# FIRST EUROPEAN CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS

Munich, Germany

10th to 13th October 1966

# FIRST EUROPEAN CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS

To be held from 10th to 13th October 1966

at the "DREIER-INSTITUT"
LUDWIG-MAXIMILIANS-UNIVERSITÄT
SCHELLINGSTRASSE 2-8
8 MUNICH 13

Organized by the INSTITUT FÜR PLASMAPHYSIK
8046 GARCHING bei MÜNCHEN
Germany

Organizing Committee: G.v.GIERKE
W.OTT
F.RAU

# General Information

The FIRST EUROPEAN CONFERENCE
ON CONTROLLED FUSION
AND PLASMA PHYSICS

is intended to succeed the meetings of the "European Study Group on Fusion". It has been considered desirable to have a European conference in those years in which no world-wide conference on plasma physics takes place.

The conference is organized by the

Institut für Plasmaphysik
Garching bei München, Germany

and will be held from 10th to 13th October 1966 by kind permission of the

LUDWIG-MAXIMILIANS-UNIVERSITÄT
MÜNCHEN

in the auditorium of the "Dreier-Institut", Schellingstrasse 2-8, 8 München 13.

The conference bureau will be located in the entrance hall of the Dreier-Institut and will be open from 10th to 13th October between 8.30 a.m. and 6.30 p.m.

A cafeteria is on the first floor.

## Sessions

Morning sessions will begin at 9 a.m., afternoon sessions at 3 p.m. There will be three invited papers (45 minutes each) and nearly 90 contributed papers (mostly 15 minutes plus 5 minutes for discussion). Rather than limit the number of contributions it has been decided to organize parallel sessions (A and B) on Wednesday and Thursday. As usual, strict adherence to the time-table will be enforced by the Chairmen.

The official conference language is English; there will be no translations into other languages.

Slides should be 5 x 5 cm in size and should be marked with a dot at the lower left-hand corner (as seen by eye). Speakers are kindly requested to give their slides to the projectionist before the session or in the break between sessions.

A visit to the Institut für Plasmaphysik, Garching, will be arranged for Friday, 14th October 1966 (see special announcement).

# Scientific Programme

Monday, 10th October 1966

9.00 a.m. - Opening of the conference
(A. Schlüter)

- Invited Paper I:
H.P. Furth
Livermore, Cal., USA
STABLE CONFINEMENT IN
TOROIDAL VACUUM FIELDS

Break

10.40 a.m.

- K. Uo, Culham, England MON 1
BEHAVIOUR OF A CHARGED PARTICLE IN A TOROIDAL MAGNETIC FIELD WITH ROTATIONAL TRANSFORM

- A. Gibson, Culham, England MON 2
THE BEHAVIOUR OF MAGNETIC FIELD LINES IN TOROIDAL STELLARATORS

X D. Lortz and A. Schlüter, Garching, Germany MON 3
TOROIDAL LOW β EQUILIBRIUM AND MAGNETIC MAPPING

- M. Vuillemin, C. Gourdon, Fontenay-aux-Roses, France MON 4
NUMERICAL STUDY OF THE FINE STRUCTURE OF THE MAGNETIC LINES ON A TOROIDAL MAGNETIC CONFIGURATION

- J.G. Linhart et al., Frascati, Italy MON 5
INERTIA CONFINEMENT OF DENSE PLASMAS. THEORY

3.00 p.m.

- B. Lehnert, Stockholm, Sweden MON 6
ON THE STABILITY OF A PLASMA BOUNDARY

X - P.P.J.M. Schram and H. Tasso, Garching, Germany MON 7
PERSISTENCE OF M.H.D. STABILITY IN THEORY INCLUDING HALL-TERM

- M. Brambilla and E. Canobbio, Saclay, France MON 8
ON THE STABILITY OF A MAGNETOPLASMA WITH LARGE ELECTRON TRANSVERSAL ENERGY

- J.G. Cordey, Culham, England MON 9
CLASSIFICATION OF ION CYCLOTRON ELECTROSTATIC INSTABILITIES AND THE EFFECT OF ENERGY SPREADING UPON THEIR STABILISATION

X - R. Saison and H.K. Wimmel, Garching, Germany MON 10
ON MINIMUM-B STABILIZATION OF ELECTROSTATIC DRIFT INSTABILITIES

Break

5.00 p.m.

- T. Kammash, University of Michigan, Ann Arbor, USA MON 11
  HIGH FREQUENCY DRIFT INSTABILITY IN A PLASMA WITH TEMPERATURE AND FIELD GRADIENTS
- J. Weisse et al., Saclay, France MON 12
  DIFFUSION AND MICROINSTABILITIES
- C.F. Kennel, Trieste, and F. Engelmann, Frascati, Italy MON 13
  QUASI-LINEAR THEORY OF ARBITRARY MODES IN A MAGNETO-PLASMA
- E. Minardi and F. Santini, Rijnhuizen, Jutphaas, Holl. MON 14
  THE THERMODYNAMICS OF A COLLISIONLESS PLASMA AT EQUILIBRIUM IN A MAGNETIC FIELD

Tuesday, 11th October 1966

9.00 a.m. - Invited Paper II:

W.E. Quinn
Los Alamos, New Mexico, USA
REVIEW OF THETA-PINCH EXPERIMENTS

Break

10.00 a.m.

- A.A. Newton et al., Culham, England TUE 1
  ELECTRON TEMPERATURE VARIATIONS IN MEGAJOULE THETA-PINCH EXPERIMENTS
- H.A.B. Bodin et al., Culham, England TUE 2
  AN ANALYSIS OF THE SPATIAL VARIATION OF ELECTRON DENSITY IN A MEGAJOULE THETA-PINCH
- P. Noll et al., Jülich, Germany TUE 3
  EXPERIMENTAL INVESTIGATIONS ON A 600 kJ THETA-PINCH

Break

11.20 a.m.

- H. Fisser, Garching, Germany TUE 4
  NUMERICAL SOLUTIONS OF THE MAGNETOHYDRODYNAMIC EQUATIONS FOR ONE-DIMENSIONAL THETA-PINCH GEOMETRY
- G.H. Wolf et al., Garching, Germany TUE 5
  PRELIMINARY INVESTIGATION OF A CORRUGATED THETA-PINCH ("LIMPUS") AT ISAR I
- F.A. Haas and J.A. Wesson, Culham, England TUE 6
  THE STABILITY OF THETA-PINCH
- H. Zwicker et al., Garching, Germany TUE 7
  PRELIMINARY RESULTS OF A VERY FAST LOW-PRESSURE THETA-PINCH EXPERIMENT
- P. Bogen, J. Schlüter, Jülich, Germany TUE 8
  PARAMETER STUDY OF PLASMA HEATING IN A THETA-PINCH

3.00 p.m.

