 8 and 12 μsec, respectively. At 8 μsec, a measured $T_i \approx 50$ eV is found.

The results are compared with theory, mainly with the fluid model of HOBBS and SPALDING [5].

* Presented by E. KUGLER. Paper available as an internal report.

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Plasma investigation in the TUMAN machine*

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EXPERIMENTS undertaken in a study of ohmic heating and plasma compression in the toroidal TUMAN device are described in this paper. The TUMAN discharge chamber has the shape of a racetrack. In the toroidal sections the magnetic field reaches approximately 30 kOe and changes in the straight sections from 1–2 kOe during the ohmic heating phase to up to 30 kOe for the compression regime. The length of the plasma column is 250 cm. The volume filled with plasma is 15 litres for the ohmic heating stage and 1 litre for the maximum compression stage.

The first experiments indicated a limitation of ohmic heating caused by a transverse magnetic field existing in the device. In order to reduce the transverse field the design of the magnetic field was improved. In the toroidal sections an additional transverse field was produced by special coils. The optimum choice of the additional transverse field strength was 10^{-3} of the longitudinal one and permitted us to ignite the discharge at a much lower pressure and to cause an increase in plasma conductivity. The latter grows with the magnetic field and at a value of 24 kOe in the toroidal parts it attains 4×10^{14} CGSE ($T_e = 10$ eV). The plasma density for the ohmic heating regime equals $1{\cdot}5 \times 10^{14}$ cm^{-3} at a gas pressure 3 μ.

The plasma compression was effected by an increase in magnetic field in the straight sections of the racetrack from 0·5 to 10 kOe during a period of 20 μsec. In the toroidal sections the magnetic field was 12 kOe. The plasma compression was induced 150 μsec after the ohmic heating was switched on, at an instant when the plasma concentration reached its maximum. Optical measurements showed that the luminous radius of the plasma column diminished 3–4 times by compression. The plasma density inside the column increases by 5–7 times. Experiments on the microwave location of plasma showed that, at compression, a sharp decrease of plasma concentration was observed near the diaphragm. It appeared that the plasma column was displaced at compression to the external wall of the discharge chamber in the direction of the toroidal drift.

* Presented by A. B. BEREZIN.

Diffusion and space and time correlation measurements in DAPHNIS II*

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THE experiment DAPHNIS II was designed to produce a dense and macroscopically stable hydrogen plasma in order to study the diffusion of particles in a medium which avoids the difficulties arising from the presence of fast ionising particles (reflex discharge) or longitudinal current (positive column).

Production of the plasma required a proper choice of the magnetic field configuration in the source. In particular it was necessary to avoid the development of the flute type instability which was observed under certain conditions.

It was then possible to obtain a macroscopically stable plasma with a density of about 5×10^{12} cm^{-3} in a strong magnetic field (up to 7 kG).

To make our diffusion measurements we employed classical techniques such as Langmuir probes (also 'plasma eater') and u.h.f. interferometry. We also developed correlation techniques which enabled us to relate the radial diffusion to the instabilities by measuring the statistical product $\langle n(t) . E_0(t) \rangle$. These measurements indicated that the diffusion coefficient is one order of magnitude lower than Bohm's value [1].

Preliminary studies of the microinstabilities present in the plasma show that the frequency range and the radial correlation length are not incompatible with the theoretical characteristics of the drift instability [2].

* Presented by R. FRANK. Paper available as an internal report.

[1] M. BERNARD, G. BRIFFOD, M. GREGOIRE and J. WEISSE, *Proceedings of Conference on Physics of Quiescent Plasmas, Frascati* Part I (10–13 January 1967).
[2] See, for instance, S. S. MOISEEV and R. Z. SAGDEEV, *Sov. Phys. JETP* **17**, 515 (1964) and G. LAVAL and R. PELLAT, *Proceedings of Conference on Physics of Quiescent Plasmas, Frascati*, Part I (10–13 January 1967).

Two microwave cavity device for the study of wave scattering*

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Two spherical Fabry–Perot interferometers with focussing optics, at 4 mm wavelength, the characteristics of which have been already published, are used for measurements of the scattering of a millimetre wave by a plasma. The plasma is obtained by break-down in the air at the focus of a laser beam. The first interferometer focusses the incident h.f. beam of 35 W and produces a high electric field because of the high Q-factor of the cavity.

The second is used as a filter with high selectivity. The scattered wave, after passing through this interferometer, is amplified by a superheterodyne receiver with a sensitivity of 10^{-11} W.

We have observed a scattered wave and are studying its spectrum.

* Presented by L. SLAMA. Paper available as an internal report.

Some peculiarities of the plasma behavior in Tokamak TM-3*

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AS HAS been shown theoretically [1] and confirmed experimentally [2] under Tokamak conditions, that the shift of the plasma ring under the action of the transverse magnetic field is given by

$$\Delta_{B_\perp} = \frac{b \cdot B_\perp}{B_\nu(b)}, \tag{1}$$

where $\Delta_{B_\perp}$ is the shift of the equilibrium position, $B_\perp$ is the transverse magnetic field, b is the inner radius of the copper shell and $B_\nu(b)$ is the azimuthal magnetic field at the shell. The experiments using the model TM-3 disclosed certain conditions under which equation (1) was not valid. This discrepancy

* Presented by K. A. RAZUMOVA.

occurs within a definite range of the constant $B_\perp$ perpendicular to the plane of the toroid when the initial hydrogen pressure p_0 exceeds a critical value $(p_0)_{cr}$. The value of $(p_0)_{cr}$ increases when the discharge current and the longitudinal magnetic field increase. The phenomenon depends essentially on the conditions under which the plasma column is formed.

Another interesting effect in the discharges was observed at high energy input per particle. The transverse plasma energy determined under these conditions by the diamagnetic method was found to be higher than the electron temperature calculated from conductivity measurements, assuming that electron–ion Coulomb collisions take place. The value of the particle energy is about 1–2 keV.

The investigations of the absolute intensity and spectra of soft X-rays emitted from electron–ion collisions in the energy range 3–12 keV were used as an independent method of electron energy measurements. If we regard the electron energy distribution within the range mentioned above as a part of the Maxwellian distribution, then the effective electron temperature determined by this method is in a good agreement with the value measured by the diamagnetic method. The possible reasons for the existence of both anomalous effects are discussed.

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[2] V. S. Mukhovatov, *Plasma Physics and Controlled Nuclear Fusion Research*, Vol. II, 577, IAEA (1966).

Diffusion and stability in an 8-metre theta pinch*

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In order to study diffusion and stability a coil 8 metres long and 11 cms. in diameter was chosen. Using a Megajoule bank at 40 kV the magnetic field rises to 25 kG in 5 μsec and decays in 160 μsec when crowbarred. At 34 kV the measured temperature is 100 eV and the density on the axis is 3×10^{16}. The plasma in the mid-plane was free of energy loss by axial conduction or convection and unaffected by the ends due to disturbances propagating at the Alfvén speed, for 30 μsec. It remained stable and drift-free along its whole length for this time although some lateral motion developed with an amplitude less than the plasma diameter.

Preliminary results at 34 and 40 kV indicate a radial diffusion velocity much faster than that expected from binary collisions during the early stages of the discharge; after 5 μsec the time variation of the radial density distribution agrees with computations using classical resistivity and assuming no energy loss.

A 25 cm long axisymmetric region of adverse curvature, in which the plasma radius has been increased locally by a factor of 2 or 3, was generated in the mid-plane 2 μsec after the implosion. Streak photographs show a transverse ($m = 1$) motion of the plasma in the region at about 7 μsec but there is no evidence for higher modes. Ideal MHD computations for this configuration predict a growth time for an $m = 1$ instability of a few microseconds.

* Presented by H. A. B. Bodin. Full text of paper not available.

Recent results from the Julich theta pinch experiments*

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In the 600 kJ experiment, the decay and the axial variation of closed field configurations produced by compressing plasmas with reverse bias fields have been studied. For typical experimental conditions (50 mtorr D_2, 1·9 kG bias field, $B_{max} = 35$ kG, half-period 11 μsec) the antiparallel trapped magnetic flux was roughly constant during the adiabatic compression and decompression phases. After a rapid axial contraction, the length of the configuration remained approximately constant ($\approx 2/3$ of initial value).

* Presented by F. Waelbroeck. Paper submitted to the *Proceedings of the APS Topical Conference on Pulsed High Density Plasma, Los Alamos*, September 1967.

In another experiment the continuum intensity emitted in the visible part of the spectrum was measured and compared to the theoretically expected values; the electron density distribution was obtained by side-on interferometry. The results show a deviation which is greater than the estimated experimental error. The wavelength dependence of this emission was measured between 0·3 and 6 μ in a third experiment. Although a rough agreement with theoretical expectations was obtained, the observed deviations are here also greater than the experimental errors.

Breakdown and compression in superposed fields theta-pinch*

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EFFICIENT production, fast heating and a long containment time of high density plasmas may be obtained, in principle, with the 'sustained field theta pinch', in which a high frequency oscillating magnetic field with appropriate damping is superimposed on a constant, or nearly constant field of opposite direction and slightly smaller maximum amplitude, already present in the gas region.

The paper describes some experiments in which the superposition has been obtained by means of two independent coaxial coils designed to give fields of good azimuthal symmetry [1].

Measurements are reported on hydrogen discharges at different pressures, by means of external magnetic probes, photomultipliers and a streak-camera. The results are discussed in relation to a normal theta-pinch.

Field maps in the actual coils and in electrolytic analogue are shown; the influence of the configuration (in particular end effects and asymmetries) and wave-form of the field on the behaviour of the discharge is analysed.

* Presented by G. ROSTAGNI. Paper available as an internal report of Istituto di Elettrotecnica, University of Padova, Italy.

† The untimely death of the co-author, Dr. ITALO FACCINI, occurred on 15 December 1966.

[1] G. ROSTAGNI, Magnetic field superposition technique for fast compression and long containment time of plasma in theta pinches, *Alta Frequenza* **36**, 155 (1967).

Experimental study of ion–cyclotron plasma instability in a mirror machine*

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ION–CYCLOTRON oscillations in a hot ion plasma have been investigated. The experiments were carried out in the mirror machine 'AC' [1]. In contrast to previous experiments [1] the plasma was generated by injection of accelerated hydrogen ions in a source which was placed at the machine axis. The fast ions were captured by a magnetic field growing in time in the quasistationary mirror. The injection current varied from 0·1 mA to 6 mA, the plasma density being from 4×10^5 to 2×10^7 cm^{-3}.

As the current increased from 0·1 to 0·8 mA a threshold was observed which caused a sharp increase in the alternating electric field amplitude at the ion–cyclotron frequency and its harmonics (more than two orders of magnitude). This was observed even when the ion life-time was limited by the time of its flight from the source to the stationary mirror (the quasistationary mirror was switched off). At higher injection currents the amplitude of the high-frequency oscillations was directly proportional to the injected current.

As a result of the oscillations some of the fast ions escape to the wall of the chamber. The angular distribution of the ions broadens and they penetrate deeper into the magnetic mirror.

The threshold value of the plasma density depends on the magnitude of the magnetic field and satisfies the criterion that the ion–cyclotron instability must develop with maximum increment if the fast ion distribution function has a positive derivative with respect to the transverse energy. This criterion corresponds to the cyclotron-cone instability. When a plasma is trapped, the high-frequency oscillations are damped during a time less than 100 μsec at the same time as low-frequency flute oscillations appear. They determine the life-time of the fast ions.

* Presented by I. N. GOLOVIN. Paper has been published in *JETP* **53**, 53 (1967).

[1] А. Б. Бортников и др. Атомная Энергия **18**, 3 (1965).

The ICARE experiment*

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FOLLOWING the work reported at the Munich Conference (1966), ICARE has been operated with pulsed high frequency power in an accelerating B-configuration at $\sim 10^{-5}$ torr argon.

The evolution of the discharge during the pulse is described.

It is shown that the energy of the ions is equal to the electrostatic potential in the vicinity of the resonance region.

The energy is accounted for by the relativistic theory of electron–cyclotron resonance.

The gas injector has proved capable of injecting 50 times more particles than was hoped, because of the pulsed mode of operation.

An ion current density of 50 μA/cm² has been obtained at 10 keV.

Approximately 15 per cent of the useful r.f. energy is converted into ion kinetic energy.

The efficiency of the device increases with particle density and flux.

Preliminary results with an intense source driven by a laser show an increase in ion energy (20–40 keV) and instantaneous flux density, and an improvement in microwave absorption by the plasma.

* Presented by G. MOURIER. Paper available as an internal report.

† From Compagnie Générale de Télégraphie sans Fil, Corbeville, 91-Orsay, France.

Ion–cyclotron instability in DECA II*

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AS SHOWN in 1966 (Munich conference), an ion–cyclotron instability has been detected in the magnetic well stabilized plasma of DECA II (deuterons, $n_i = 2 \times 10^{10}$ cm^{-3}, $\bar{E}_i = 1{\cdot}5$ keV).

Phase measurements showed that, for the first harmonic, the azimuthal mode is $m = 2$ (i.e. $\lambda_\perp \simeq 5a_i$, where a_i is the mean Larmor radius) and that the longitudinal wavelength is greater than 14 cm.

The experimental observations which support the identification of this instability as the double-distribution cyclotron instability are presented.

The plasma anisotropy, deduced from energy analysis of fast neutral atoms emitted by the plasma [1], is not sufficient to produce a Harris-type instability.

The start of the oscillation seems to correspond to the arrival of the cold plasma.

The amount of cold plasma (up to 50 per cent in density) is sufficient to produce a double-distribution instability [2].

* Presented by the author. Paper published in *C.R. Acad. Sci.* **264,** 1787 (1967).

[1] P. LECOUSTEY and C. RENAUD, *Plasma Physics* **9**, 527 (1967)
[2] L. S. HALL, W. HECKROTTE and T. KAMMASH, *Phys. Rev.* **139,** 1117 (1965).

Heating of plasma at the electron–cyclotron resonance in non-uniform fields*

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WE HAVE studied, theoretically and experimentally, the transfer of energy of a circularly polarized h.f. wave to a plasma at the electron–cyclotron resonance in a decreasing axial magnetic field combined with a transverse magnetic field created by 6 axial conductors.

* Presented by L. DUPAS.

† On leave of absence from Gruppo Gas Ionizzati del C.N.R., Padova University, Italy.

The set-up is a new version of the CIRCE experiment with a higher power (2·5 kW instead of 300 W at 10 GHz). The B_z field is about 4 kG with a gradient $\Delta B/l$ of the order of 300 G cm^{-1} and the transverse field B_{max} near the waveguide of about 2 kG.

The study with an analogue computer shows that the plasma is maintained far from the walls. Moreover, with the same h.f. power fed to the plasma, the parallel energy of the ions is greater because the coupling is better in the new version with Ioffe-bars. Also the losses by radial diffusion are decreased.

Second order magnetodynamic stability of an infinite cylinder*

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THE problem of the stability of an infinitely long liquid jet is solved analytically to second order for axisymmetric and incompressible perturbations. The method is extended to include the effect of a uniform axial magnetic field. No frequency or wavenumber shift occurs. It is also shown that the 'bandwidth' around the mode of maximum instability is quite large.

Good agreement is obtained with experimental data which definitely cannot be explained by a linearized theory.

* Presented by the author.