- G. Decker et al., Garching, Germany TUE 9
  DYNAMICS OF A PLASMA IN A HIGH FREQUENCY THETA-PINCH DISCHARGE
- H. Röhr et al., Garching, Germany TUE 10
  INVESTIGATION OF COLLISIONLESS HEATING PROCESSES BY MEANS OF LASER SCATTERING
- P.C.T. van der Laan et al., Rijnhuizen, Jutphaas, Holl. TUE 11
  FORMATION OF A SECOND CURRENT LAYER AROUND A PINCHED PLASMA

- C. Bobeldijk et al., Rijnhuizen, Jutphaas, Holland TUE 12
  EQUILIBRIUM AND STABILITY OF A TOROIDAL SCREW PINCH
- B.A. Ward, Culham, England TUE 13
  EXPERIMENTAL AND COMPUTED OBSERVATIONS OF THE LINEAR AND SEMI-TOROIDAL INVERSE PINCH DEVICES, FAUST B & C
- F. Koechlin et al., Fontenay-aux-Roses, France TUE 14
  EXPERIMENTAL STUDY OF THE STABILITY OF A CURRENT SHEET

6.30 p.m.:

Reception given by the
Bavarian State Government,
held at the "Schackgalerie",
Prinzregentenstrasse 9,
Munich 22.

Wednesday, 12th October 1966

9.00 a.m. - Invited Paper III:

J.W.M. Paul
Culham, England
EXPERIMENTAL STUDIES OF COLLISIONLESS SHOCK WAVES

Break

10.00 a.m.

Session A (Auditorium)

- P. Lecoustey and C. Renaud, Fontenay-aux-Roses, France — WED A 1
  CHARGE EXCHANGE LOSSES ANALYSIS IN DECA II
- P. Brossier, presented by J. Tachon — WED A 2
  Fontenay-aux-Roses, France
  ION CYCLOTRON OSCILLATIONS IN DECA II
- C. Leloup et al., Fontenay-aux-Roses, France — WED A 3
  THE 'BILLE-EN-TETE' B EXPERIMENTS: RESULTS
- E. Thompson et al., Culham, England — WED A 4
  CHARACTERISTICS OF MICRO-INSTABILITIES AND STABILISATION EXPERIMENTS IN SIMPLE MIRROR AND MAGNETIC WELL GEOMETRY

Break

11.40 a.m.

- H.J. Belitz, E. Kugler, Jülich, Germany — WED A 5
  INVESTIGATION ON THE COMPRESSION AND THE CONTAINMENT OF A PLASMA IN CUSP-GEOMETRY
- I.J. Spalding, Culham, England — WED A 6
  HIGH ß INJECTION EXPERIMENTS
- B. Brandt et al., Rijnhuizen, Jutphaas, Holland — WED A 7
  MEASUREMENTS ON A PLASMA FORMED BY INJECTION OF ENERGETIC IONS INTO A MAGNETIC QUADRUPOLE FIELD
- M.G. Haines et al., Imperial Coll., London, England — WED A 8
  THE POLYTRON: A TOROIDAL DEVICE FOR THE CONTAINMENT OF A HOT MOVING PLASMA

3.00 p.m.

- P. Deschamps et al., Fontenay-aux-Roses, France — WED A 9
  COAXIAL GUN WITH ANNULAR PREIONIZATION SYSTEM. CHARACTERISTICS OF THE PLASMA PRODUCED IN THE HIGH-DENSITY MODE
- H. Schindler, SIEMENS Erlangen, Germany — WED A 10
  ACCELERATION AND CONFINEMENT OF PLASMA IN A THREE-STAGE PLASMA GUN

- J. Lasry, D. Véron, Fontenay-aux-Roses, France — WED A 11
  DRIFTS OF A PLASMOID INJECTED INTO A CURVILINEAR MAGNETIC FIELD. APPLICATION TO THE PURIFICATION OF THE PLASMA
- D.E.T.F. Ashby and J.N. Burcham, Culham, England — WED A 12
  THE INJECTION OF TENUOUS PLASMA INTO A MAGNETIC GUIDE FIELD

ca. 7.00 p.m.:

Opera Performance
Nationaltheater Munich

Wednesday, 12th October 1966

9.00 a.m. - Invited Paper J.W.M. Paul

B r e a k

10.00 a.m.

S e s s i o n B (Lecture Hall)

- W.M. Jones et al., Fontenay-aux-Roses, France — WED B 1
  THE HARMONICA EXPERIMENT
- G. Grieger et al., Garching, Germany — WED B 2
  RESISTIVE DIFFUSION OF CESIUM PLASMA IN A STELLARATOR
- M. Hashmi et al., Garching, Germany — WED B 3
  EFFECT OF ION-NEUTRAL COLLISIONS ON THE ION DENSITY IN A Q-MACHINE
- B. Lehnert et al., Stockholm, Sweden — WED B 4
  CRITICAL VOLTAGE OF A ROTATING PLASMA

B r e a k

11.40 a.m.

- J.G. Bannenberg et al., Amsterdam, Holland — WED B 5
  CHARACTERISTICS OF AN $\bar{E} \times \bar{B}$ DISCHARGE
- E.P. Barbian et al., Amsterdam, Holland — WED B 6
  INSTABILITY IN A ROTATING PLASMA
- E. Hintz, Jülich, Germany — WED B 7
  EXPERIMENTAL RESULTS ON THE STRUCTURE OF HYDROMAGNETIC SHOCK WAVES IN A COLLISION-FREE PLASMA
- R. Chodura and P. Igenbergs, Garching, Germany — WED B 8
  NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON COLLISION-FREE COMPRESSION OF A PLASMA WITH ANOMALOUS FRICTION

ca. 7.00 p.m.:

Opera Performance

Nationaltheater Munich

Thursday, 13th October 1966

9.00 a.m.

S e s s i o n A (Auditorium)

- L. Enriques, Frascati, Italy — THU A 1
  DRIFT WAVES EXCITATION IN ALKALI-HALOGEN PLASMAS
- W.H. Kegel, Garching, Germany — THU A 2
  RADIATION FROM A PLASMA STIMULATED BY TWO SHORT MICROWAVE PULSES AT THE GYROFREQUENCY AND ITS SECOND HARMONIC
- M. Ianuzzi and F. Magistrelli, Frascati, Italy — THU A 3
  INVESTIGATION OF MICROWAVE SCATTERING FROM ALKALI PLASMAS
- R.A. Blanken and A.F. Kuckes, Princeton, N.J., USA — THU A 4
  MICROWAVE RADIATION AND SCATTERING FROM A HOT ELECTRON PLASMA

B r e a k

10.30 a.m.

- J. Olivain et al., Fontenay-aux-Roses, France — THU A 5
  GENERATION OF HARMONICS OF HALF THE ELECTRON GYROMAGNETIC FREQUENCY IN A TWO-BEAM SYSTEM
- G. Landauer and G. Müller, Garching, Germany — THU A 6
  RADIATION OF HARMONICS $n\omega_e$ AND $n\omega_e/2$ FROM A BEAM-GENERATED PLASMA
- F. Parlange et al., Saclay, France — THU A 7
  STUDY OF A PLASMA BEAM CREATED BY A RIGHT HAND CIRCULAR WAVE IN A DECREASING STEADY MAGNETIC FIELD AT THE ELECTRON CYCLOTRON RESONANCE.
- T.K. N'Guyen, T. Consoli, Saclay, France — THU A 8
  REALIZATION OF A RADIOMETER FOR ELECTRONIC DOPPLER SHIFT MEASUREMENTS IN PLASMAS

B r e a k

12.00 a.m.

- P.E. Vandenplas et al., École Royale Militaire, Bruxelles, Belgium — THU A 9
  EVOLUTION OF COLD PLASMA RESONANCES AS A FUNCTION OF MAGNETIC FIELD
- P.G. Schüller et al., Stuttgart, Germany — THU A 10
  INVESTIGATION OF ALFVÉN WAVES IN A PLASMA-FILLED WAVE GUIDE
- B. Agdur, Stockholm, Sweden — THU A 11
  HIGH FREQUENCY INSTABILITIES IN A PIG-DISCHARGE

3.00 p.m.

- B. Brunelli, Frascati, Italy — THU A 12
  OBLIQUELY PROPAGATING LARGE-AMPLITUDE WAVES IN A LOW-DENSITY PLASMA
- J. Kistemaker et al., Amsterdam, Holland — THU A 13
  NON-LINEAR EFFECTS IN A BEAM-PLASMA SYSTEM
- T. Matitti et al., Amsterdam, Holland — THU A 14
  LOW FREQUENCY WAVES IN A BEAM-PLASMA SYSTEM
- C. Etiévant et al., Fontenay-aux-Roses, France — THU A 15
  NON-LINEAR PROCESSES IN BEAM-PLASMA SYSTEMS

Break

4.40 p.m.

- M. Perulli et al., Fontenay-aux-Roses, France — THU A 16
  STUDY OF THE "ELECTROSTATIC" CHARACTER OF ION CYCLOTRON OSCILLATIONS
- J.F. Bonnal et al., Saclay, France — THU A 17
  CREATION OF A SYNTHESIZED PLASMA BEAM AND APPLICATION TO THE STUDY OF A TWO BEAMS-PLASMA INSTABILITY
- W. Herrmann, Garching, Germany — THU A 18
  EXCITATION OF ELECTRON PLASMA OSCILLATIONS BY THE INTERACTION OF AN ION BEAM WITH A PLASMA
- E. Gadda et al., Fontenay-aux-Roses, France — THU A 19
  EXPERIMENTAL STUDY OF A STRONG BEAM-PLASMA DISCHARGE

8.00 p.m.:

Official Conference Dinner
offered by the
Institut für Plasmaphysik,
held at the "Künstlerhaus",
Lenbachplatz 8, Munich.

Thursday, 13th October 1966

9.00 a.m.

S e s s i o n B (Lecture Hall)

- D. Pfirsch, München, Germany — THU B 1
  THE APPLICATION OF HAMILTON-JACOBI-THEORY TO VLASOV's EQUATION
- B. McNamara and K.J. Whiteman, Culham, England — THU B 2
  HAMILTONIAN FORMULATION OF MAGNETIC FIELD EQUATIONS
- J. Jäger and W. Lochte-Holtgreven, Kiel, Germany — THU B 3
  EXPLODING LIQUID JETS AND THEIR USE FOR PERIODICALLY WORKING HIGH TEMPERATURE DEVICES
- Ch. Maisonnier, J.G. Linhart, Frascati, Italy — THU B 4
  EXPLODING FOILS AS LINERS

B r e a k

10.30 a.m.

- B. Bonnevier, Stockholm, Sweden — THU B 5
  DIFFUSION DUE TO ION-ION COLLISIONS IN A MULTI-COMPONENT PLASMA
- M. Bernard et al., Saclay, France — THU B 6
  ABOUT SOME MEASUREMENTS OF PARTICLE FLOW, DIFFUSION COEFFICIENT, AND NOISE IN 'DAPHNIS' EXPERIMENT
- M. Haegi, Frascati, Italy — THU B 7
  OHMIC HEATING OF HYPERSONIC DEUTERIUM JET
- F. Herrnegger et al., Innsbruck, Austria — THU B 8
  RESEARCH ON NON-LINEAR INTERACTIONS BETWEEN A PLASMA FLOW AND A MAGNETIC FIELD

B r e a k

12.00 a.m.

- R. Wienecke and H. Wulff, Garching, Germany — THU B 9
  EXPERIMENTAL DEVICES "BOGEN" AND "EIERUHR" FOR THE PRODUCTION OF HIGH DENSITY STEADY-STATE PLASMA IN THE TEMPERATURE RANGE ABOVE 10 eV
- H. Wulff, Garching, Germany — THU B 10
  SPECTROSCOPIC TEMPERATURE DETERMINATION IN THE "BOGEN" AND "EIERUHR" EXPERIMENTS
- P.H. Grassmann, Garching, Germany — THU B 11
  MEASUREMENTS OF THE RADIAL DEPENDENCE OF THE NUMBER DENSITY OF FREE ELECTRONS AND ELECTRON TEMPERATURE IN AN "EIERUHR" PLASMA
- O. Klüber, Garching, Germany — THU B 12
  INVESTIGATIONS ON THE PRESSURE DISTRIBUTION INSIDE THE "EIERUHR" BY MEANS OF DIAMAGNETIC SIGNALS
- C. Mahn et al., Garching, Germany — THU B 13
  MEASUREMENTS OF ELECTRIC FIELDS AND PLASMA VELOCITIES IN THE "BOGEN"

3.00 p.m.

- C.M. Braams, Rijnhuizen, Jutphaas, Holland — THU B 14
  SCALING LAWS FOR COLD-GAS BLANKET CONFINEMENT
- J. Sheffield, Culham, England — THU B 15
  A NEW THEORY OF THE HIGHLY MAGNETISED POSITIVE COLUMN AND ITS EXPERIMENTAL VERIFICATION
- A. Torossian et al., Fontenay-aux-Roses, France — THU B 16
  HARD CORE EXPERIMENTS AT FONTENAY-AUX-ROSES

B r e a k

4.20 p.m.