Ion–cyclotron instabilities in a plasma confined in a magnetic well*

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IN the PHOENIX II magnetic well plasma, formed by the injection of 20 keV hydrogen atoms, ion–cyclotron instabilities are observed to occur in millisecond bursts and electric field oscillations are observed at the ion–cyclotron frequency (20 Mc/s) and its harmonics. The frequency spectrum, though relatively simple at densities below 10^9 protons cm^{-3}, becomes much more complicated as the density is increased. The high frequency activity can be divided into three regimes with the following properties. The emission predominates at:

(a) the ion–cyclotron frequency;

(b) the second and fourth harmonic of cyclotron frequency;

(c) the third harmonic.

These three regimes have been observed at the densities corresponding to the value of ω_{pe}/ω_{ci} of 10, 20, and 23 respectively. In regimes (b) and (c) the fundamental cyclotron frequency is virtually absent while in (c) second and fourth harmonic are less intense than in (b). It should be added that while the fundamental, second and fourth harmonic seem to belong to the same sequence, the third has a frequency 5–10% lower than that expected for the third member of the sequence. Emission at 3 Mc/s above and below these frequencies is also observed. As the density is increased the discrete frequencies merge into bands 6–10 megacycles wide.

The emission at the second and fourth and the third harmonic is accompanied by particle losses. Despite this the central density is always equal or above that expected on the basis of simple Lorentz trapping of the beam and charge exchange losses only.

Information about the wavelengths exists only for the second harmonic. It is found that the dominant mode has half the wavelength within the plasma, along the field lines, with a zero in the potential on the median plane. Preliminary measurements indicate the same result for the other observed frequencies. Also the currents in the plasma are predominantly axial indicating that the fluctuating electric and magnetic fields are due to axial motion of electrons.

The instability thresholds, and weakening of the lower harmonics at higher densities are in quantitative agreement with the theory of BEASLEY and CORDEY [1] for the absolute ion–cyclotron instability due to both the monoenergetic and highly anisotropic ion distribution in the PHOENIX II

* Presented by M. PETRAVIĆ. Paper will be available as an internal report.

† On attachment to Culham Laboratory from Aeronomy Laboratory, Boulder, Colorado, U.S.A.

experiment. In particular the theory predicts an increase of the parallel wavelength with density for each harmonic, suggesting that the weakening of the lower harmonic is due to the parallel wavelength becoming too long to fit in the plasma.

[1] C. O. BEASLEY and J. G. CORDEY, *Plasma Physics* to be published.

High frequency electron acceleration in a mirror region*

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AN ANALYTICAL method is presented to approximate particle trajectories in a high frequency plasma accelerator placed in a magnetic mirror. Neither adiabatic assumptions nor the time averaged Miller's forces are utilized.

The analytical expressions found are tested numerically in a number of characteristic cases.

The effect of relativity, Doppler frequency shift, large injection energy and initial particle position on the acceleration process is calculated.

* Presented by the author. Paper available as an internal report, IGn, RT 540.

† Association CEA-EURATOM.

Ion acceleration and shock waves in a high frequency plasma structure*

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WHEN a resonant electromagnetic field accelerates electrons in a mirror region, an axial ion flux is produced by the self-consistent space charge field.

Steady electrostatic shock waves appear in the resonance region in the high power regime and when the electron axial velocity exceeds a critical value.

The self-consistent axial field and particle velocities are computed in a number of typical cases.

* Presented by E. CANOBBIO. Paper available as an internal report, IGn, RT 539.

† Association CEA-EURATOM.

A study of some technological aspects and economic problems associated with a possible fusion reactor*

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IT IS assumed that the problems of plasma containment have been solved and consideration is given to some of the technological requirements of a fusion reactor which could generate power economically.

Important engineering parameters are, the strength of the magnetic field, the power flux through the wall, the percentage of circulating power and the tritium breeding arrangements. Simple relationships are established which place definite limits on the plasma parameters which must be achieved if these engineering requirements are to be satisfied. One important result is the need for a high β, 5–10%.

Various containment geometries are considered to assess their reactor potential. A steady state, closed line device leads to the smallest unit size which satisfies the engineering and economic requirements. Even so, the minimum sized unit is one which would generate about 2000 MW of electrical power.

A 2000 MW(e) unit is used as the basis of a design study to establish whether we can envisage a fusion reactor being competitive with other power sources. The study shows that this is possible but reveals some stimulating technological problems which must be solved before its realisation.

The work has been mainly concerned with the D–T reaction but some of the requirements for a D–D reactor have been established. Most significant is the requirement for a much higher β, 30–60% for an economic, 2000 MW(e) unit.

* Presented by the author. Paper will be available as a Culham Laboratory Report.

Collision effects on the CIRCE device*

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SOME of the properties of the CIRCE device as well as its principle of operation have been presented elsewhere[1]. This paper concerns the extension of our CIRCE studies to include the effects of collisions on the acceleration mechanisms (ionization, momentum transfer, and charge exchange). Their effects on the CIRCE mechanism of producing high energy spiralling electrons along with energetic unidirectional ions is studied with extraction, gridded probes, Langmuir probes and optical diagnostic. Also, the properties of the background plasma (produced through collisions of the primary charged constituents with the gas molecules), both inside and exterior to the wave–plasma interaction region, are investigated and their effects on the collision processes are deduced.

Finally, the interaction between the primary and background plasmas through collective 'collisions' (collective space charge interactions) is evaluated experimentally to ascertain the role of instabilities in the CIRCE performance (Energy exchange from the 'hot' primary plasma to the cold background plasma is the principal consideration).

* Presented by R. GELLER.

[1] R. BARDET, M. CADART, T. CONSOLI, L. DUPAS, R. GELLER, J. LEROY and F. PARLANGE, Coll. INT. UHF, Saclay, Sept. 1964; Rep. PA. IGn/RT 301; *Proc.* VII *Conf. Phenomena in Ionized Gases*, Belgrad, Vol. III, p. 318, Aug. 1965.

The ion–cyclotron drift loss-cone instability in mirror magnetic wells*

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WE HAVE examined the additional effect upon the ion cyclotron drift loss-cone instability [1] of the following:

(1) *Ion density gradient*

Following the work of POST and ROSENBLUTH [1], we have calculated numerically the effect of inclusion of the ion density gradient term in addition to the electron density gradient term. It is found that a high density and high gradient stable region no longer exists when this term is included.

(2) *Magnetic field gradient*

The dispersion relation is solved and the real and imaginary parts of the frequency are found for various values of density and $k_y\bar{a}_i$, where k_y is the wavenumber in the direction perpendicular to the density gradient, and $\bar{a}_i$ the average in Larmor radius. Both the uniform magnetic field case and the case of a realistic magnetic well are examined in the local approximation. The effect of the field gradient is to alter the frequency of the wave ω to $\omega + (k_y v^2/2\Omega_{ci}^2)(\mathrm{d}\Omega_{ci}/\mathrm{d}x)$. The peak growth rate around $k_y\bar{a}_i \simeq 2{\cdot}5$ is slightly reduced but the resonance in $k_y\bar{a}_i$ is also broadened so that the plasma is now unstable for $k_y\bar{a}_i < 2$.

(3) *The potential distribution inside a plasma slab*

In order to approximate more closely to a finite cylinder of plasma, we consider here a plasma slab with maximum density at one boundary decreasing linearly to zero density at the other. To improve on the local approximation we use the general form for the potential $\Phi = \phi(x)\,\mathrm{e}^{ik_y y}$ and obtain a second-order differential equation for $\phi(x)$ with the assumption that $\phi(x)$ is slowly varying over distances of an ion Larmor radius. This equation is solved numerically for the boundary conditions $\phi(0) = 0$ and

$$\frac{\dfrac{\mathrm{d}\phi(x_0)}{\mathrm{d}x}}{\phi(x_0)} = \frac{-k_y}{\kappa}$$

where x_0 is the plasma boundary and κ is the first diagonal component of the dielectric tensor. The second condition was obtained by integrating the differential equation for $\phi(x)$ across the boundary. The roots ω_x, corresponding to different radial wavenumbers k_x are plotted as a function of density and the point at which the plasma goes unstable is found in the usual manner as the point in density at which

* Presented by L. G. KUO-PETRAVIĆ. Paper to be submitted to *The Physics of Fluids*.

the two real roots, in the frequency ω, disappear. It is found that for small radial wavenumbers, a plasma slab with a maximum density D is only marginally more stable than a point with the same density D treated in the local approximation. Interesting information is obtained, however, concerning the ratio of the potentials inside and outside the plasma.

[1] R. F. Post and M. N. Rosenbluth, *Physics Fluids* **9**, 730 (1966).

Some studies of transverse plasma wave instabilities*

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This paper describes studies of the plasma microinstability in which an electromagnetic plasma wave, circularly polarized in the right-hand sense, and propagating parallel to a uniform magnetic field (= 'whistler' mode) can be driven into instability by a non-Maxwellian charged particle velocity distribution. The results of the work are, first, some numerical estimates of the growth rates, and second, a demonstration of the necessity for carrying out a thorough analysis of the instability according to the recently developed criteria of Briggs and Bers, and Derfler, rather than just examining the dispersion relation for absolute instability. In this case, if the plasma is assumed to be cold, and is assumed to contain a small group of particles with high transverse energy, an absolute instability (complex ω for real k) is predicted. Even a modest electron temperature stabilizes this instability. Under these circumstances, however, an equally strong convective instability remains (complex k for real ω) which is not so easily quenched. Preliminary comparisons with the growth rates of electrostatic instabilities occurring for the same parameters suggest that these would dominate in a practical situation. Experiments are being carried out to check this point.

* Presented by F. W. Crawford. Paper available as an internal report, SU-IPR 151.

Fourier-Hermite expansion of the non-linear Vlasov equation*

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As an approach to the non-linear problem, Grant and Feix [1, 2] have applied a Fourier series expansion in configuration space and a Hermite polynomial expansion in velocity space to the Vlasov problem. They showed the relation between the F.–H. method and Landau's and van Kampen's solutions to the linearized problem. They showed that instabilities due to truncation in Hermite space can be avoided by introducing a small collision term of Fokker–Planck form (there is no truncation error in Fourier space for the linearized problem). We have recently found that improved convergence to the Landau result can be obtained by using a very small collision frequency but applying the Fokker–Planck operator several times.

For linearly stable initial conditions and for small level of non-linearity, we find that convergence in Hermite space is rather slow. This is due to the necessity of representing an important modification of the distribution function for velocities in a region $\Delta v = \gamma_k/k$ near the phase velocity [3] (γ_k is the Landau damping). The fundamental Fourier component exhibits a relatively quick convergence in the number of Hermite coefficients retained, and behaves in a quasi-linear way. This is not true for the higher harmonics. For a linearly unstable (two-stream) initial condition, a pronounced instability occurs, arising first for the higher harmonics (only the fundamental was initially excited) and rapidly propagates to lower wavenumbers. The meaning of these results will be discussed.

* Presented by F. R. Crownfield. Paper being prepared for submission, possibly to *The Physics of Fluids*.

† NAS Senior Research Associate, on leave from Euratom. Now at: Université de Nancy, Nancy, France.

[1] F. C. Grant and M. R. Feix, *Physics Fluids* **10**, 696 (1967).
[2] F. C. Grant and M. R. Feix, *Physics Fluids* **10**, 1356 (1967).
[3] Cf. S. P. Gary, *Physics Fluids* **10**, 570 (1967).

Explicit solution of loss-cone dispersion relations*

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A CONVENIENT technique for solving dispersion equations of the kind encountered in plasma physics has been described previously [1]. Application of this method to the dispersion equations associated with a collisionless, magnetized plasma has been demonstrated effectively with the use [2] of an on-line digital computer which provides easy access to functional operations in the complex plane, as well as immediate displays of arcs or contours [3]. New features and recent refinements of this method are discussed and the technique is then applied to the case of the Rosenbluth–Post 'loss-cone' instability in its most virulent form, i.e. when the distribution function is of the form $\exp(-v_{\parallel}^2/a_{\parallel}^2)\delta(v_{\perp} - a_{\perp})$. The transition from the case of small $x \equiv (k_{\perp}a_{\perp}/\omega_{ci})$, where a few terms of the Bessel function series dominate the behaviour, to the case of large x is illustrated. The relation of these exact solutions to those obtained in the high-density, short-wavelength limiting case studied by Rosenbluth and Post [4] is shown. Some aspects of the convective vs. non-convective nature of this instability are discussed.

* Presented by J. E. McCUNE. Paper available as an internal report, Center for Space Research Report No. CSR-TR-67-1, M.I.T. (1967).

[1] J. E. McCUNE, *Physics Fluids* 9, 2082 (1966).
[2] B. D. FRIED, *On-line root finding in the complex plane*, Report No. 9990-7308-R0000 [TRW Systems, Redondo Beach, Calif. (1966); J. E. McCUNE and B. D. FRIED, *The Cauchy-integral root-finding method and the plasma loss-cone instability*, Center for Space Research Report No. CSR-TR-67-1, M.I.T. (1967).
[3] B. D. FRIED, *Solving mathematical problems*, in *On-line Computing* (Ed. W. KARPLUS) Chap. VI, McGraw-Hill. Also G. J. CULLER, *Users manual for an on-line system*, Appendix, *loc. cit.*
[4] M. N. ROSENBLUTH and R. F. POST, *Physics Fluids* 8, 547 (1965); 9, 730 (1966).

Investigations of plasma equilibrium in a torus with high frequency and longitudinal static magnetic fields*

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TOROIDAL systems in which a strong static magnetic field is combined with a relatively small high-frequency field appear important. The static magnetic field confines the plasma within a small radius, while the high-frequency magnetic field serves as a small stabilizing factor.

In the case of a longitudinal toroidal magnetic field, a superimposed h.f. multiple magnetic field with $E_{\sim}//H_z$ can compensate a toroidal drift at a h.f. field pressure of a value lower than the plasma gas kinetic pressure.

In the case of a helical static magnetic field, where the equilibrium problem has been resolved, a h.f. field, according to the theory, can stabilize some modes of drift instabilities.

Toroidal drift compensation and h.f. skin problems in a magnetoactive plasma have been studied in the present experiments in the equipment "RT-O" representing an extension of a previous investigation [1].

The range of effective interactions of a rotating helical quadrupole h.f. magnetic field with a plasma in a quasistatic longitudinal toroidal magnetic field has been investigated. It is shown, that at $H_z < H_{z\,\mathrm{crit}}$ the plasma energy parameters ($nT \simeq 2 \cdot 10^{16}$ eV/cm^3, $T_{e\,\max} \lessapprox 50$ eV) are considerably higher than in [1], where $H_z > H_{z\,\mathrm{crit}}$.

The critical field corresponds to a value of H_z at which the h.f. field phase velocity component along the torus longitudinal axis is higher than the Alfvén velocity; this fact corresponds fairly well to the relevant theory.

* Presented by A. G. KIROV.

At $H_z < H_{z\,\mathrm{crit}}$ a h.f. skin effect is observed; it is measured by means of magnetic probes, the skin depth being in rather good agreement with the expression

$$\delta = \frac{c}{\omega_p}\left(\frac{2\nu_{ei}}{\omega}\right)^{1/2}.$$

Measurements of the main parameters of the toroidal plasma such as its diameter $d_p = 2r_p$, the displacement to the external wall Δ, the plasma gas-kinetic pressure, the h.f. field pressure on the plasma boundary, and their interrelations allowed us to compare the experimental results with the theory of toroidal drift compensation by means of the h.f. field.

It is shown that the plasma column position is satisfactorily described by the expression:

$$\Delta = \frac{2r_K^{2(m-1)}}{R(m-1)r_p^{2(m-1)}}\,\frac{nT}{\tilde{H}_K^2/8\pi},$$

where r_K is the minor radius of the toroidal current surface; R is the major radius of the plasma column; $\tilde{H}_K$ the h.f. field on the current boundary; and m the h.f. field multipole index.