- C.T. Chang, Risö, Roskilde, Denmark — THU B 17
  ON THE ENERGY SOURCE OF A MAGNETICALLY DRIVEN SHOCK TUBE
- B. Mayser et al., Stuttgart, Germany — THU B 18
  DEVELOPMENT AND STRUCTURE OF A SHOCK WAVE IN A NOT FULLY IONIZED MAGNETO-PLASMA
- W. Bieger et al., Jülich, Germany — THU B 19
  PLASMA ACCELERATION WITH AN ELECTROMAGNETIC TRAVELLING WAVE
- T. Consoli et al., Saclay, France — THU B 20
  HIGH POWER R.F. ACCELERATOR

8.00 p.m.:

Official Conference Dinner
offered by the
Institut für Plasmaphysik,
held at the "Künstlerhaus",
Lenbachplatz 8, Munich

# A B S T R A C T S

The following abstracts are listed in the order of presentation.

Proceedings of the First European Conference on Controlled Fusion and Plasma Physics will not be issued.

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N o t e :
Contributions by members of the Institut für Plasmaphysik, Garching bei München, Germany, have been carried out as part of the joint research programme of the Institut für Plasmaphysik and EURATOM.

UCRL-70067 (Abstract)

# STABLE CONFINEMENT IN TOROIDAL VACUUM FIELDS*

Harold P. Furth
Lawrence Radiation Laboratory, University of California
Livermore, California

In toroidal confinement experiments an anomalous loss-rate comparable to Bohm diffusion is often seen. Possible causes of loss are non-closure of magnetic flux surfaces, wall-interception of particle drift surfaces, and, most importantly, anomalous diffusion due to small-scale instability.

Axisymmetric vacuum fields are especially useful for the study of this problem, since they can eliminate uncertainties about flux and drift surfaces (thanks to the existence of exact flux and momentum integrals), while at the same time reaching optimum conditions for plasma stability: strong shear or line closure, strong minimum-average-B, and little or no $J_{\|}$.

(1) The simple toroidal field, of course, provides no equilibrium. (2) The poloidal field of a single ring (levitron) is MHD-unstable. (3) The poloidal field of two or more rings (floating multipole) can be made minimum-average-B stable; the closure of field lines additionally inhibits drift modes. Adding toroidal field to the levitron can provide shear (4) as well as minimimum-average-B (5). Adding toroidal field to the multipole (6) spoils closure of lines, but can add strong shear, and maintains minimum-average-B.

A review of experimental results confirms the unfavorable predictions for (1) and (2); whereas (3) is found highly stable (with long-time containment remaining to be studied). Partial exploration of (4) and (5) has deomonstrated shear and minimum-average-B effects, but thus far imperfect stability. Alternative (6) is still to be tested.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

# Behaviour of a Charged Particle in a Toroidal Magnetic Field with Rotational Transform

Koji Uo

U.K.A.E.A., Culham Laboratory, Abingdon, Berks., England

## Abstract

The motion of a charged particle in a Tokomak type magnetic field is analysed. By using the $\phi$-component of the canonical angular momentum in the toroidal coordinate system ($r$ , $\theta$ , $\phi$ ) and the total energy as the constants of motion, the region of allowed particle motion has been calculated. This region is given by a function of the $\phi$-component of the magnetic vector potential $A_\phi$ , the vertical magnetic field, the electric field and the initial position and motion of the particle. Then, we determine the allowable range of energy and velocity of a particle to be confined within a limiting surface. For given initial position of the particle, the maximum energy of the confined particle shows strong dependence on $\gamma \equiv v_\phi/v$ , and strong asymmetry on the sign of $\gamma$ . The energy and the velocity distributions of the confined particle have strong radial dependence. In the region near the limiting surface, almost uni-directional $\phi$-motion alone is allowed for high energy particles. This stems from the fact that the $\theta$-component of the magnetic field is the effective agent for single particle confinement in a toroidal system. The effects of the radial electric field $E_r$ and the vertical electric field $E_v$ are discussed. $E_r$ is favourable for particle confinement and $E_v$ unfavourable.

# The behaviour of magnetic field lines in toroidal stellarators

A. Gibson

U.K.A.E.A., Culham Laboratory, Abingdon, Berkshire, England

## ABSTRACT

In a toroidal $\ell = 3$ stellarator, in addition to the well known inward shift of the magnetic axis from the centre of the $\ell$-winding and some distortion of the triangular surface, numerical calculations indicate that the following effects occur:

(i) The rotational transform on the last closed surface is substantially less than the winding transform.

(ii) The closed and open surfaces are separated by a complex region.

(iii) The shape of the surfaces in the central region is modified essentially as predicted by Aleksin*.

The maximum shear available in a feasible stellarator is evaluated and compared to that required for stability. The effect of perturbations on the perfect toroidal system is computed.

The motion of electrons in this type of trap is discussed.

*Kharkov Conf. Proc. Pt. 3, 216-224, TF.1963.

# TOROIDAL LOW $\beta$ EQUILIBRIUM AND MAGNETIC MAPPING

D. Lortz and A. Schlüter
Institut für Plasmaphysik, Garching bei München

## Abstract

A magnetic field with non-closing lines of force yields a so-called magnetic mapping of a meridional plane to itself. The closed invariant curves of a magnetic mapping, if they exist, can be considered as the meridional cuts of so-called magnetic surfaces. These surfaces were computed asymptotically for the limit of small rotational transform. If the fundamental field is the toroidal vacuum field and the magnetic surfaces are nested toroids then the quantity $d^2V/d\phi^2$ is usually negative, where $V$ is the interior volume of the toroid and $\phi$ the azimuthal magnetic flux. Extensive numerical calculations were made for larger rotational transform, yielding many configurations with negative $V''$. However, field line integrations of analytical magnetic vacuum fields show that magnetic surfaces do not exist in general. The linearization in the neighbourhood of a closed field line yields a necessary condition for the field line to belong to a magnetic surface. It was possible to satisfy this condition numerically with a high degree of accuracy by a certain field combination. It turned out that the so-called $q$ -condition, necessary for a low $\beta$ equilibrium to exist, was then also satisfied with the same accuracy.

# NUMERICAL STUDY OF THE FINE STRUCTURE OF THE MAGNETIC LINES ON A TOROIDAL MAGNETIC CONFIGURATION

M. Vuillemin, C. Gourdon

Groupe de Recherches de l'Association Euratom-CEA sur la Fusion Contrôlée
92 Fontenay-aux-Roses (France)

A numerical study of the topological structure of a toroidal vacuum magnetic field has been performed using an analytically exact solution with a circular magnetic axis.

On the macroscopic scale two types of behaviour are found for the magnetic lines of force. Near the magnetic axis the lines are stable and generate "pseudo surfaces". Away from the magnetic axis the lines are unstable and leave the configuration after a small number of turns.

We investigated the fine structure of the "pseudo surfaces" in the neighbourhood of some particular closed lines of force, and have observed the filamentary structure described by MOROZOV and SOLOVIEV (1963).

The existence of resonant zones having finite width and the unstable behaviour in regions where these zones overlap is in agreement with the recent theory of ROSENBLUTH and SAGDEEV (Trieste, 1966).

# INERTIA CONFINEMENT OF DENSE PLASMAS. THEORY.

J.G. Linhart, Ch. Maisonrier, J.P. Somon
Laboratorio Gas Ionizzati (EURATOM-C.N.E.N.)
Frascati (Roma), Italy

ABSTRACT - Having demonstrated that a critical energy exists for unconfined or marginally confined fusion reactors, and that the geometry of the hollow linear pinch seems to lead to the minimum critical energy, the critical parameters (voltage and energy) of the energy source can be deduced from the dynamics of such a pinch. It appears that unconfined devices are technically unfeasible, with the possible exception of microbombs triggered by the impact of a very fast ($10^8$ cm/sec) solid projectile. On the other hand, marginally confined devices could be of interest: the confinement could be obtained either by the use of magnetic fields larger than $10^7$ gauss (generated by flux compression) or by means of an auxiliary dense plasma working by inertia. The necessity of further theoretical investigations is pointed out.

# ON THE STABILITY OF A PLASMA BOUNDARY

B. Lehnert
Royal Institute of Technology, Stockholm 70, Sweden

In absence of shear and minimum-B or minimum-average-B properties there are experimental indications that flute instabilities can be suppressed under certain conditions. These occur mainly under the influence of conducting end plates and finite Larmor radius effects. In particular, the momentum balance and the behaviour of the plasma boundary in a rotating plasma device indicate stability, whereas flute instabilities are often observed in the rotating plasma column of a theta pinch.

In a rotating plasma device the plasma boundaries run along the magnetic field lines which are tangent to metal electrodes. On the other hand, the plasma column is separated from surrounding walls in a theta pinch. When there is a contact between the plasma boundary and a conducting wall, it can be shown that the joint action of the finite Larmor radius and the line-tying effect at the boundary will stabilize the plasma more easily than the finite Larmor radius effect alone. This is the case especially when the density falls off steeply near the boundary, i.e. when there is a boundary region of limited thickness.

Even if the outermost layers of the plasma are in contact with a metal wall, the energy losses can be kept at a low level, provided that these layers have a moderately high temperature.

# PERSISTENCE OF M.H.D. STABILITY IN THEORY INCLUDING HALL-TERM

by

P.P.J.M. Schram and H. Tasso

Institut für Plasmaphysik GmbH, Garching b. München

Abstract

For general static equilibria with surface currents, it is possible to show that the stability is not affected by the presence of a Hall-term in the ohmic-law.

# ON THE STABILITY OF A MAGNETOPLASMA WITH LARGE ELECTRON TRANSVERSAL ENERGY

M. Brambilla and E. Canobbio
C.E.A. - Centre d'Études Nucléaires de Saclay
Gif-sur-Yvette, France

Abstract

Plasma injection, acceleration and containment in open ended magnetic configurations by means of H.F. fields, has been realized in several devices (1), having a preponderance of electrons with large transversal energy.

In this note the eletrostatic instability of such a plasma is considered in the case that the electron distribution function is anisotropic in velocity space while uniform in the real space and second in the case of rotating coaxial cylinders of charged particles with an important charge separation and axial drifts.

In the first situation, which corresponds to the high flow regime of the Saclay machines (1), the Harris dispersion relation has been investigated both numerically and analytically. Severe conditions for the upset of instability have been found. For monoenergetic electrons one has

$$Im\{\omega\} \lesssim \frac{\omega_c}{\pi} \ln\left(4\sqrt{\frac{2}{\pi}}\,\frac{\omega_c}{\omega_p}\right),$$

the largest growth rate being reached if $k_\perp v_\perp \sim \omega_p \gg \omega_c$. Shorter wavelengths are stable. If the velocity distribution has a spread $\Delta v_\perp$, an upper limit for $Im\{\omega\}$ is

$$Im\{\omega\} \lesssim \frac{\omega_c}{\pi} \ln\left(\frac{\langle v_\perp \rangle}{\Delta v_\perp}\right),$$

while only wavelength such that $K \langle R_L \rangle \lesssim \frac{\Delta v_\perp}{\langle v_\perp \rangle}$ can be instable. For physical plasma these inequalities show that the electrostatic instabilities should hardly be very dangerous, especially if compared with the Whistler mode-instability.

In the case of the rotating cylinders the low density flow situation (1), due to the radial charge separation, the differential equation for the perturbations is in general no longer of the Bessel type. We suppose to have two counter-streaming electron beams with unperturbed axial velocities $v_{z0(1)} = - v_{z0(2)}$ and unperturbed azimuthal velocity $v_{\theta 0} = - r \omega_c - \frac{e E_{0r}(r)}{m \omega_c}$ and consider for simplicity cylindrical symmetric perturbations only $(m = 0)$. It turns out that the plasma-plasma wave interaction can be stabilized by the r-dependence of the electron density (for a typical density profile, the wave equation is solved by Bessel functions of complex index).

The cyclotron-cyclotron wave interaction, on the other Rand, can be stabilized by the velocity shear. We consider for simplicity the case of a uniform imperturbed electron density in a cylindrical shell $R_1 \leq r \leq R_2$ and suppose for the perturbations that $|K| R_1 \gg 1$, $m = 0$, and $|\omega| \ll |K|$. In the neighbourhood of the frequency and axial wave number which are the most instable in the absence of charge separation, the differential equation for the perturbad electric potential reduces to a Bessel equation of complex index. The dispersion relation one obtains does not admit unstable roots anymore.

Finally, the cyclotron-plasma wave interaction is stabilized by both the density profile and velocity shear.

(1) T. Consoli, Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham, U. K. (1965).

# Classification of Ion Cyclotron Electrostatic Instabilities and the effect of Energy Spreading upon their Stabilisation

by

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## A B S T R A C T

The various types of ion cyclotron electrostatic instabilities occurring in a homogeneous plasma, are examined using equilibrium particle distribution functions appropriate to mirror machine confinement. We show that not all of these instabilities are convective and discuss the finite length of machine necessary for the existence of each type of instability. The effects of spreading the particle energy are examined, and it is found that spreading particle energy parallel to the magnetic field is more effective in quenching these instabilities than spreading particle energy perpendicular to the magnetic field.