On the basis of the experimental results, a model of the plasma column behaviour in an 'RT-O' equipment has been built at $H_z < H_{z\,\mathrm{crit}}$. Further, the preliminary results indicate the dependence of plasma parameters on the direction of the h.f. field rotation.

The results described were obtained in the following range of conditions: $H_z = (1-8)\times 10^3$ Oe, $H_\varphi = 250$ Oe on the plasma boundary, the h.f. field frequency being 740 kc/sec and the filling gases H_2 and He having initial pressures between 8×10^{-4} and 6×10^{-3} torr.

[1] R. A. DEMIRKHANOV *et al.*, CN-21/191, Culham (1965).

Invariants in the motion of a charged particle in a spatially modulated magnetic field*

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THE invariants of particle motion play an important role both in the trapping and containment of charged particles in magnetic confinement systems. For sufficiently smooth fields the magnetic moment $\mu = v_\perp^2/B$ is an adiabatic invariant. This paper considers the effect of a small spatial modulation on the behaviour of μ.

When the modulation wavelength is comparable with the gyromagnetic radius of the particle, μ is no longer an adiabatic invariant; the aim is to discover whether a new invariant exists which replaces μ. We have analysed numerically and analytically the special case of axial symmetry with the axial magnetic field $B_z = B_0(1 + \varepsilon f(z))$, and $f(z)$ a square oscillation, alternately ± 1. In this case the orbit equations reduce to a set of algebraic equations.

We find numerically that, as initial values are varied, orbits are of two types, (a) orbits which generate an invariant of the motion, (b) orbits which fill quasi-ergodically that part of phase space not mapped by orbits of type (a).

Analytically, we have considered the motion from the point of view of perturbation theory with ε as a small parameter. One can then seek an adiabatic invariant J as a power series in ε. The usual methods for generating such an invariant break down because of the resonance between the period of the perturbation and the cyclotron period. A modified form of perturbation theory is, therefore, introduced which overcomes this difficulty. The resulting invariant shows very good agreement with the numerical calculations in the regions of phase space occupied by orbits of type (a). The quasi-ergodic behaviour is, of course, not found analytically but the much more complicated topology of the invariant curves in these regions may be a clue to its origin.

* Presented by E. W. LAING. Paper is available as an internal report and has been submitted to the *Journal of Mathematical Physics*.

Preliminary study of the effect of density gradients in a large diameter 'Q'-machine

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THE stability of a large diameter (up to 8 cm), magnetized potassium plasma column is being investigated. The temperature profile of the hot plate can be changed at will and hence different density profiles can be obtained. In particular a plasma having lower density on the axis than at the edge can be produced. Reasonable agreement has been found between the measured density and voltage profiles and a modified equilibrium model. In the low density regime (from $\sim 10^9$ cm^{-3} to $\sim 5 \times 10^{10}$ cm^{-3}) and with magnetic fields between 2 and 7 kG, no evidence of large amplitude spontaneous oscillations has been found.

* Presented by L. ENRIQUES. Full text of paper not available.

Investigation of 'overturning' of the strong shock wave in a plasma*

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THE change of the shock front structure caused by the change of the Mach number beyond the critical value Mach M_{cr} was investigated. The following questions were considered: (1) transitional processes within the shock front on the stage before 'overturning' ($M \leqslant M_{cr}$); (2) the stationary state after the 'overturning' ($M > M_{cr}$); (3) non-stationary process and instabilities due to the multiple-velocity current arising after an 'overturning'.

Shock waves of cylindrical type were exited in a plasma with density $n = 10^{12}$–2×10^{14} cm^{-3} and initial magnetic field $H = 200$–500 G. Velocity and direction of the propagation of the shock and the magnetic and density profiles were determined by using a system of magnetic and u.h.f. probes.

Investigations in different gases (hydrogen, helium, argon) show that the critical Mach number M_{cr} and the width of the shock front Δ depend in a general way on the parameters of the experiment if $\Delta/R < 1$ (R radius of the system).

Microfluctuations of the electric and magnetic field within the shock front are studied by means of the electric and magnetic measurements. These fluctuations may arise due to the instability of a multiple-velocity motion of ions after the 'overturning' of the shock front. As a result of the instability caused by the ion velocity anisotropy the appearance in the experiments of the radial component of the magnetic field (H_r) behind the front of the straight shock wave can be explained.

* Presented by R. H. KURTMULLAEV.

Properties of a pulse heated plasma in a magnetic mirror geometry*

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A FAST and strong magnetic disturbance of a warm plasma drifting slowly along a static magnetic mirror system produces *in situ* a hot electron and a hot ion plasma. The main parameters before the heating procedure have been varied in the range $10^{13} > n_e > 10^{12}$ cm^{-3}, $7 < T_e < 15$ eV and $10 < T_i < 150$ eV. After heating, these parameters become $n_e < 5 \times 10^{11}$ cm^{-3}, $T_e \simeq 10$ keV for the hot electrons and $T_i \approx 400$ eV for the ions. Microwave and light measurements suggest the presence of a cold plasma with a density of about 10^{12} cm^{-3}. The loss rate of the hot ions is much higher than expected from charge exchange. Their number appears lower than that of the hot electrons. During their short existence (60 μsec), the plasma exhibit radial motions and electrical fluctuations with frequency in the 1 to 10 MHz range. After the disappearance of the hot ions, the hot electron component can be confined with e-folding times of several milliseconds. Above a critical density however,

* Presented by J. JACQUINOT. Paper submitted to the *Proceedings of the APS Topical Conference on Pulsed High Density Plasma, Los Alamos* (1967).

the plasma transverse energy decreases step-wise. Two different types of instability have been identified. At low density (somewhat above 3×10^{10} cm^{-3}) a velocity space instability occurs with important particle scattering into the loss cone. At higher densities ($\simeq 1{\cdot}5 \times 10^{11}$ cm^{-3}) the plasma exhibits a motion in one radial direction and a considerable amount of plasma is lost on one side of the vacuum chamber. In both cases polarized microwave radiation in the vicinity of the electron–cyclotron frequency is emitted during the instability. The anisotropy in velocity space of the electron distribution can be measured. It is found that $p_{e\parallel}/p_{e\perp}$ is usually about 15% and it increases during the instability.

Toroidal confinement with temperature gradients*

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THIS paper deals with a model steady-state plasma in the toroidal magnetic field of stellarator geometry ($\beta \ll 1$) in which a temperature gradient forms as a result of the input energy being transported to the wall by thermal conduction. No particle source is needed to maintain steady-state conditions. There is a region where the thermal conductivity parallel to the field lines is sufficiently high to keep the temperature constant in zeroth order on a magnetic surface. In this region the energy equation can be expanded and the temperature profile can be obtained from an ordinary second-order differential equation, just as in a linear discharge. Here, however, the thermal conductivity is increased by the amount of the reciprocal of the rotational transform compared with the linear case. The density profile can be derived from a solubility condition that has to be imposed on the equation of continuity. The thermal diffusion coefficient thereby plays an important part in Ohm's law because it establishes a relation between the density and temperature gradients.

* Presented by the author.

Destruction of magnetic surfaces in toroidal systems

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THE problem of resonances in the magnetic surface structure is discussed. The equations for the magnetic field lines are transformed into Hamiltonian form and asymptotic perturbation theory is developed which helps to determine the resonance destruction of the magnetic surfaces due to violation of rotational symmetry. The results of analytic considerations are compared with numerical values for the vacuum magnetic field which is of toroidal shape like that of the stellarator. It was assumed to have the form

$$\varphi = z + \tfrac{1}{3}z^3 \sin 3(\varphi - z) + \varepsilon r^q \sin (m\varphi - pz),$$

where φ is the potential of the magnetic field and the parameters are $\varepsilon = 10^{-2}$–10^{-4}, $m = 2, 4, 90$; $q = 2, 3, 4$; $p = 0{,}3$.

* Presented by G. ZASLAVSKI. Paper submitted to *Nuclear Fusion*.

Equilibrium and stability in toroidal systems

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A GENERAL survey of equilibrium and stability in low-β collisionless plasmas is given with special emphasis on new results obtained by the author in collaboration with P. H. Rutherford. We first discuss the general problem of the containment of magnetic field lines in toroidal configurations. We then go on to discuss single particle confinement in these fields using the small Larmor radius approximation. It is pointed out that different forms of the particle distribution function are imposed depending on whether equilibrium is required on the short time scale $t \approx L/v_{\parallel}$ or on the long time scale

L/v_D. We next turn to discussion of a new theory of the stability of low frequency modes in general magnetic field configurations. We point out that absolute stability criteria can be achieved in a few cases. For example, $\partial F/\partial\varepsilon|_{\mu\alpha\beta} < 0$ and $\partial F/\partial\varepsilon|_{\mu J} < 0$ are required for the trapped particle mode and

$$\sum \frac{e^2}{m} \int \frac{d\mu\, d\varepsilon}{|q|} \left\{1 - J_0^2 \left(\frac{|\nabla S|\,(2\mu B)^{1/2}}{\Omega}\right)\right\}\left\{\frac{1}{B}\frac{\partial F}{\partial \mu} + \frac{\partial F}{\partial \varepsilon}\right\} < 0$$

and $\partial F/\partial\varepsilon < 0$ for minimum B, $F(\varepsilon, \mu)$ distributions. In other cases, a normal mode analysis must be done. Detailed results for axisymmetric geometries, such as multipoles, both with and without shear are given.

* Presented by the author.

Kinetics of the formation of a plasma by injection of fast atoms into a closed magnetic configuration*

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WE STUDY the build-up of a plasma by the injection of 5 keV hydrogen atoms in a closed magnetic configuration.

We investigate the detailed balance of particles by writing down the equation of evolution for the four following populations: fast protons, slow molecular ions, slow protons and neutral gas molecules. To do so, we take into account fifteen different processes producing ionization, dissociation and charge exchange between the different populations including the electrons. The energy dependence of the cross sections is also taken into account. A detailed balance of energy enables us to calculate the distribution function of fast ions and the temperature of electrons as well as of slow ions. The only energy source introduced into the system is due to the fast captured ions which give their energy to the electrons, the latter losing it by various reactions with the slow ions and the neutral gas. The study includes the temporary variation of the seven quantities quoted before, for different values of the injected current and pressure. We show that, if the diffusion is collisional, the cold plasma effectively supports the decay of the hot plasma. Currents of about 10 to 100 mA injected for a few seconds allow the formation of a hot plasma with high density.

The role played in the build-up by some important factors such as capture by Lorentz forces, cascading, the presence of impurities, and the lifetime of the plasma is specified.

* Presented by J. P. GIRARD.

Equilibria, stability and transport coefficients of plasma in a toroidal geometry

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THE transport coefficient of plasma in a toroidal trap is of special interest. We start by the following model of the magnetic field

$$\mathbf{H} = H_0[(1 - \varepsilon \cos\vartheta)\mathbf{e}_z + \vartheta \mathbf{e}_\vartheta]; \quad \varepsilon = r/R; \quad \vartheta = ir/2\pi R$$

where r, ϑ are the polar co-ordinates in the cross section of the toroidal discharge tube of radius R, and $\vartheta(r)$ is a rotational transform. The particles are assigned to two species according to the set of their constants of motion: energy E and adiabatic invariants $\mu_\perp = v_\perp^2/2H$,

$$J = v_\| + \omega_c \int_0^r \vartheta\, dr\,; \quad \omega_c = \frac{eH}{mc}, \quad v_\| = \sigma \sqrt{\frac{2}{m}(E - \mu_\perp H)},$$

(where $v_\|$ is the velocity component parallel to the magnetic field) for particles oscillating between the magnetic mirrors, and $E, \mu_\perp, J$ and $\sigma = \text{sign}\ v_\|$ for particles circulating around closed field lines.

* Presented by A. A. GALEEV. Parts of paper published in *Z. exp. teor. Fiz.* **53**, 348 (1967).

The velocity distributions of these particles in the absence of collisions are functions of their invariants and are different.

In the singular domain between the regions of trapped and untrapped particles we solve the Boltzmann equation with the collisional term in a form proposed by Landau. The enhanced collisions in this domain lead to large transport coefficients of plasma. The toroidal correction to the ion thermal conductivity, for example, is

$$\chi_{\perp i} \approx 0{\cdot}4\nu_{i/i} r_{ci}^2\, 4\pi^2 \varepsilon^{-3/2}/i^2 \quad \text{for} \quad \tau_i \nu_{i/i}/\varepsilon \ll 1$$

$$\chi_{\perp i} \approx 1{\cdot}5(\sqrt{\pi})\varepsilon^2 (r_{ci}/\tau\vartheta)(cT_i/eH_0) \quad \text{for} \quad 1 \ll \tau_i \nu_{i/i}/\varepsilon \ll \varepsilon^{-3/2},$$

where $\nu_{i/i} \approx 16(\sqrt{\pi})\lambda_e^4 n/3m_i^2 v_{thi}^3$ is the ion–ion collision frequency, $\tau_i = r/v_{thi}\vartheta\sqrt{\varepsilon}$ is the period of trapped ion oscillation between the magnetic mirrors. The hydrodynamic approach is valid for the dense plasma where $\tau_i \nu_{i/i}\sqrt{\varepsilon} \gg 1$.

In the second part of the paper some instabilities of the trapped particles due to the density gradient are discussed.

The ion Landau damping stabilizes the resistive drift instability of the trapped particles if

$$\nu_{e/i}\tau_e/\varepsilon \geqslant 0{\cdot}37 \left(\frac{m_e}{m_i}\right)^{1/3} \left(\frac{T_i}{T_e}\right)$$

The energy replacement time in the Tokamak-3 at various discharge parameters*

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Plasma confinement in the toroidal device Tokamak-3 (the major radius of the torus is 100 cm, the bore radius 20 cm, the longitudinal magnetic field up to 35 kG) was investigated. The energy replacement time characterizing the plasma confinement is determined by the expression $\tau_E = W/(\chi - \dot{W})$ where W is the plasma energy, χ is the ohmic heating power. It is shown that one can exactly determine τ_E without any assumption on the space distributions of the plasma parameters and heavy atom impurity concentrations, provided that plasma ring equilibrium takes place and the charged particle temperature is isotropic. τ_E is calculated as a result of the measurements of plasma diamagnetism and of the plasma ring displacement together with the plasma current and e.m.f. at the wall. The final calculations were made by the computer. τ_E was obtained as a function of the discharge parameters: the plasma current, charged particle concentration and longitudinal and transverse magnetic fields. Using a multi-channel probe, the distribution of electron concentration over the plasma column cross section was obtained. Under the assumption of the parabolic distribution of temperature over the plasma column cross section, the mean plasma temperature $\overline{T_e + \gamma T_i}$ was calculated, where γ is the factor which takes into account the existence of heavy impurities. It is shown that the observed electrical conductivity is several times lower than that calculated for a pure hydrogen plasma. In the concentration range (1–3) $\times$ 10^{13} cm^{-3} this difference may be explained by the effect of heavy atom impurities.

* Presented by K. A. Razumova.

High frequency stabilization and heating of a current carrying plasma column in a longitudinal magnetic field*

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The possibility of dynamic stabilization of the Kruskal–Shafranov instability in a high current discharge in hydrogen was studied. The experiments were performed in a spatially homogeneous magnetic field, $H_z \approx 0{\cdot}5$–2 kOe, with a discharge current from 2 to 10 kA at an initial gas pressure of 10^{-3}–10^{-2} mm Hg. The plasma column diameter was $d = 5$ cm, its length $L = 100$ cm and the quartz chamber diameter $D = 12$ cm.