# On Minimum-B Stabilization of Electrostatic Drift Instabilities

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## Abstract

A check is made of a stabilization theorem of ROSENBLUTH and KRALL (Phys. Fluids 8, 1004 [1965] ) according to which an inhomogeneous plasma in a minimum-B field ($\beta \ll 1$) should be stable with respect to electrostatic drift instabilities when the particle distribution functions satisfy a condition given by TAYLOR, i.e. when $f_0 = f(W, \mu)$ and $\partial f / \partial W < 0$. Although the dispersion relation of ROSENBLUTH and KRALL is confirmed to first order in the gyroradii and in $\varepsilon \equiv d \ln B / dx$ the stabilization theorem is refuted, as also is the validity of the stability criterion used by ROSENBLUTH and KRALL, $\langle \underline{\underline{j}} \cdot \underline{\underline{E}} \rangle \gtrless 0$ for all real $\omega$ . In the case $\omega_{pi} \gg |\Omega_i|$ equilibria are given which satisfy the condition of TAYLOR and are nevertheless unstable. For instability it is necessary to have a non-monotonic $v_\perp$-distribution; the instabilities involved may thus be termed loss-cone unstable drift waves. In the spatially homogeneous limiting case the instability persists as a pure loss cone instability with $Re(\omega) = 0$. A necessary and sufficient condition for stability is $D(\omega = \infty \, , k, \ldots) \leq k^2$ for all k, the dispersion relation being written in the form $D(\omega \, , k, K, \ldots) = k^2 + K^2$. In the case $\omega_{pi} \ll |\Omega_i|$ adherence to the condition given by TAYLOR guarantees stability.

# HIGH FREQUENCY DRIFT INSTABILITY IN A PLASMA WITH TEMPERATURE AND FIELD GRADIENTS*

Terry Kammash

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Abstract

The stability of longitudinal oscillations at or near integral multiples of the ion cyclotron frequency in an anisotropic plasma with density and temperature gradients is investigated. The effect of magnetic field curvature as simulated by a gravitational force is included and for waves propagating normal to the magnetic field it is shown that large temperature gradients as given by $\eta = \frac{d\ell n\, T}{d\ell n\, n} > 2$ are stabilizing. This is contrasted with the destabilizing effect of $\eta > 2$ on the low frequency universal modes.[1] A stability criterion relating curvature, temperature and density gradients will be presented and discussed.

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*Work supported by the U.S. Atomic Energy Commission.

[1]A. A. Galeev, V. N. Oraevskii, and R. Z. Sagdeev, JETP 17, 615 (1963).

# DIFFUSION AND MICROINSTABILITIES

by

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ABSTRACT NOT RECEIVED

# QUASI-LINEAR THEORY OF ARBITRARY MODES IN A MAGNETOPLASMA

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ABSTRACT - We consider quasi-linear velocity space diffusion induced by waves of any oscillation branch propagating at an arbitrary angle to an uniform magnetic field in a homogeneous plasma. The space-averaged distribution function is assumed to change weakly during the time typical for the motion of the waves and gyration periods of the particles. Non-linear mode-mode coupling is neglected. An explicit formula for the diffusion coefficient in terms of the wave amplitudes excited is derived.

An H-like theorem is formulated, from which follows that the system tends towards a stable steady state. A necessary and sufficient condition for this state to be consistent with a finite excitation of waves is derived. Furthermore it is shown that in the case of resonant diffusion, i.e., if the growth rates of the waves are small, particles with parallel velocities much larger than typical phase velocities in the excited spectrum are scattered primarily in pitch angle.

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# THE THERMODYNAMICS OF A COLLISIONLESS PLASMA AT EQUILIBRIUM IN A MAGNETIC FIELD

by

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## ABSTRACT

The free energy and entropy functionals describing the equilibrium of a collisionless low $\beta$ plasma in a general adiabatic magnetic field are constructed following the rules described in previous articles (Physica, 32, 497 (1966); Symp. on Theor. Plasma Phys., Varenna, Italy, May 9-12,1966). The close connections between the conditions insuring the minimum entropy of a given equilibrium configuration and the negative energy variation in a general type of interchanges involving the magnetic energy is discussed. These conditions are expressed in a form which is invariant with respect to transformations between all possible curvilinear coordinate systems defined by the given external magnetic field. The conditions in the invariant form can be used for the calculation of the regions of minimum entropy, where the plasma should be expected to be unstable. When a locally Cartesian system is used the invariant conditions reduce to conditions given previously (see the Proceedings of the Varenna Symposium), which only hold in the local Cartesian region. The relation between configurations with maximum entropy and minimum B configurations is pointed out. In the zero $\beta$ limit and when the longitudinal invariant J is a constant of motion our conditions averaged along the magnetic field reduce to the conditions given by Taylor.

# REVIEW OF THETA-PINCH EXPERIMENTS

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The experimental arrangements of the present generation of large $\theta$-pinches and the experimental studies of plasma production and confinement in the $\theta$-pinch configuration are reviewed. The regimes of operation of the present linear $\theta$-pinches are discussed. Observations on the plasma structure, density profiles, impurities and electron temperatures and their spatial distribution and temporal development have been made using time-resolved photographic, interferometric, and spectroscopic methods in the visible and soft x-ray regions. Ion energies have been determined from measurements involving nuclear reaction products, Doppler shift of radiation from impurity ions, and by direct measurement of the energies of ions leaving the $\theta$-pinch along the z axis. The experimental evidence is reviewed that end loss is a dominant loss mechanism in the present, large, linear $\theta$-pinches. The evidence consists primarily of the following: Interferometric measurement of radial density distributions, well isolated from the wall, and with diminishing total number of plasma particles; similar photometric measurements; direct photography of plasma escaping out the ends; pressure-probe measurements of axially escaping plasma; and measurement of the energy spectrum and flux of axially escaping ions in such quantity as to account approximately for the observed loss of total particles. The scaling of the end loss results is discussed in terms of various theoretical models. Anticipated trends of future work, directed toward closed and open systems with longer containment will be discussed.

# ELECTRON TEMPERATURE VARIATIONS IN MEGAJOULE THETA PINCH EXPERIMENTS.

by

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## Abstract

Measurements of electron temperatures in plasma heated and compressed in Megajoule theta pinches are described. Results obtained from the intensity of soft X-rays transmitted through thin foils are compared with those found from the wavelength of maximum intensity of the bremsstrahlung continuum in the grazing incidence region. The time dependence and variation of the temperature is determined by the heating mechanism, energy transport and radiation losses. The role of impurity has been established by reducing the contamination to a negligible level and adding carefully controlled amounts of oxygen. Effects dependent on coil length are differentiated in a series of experiments where energy loss is studied through the decay of plasma diamagnetism. A more direct comparison has been made by measuring the electron temperature of plasma produced in coils of one and two metre lengths. Finally the effects of various loss processes on the properties of the plasma at lower initial densities are studied using the standard one-dimensional MHD code.

# AN ANALYSIS OF THE SPATIAL VARIATION OF ELECTRON DENSITY IN A MEGAJOULE THETA PINCH

by

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## ABSTRACT

This paper describes measurements carried out on the Culham I Megajoule Theta Pinch experiment. The general properties of this discharge have already been described and here a more detailed analyses of the radial and axial variation of the electron density is presented, for both zero and small anti-parallel initial trapped flux. These distributions can be obtained from either an absolute measurement of the intensity of the continuum in the visible or from laser scattering. The plasma $\beta$ can be deduced from the data by several independent methods and these are compared and spatial dependence of $\beta$ is discussed. The axial variation of plasma density is interpreted with the help of computations based on an ideal model of the flow of plasma from the ends; this gives information about end losses, which is compared with direct measurements of the plasma escaping from the ends. The variation of the electron density distribution is compared with the theoretical predictions of the Hain-Roberts programme; whereas the time variation of the electron density on the axis is in reasonable agreement with theory certain other features show discrepancies, which are discussed in terms of possible anomalous radial effects.

# EXPERIMENTAL INVESTIGATIONS ON A 600 kJ THETA-PINCH

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ABSTRACT

The current experiments with the 600 kJ theta-pinch in Jülich (mirrorless coil 120 cm long, 10.5 cm diameter) concern the stability of plasma with trapped reverse flux. A closed magnetic field configuration within the coil should reduce the plasma flow through the coil ends provided instabilities do not lead to enhanced diffusion.

Bias fields up to 4 kGauss are used to produce a closed field configuration within the preionised and preheated deuterium plasma (initial gas pressure 30 - 100 mTorr). The plasma and the magnetic field structure are studied at different axial positions by side-on streak photography and by compensated magnetic loops around the discharge tube, resp.. Axial contractions and, in many cases, splitting into different plasmoids are observed by both methods. Electron temperatures are about 200 eV without bias field and considerably higher with reverse field at comparable initial conditions.

# NUMERICAL SOLUTIONS OF THE MAGNETOHYDRODYNAMIC EQUATIONS FOR ONE-DIMENSIONAL Θ-PINCH GEOMETRY

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## Abstract

A new Eulerian conservative (as defined by K.V. Roberts and N.C. Weiss [1]), one-dimensional difference scheme was developed. The equations for mass density, momentum magnetic field, thermal energy density of ions and electrons and the difference $p_\perp - p_\parallel$ between the components of the ion pressure tensor were solved by this scheme for a Θ-pinch geometry. In order to provide more reliable estimates of the energy fed to the plasma the scheme was made to conserve not only mass, momentum, and magnetic flux, but also energy. The "source terms" - Joule heating and compressional work - were calculated by using the differential equations for the magnetic and kinetic energy.
Machine runs were carried out with the data of the ISAR I Θ-pinch experiment at Garching. The calculated ion temperatures agree well with the measured values.

1) Mathematics of Computation, 20, 272 (1966)

# PRELIMINARY INVESTIGATION OF A CORRUGATED THETA-PINCH ("LIMPUS") AT ISAR I.

by

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Abstract

The stability properties of a corrugated theta pinch plasma are of interest in connection with the periodically bulging M + S configurations. In a preliminary experiment at the Isar I bank a steplike theta pinch coil was used to produce the corrugated plasma column ("Limpus"). The measured amplitude of corrugation of the plasma surface is nearly as large as that of the inner coil surface. This result agrees with numerical calculations of the magnetic field. The eccentric final position of the pinched plasma in the normal straight geometry is not influenced by the corrugated field, the plasma reaches its final position more quickly, however. Smear camera pictures of discharges in 20 μ $D_2$ show filaments which leave the main plasma column. This effect occurs around the regions of maximum plasma diameter (bad curvature) and it is taken as an indication of instability. Smear camera pictures of discharges in 10 μ $D_2$ give no indication for instabilities.

The ion temperature is in the range of 6 keV and does not differ from the normal case with straight magnetic field.

# THE STABILITY OF THE THETA-PINCH

by

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Abstract

Experiments on the Culham Laboratory Theta-pinch, using the parallel field configuration, have revealed the presence of a low amplitude m = 1 instability[1]. A model of an axisymmetric plasma is set up in which the plasma is separated from the vacuum field by a sharp boundary, and in which the equilibrium quantities are assumed to vary slowly in the axial direction. The hydromagnetic energy principle is used to investigate stability.

For an axisymmetric $\beta = 1$ plasma in which the pressure is constant it is shown that m = 1 is stable for a configuration similar to that of the Theta-pinch. It is further shown that all perturbations which leave the magnetic field unchanged are stable for all m. The normal mode equation is applied to such a configuration and shows that the outer favourable curvature regions may be used to stabilise low m numbers.

For a $\beta < 1$ plasma it is shown that for an infinite periodic system all modes $m \geq 1$ are unstable for $\beta$ such that $\frac{1}{2} < \beta < 1$ everywhere. However, numerical results again indicate that for a Theta-pinch type configuration there is again a tendency for the outer-regions to stabilise the low m-numbers.

Finally, it is shown that an axial variation in pressure can be important in determining stability.

(1). BODIN, H.A.B. et al I.A.E.A. Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham Paper No. CN-21/34 (1965)

# PRELIMINARY RESULTS OF A VERY FAST, LOW PRESSURE THETA PINCH EXPERIMENT

by

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Abstract

To study the effect of a very fast compression in the theta-pinch an extremely low-inductive, 115 kJ condenser bank with crowbar was constructed. With a divided coil ( l = 14 cm, d = 7 cm) and working at 2 x 4o kV the induced field after ignition is 3,5 kV/cm at the inner surface of the discharge tube. The compression field rises within 1,7 µsec to 22o kΓ .

Preionization is performed by a z-pinch driven at 12o kV by a single current pulse.

First experiments were carried out at a voltage of 2 x 3o kV with $D_2$ at 1o µ filling pressure. Per discharge about $10^8$ neutrons are produced over a time of 2 µsec. Spectroscopic measurements of the continuum in the visible show that the neutron flux corresponds to a plasma having a mean deuteron energy of about 9 keV. The duration of the neutron pulse at the small length of the compression coil and the time behaviour of the continuum intensity indicate relatively small end losses. It is, therefore, supposed that as a consequence of the fast implosion the deuterons have mainly a two-dimensional velocity distribution perpendicular to the coil axis. Results of further measurements shall be reported.

# PARAMETER STUDY OF PLASMA HEATING IN A THETA-PINCH

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ASSOCIATION EURATOM-KFA

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ABSTRACT

Results of a parameter study of plasma heating in theta-pinch experiments are reported, where the bank voltage (20 - 40 kV) and the line density are varied over a large range. For the investigation a specially fast capacitor bank (15 kJ) has been built with a $B_{max}$ of 200 kG/ /usec at 15 cm coil length and with a U of 1 kV/nsec.