It is shown that at the quasi-stationary discharge with the 500 msec pulse length and current $I_0 =$ const. the discharge is unstable if the expression $(H_z/H_\varphi) = q(L/\pi c)$ (where H_φ is the field of the current I_0 and $q < 1{\cdot}5$) is satisfied. Typical rise times of instability τ are approximately 10^{-5} sec. The plasma column accomplishes quasi-harmonic oscillations near its equilibrium position with the frequency $f_0 \sim (1/\tau)$ and contacts the chamber walls periodically. For stabilizing the plasma column in the region of values $q < 1{\cdot}5$ the discharge current was being oscillated at the frequency $f = 2$ Mc/s so that $I(t) = I_0 \cos 2\pi f t$ and always $f \gg f_0$. As the experiments have shown, the current column is macroscopically stable under these conditions in the whole range of the discharge parameters given by $0{\cdot}3 < q < 5$.

In the r.f. current discharge the strong screening effect of r.f. fields with a measured skin-depth less than 1–0·5 cm is observed. The diamagnetic measurements show that when the current density in the surface layer of the column exceeds some critical value, skin-effect is accompanied by an anomalously strong plasma heating process which leads to $kT \approx 10^{16}$ eV . cm^{-3}. As follows from the experimental data, the observed heating effect can be explained by a beam type instability in the skin-layer region. When the transition to the turbulent state of the plasma takes place, the enhanced level of the r.f. field energy dissipation in the skin-layer can be used for the development of plasma heating methods. In developing any methods of plasma r.f. confining and stabilization one must take into account the possible turbulent state of the skin-layer.

Presented by R. Z. SAGDEEV.

Stellarator configurations with strong shear and negative V''

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WE HAVE studied toroidal configurations with helical windings $l = 2, 3, 4$ for different values of m, the number of periods of the conductors along the torus.

The negative V'' property can be obtained simply by adding uniform magnetic fields parallel to the axis of the torus. Results of numerical calculations showing magnetic surfaces, variations of rotational transform and $V' = \oint \mathrm{d}l/B$ are presented.

$l = 2$ configurations have a non-zero mean rotational transform but practically no shear. $l = 3$ configurations have strong shear without correcting B_z. But coupling between helical field ($l = 3$) and uniform $B_z(l = 1)$ gives an $l = 2$ component near the magnetic axis and the shear is strongly decreased. This effect does not appear in the case of $l = 4$ helical windings. The shear is not destroyed by adding a uniform B_z.

However, the maximum rotational transform we can obtain does not increase continuously with m. For an aspect ratio of 5, no gain was observed from $m = 3$ to $m = 5$.

A typical configuration with $l = 4$ and $m = 3$ is described. The average magnetic well depth is about 20 per cent and the variation of the rotational transform from the magnetic axis to the external surface ($\Delta\iota/2\pi$) is approximately 0·6.

* Presented by E. K. MASCHKE.

Research on a new type of plasma injector*

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WITHIN the scope of research work on producing hot plasma of densities and energies of interest from the view point of thermonuclear investigations, a new type of injector has been developed [1–7]. The main idea of the injector lies in substituting, in the coaxial plasma gun, the solid electrodes by grid-type electrodes 'penetrable' for particles and ensuring their free radial motion. This modification

* Presented by M. GRYZINSKI. Papers concerning the subject are submitted to *Nuclear Fusion* and are available as Internal Reports INR, No. 711–720/XVIII (in Polish).

permits a strong particle concentration at the axis of injector. Making the 'penetrable' cylindrical electrodes in the form of coaxial rims of rods, it is possible at properly chosen potentials and currents to eliminate the defocussing action of the aximuthal component of the electric field existing in the real construction of electrodes.

The focus radius evaluated on the basis of the single-particle model, for the injector with close diameters of the inner rim R_1 and the outer rim R_2, is given by:

$$R_{\text{foc}} = \frac{\pi \,.\, l}{2} \frac{R_2 + R_1}{R_2 - R_1} k,$$

where l is the distance between the rods at the periphery of the rim and k is the magnetoelectric focussing coefficient, given by

$$k \approx 1 - 8 \frac{Ze}{Mc^2} \frac{(R_2 - R_1)l}{(R_2 + R_1)^2} \frac{I_0^2}{U_0},$$

which depends on the actual current value I_0 in the electrodes and on the potential difference U_0 existing between them.

For the verification of the concept of the injector, the following comprehensive measurements have been carried out:

1. Measurements of currents and voltages in a circuit;
2. Visual observation by means of high-speed photography;
3. Magnetic probe measurements of fields inside the plasma;
4. Spectroscopic measurements (static with the aid of spectrographs and dynamic with monochromator and photomultiplier sets).

To gain a better understanding of the processes, some measurements have been performed in the presence of a 5 kG magnetic axial field. The measurements have been carried out for a small injector ($R_1 = 20$ mm, $R_2 = 30$ mm, number of rods in a rim 16, length of rods 80 mm) supplied from a 6·4 μF condenser bank at a voltage of 20 kV (circuit frequency 75 kc/s, maximum value of the discharge current 50 kA). Air was normally used as the working gas, filling the whole experimental chamber uniformly.

From the pictures obtained with a high-speed camera it has been stated that the injector operates as a conventional plasma gun at pressures of the order of 10^{-1} torr (when the Larmor radius of ions is much smaller than the distance between electrodes) and it operates as a focussing injector at pressures of 10^{-2}–10^{-3} torr (then the Larmor radius of ions is greater than the distance between electrodes). In the latter case, with negative polarization of the inner electrode rim, a high concentration of particles at the axis has been observed.

In spite of numerous defects in the first construction of the injector (occurrence of highly unfavourable surface breakdowns), it has been estimated from electric measurements that the energy introduced into the plasma is at a level of a few per cent. The particle densities observed in the focus were of the order of 10^{14}–10^{15} particles/cm^3 whereas the focus diameters observed were within the limits of several millimetres, thus being indicative of the afore-mentioned magnetic focussing mechanism. The energies of axial motion depended on the initial pressure and varied from 10^6 cm/sec at 10^{-1} torr to (5–6) $\times$ 10^6 cm/sec at 10^{-4} torr. For the injector working in the focussing regime the energies of radial motion, as anticipated, were approximately of the order of the axial motion energies.

The ion temperature as measured from Doppler broadening amounted to $1{\cdot}6 \times 10^{6}$°K. An ion temperature dependence on the charge, typical for ion acceleration in an electric field, has been observed. The electron temperatures in all the experiments were at the level of several electronvolts.

Detailed data concerning the injector concept and the experimental measurements will be published later.

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Ionization and heating of a hypersonic deuterium jet*

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IN ORDER to achieve (as initial condition for some pinch devices) a discontinuous plasma density distribution, an experimental study on hypersonic neutral gas injection has been carried out.

The hypersonic jets were obtained by means of nozzles whose throat diameters were of the order of 100 μ; the density at the exit of the nozzles could be varied in the range of 10^{20}–3×10^{17} particles/cm^3, the Mach number of the jet being from 4 to 8.

The ionization, the heating and the containment of such a jet by means of a Z-pinch is described. A string of dense plasma focuses of diameters of about 0·2 mm are visible in the soft X-ray radiation spectrum.

* Presented by the author. Full text of paper not available.

Propagation and growth of a pulse disturbance in an unstable medium*

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THE response of a medium to a pulse disturbance is determined by the behaviour of the zeroes of the dispersion function $D(k, \omega)$ in the complex domain of both the wavenumber k and the frequency ω, and the asymptotic nature of the response near the origin depends upon the velocity, V, of the frame of reference of the observer. In particular, a crucial feature for an unstable medium is the behaviour, as a function of velocity, of the position of the saddle-points of $\tilde{\omega}(k) = \omega(k) - kV$, defined by the requirements

$$D(k, \omega) = 0, \qquad \frac{\partial D}{\partial k} + V\frac{\partial D}{\partial \omega} = 0,$$

since $\mathscr{I}(\tilde{\omega})$ for suitably defined saddle-points gives the asymptotic growth in the frame V. Thus, if $\mathrm{d}^2\omega/\mathrm{d}k^2$ is taken along the contour $D(k, \omega) = 0$, the differential equations for the variation of a saddle-point,

$$\frac{\delta k}{\delta V} = \left(\frac{\mathrm{d}^2\omega}{\mathrm{d}k^2}\right)^{-1}, \qquad \frac{\delta \omega}{\delta V} = V\left(\frac{\mathrm{d}^2\omega}{\mathrm{d}k^2}\right)^{-1}, \qquad \frac{\delta \tilde{\omega}}{\delta V} = -k,$$

(only two of which are independent) can be used to plot the asymptotic pulse shape.

The theory is applied to examples of importance to plasma physics, and a number of quantitative results obtained. Of particular interest is a new phenomenon to be described, which occurs as an interaction between pairs of saddle-points separated by a finite distance in the (k, ω)-domain, and which can alter the significance or insignificance of a given saddle-point at some critical velocity with respect to its correspondence to an actual physical mode.

* Work performed under the auspices of the United States Atomic Energy Commission. Presented by L. S. HALL. Paper included as a part of a report submitted to *The Physical Review.*

Rapid plasma heating by current induced turbulence in a torus*

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AN ELECTRIC field $E_\phi \approx 200$ V cm^{-1}, ringing frequency 1 Mc/s is suddenly applied to a partially ionized hydrogen plasma (density $\approx 10^{12}$ cm^{-3}) immersed in a toroidal magnetic field $B_\phi \approx 3$ kG. The plasma exhibits a high resistance and the electric field and current are heavily damped. During the first current pulse intense microwave emission ($\approx$20 Gc/s) is observed, and large amplitude electric field fluctuations ($\approx$10 kV/cm, frequencies $\approx$30–200 Mc/s) are seen with electrostatic probes. Soft X-ray

* Presented by S. M. HAMBERGER. Paper published in *Phys. Rev. Lett.* 14 August (1967).

emission from a carbon target in the plasma occurs at the same time, and absorption measurements show this corresponds to $T_e \approx 2$–3 keV. A neutral particle detector shows that a large flux of fast hydrogen atoms leave the plasma perpendicular to the magnetic field, and are emitted in a time interval shorter than an ion-gyro period. The ions responsible (by charge exchange) for their ejection have a continuous spread of energies between 0·2 and 3 keV. On assumption that the ion energy distribution is isotropic and Maxwellian the measured rate of charge exchange for 2 keV ions is consistent with an ion temperature $\approx 0{\cdot}7$ keV.

It is argued that these observations are consistent with the development of a turbulent spectrum of longitudinal plasma waves excited by a two-stream instability, and that the electron and ion heating which occurs results from interaction of particles with the microfields of the wave spectrum, and not from binary collisions or from large-scale hydromagnetic turbulence.

Application of microwave diagnostics to a collision-free shock wave experiment*

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Shock front structures are generally investigated by measuring magnetic field profiles. Depending on the shock wave type it may also be desirable to observe the density profile. This becomes a necessity if the initial magnetic field is very small, i.e. if $\beta_0 = 8\pi n_0 k T_0/B_0^2 \gg 1$. For this reason a 2 mm microwave probe with high space resolution (≈ 3 mm) has been developed which can be used between $n_e = 10^{13}$ and $n_e = 2 \times 10^{14}$ cm^{-3} [1].

Shock waves were produced in θ-pinch geometry. Radial and axial density profiles in the initial plasma have been determined as a function of time with probes of this type. In order to resolve the density jump in a collisionless shock wave, a response time of about 10 nsec is needed. Due to the high impedance of 2 mm detectors and the stray capacitance of the detector mount, the time constant of the system is presently limited to 20 nsec.

Interferometer measurements with this time resolution will be presented. From the observed phase shift, the density jump in the shock front is determined. In addition one can relate the attenuation of the signal to the effective conductivity of the plasma [2]. These measurements are compared with other observations, in particular with measured magnetic field profiles.

* Presented by H. Hartwig.

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On the use of Langmuir probes in a *Q*-Device*

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The complexity of the theories of Langmuir probes in a magnetic field and their wide application in magneto-plasmas as a diagnostic tool suggests a comparison of the probes with other diagnostic techniques. Recently, such a comparison has been performed in a singly ionized barium plasma for the single-ended operation of a *Q*-device using resonance fluorescence scattering of the 4554 Å line by barium ions and microwave cavity as independent methods [1].

In the present work a comparison of the probe density is performed with the above-mentioned methods in double-ended and single-ended operation under various operating conditions, namely, by changing the density, magnetic field, plate temperature, degree of ionization and ion temperature. The last two being changed by introducing a noble gas [2]. The density was evaluated from the extrapolated value of the ion saturation current at the plasma potential. It is found that

$$\frac{n_m}{n_s} = 0{\cdot}6, \quad \frac{n_p}{n_s} = 2, \quad \text{and} \quad \frac{n_{p'}}{n_s} = 1{\cdot}4,$$

* Presented by M. Hashmi. Paper to be submitted to *The Physics of Fluids*. This work was performed under the terms of the agreement between the Institut für Plasmaphysik Gmbh, Munich-Garching, and EURATOM to conduct joint research in the field of plasma physics.

where n_m and n_s are the microwave and spectroscopic densities and n_p and $n_{p'}$ are densities evaluated from the classical Langmuir formula and Bohm's formula for strong magnetic fields respectively [3]. These factors appear to be independent of all operating conditions.

In addition to density, total ion input flux measurements were also performed. These measurements yield information on the particle loss rate under various operating conditions. According to equilibrium theory $\Phi \sim n^2$ [4]. However, in the low density range ($n < 10^{11}$ cm^{-3}), the particle losses become much larger than predicted by equilibrium theory. In this regime, instead of $\Phi \sim n^2$ dependence, we observe $\Phi \sim n$.

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Drift instability in general magnetic fields*

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A THEORY is described which provides a basis for the detailed investigations of electrostatic instabilities in real experimental geometries and, in particular, of drift instabilities in the multipole. Such instabilities have frequently been discussed in the plane slab model, and modifications of it in which geometrical effects are added or simulated, but our aim is to include all geometrical effects from the outset.

The starting point is the collisionless Boltzmann equation and the method is based only on the approximation that the scale length of the equilibrium is long compared to the ion gyroradius. The main interest is in electrostatic perturbations of low frequency but of arbitrary wavelength, which may be comparable to the ion Larmor radius. Thus several classes of instability such as drift wave, flute or trapped particle instabilities come within the scope of the theory.

An expression is first obtained for the contribution to the charge density produced by an arbitrary electrostatic perturbation affecting particles whose unperturbed orbits are (i) trapped between magnetic mirrors; (ii) circulating around closed field lines; (iii) tracing out a magnetic surface. In conjunction with Poisson's equation these expressions for the charge density lead, via a study of the appropriate Nyquist contours, to stability criteria valid for arbitrary equilibria.

Finally it is shown how this method leads to a differential equation whose solution will determine the stability of any specific experimental configuration such as the multipole.

* Presented by R. J. HASTIE. Full text of paper not available.

Stability of Helmholtz plasma flow in a discontinous magnetic field*

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THE stability of time-dependent plasma flow of the Helmholtz type in a discontinous magnetic field and unstable density gradient is investigated in the Boussinesq approximation. The stabilities are due to the tangential discontinuity of the kinetic energy of the different layers.

Incompressible inviscid plasma stratifications with infinite electrical conductivity are embedded in a uniform constant gravitational field and in a shear-free magnetic field. Linearizing the basic equations one obtains a third-order differential equation for the z-component of the disturbed flow velocity. Investigating this differential equation with the help of integral transformations it is shown that there are modes with a significant effect on plasma confinement not having the form exp ($i\alpha t$) and not fitting into the framework of normal mode analysis.

* Presented by the author. Paper available as an internal report, Scientif. Report No. 47, Contract No. F61052-67-C-0014.

A two-dimensional computer-program for end losses from a theta-pinch*

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THE axial losses of mass and energy at the end of a theta-pinch are investigated.

The plasma is described by a one-fluid model with the following assumptions: infinite electrical conductivity ($\sigma = \infty$), electron temperature equal to ion temperature, isotropic pressure and radial equilibrium.

As boundary conditions for the magnetic field **B** it is assumed that the current in the coil is constant in time and that **B** is continued periodically at the end-plane. For the dynamic quantities ρ, **v** and the heat flow **q** boundary conditions are used, which allow free outflow at the end-plane. The initial condition corresponds to an already compressed plasma in radial equilibrium.

The resulting system of partial differential equations for the quantities ρ, **v**, p and **B** as function of r, z and t is solved numerically in magnetic field line co-ordinates. The main advantage of this co-ordinate system is the more accurate computation of effects parallel to the magnetic field lines, because there is no numerical diffusion.

It is investigated how the disturbance due to mass and energy losses at the end of the theta-pinch propagates into the inner part of the vessel. The relative importance of kinetic energy, heat conduction and convection for the endlosses is calculated.

This program is intended as a first step towards a more sophisticated program with a two-fluid model including anisotropic pressure.

* This work was performed as part of the joint research program of the Institut für Plasmaphysik. Garching and Euratom. Presented by W. SCHNEIDER.

Electron line density measurements in a magnetic rotating field pinch*

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Two high power generators deliver r.f. pulses each of which consists of 8 periods at a frequency of 2 Mc. They generate a plasma in a tube of 5 cm diameter and 50 cm length. One generator produces an axial current of 18 kA peak amplitude while the other, which feeds a 3 turn coil, induces an azimuthal current of 56 kA peak amplitude in the plasma. When the two currents are 90° out of phase, the plasma experiences a rotating magnetic field of 1·8 kG.

We have measured the temporal and spatial evolution of the electron line density in such a discharge with a Mach Zehnder interferometer. This apparatus is equipped with a photomultiplier detection system which allows the electron line density to be measured without ambiguity.

These measurements were made in 25 mtorr He which was preionized by an axial current pulse of 13 kA amplitude and 15 μsec duration.

The formation of a pinch is demonstrated. The electron density on the axis of the discharge tube grows during the first two microseconds until the value of $1{\cdot}6 \times 10^{16}$ electrons cm^{-3} is reached. At this time the density within 4 mm of the wall is zero and the integral of the electron density over the cross section indicates complete ionization. After about 2·5 μsec, evolution of gases from the wall causes the current to switch back to the wall bringing about the formation of a 'hang-up' pinch which lasts for the remainder of the discharge.

* Presented by the author.

Theoretical and experimental results on the electrostatic plugging of a cusp containment system*

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IT HAS been generally assumed that the use of electrostatic fields to suppress cusp losses, due originally to LAVRENTEV [1] is limited to low densities such that the Debye length is not less than ρ_i, the ion

* Presented by A. A. WARE. Work sponsored by Air Force Aero Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, United States Air force.

Larmor radius. Calculations are presented which show that the limitation is much less stringent and that useful fusion reactor densities can be contained because (1) the penetration of the electric field depends on the applied voltage and not on T_e; (2) the electric fields can be used to maintain sheath electric fields so that the line cusp plasma thickness can be reduced to $2\rho_e$; and (3) the double electrostatic fields can be applied more than once in sequence.

Electrodes to produce such potentials have been placed around the axial and line cusps of a simple cusp confinement system. The magnetic field strength in the cusps was 7 kG, plasma volume ~1 l., base pressure about 5×10^{-7} torr. A 20 mA beam of 16-KeV hydrogen molecular ions was injected through an axial cusp. A collimated secondary emission detector, positioned outside the containment volume away from the cusps to detect the charge exchange and dissociation neutrals, showed a 100-fold increase when +8 kV and −2 kV were applied to the appropriate electrodes. It is estimated that a plasma density approaching 10^9 cm^{-3} was obtained. Penning discharges are at present limiting the maximum voltages which can be applied. Preliminary measurements with lower beam energies show similar enhancements.

[1] O. A. LAVRENTEV, *Ukrainian. J. Phys.* 8, 440 (1963); 8, 446 (1963). The scheme has been considered also by the cusp group at Jutphaas; private communication.

Some theoretical aspects of multipole devices*

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THE basic properties of a multiple device are determined by its flux distribution $\chi(r)$ and in particular by a set of line integrals. These include the volume per flux tube, $U(\chi) = \oint dl/B$, the length of a tube, $L(\chi) = \oint dl$, the magnetic potential $\Phi(\chi) = \oint B dl$ etc. The determination of these fundamental quantities and their relation to the current structure in the multipole is discussed. In linear sysetms the complex potential $\Psi = \chi + i\phi$ greatly simplifies the problem and permits a full discussion of multipoles based on filamentary conductors. Detailed results are presented for the quadrupole.

The basic line integrals are also involved in the determination of plasma diffusion in linear multipoles, for the diffusion equation can be reduced to

$$\frac{\partial}{\partial \chi} D(n, \chi) \frac{\partial n}{\partial \chi} = U(\chi) \frac{\partial n}{\partial t}$$

where $n(\chi, t)$ is the particle density. The form of $D(n, \chi)$ depends on whether diffusion is classical, ($D \propto nU(\chi)$) or Bohm, ($D \propto L(\chi)$). Characteristic diffusion times are given for both cases and for several multipole configurations.

Analogous results have also been obtained for toroidal, axisymmetric multipoles by numerical integration. The asymmetry introduced by toroidal effects and the associated changes in the basic line integrals are in general small. The properties of a toroidal device only differ significantly from those of the equivalent linear system at aspect ratios less than 2:1.

* Presented by G. D. HOBBS. *Plasma Phys.* 10, 207 (1968).

Instability of hot-electron plasma*

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THIS is a report of the experiment on a hot-electron plasma generated by a microwave discharge in a vacuum tank which served as a microwave resonant cavity (30 cm dia. × 40 cm) in a simple mirror field (4000G–1200G–4000G). The temperature of the electrons in the plasma exceeded 100 keV and the electron density was about 10^{12} cm^{-3}. The plasma ions in helium are cold, having a temperature of about 10 eV.

Several methods [1] were found to trigger the instability in a quasi-stable plasma. In our hot-electron plasma (named TPM after Test Plasma by Microwave discharge), an instability can be triggered at will by introducing an additional small microwave pulse of the same frequency as the heating

* Presented by K. TAKAYMA. Paper to be published in *The Physics of Fluids* and is also available as an internal report, IPPJ Report No 59.

microwave pulse at some arbitrary time (1–50 msec) after turning off the main heating pulse. No difference is observed between the triggered instability and the spontaneous one which occurs uncontrollably under some conditions. The excitation of the instability is seen about 50 μsec behind the front of the triggering pulse.

The instability is accompanied by a sudden decay of plasma, a burst of X-rays from the cavity wall, fast-rising scintillator probe signals due to the high energy electrons through the mirror throats and an intense microwave burst. Correlations are not found between the signal to the probe at the centre of the cavity wall and that to the probe close to the cavity end-wall. Both probes are situated on the same magnetic field lines. This implies that the instability may not be a type of macroscopic flute instability.

[1] W. A. Perkins and R. F. Post, *Physics Fluids* 6, 1537 (1963).

Plasma acceleration using a high power microwave and a static magnetic field*

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Plasma acceleration in mixed fields (h.f. + static magnetic) has been actively studied by Consoli and his co-workers. We made a similar study in a high power range of the accelerating wave (0·2–1 MW pulsed, 2998 Mc/s). Plasma was injected into an accelerating structure, e.g. a resonant cavity having a Q-value of 100, by means of a spark source. The static magnetic field B_s at the centre of the cavity was variable up to 2700 G. In case of low plasma density ($\leqslant 10^{10}$ cm^{-3}), only electrons were strongly accelerated along the magnetic axis. The acceleration was most effective when the electron cyclotron resonance occurred near the centre of the cavity ($B_s \approx 1070$ G). Electrons then gained the axial energy of 100 keV or higher in agreement with numerical calculations. In case of high plasma density (10^{12}–10^{13} cm^{-3}), ions were accelerated together with electrons. The maximum ion energy increased with increasing B_s and reached the 100 keV range at $B_s \approx 2000$ G. Such a feature was, of course, affected by experimental conditions: e.g. the maximum ion energy was reduced to 70 keV, nearly independent of B_s for $B_s \geqslant 1000$ G, by replacing the cavity by a uniform waveguide. The total ion energy flux reached 10 per cent of the incident microwave energy. When the magnetic field was strong enough to push the position of electron–cyclotron resonance outside the accelerating structure, the h.f. field extended beyond that position. These results can be qualitatively explained by the excitation of right-handed waves in the plasma.

* Presented by H. Ishizuka. Paper submitted to *Plasma Physics*.

A rotating magnetic field pinch*

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Helium gas at a pressure of 60 mtorr is contained in a discharge tube of 4·8 cm dia. and 49 cm length which is equipped with end electrodes and is situated within a multi-turn solenoid. The gas is preionized by means of an axial current pulse of 9·5 kA amplitude and 32 μsec duration. Following the preionization pulse, two high power r.f. generators, each capable of delivering pulses of 7 periods at a frequency of 3·10 Mc/s, are triggered. One generator produces an oscillating axial current in the preionized plasma while the other induces an oscillating azimuthal current. The generators are adjusted to give equal B_θ and B_z peak amplitudes at the inner wall of the discharge tube. Peak amplitudes of 2·2 kG are obtained.

When the two oscillating currents are 90° out of phase, the plasma experiences the continuous magnetic pressure exerted by a rotating field. Streak photographs show that the plasma separates from the tube wall and implodes towards the axis. Framing pictures show that cylindrical symmetry is maintained during this implosion. The implosion stage of the pinch is shown to be well represented by a solution of the appropriate snowplow equation.

At 1·1 μsec after the initiation of the r.f discharge, luminosity again appears in the region of the tube wall and stays there for the remainder of the discharge. It is surmised that this light appears because the current sheath which is driving the pinch returns to the wall and subsequently flows there for the remainder of the discharge. Measurements made of the time variation of the inductance of the pinch support this supposition.

* Presented by I. Jones. *Plasma Phys.* 10, 213 (1968); and is also available as an internal report, LRP 31/67.

Recent investigations on plasma instabilities*

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A SHORT survey of recent theoretical and experimental papers on the plasma instabilities in strong magnetic fields is given. The main attention is paid to the instabilities of an inhomogeneous plasma. Their relation to nuclear experiments is discussed.

* Presented by the author.

Resistivity of the plasma in strong magnetic fields*

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THE effect of anomalous resistivity of a nonisothermal plasma is considered under the conditions when the Larmor frequency is greater than the Langmuir frequency. It is shown that the ion-sound instability does not give rise to an appreciable increase in the resistivity. When runaway electrons are produced their distribution function tends to be isotropic due to the anomalous Doppler effect. The increase in the plasma pressure and effective temperature caused by these electrons can be observed experimentally in the form of the anomalous resistivity.

* Presented by B. B. KADOMTSEV.

Electron and ion waves in fully ionized plasmas*

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THE influence of inter- and self-particle collisions on the propagation of electron and ion disturbances in fully ionized thermonuclear plasmas is studied. Beginning with Maxwell's equations and the (collisional) Boltzmann equations for the electron and ion velocity distribution functions, a set of coupled equations, truncated in third order (containing the stress and heat flow terms) is derived. The analysis is simplified by considering only small amplitude disturbances in the presence of a purely longitudinal (or zero) external magnetic field. The dispersion relation for electron and ion waves is derived, and solved for the absorption and dispersion coefficients as a function of the electron–ion, electron–electron, and ion–ion collision to wave frequency ratios; as well as of the electron and ion plasma to wave frequency ratios, for cases where the self-collision frequencies are both less and greater than the corresponding plasma frequencies. In the limit of infinitely large self-collision to wave frequency ratios the dispersion relation reduces to that derived from continuum theory [1]; for finite values of the self-collision frequencies we found a rather strong absorption function dependence both on the self-collision to wave frequency and self-collision to plasma frequency ratios. The precise dependence predicted by this collisional theory on the collision, wave, and plasma frequency ratios are given by numerical solution of the dispersion relation.

* Presented by the author.

[1] D. KAHN, *Physics Fluids* 7 (1964).

Thermally anisotropic plasma instabilities*

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A THERMALLY anisotropic plasma, whose zero-order velocity distribution function is anisotropic, presents an essential electromagnetic instability, produced by the magnetic interactions of current

* Presented by C. MONTES. Paper submitted to *The Physics of Fluids*.

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fluctuations. WEIBEL [1] was the first to show this type of instability in a thermally anisotropic electron plasma with a background of stationary ions, in the absence of magnetic field. He analysed the limited case of large phase velocity compared with the lowest thermal velocity $[(\omega/k) \gg b]$. The physical mechanism responsible for these instabilities has been discussed by FRIED [2]. They have shown that for strong anisotropy the amplification rate of such an instability is of the order of $(a/c)\omega_0$, (where ω_0 is the plasma frequency, a the transverse thermal velocity and c the speed of light) and thus much smaller than ω_0, the amplification rate of the electrostatic instabilities [3]. Under certain conditions where electrostatic longitudinal instabilities are not present, however, electromagnetic instabilities might be important. We have extended the analysis of the transverse instability beyond the Weibel approximation, to an anisotropic collision-free Vlasov plasma. Our general dispersion curve $\mathscr{I}\,\omega$ vs. k exhibits a maximum for $\mathscr{I}\omega$, for any arbitrarily small anisotropy. Furthermore, we find the marginal stability criterion for finite value of k [4]. If we take as a principal axis of anisotropy the direction of the lowest thermal velocity, we can define an angle θ between the direction of this axis and the wave vector k. Taking into account the θ-dependence of dispersion curves, we show that, when θ increases the domain of instability with respect to k will be reduced, at the same time the maximum growth rate decreases. An anisotropic velocity distribution function introduces a coupling for waves propagating obliquely with respect to the principal axis of anisotropy. Considering an electron–ion plasma, we show that the longitudinal ion acoustic mode becomes also unstable in the case of the oblique propagation. This ion acoustic mode, when coupled with the transverse one, is found to be overstable [5].

[1] E. S. WEIBEL, *Phys. Rev. Lett.* **2**, 83 (1959).
[2] B. D. FRIED, *Physics Fluids* **2**, 337 (1959).
[3] O. PENROSE, *Physics Fluids* **3**, 258 (1960).
[4] C. MONTES, Thèse 3e Cycle, Université de Paris (1966).
[5] G. KALMAN, C. MONTES and D. QUEMADA, submitted to *Physics Fluids*.

Stationary equilibrium of a toroidal plasma*

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THE stationary equilibrium of a low-density plasma in toroidal geometry is studied theoretically. The effects of finite resistivity and inertia are taken into account. It is assumed that plasma is injected with a source density Q and a velocity $\bar{u}$ which may or may not be equal to the local plasma velocity $\bar{v}$. If $\bar{u}$ is small enough there is always a unique equilibrium solution. If the streaming velocity along the magnetic field lines becomes equal to the sound velocity in the plasma, there is no longer a unique equilibrium solution. The connection between this result and the character of the differential equations governing the motion is discussed.

* Presented by the author.

Principles of electrostatic containment of an ionized gas in the MAYA apparatus*

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Two of the objections to electrostatic containment, charge separation and Earnshaw's theorem, are irrelevant in an arrangement where a state of static equilibrium is not demanded and expansion of the ionized gas to the container walls can occur slowly. The initial arrangement consists of a plasma cylinder situated on the axis of a conducting cylinder which is negatively charged with respect to the plasma; an outward radial electric field in the plasma must also exist. Polarization of the plasma sets in with the formation of an electric double layer, the inner electron layer of which is attracted by the positively charged core on the axis. The containment time, given by the speed of expansion of the

* Presented by the author. Full text of paper not available.

This research has been sponsored in part by the Air Force Cambridge Research Laboratories through the European Office of Aerospace Research, OAR, United States Air Force under contract AF61(052)-891.

ion layer, is essentially determined by the ion pressure (and not the electron pressure) outwards, and the electrostatic pressure inwards due to the plasma radial field. The results with the MAYA apparatus (AVIVI *et al.* [1]) are qualitatively in agreement with this scheme. The prediction is made that the expansion of the ions can be prevented by increasing sufficiently the negative potential on the outer cylinder.

[1] P. AVIVI, N. BEN-YOSEF, F. DEUTSCH and A. S. KAUFMAN, Slow expansion of a plasma column without the application of a magnetic field, *Nature, Lond.* **199**, 1244–1246 (1963).

Confinement of electrons in 'Tornado' traps*

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THE paper contains information about the method and research results on the behaviour of electrons in 'Tornado' traps. The filling of the trap with electrons has been carried out by means of an injector located in the middle region. The electrons have been injected into the trap continuously within a solid angle near to 4π. A 4π-geometry collector surrounding the trap has been used for the detection of escaping electrons. Simultaneously with the collector current measurements other measurements have been carried out, that is: of the flow of escaping electrons on the trap spirals and of the current on the constructive elements of the injector. Two traps have been investigated: a 'skin' trap, 'Tornado-1', and a double spiral trap, 'Tornado-2'. In the case of the skin trap the flow of escaping electrons decreased abruptly as soon as the current in the spirals appeared and became less than the sensitivity threshold of the detecting system in about 2 msec. The collector flow increased (here the sphere was used as a collector) whilst the value of the magnetic field of the trap continued to be at a maximum level and in about 3 msec after current switching there appeared a special break on the electron flow curve. After that the flow of escaping electrons reached a constant value approximately equal to one-half of the electron flow in the absence of magnetic field. The time when there was no flow of escaping electrons became approximately equal to the time of field penetration through the skin trap sphere. In the trap 'Tornado-2', when the currents in both internal and external spirals were equal, there was no flow of escaping electrons. The perturbation into the system was introduced by disturbing the equality of currents in the spirals. With decreasing current in the external spiral the collector flow appeared and increased sharply. It is possible to suggest that these phenomena are connected with the toroidal structure of the magnetic field in the trap and with its destruction at definite conditions. The results permitted to estimate the life-time of electrons leaving the traps at different experimental conditions. It turned out that this time was of the order of 10^{-3} sec.

* Presented by A. B. BEREZIN. Full text of paper not available.

Plasma heating and wave propagation at harmonics of the ion–cyclotron frequency*

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WAVE propagation and plasma heating at harmonics of the ion–cyclotron frequency (Ω_i) have been investigated in a moderately hot plasma. The transverse plasma temperature is $T_\perp \gtrsim 50$ eV equivalent and the plasma density is $n \simeq 6 \times 10^{17}$ m^{-3}. A Faraday shielded 'Stix coil' couples r.f. power into the

*Presented by M. KRISTIANSEN. Paper will be submitted to *The Physics of Fluids* or to *Physical Review Letters* and is also available as an internal report, Laboratories for Physical Electronics, Texas Tech. College, Tech. Report No. 3.

Work supported by the National Aeronautics and Space Administration and by the National Science Foundation.

plasma from a 30 kW, 5·8 MHz driver. A 'magnetic beach' geometry is employed for the wave propagation studies. Diagnostic equipment includes magnetic and diamagnetic probes, microwave interferometry, directional couplers, voltage and current probes and photomultipliers with narrow band pass filters. Waves are observed to progapate for $\omega < G\Omega_i$, where G is an integer. Wave attenuation and enhanced plasma heating takes place at $\omega = G\Omega_i$. The existence of higher order transverse modes is indicated. Theoretical calculations based on the hot plasma theory and the existence of the higher order transverse modes qualitatively predict the wave propagation and plasma heating at the measured plasma density and temperature. Stop bands in the wave amplitude vs. frequency curve are predicted and observed.

Use of a monochromator for the velocity and temperature measurements in a coaxial plasma accelerator*

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The axial speeds of different groups of ions as a function of a delay time τ for two test gases, hydrogen and air, were measured in a coaxial plasma gun with the aid of a monochromator. The gun had the following parameters: the total length $l = 30$ cm, inner radius $r_1 = 4{\cdot}2$ cm, outer radius 6·2 cm, capacitor $C = 6{\cdot}4\ \mu$F charged to $V_0 = 20$ kV, peak current $I \approx 60$ kA, period of discharge $T \approx 11\ \mu$sec, initial pressure in the gun $p_0 = 5 \times 10^{-7}$ mmHg. In each pulse 0·7 cm^3 of the gas at atmospheric pressure was supplied to the gun. The measurements were done with the aid of monochromator UM-2 combined with a photomultiplier FEU-33. The speed measurements were done for the following ions: H_I(4861), C_{II}(4267), N_{II}(4630), C_{III}(4647) and N_{III}(4097) for delay times $\tau_H = 90$, 240 and 370 μsec. and $\tau_A = 60$ and 240 μsec. Here τ_H corresponds to the hydrogen gas and τ_A to air.

Besides the measurements of the speeds, the electron temperature was also measured from the ratio of the intensities of the lines C_{III}4647 Å and C_{II} 4267 Å.

The salient features of the results obtained can be formulated as follows:

1. There are at least two different plasmoids: a slow one propagating with the speed of about 2×10^6 cm/sec and a fast one with the speed of about 5×10^6 cm/sec.
2. The speeds of different ions were approximately equal for a given plasmoid.
3. There is only a small difference in the axial speeds when, instead of hydrogen, air was used as a test gas.
4. The speed of a given ion only slightly depends on the delay time.
5. The average temperature of the electrons is approximately equal to 4 eV.

A qualitative discussion of the results based on a single particle model of acceleration is given. It indicates that two groups of accelerated particles can emerge from the gun, one in which the energy of a particle is proportional to its mass and another one with energy independent of the mass of a particle but proportional to its charge.

* Presented by M. Gryzinski, Paper to appear in *Plasma Physics* and is also available as Institute of Nuclear Research, Swierk, Report No. 781 XVIII PP (1967).

Toroidal screw pinch experiments*

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To obtain a better understanding of the unexpectedly stable behaviour of the screw pinch we are applying more diagnostic methods in the present arrangement [1] and are extending the parameter range in two new screw pinch devices.

In the present arrangement all diagnostic methods used so far yield completely reproducible signals; recent measurements with electrostatic probes will be presented.

A higher temperature is obtained in a small-scale experiment ($2R = 32$, $2r = 8$ cm) in which a

* Presented by P. C. T. van der Laan.

higher value of dB/dt is applied by a fast capacitor bank. A slow capacitor bank has been installed whereby the ratio of confinement time to the theoretically predicted growth time of instabilities is increased beyond its present value of about 7.

At the moment of writing a third assembly is under construction. Herein a combination of capacitor banks similar to that of the small-scale experiment supplies energies up to 75 kJ to a torus with the same dimensions as the one in the first assembly ($2R = 72$, $2r = 12$ cm). A system for preionization at filling pressures below 5 μ is being developed.

[1] C. BOBELDIJK *et al.*, *Plasma Phys.* 9, 13 (1967).

Equilibrium of plasma in axially symmetric magnetic fields*

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THE relations that exist between the pressure tensor, the electric current in plasma and the self-consistent magnetic field for equilibrium plasma configurations in magnetic mirror systems are derived and discussed. The analysis starts from the distribution function of equilibrium plasma derived earlier [*Nucl. Fusion* 6, 268 (1966), *Nucl. Fusion* 6, 276, (1966)]. It is found that the pressure tensor (appearing in these relations) is diagonal, with $P_{\xi\xi} \neq P_{\varphi\varphi} \neq P_{\eta\eta}$ ($P_{\xi\xi}$, $P_{\varphi\varphi}$ are the pressure components perpendicular to the lines of force, $P_{\eta\eta}$ that along the lines of force). The plasma pressure in magnetic mirror systems is usually strongly anisotropic also in the plane perpendicular to the lines of force ($P_{\xi\xi}$ differs considerably from $P_{\varphi\varphi}$) and the approximation $P_{\varphi\varphi} \approx P_{\xi\xi} \equiv P_{\perp}$ can no longer be used. This anisotropy is due to the strong dependence of the distribution function on the integral $p_{\varphi} = mrV_{\varphi} + e/crA_{\varphi}$; the cause of this strong dependence lies in the finite Larmor radius (real plasma consists of spatially bounded beams with Larmor radius of the same order as the plasma radius). Because of the curvature of the magnetic surfaces, the relations between the macroscopic quantities are affected by both longitudinal and perpendicular plasma anisotropy. Equations describing these relations are derived in the paper for finite $\beta = 8\pi P/B^2$ and in the approximation $\beta \ll 1$ as well.

* Presented by the author. Paper submitted to *Nuclear Fusion.*

Investigation of plasma turbulence in a high-current toroidal discharge by a microwave probing method*

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AN ELECTROMAGNETIC wave passing through a turbulent medium is scattered by the refractive index inhomogeneities. This scattering leads to the formation of amplitude and phase fluctuations of the received signal. These fluctuations are often observed when a turbulent plasma is being probed by microwave signals. One can use this effect in a study of turbulence.

For a wavelength of 4 mm, we observed the passage of signals through the plasma in the 'Alpha' machine. The plasma thickness between the transmitting and receiving horn antennas was about 90 cm. In the received signal fast random fluctuations of power reaching 10–15 dB were observed. The frequency spectrum of fluctuations was studied by a set of resonance filters and by correlation technique. It was found that in the frequency range 100 kHz–2 MHz the fluctuation power steadily falls as the frequency increases.

To explain the data obtained, we used the theory of radiowave propagation in a turbulent atmosphere. It is shown that the frequency spectrum of signal fluctuations is determined by the spectrum of refractive index fluctuations in the turbulent medium, and the mean square of fluctuation amplitude depends on the parameter $\overline{\Delta N^2 a}$, ΔN being the change of refractive index in the turbulence, and a being the mean size of the turbulence elements.

We used the mean size a obtained from probe correlation experiments. From the data on microwave signal fluctuations we calculated the mean fluctuation of refractive index and eventually the mean fluctuation of electron density in plasma turbulence. In the plasma of the high-current toroidal discharge with force-free field configuration this value is of the order of 10 per cent, and a spectrum of density fluctuations covers the frequency range from tens of kHz to the frequency limit of the apparatus which is 2 MHz.

* Presented by M. LARIONOV. Paper submitted to *Journal of Technical Physics*, U.S.S.R.

Stabilization of density gradient instabilities by the dispersion of curvature drift velocity*

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THE effect of magnetic field curvature on the drift instability in an ion–electron plasma is usually simulated by introducing fictitious gravitational forces which produce particle drifts equal to the average drifts caused by the curvature. This procedure is justified as long as the drift velocity of the ions caused by such an equivalent gravity, v_{gi}, is much smaller than the phase velocity ω/k_y of the unstable mode in the direction of this drift. However, for large wavenumbers k_y, and also for small ratios of electron to ion temperature, T_e/T_i, the phase velocity ω/k_y becomes of the order of v_{gi}. In this case there will be a Landau effect for the ions in the direction of the drift motion, in addition to the usual Landau effect in the direction parallel to the magnetic field lines. In the present paper the influence of this effect on the drift instability is investigated for the case of a plasma slab in a magnetic field of constant favorable curvature. It is found that the Landau effect in the drift direction acts strongly stabilizing, particularly for large wavenumbers k_y. The reason is that the poles in the dispersion relation which yield this effect are much nearer to the thermal velocity of the ions than in the case of gravity. Marginal stability curves have been obtained by machine calculations. They are markedly different from the corresponding curves calculated with gravity. For instance, with a radius of curvature twenty times the characteristic length of the density profile, and with $T_e/T_i = 1$, there are unstable waves only for $0{\cdot}5 \leqslant k_y a_i \leqslant 4$ (a_i the ion Larmor radius) and $k_\parallel v_{th,e} < 6{\cdot}5\, k_y v_{de}$ but the gravity calculation yields instability for $0{\cdot}5 \leqslant k_y a_i \leqslant 24$ and $k_\parallel v_{the}' < 12 k_y v_{de}$ (with v_{de} denoting the electron diamagnetic velocity).

* Presented by E. K. MASCHKE. Paper submitted to *Physical Review Letters* and is also available as an internal report, EUR–CEA-FC-440 (in French).

Plasma confinement in ring-current configurations*

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THE field from one or several ring-chaped coils can be used as a magnetic bottle for plasma confinement. In stationary operation as a fusion device the coils have to be suspended. A possible method is provided by magnetically screened leads. Earlier investigations by the author on this problem are extended by the following results:

(i) In the confinement volume defined by field lines encircling one or several ring-shaped coils a static plasma equilibrium should be possible even in presence of the magnetic field from the leads.

(ii) The particle losses introduced by the leads are mainly non-adiabatic. They are partly due to deviations from the constancy of the equivalent magnetic moment in some very small regions where the field is weak, partly to deviations from the constancy of the longitudinal invariant which arise when a particle passes the lead region repeatedly and in finite steps.

(iii) These effects produce a scattering which displaces a particle randomly across the magnetic field by about one Larmor radius for each complete lead passage. It is equivalent to a kind of ambipolar diffusion across the magnetic field.

(iv) Under thermonuclear conditions the losses due to the leads become negligible compared to the thermonuclear power when the main field is purely poloidal. In a sheared field the same losses are larger, but it should still be possible to make them less than the thermonuclear power.

A device based on these principles is being accomplished.

* Presented by the author. Paper published in the form of two articles in *Plasma Phys.* **10**, 263, 281 (1968).

Theory of inertial confinement of dense plasmas*

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CYLINDRICAL devices in which a central medium (such as a magnetic field or a deuterium plasma) is compressed by means of a collapsing liner, are considered. The liner is supposed to be either a

* Presented by C. MAISONNIER. Paper submitted to *Nuclear Fusion.*

metallic shell, accelerated by explosives, or a polytropic plasma shell, accelerated by magnetic pressure. The results of several studies on the dynamics of the motion are presented [1–3]. They give in particular the efficiencies of the energy transfers from the external source to the liner and from the liner to the central medium, the confinement time, and the maximum energy density attainable in the compression. A more detailed analysis will soon be published.

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Use of exploding foils in a rapid theta-pinch*

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THE technique of rapidly transferring magnetic energy by means of exploding foils is used in providing a rapid rise of magnetic field in a small theta-pinch. In this way rise-times of about 1/2 μsec are achieved. The electrical and optical measurements on pinches in hydrogen and inert gases are presented.

These are used to calculate the over-all energy transfer efficiencies.

* Presented by G. SCHENK.

Fluctuations and diffusion in a lithium plasma*

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STUDIES of lithium plasmas are of interest because the ion Larmor radius can be made very small compared to the scale length of the radial density gradient. In experiments here a rhenium plate 2·5 cm in diameter and 1·5 mm thick is mounted in a thin tantalum cylinder and backed by a similar disk of tungsten heated by electron bombardment. The temperature differential across the rhenium plate is 50°K when the plate temperature is 2300°K. A beam of lithium atoms from an oven at 900°K is directed onto the rhenium plate, creating a plasma of density $n_0 \leqslant 10^{10}$ cm^{-3} in a straight magnetic field of 2000 G.

The apparatus is not accurately constructed for detailed studies of the plasma, but some measurements are made to establish the feasibility of working with probes in lithium. One probe that can move radially and a second probe capable of axial and azimuthal motion are inserted into the plasma. Both show a spectrum of density fluctuations $\tilde{n}$ similar to that observed in other alkali-metal plasmas where drift waves have been identified. With about 1 cm axial separation between the probes the radial correlation length for the density fluctuations is found to be about 2 mm, by measuring $\langle \tilde{n}_1 \tilde{n}_2 \rangle$ as a function of radial separation. The ion Larmor radius R_L is 0·8 mm, so $k_\perp R_L \approx 1$ as predicted for the drift instability.

The correlation between $\tilde{n}$ and the potential fluctuations $\tilde{V}$ is measured at one radius at $n_0 \approx 10^{10}$ cm^{-3}; $\langle \tilde{n}_1 \tilde{V}_2 \rangle$ is constant within experimental error when probe 1 is fixed and probe 2 moved azimuthally. The radial flux

$$\frac{n_0}{B}\frac{\partial}{\partial\theta}\langle \tilde{n}_1 \tilde{V}_2 \rangle$$

is thus too small to observe in this crude system. The radial density profiles $n_0(r)$ in two axial planes 10 cm apart show no significant difference, confirming that the radial flux is small; low diffusion rates have been seen by other workers in plasmas of comparable density.

* Presented by P. F. LITTLE. Full text of paper is not available.

Electro-magnetic emission from plasma focus*

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A SUPERDENSE pinch [1, 2] has been set up with dimensions of the inner and outer coaxial electrodes of 5 and 10 cm respectively, using a capacitor bank of 21·6 kJ at 30 kV. The initial gas current is formed across a pyrex insulator at the closed end of the electrode system and the sheath is driven at a velocity of 10^7 cm/sec towards the open end, arriving at peak current. The maximum current of 800 kA is reached in 2·6 μsec.

Framing camera and X-ray pin hole photographs show that in 0·1 μsec the current sheath collapses to a narrow filament (∼0·5 mm dia.) which breaks up in less than 50 nsec, although neutron and X-ray emission continue for 0·3 μsec. Filter absorption data at short wavelengths show that the electron temperature is several kilovolts, and measurements of the radiated power using Si surface barrier detectors indicate an electron density of $>10^{19}$/cm³.

The spectrum has been recorded using diffraction grating spectrographs at grazing angles of between 2° and 10 min of arc. A 2-m Rowland circle, concave grating instrument is used down to about 7 Å and a plane-grating instrument with approximately 2 arc min collimation is used between 1 and 10 Å. When 10 per cent argon is added to the gas filling lines at about 3·8 Å are observed. These are interpreted as emission lines from He-like AXVII at 3·95 Å and H-like AXVIII Lyman α at 3·75 Å. These optical transitions are more energetic than have been previously observed in the laboratory.

* Presented by N. J. PEACOCK. Full text of paper not available.

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Collisionless damping of large amplitude plasma waves*

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ELECTRON plasma waves in a collisionless plasma are damped even in the absence of close collisions. This Landau damping [1] has been experimentally verified to high precision [2, 3]. Landau's treatment is a perturbation theory in which the electric field is assumed small. The theory does not apply to large amplitude waves. The time case for large amplitude waves with negligible damping has been treated theoretically [4]. We have compared, experimentally, the damping of large amplitude plasma waves with that of small amplitude waves with all other conditions unchanged. The small amplitude waves are exponentially damped as predicted by Landau. The large amplitude waves exhibit a series of peaks associated with exchange of the energy between the wave and the resonant electrons analogous to the effect predicted by theory [4].

* Presented by J. H. MALMBERG. Paper submitted to *Physics Review Letters*.

This work was supported under contract DA-49-146-XZ-486 of the Defense Atomic Support Agency.

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Methods for the exploration of plasma confinement*

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IN THE study of plasma confinement experimentally two main objectives are involved. These are, firstly to investigate the containment properties of the device studied, i.e. to evaluate the confinement

* Presented by the author.

time and measure the magnitude of the classical plasma losses processes such as charge exchange and recombination and secondly to determine the presence, or otherwise, of instabilities and to identify them where possible.

The experimental techniques employed in the measurement of confinement time depend greatly on the means of generating the plasma. There are three main methods of plasma production currently in use:

(a) energetic particle injection (e.g. ALICE, OGRA, PHOENIX, DCX etc.);

(b) plasma generation by ionization within the trap (e.g. Stellarators, Pinches, Tokamaks);

(c) pulsed plasma injection (e.g. DECA II, Table Top, PR-5, M.T.S.E., Multipoles).

Instabilities in plasmas manifest themselves in a number of ways. In general, similar types of confinement geometry yield characteristic symptoms. Thus, for example, r.f. activity at the ion–cyclotron frequency is often observed in mirror machines whilst toroidal systems such as Stellarators, Tokamaks and ZETA exhibit anomalous plasma diffusion. Some of the symptoms of the presence of instabilities are as follows:

(a) anomalous diffusion;
(b) fluctuations in magnetic field, electric field and plasma density;
(c) current and voltage fluctuations;
(d) anomalous resistivity;
(e) scattering of microwaves;
(f) ion–cyclotron radiation;
(g) anomalous energy spreading.

In this paper the most commonly used methods for measuring confinement time and detecting non-classical behaviour are outlined for each of the three methods of plasma production listed above and the relationship, between energy confinement time and particle confinement time, is discussed. Finally some of the observations of plasma instabilities in a number of containment devices are described and some of the difficulties associated with the indentification of these instabilities is noted.

Finite Larmor radius effect on the Kelvin–Helmholtz instability*

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EXCITATION of the Kelvin–Helmholtz instability has been observed in a Q-machine when sufficiently large velocity shear exists between adjacent layers of the plasma column.

In an interpretation of this work possible effects of finite Larmor radius and collisional viscosity were neglected. The purpose of our study is to remove the first of these simplifications. With finite Larmor radius included, the growth rate for the instability has been computed for several values of the velocity shear and different e-folding lengths of the density profiles.

* Presented by H. MELCHIOR. Paper submitted to *The Physics of Fluids* and is also available as an internal report, Risö Report No. 158.

Motion of charged particles in toroidal geometry*

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THE motion of charged particles in the region of an axis Γ of general form is studied. This axis is defined by its curvature and torsion which are functions of the curvilinear abscissa.

* Presented by the author. Paper available as Report EUR. CEA. FC-446.

If the particle remains inside a thin tube of radius r_0 centred about Γ where r_0 is of the order of the characteristic distance of the field variation, then the particle is said to be confined and r_0 is called the 'plasma radius'.

By taking into account the expansion parameters a_0 (Larmor radius/plasma radius) and ε (plasma radius/mean radius of curvature) together, an adiabatic type theory can be developed, which takes finite Larmor radius effects into account in the basic periodic solution of the problem. The expansion parameter is in fact:

$$\varepsilon a_0 = \frac{\text{Larmor radius}}{\text{mean radius of curvature}}.$$

In the first-order approximation εa_0, the principal terms which appear only in the second-order approximation of the classical adiabatic theory (parameter a_0) are found.

The equations are no longer valid if the particle departs too far from the tube, but this case is not of interest since these particles are no longer confined.

The 'guiding centre' equations obtained are thus valid in the thin tube approximation, even if the Larmor radius is of the same order as the plasma radius.

The effect of singularities in the magnetic field at integral values of the rotational transform on the magnetic axis, can be studied, as well as the reflection of particles with low $v_{\parallel}$ due to a mirror effect of the toroidal field. Certain cases are completely integrable to this order, and provide a simple illustration of the phenomena.

Non-linear resonance effects at high power in a cylindrical plasma*

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A PLASMA column exhibits a main resonance and series of secondary resonances when a low power electromagnetic wave (with $\bar{E}_{\perp}$ axis and $\bar{B}_{\parallel}$ axis) is directed on it and when the density is varied by altering the discharge current. The corresponding phenomena are now investigated at high power (E-fields up to 10^4 Vm^{-1}). A luminosity curve gives an independent measurement of plasma density as a function of discharge current. When $E > 10^3$ Vm^{-1}, strong non-linear effects appear: deformation of the different resonance peaks and hysteresis, the corresponding luminosity curve exhibits kinks indicating greater perturbation of the average plasma density over a wider resonance domain. As the power increases, the kinks become plateaux indicating preferential absorption of energy at resonance and a tendency of the plasma to remain in a resonant state through h.f. ionization.

With high incident energy, the high amount of energy absorbed at resonance is sufficient to sustain the plasma in a resonant state in the absence of a d.c. discharge current. The absorbed h.f. energy remains practically constant as a function of increasing incoming energy when the plasma is self-sustained in one of its eigenmodes; the corresponding density also remains practically constant as indicated by the luminosity. When the incoming h.f. energy is decreased below a certain minimum, there is a jump to the next resonance characterized by a lower density.

* Presented by P. E. VANDENPLAS. Paper published in *Phys. Lett.* **25A**, 339 (1967).

Kinetic equations for microscopic turbulence*

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Two types of kinetic equations for the homogeneous microscopic turbulence of a one-dimensional plasma are compared with each other. These are the usual quasilinear approach and a theory based on the Hamilton-Jacobi formalism. Both theories should yield the same results as long as particle trapping can be neglected. We estimate that this becomes important for times of the order of

$$T = \frac{1}{\omega_p} \cdot \frac{m^2 v_p (\Delta v_p)^3}{e^2 \phi^2}$$

* Presented by D. PFIRSCH.

here v_p is a typical phase velocity in a reference system with vanishing group velocity and Δv_p is the range of phase velocities for the unstable modes. For times small compared to T the two theories agree, whereas for times of the order of T the Hamilton–Jacobi approach deviates from the quasi-linear theory in a way which can be interpreted as a relaxation effect.

Instability and anomalous diffusion of a weakly ionized magnetized radio-frequency plasma*

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THE influence of a magnetic field on the transverse diffusion of a weakly ionized radio-frequency hydrogen plasma has been investigated by measuring the density decay of the plasma along the magnetic field, directed parallel to the discharge tube (inner diameter 5 cm, length 200 cm). The plasma is created at one end of this tube. The axial decay length is inversely proportional to the square root of the transverse diffusion coefficient. The range of pressures used was 0·02–0·07 torr. At low values of the magnetic field ($\leqslant$50–70 G) the transverse diffusion coefficient behaves classically, while at higher fields the transverse diffusion becomes anomalous, its coefficient being independent of gas pressure and magnetic field. At the critical field B_{cr}, where anomalous diffusion begins, the plasma becomes unstable, showing oscillations with frequencies of about 100 kc/s and higher harmonics of this frequency. At higher fields the oscillations disappear in strong random fluctuations. B_{cr} is proportional to the square root of the gas pressure. An explanation of the above phenomena, based on the theory of the ion acoustic instability of a weakly ionized inhomogeneous plasma by Timofeev, can be given, from which the values of the critical field and the oscillation spectrum can be derived. The results of the diffusion coefficient measurements can be explained by introducing the turbulent mixing length concept in the theory of a plasma, subjected to ion acoustic instability.

* Presented by the author. Paper published in *Plasma Phys.* 9, 471 (1967); also available as a Thesis, University of Groningen, Natuurkundig Lab. der R.U., Groningen, Netherlands.

Fusion efficiency for revolving fields*

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IN A d.c. magnetic bottle a hydrogen plasma has been created by the magnetic and electric fields induced by two sets of four coils. One phase of a two-phase 4·0-MHz oscillator energizes two coils of each set, and the other phase energizes the other two coils. The strength of the magnetic bottle field is that required for ion–cyclotron resonance. Thomson scattering from a ruby laser beam indicates a particle density of 2×10^{13} cm^{-3} to date. The salient ability of the coil ensemble to (a) walk ions to the centre of the plasma and (b) to give them an energy corresponding to that in an orbit of a radius which is 5 per cent less than the radius of the vacuum chamber but no more energy, is corroborated.

An extension of this coil ensemble is proposed. Two such ensembles as above would be placed in the same magnetic bottle field and made to operate upon two parallel and continuously connected vacuum chambers. One coil ensemble would be energized at a cyclotron frequency of A and the other ensemble, properly phased, at a frequency of B, where $A/B = 3/2$. A mixture of deuterium and tritium would be admitted. The two cyclotronic beams would react in the connected regions of the chambers. Calculations indicate that for the two ion beams, each at the terminal energy of 44·5 keV and at regional densities of about 10^{15} cm^{-3}, an energy yield could be obtained which is equal to the energy inherent in the beams.

* Presented by M. L. POOL.

Work sponsored by a grant from the Air Force Office of Scientific Research, Washington D.C. and in part by the Air Force Flight Dynamics Laboratory.

The outer regions during a period of improved stability in Zeta

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THE existence of a period (~1 msec) of improved stability and confinement is experimentally well-established [1]. The conditions under which this is observed are not fully in agreement with the early predictions of MHD stability for a low-β diffuse pinch [2, 3]. A region of low conductivity at the outer edge of the discharge will generate instability unless the stabilizing field (B_z) is reversed there. Measurements show a reversal in sign shortly before and during the period of stability. The reverse B_z is generated during the earlier part of the discharge, presumably by the instabilities, if the discharge is sufficiently constricted. Unless this reverse B_z is generated, no stable period is observed. Measurements made by laser light scattering show an electron temperature of about 100 eV in the central region of the discharge at the start of the period, compared to ~25 eV at the wall. The resistive decay of the reverse B_z is calculated to be about 10^{-3} sec. Energy replacement times inferred from the central temperature are $(1–2) \times 10^{-3}$ sec. This time is also comparable with the Bohm diffusion time.

Measurements to determine the radial variation of the electric field components, the density, plasma potential and their fluctuations, in the outer high shear region of the discharge, have been made. The results show an outer region which is relatively quiet during the period of improved stability. The fluctuation increases towards the centre of the discharge. The observed improvement in stability is consistent with the field configuration in the outer region conforming to the detailed requirements of MHD stability theory.

* Presented by D. C. ROBINSON. Paper is available as an internal report.

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A 90° laser scattering experiment for measuring temperature and density of the ions and electrons in a cold dense theta-pinch plasma*

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IN A 90° scattering experiment performed on a plasma with a density of approximately 10^{17} cm^{-3} and a temperature of some eV a scattering spectrum is expected which consists essentially of an intense central part and two very weak satellite peaks.

In this investigation the spectrum of the central part (ion line) was resolved. From the ion line alone which was in good agreement with calculated spectra, the ion temperature, electron temperature and electron density were determined.

At some plasma parameters only a few particles were included in the Debye volume. Also in these cases no deviations from calculated spectra have been observed. In addition, the position and half width of the satellite peaks were measured. The position of the satellite peaks yields an independent value of the electron density which agrees very well with that determined from the ion line.

The half-width of the satellite peaks was much broader than expected theoretically due to fluctuations of the electron density within the scattering volume.

The measurement was performed on a theta-pinch plasma. The energy of the condenser bank was 7·5 kJ and the voltage 18 kV. As a light source a Q-switch laser was used with a power of approximately 100 MW. Because of beam stops to prevent stray light only a quarter of the whole power reached the plasma.

* Presented by the author. Paper is available as an internal report, JPP 1/58.

This work was performed as part of the joint research program of the Institut für Plasmaphysik, Garching and Euratom.

Research on magnetic fields and integral visible radiation of a plasma generated by a new type injector*

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THE authors present the results of measurements carried out by means of magnetic probes and a telescopic photomultiplier set for a plasma generated by a multi-rod plasma injector [1, 2] described also in another paper of the present conference.

On the basis of oscillograms from outer magnetic probes the mean values of the plasma magnetic field components as well as the propagation velocities of uncompensated charges and plasmoids have been determined. Without outer magnetic field the velocity of uncompensated charges varied from 10^7 cm/sec at 10^{-1} torr to 8×10^7 cm/sec at 10^{-4} torr, but in the presence of an outer field of 5 kG the velocities of the plasmoids were reduced to half the values just mentioned.

The time correlation analysis of probe signals and oscillations of the discharge current has shown that the generation time of the first groups of charges depends very strongly on the initial pressure. At a pressure of 10^{-4} torr the first uncompensated charges are ejected from the gun before the first current maximum. At higher pressures, e.g. 10^{-2} torr, such groups are emitted after the maximum, but still before the sign reversal of the current takes place.

The measurements carried out with small inner magnetic probes have also delivered some information on the operation of the injector. The inner probes enabled the control of the recurrence of discharges and the ageing effects of the electrodes. On the basis of the oscillograms obtained, the space and time distributions of the local magnetic field components and also the local values of the current density vector components have been determined. Information about the space distribution of the axial current component j_z made it possible to determine the conditions under which a phenomenon of a plasma focus occurs. The above effect shows up in the form of a jet at pressures of 10^{-2}–10^{-3} torr.

With the aid of the inner probes it has been found that the axial component j_z with a maximum of 80 A/cm^2 has a dominant role in the plasma generated by the multi-rod injector. The radial component j_r is smaller, approximately by one order of magnitude, and the azimuthal component j_θ by two orders.

The analysis of the results obtained from the inner and outer probes has shown, however, that in spite of the importance of the component j_z, the azimuthal component j_θ plays a significant role. From computations based on the inner probe measurements the j_θ time plots have been shown to agree with oscillograms of the average field $\tilde{B}_z$ as obtained from the outer probe measurements. This conformity of character and time correlations of appropriate plots [3] indicates that, in the plasma generated by the multi-rod injector, the leading role is played by azimuthal currents circulating at greater radii and ejected from the space between the rims of the rod electrodes.

The results of luminous front velocity measurements, carried out with a telescope of photomultipliers [4] were consistent with measurements performed by means of high-speed photography [5]. The axial velocity varied from (1–2) $\times 10^6$ cm/sec at 10^{-1} torr to (5–6) $\times 10^6$ cm/sec at 10^{-4} torr. Because the velocities determined on the basis of magnetic probe measurements are greater by at least one order of magnitude, one cannot identify the motion of uncompensated charges with that of a luminous plasma front. Time correlations of the integral visible radiation of a plasma with the discharge current and magnetic probe signals have also been studied [4]. A considerable conformity has been found, but at the same time there are some time shifts of the integral radiation maxima relative to the subsequent maxima of the discharge current. Alternatively, the results obtained from measurements of the correlation between the signals from photomultipliers and magnetic probes give evidence that the plasma radiation is well-correlated with space charge motions.

Attention should be paid to the fact that the best conformity of signals is obtained for axial magnetic probes. This proves that azimuthal currents play a substantial role in processes that occur in the plasma generated by the multi-rod injector.

* Presented by M. SADOWSKI. Paper has been submitted to Nuclear Fusion and is also available as internal Reports INR Nos 716 and 720/XVIII (in Polish).

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Experiments on plasma behaviour in a stationary cusp-field combined with a theta-pinch*

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THE plasma behaviour in a stationary cusp field combined with a θ-pinch in the ring cusp region has been investigated. In a field combination of this type plasma acceleration as well as confinement and heating is possible. Acceleration experiments by means of a three-stage arrangement have shown that directed kinetic energies up to 42 keV can be achieved.

The plasma which is confined in the system is subject to an oscillatory motion between the spindle cusps synchronously with the ringing current in the theta-coil. The behaviour of the plasma in such a system was compared with that of a plasma in a stationary cusp field. Preliminary results show that in a single stage arrangement confinement times are equal. The advantage of the system with the superimposed θ-pinch is that a higher temperature can be maintained for a longer time. In addition it was found that the axial cusp losses due to the action of the theta-pinch are enhanced and because of the equal confinement time it can be concluded that the radial cusp losses are reduced. In a system of more stages the axially 'lost' plasma can be captured in the next stage and, therefore, a prolongation of the confinement time seems possible.

* Presented by H. SCHINDLER. Paper is available as an internal report.

Ponderomotive action of light*

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IF A plasma is produced by laser radiation, or if it, for other reasons, is exposed to intense light, then this light will in general exert mechanical forces on the plasma. It is shown that such a force is not only connected with the absorption, but that any spatial variation of the intensity of the light and/or of the refractive index of the plasma causes such a force. It can, under certain circumstances, contribute appreciably to the high speeds, which are, for example, observed in laser produced plasmas. This effect can also cause a self-collimation of a narrow bundle of laser light.

* Presented by the author. Full text of paper not available.

Study of torsional Alfvén waves in inhomogeneous plasmas*

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THE propagation of torsional Alfvén waves in a current-carrying inhomogeneous hydrogen plasma was investigated. The plasma is generated by a longitudinal discharge in a glass tube. The maximum current is 4·2 kA. The tube is designed as a waveguide. The initial gas pressure is approximately 0·1 mm Hg. A quasi-stationary longitudinal magnetic field up to 5 kG is applied. The device is described in Rept. No. 3-12 (September, 1966), Institut für Plasmaforschung, Stuttgart.

The Alfvén waves were excited by a short current pulse over a secondary electrode ($m = 0$ mode), or a single loop coil ($|m| = 1$ mode) and were detected by magnetic probes. The probe signals were Fourier analysed to obtain the dispersion relation. By this method, the dispersion curve was measured in a frequency range from 100 kc/s up to 1 Mc/s. The measured phase velocities are in the range of 10^7 cm/sec and the damping constant is about 10^{-1} cm^{-1}.

The inhomogeneity of the plasma density leads to non-uniform phase velocity and damping over the cross section of the plasma column. This is observed experimentally.

* Presented by P. G. SCHÜLLER. Paper is available as an internal report, Report No. 3-13, Institut für Plasmaforschung, Stuttgart (August, 1967).

In a current-carrying plasma, the inhomogeneity of the electron temperature causes a current convective instability which results in different damping constants for the $m = +1$ and $m = -1$ mode. An initially linearly polarized wave will therefore be transformed into an elliptically polarized wave. This behaviour was confirmed in our experiment.

In analysing the experimental results it must be considered that especially for the $|m| = 1$ mode the probes are strong disturbances causing reflection of the wave. The reflection at the second probe leads to standing waves between the two probes. This causes humps with regular intervals in the observed dispersion. From the maxima and minima of these curves one can calculate the true damping constant and the reflection factor.

Guiding centre plasma equations*

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STARTING from the conservation equation for the guiding centre distribution function, equations are obtained for the density and current of guiding centres, and from these the density and current of the real particles. The well-known results for the guiding centre motion of a single particle in arbitrary electric and magnetic fields are used. To include finite Larmor radius effects in the final equations, the guiding centre equations must be correct to second order in the ion Larmor radius. This provides a very general and flexible method for investigating low frequency instabilities at wavelengths greater than the ion Larmor radius. Resonant particle and collisional effects can be included. The application of these equations to a number of problems will be discussed.

* Presented by the author. Full text of paper not available.

Shock-like drift waves

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It is shown that a simple macroscopic plasma model allows for non-linear shock-like drift waves satisfying Burger's equation, when a temperature gradient is present

* Presented by the author. Paper published in *Phys. Lett.* **24A**, 618 (1967).

A Spectroscopic method of density measurement in an optically thick plasma*

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AS IS known, it is possible, in an optically thin plasma, to measure the electron plasma density and temperature by performing the three following measurements: the line intensity is measured over two different slit widths, together with the neighbouring continuum. Assuming Stark broadening to predominate, the ratio of the two first measurements yields the density, and from the density so determined one gets the total intensity, the ratio of which to the continuum yielding the temperature. In the case of an *optically* thick plasma, self-absorption leads to an increase of the line width and the method breaks down. To overcome this difficulty, we derived the following method.

Let us call the measured intensities F_1 and F_2, for the line, F_3 for the continuum. It is shown that $(F_1/F_3)/(F_2/F_3) = R^0$ may be put in the form $R^0 = (0_1/0_2)R^T$, where R^T is the value of the ratio for the same density, should the plasma be optically thin. The functions 0 depend on the optical depth and on the line-shape in absence of self-absorption. We first put $0 = 1$, neglecting self-absorption, and so we get too large a value for the density, whence too large an optical depth. From this value, assuming the geometrical depth to be known, we calculate 0 and put it into the relation giving R^T. This gives us a more correct value for the density and enables us to resume the calculation with a better starting value. We have thus derived an iteration procedure, which converges very rapidly, provided the optical depth is not too large.

* Presented by the author. Paper submitted to *Journal of Quantative Spectroscopy and Radiative Transfer*.

Singular normal modes of the Vlasov equation with BGK collision damping*

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THE linearized Vlasov equation with collision damping is solved by the method of singular normal modes of Van Kampen and Case. Collision damping is taken into account by two correct Bhatnagar–Gross–Krook terms for electron–electron collisions and electron–ion collisions, respectively. (In the case of a partially ionized plasma elastic collisions between electrons and neutrals can also be included.) The BGK terms for the electron plasma considered are obtained from the collision models for a two-component plasma by means of the straightforward limit $m/M \to 0$ (m, M: electron and ion mass, respectively). First the isothermal approximation is made, then a general theory including temperature fluctuations is given.

Two different methods of solution are developed. The first method is characterized by a complicated integral operator yielding complex normal modes of the distribution function f even if the equilibrium distribution is a Maxwellian $F_0(v)$. The solutions of the adjoint integral equation must be orthogonalized. The completeness of the set of normal solutions can be proved by comparison with the Landau theory which is generalized for a Vlasov plasma with collisions and recast into a very compact form. The second method uses an auxiliary function $h = f - vF_0\int h\, dv$ for which a generalized Case formalism is developed. By the techniques of singular integral equations the set of normal modes can be shown to be complete rendering the exact solution of the initial value problem possible. The theory given can be generalized for plasmas in constant external magnetic fields.

* Presented by G. VOJTA. Paper has been submitted to *Physica and to Beiträge aus der Plasmaphysik.*

Stability of coupling between plasma and an r.f. generator in a rotating field pinch*

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THE confinement of a cylindrical plasma by a rotating field of the form $B_z = B_0 \cos \omega t$, $B_\theta = B_0 \sin \omega t$ is examined. Due to the skin effect the magnetic field penetrates only to a depth of a few times c/ω_p and the interior of the plasma is field free. The alternating current induced in the boundary layer heats the plasma. Thus the magnetic field amplitude must increase with time to balance the rising plasma pressure. The field is produced by two orthogonal resonant circuits to which power is supplied from two r.f. pulse generators at a frequency exceeding u_i/a where u_i is the mean ion velocity and a the plasma radius. The stability of the plasma column has been investigated previously for the case of zero generator impedance [1, 2]. For optimum transfer of power from the generator to the plasma the impedance cannot be zero [3]. Under these conditions the system consisting of the plasma, the coupling circuits and the generators may become unstable at low frequencies. Only the $m = 0$, $h = 0$ deformation of the plasma is involved because it is the only one that changes its volume. The analysis takes into account the variation of the plasma impedance with time and the programming of the generator output. It is shown that very weak conditions suffice to keep the system stable.

* Presented by the author. Paper avilable as an internal report, LRP 27/66.

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A kinetic theory for quiescent and weakly turbulent plasma in nearly-adiabatic fields*

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A KINETIC theory has been developed based upon appropriate perturbation expansions for the action invariants and the adiabatic dynamic equations of non-uniform plasmas in external magnetic fields with little or no symmetry. The effects of self-consistent potentials, collisions, weak turbulence, and weak non-adiabaticities in the containing field are included in this description. The predictions of an analytical theory for the non-adiabatic transition probabilities are compared with the results of numerical integration of the exact and adiabatic equations of motion in a four-bar mirror-cusp geometry. Various forms of this quasi-adiabatic kinetic hierarchy are applicable to the investigation of equilibria, stability, and non-linear wave and plasmoid dynamics in the appropriate ranges of field and plasma parameters. The present description is particularly useful under conditions of interest for thermonuclear containment experiments in which the zero-order motion of single ions is confined to a bounded region of space by a complete set of exact or adiabatic invariants.

* Presented by the author.

Work sponsored by Aerospace Research Laboratory, Office of Aerospace Research, United States Air Force.

The influence of the axial heat losses upon the temperature of a stationary hydrogen discharge in a strong axial magnetic field*

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THE temperature profile of an infinitely long stationary high-pressure arc discharge is governed by the radial heat losses. By means of a high axial magnetic field it is possible to reduce the thermal conductivity perpendicular to the magnetic field, and hence to increase the maximum temperature.

In a discharge column of finite length there is also a heat flux in the axial direction that is not affected by the axial magnetic field and that reduces the maximum temperatures attainable.

The axial and radial temperature profiles are calculated from the two-dimensional energy balance equation for a given discharge current. The maximum temperature of an arc increases with increasing arc length and attains, for great arc lengths, a constant value, valid for an infinitely long arc (an arc without axial heat losses). With an arc length of 3 m and an arc radius of 2 cm we expect temperatures of about 800,000°K for a current of 10 kA and a magnetic field of 50 G. These values can be achieved with our experimental facilities, so it should be possible to obtain by ohmic heating a stationary plasma with temperatures of up to 100 eV and electron densities of 10^{16} cm^{-3}.

* Presented by the author. Full text of paper not available.

This work has been undertaken as part of the joint research program of the Institut für Plasmaphysik and Euratom.

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Acknowledgments—The author wants to express his sincere thanks to Mr. S. Holmberg, and to Mr. E. Christoffersen, Mr. S. Engström, Mr. G. Hägerström, Mr. L. Jonsson, Miss G. Josefsson Mr. G. Kindberg, Mr. K. Ohlén and Mrs. M. Rönn for valuable assistance with the preparation work of the conference.

Plasma Physics, Vol. 10, p. 477. Pergamon Press 1968. Printed in Northern Ireland

ERRATUM

COLOMÉS J., LASRY J. et VÉRON D. (1968) Courants de dépolarisation d'un plasma dans un champ magnetique curviligne. *Plasma Phys.* **10**, 82.

La phrase "Le courant de *polarisation* est dû à la dérive des ions . . . accumulés par le courant de polarisation", placée à la fin du paragraphe 6 (page 86), doit en fait être placée dans la note en bas de page 83, à la suite de "Définition des courants de polarisation et de dépolarisation", comme cela était indiqué dans l'épreuve envoyée aux auteurs.

The phrase "Le courant de *polarisation* est dû à la dérive des ions . . . accumulés par le courant de polarisation", positioned at the end of Section 6 (page 86), should in fact be placed at the bottom of page 83, as a footnote, after "Définition des courants de polarisation et de dépolarisation", as was shown in the author corrected proofs.