Electron density $N_e$ and electron temperature $T_e$ are determined by spectroscopic means as a function of time, the mean temperature $\overline{T} = (T_e + T_i)/2$ is derived from pressure balance. Due to the large $\dot{B}$ the heating rate during the implosion phase is high so that already at the end of the first implosion soft x-rays are observed and $T_e$ can be determined. At high densities the maximal values of $T_e$ and $\overline{T}$ increase more than linearly with voltage, while the maximum compression ratio varies only weakly.

# DYNAMICS OF A PLASMA IN A HIGH FREQUENCY THETA-PINCH DISCHARGE.

by

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Abstract

Some experiments will be described, in which the magnetic field of the theta pinch discharge oscillates with a frequency of about 1 Mc. The amplitude of the magnetic field (some kΓ) and the filling pressure of the gas ($\approx$ 0,1 Torr) are such that the compression and oscillation times of the produced plasma are roughly of the same magnitude as the half period of the magnetic field. These conditions may arise during the preionization of a gas by a theta pinch discharge.

It is found that a dynamic confinement of the plasma may be achieved if filling pressure, frequency and amplitude of the magnetic field are properly chosen. Otherwise the plasma will heavily touch the walls and impurities will be introduced into the plasma.

Three models are applied to get a description of the plasma dynamics: The snow plough model shows how the compression velocities depend on the discharge parameters. Another simple model is applied to obtain the oscillations of a plasma column in a high frequency magnetic field. Finally some experimental results are compared with the solutions of a magnetohydrodynamic three-fluid-model.

# INVESTIGATION OF COLLISIONLESS HEATING PROCESSES BY MEANS OF LASER SCATTERING.

by

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Abstract:

It is proposed to investigate processes by which the energy of external fields is transformed into the thermal energy of a plasma via drift-excited, instable plasma-ion waves. The quantities to be measured by means of light scattering are the time dependent values of the electron drift velocity $\underline{W}$ , the ion and electron temperatures $T_i$ and $T_e$, and the mean amplitude squares $|n_{\underline{k}}(\omega)|^2$ of longitudinal plasma waves with wave vector $\underline{k}$ and frequency $\omega$ . The relevant results of the light scattering theory and their limitations in case of exponentially growing waves are summarized and are used to estimate the possibilities for studying collisionless heating processes by means of light scattering. Scattering spectra obtained by $90^o$ scattering and forward scattering from a theta pinch are presented and shown to contain fine structure which may be sufficient for a determination of drift velocities and of an anomalous excitation of plasma ion waves. This cautiously optimistic evaluation of the experimental possibilities is derived from the calculated properties of light scattering by drift excited ion waves.

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# FORMATION OF A SECOND CURRENT LAYER AROUND A PINCHED PLASMA

by

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## ABSTRACT

To obtain the rotating magnetic field, which is required for the confinement of an alternating pinch, two perpendicular coil systems must be energized. The current in the first coil produces a plasma column surrounded by remaining gas. A quarter period later the second coil is energized. If this induces a strong current in the background gas the desired rotating field configuration is not obtained. In experiments such a second current layer is observed, both in streak photos and in magnetic field measurements. A new arrangement has been built in which the discontinuity due to the second switching process is avoided. In this case the configuration changes continuously from a screw pinch into an alternating pinch. Measurements indicate that even then a diffuse current layer is formed. The experiments are carried out in a torus with dimensions $2R = 72$ and $2r_1 = 8$ cm.

A discussion of the occurrence of the second current layer is given. Only if the background plasma has either a very low temperature or a very low density, no significant current will flow. In practical cases the currents induced in the moving (pressureless) plasma tend to conserve the pitch of the helical magnetic field lines. These results are thought to be important for any pulsed hybrid confinement scheme.

# EQUILIBRIUM AND STABILITY OF A TOROIDAL SCREW PINCH

by

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## ABSTRACT

In the screw pinch a toroidal plasma column is produced and confined by a rapidly rising helical magnetic field. This screw pinch is in equilibrium and is completely reproducible during the first half period of the confining field (7/usec). The plasma currents are induced by primary currents $I_z$ and $I_\theta$ which are flowing in phase. After the implosion the plasma drifts to a position slightly off the tube axis. The column is kept in this equilibrium position by the compression of the $B_\theta$-field between the plasma and the metal shells surrounding the quartz torus.

The implosion excites a large-amplitude oscillation in the column. This oscillation can be described as the stable m = 0, k = 0 mode given by the normal mode analysis. No unstable modes have been observed during the first half period. This stable behaviour is found for axial currents as high as 12 times the Kruskal limiting current; experiments show that at least 4 times this limiting current is required for equilibrium.

Typical plasma parameters are: density $2 \times 10^{16}$ $cm^{-3}$, compression ratio 3, temperature 20 eV. The screw pinch is studied in two arrangements with torus dimensions 2R = 72 and 32 and $2r_1$ = 12 and 8 cm, respectively. In the smaller arrangement an attempt is made to increase the temperature and the duration of the confining field.

# Experimental and Computed Observations of the Linear and Semi-toroidal Inverse Pinch Devices, FAUST B & C

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## Abstract

The FAUST experiments are inverse pinch devices in which a plasma is imploded by an external axial magnetic field onto the vacuum azimuthal magnetic field produced by the hardcore. Gas currents up to 250 kA can be achieved in the cylindrical geometry of FAUST B or in the semi-toroidal geometry of FAUST C. The discharge conditions are not those which should produce the maximum stability but the plasma produced displays a temperature of 20 eV and confinement of 40 μsec in spite of the observed fluctuations in the plasma parameters.

The results are described of a comparison between the mean value of some of the plasma parameters observed in FAUST B and those obtained from computed solutions of the appropriate hydromagnetic equations in one dimension. The equations assume a partially ionised, Joule heated plasma possessing electrical and thermal conductivity and separate electron, ion and neutral temperatures. The results of computer runs with an without the energy losses of impurity radiation are given. These calculations assume the impurity atoms to be initially uniformly distributed and tied to the hydrogen plasma. Excitation is assumed to originate only from the ground states.

# EXPERIMENTAL STUDY OF THE STABILITY OF A CURRENT SHEET

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A sheet of plasma carrying an electrical current of 20.000 A/cm$^2$ is built up by induction. The thickness of the sheet is 3 mm, its other transverse dimension is 6 cm. The current in the sheet produces on both sides a magnetic field of ± 3000 gauss which confines the plasma.

We study the magnetic configuration associated with this current sheet. In a first period, ( 1 μs ), the sheet is built up in Hydrogen or Deuterium at pressures of 40 - 100 mtorr. In a second period, the sheet is in a stationnary state : It is in equilibrium in the direction of its thickness, but the plasma may flow out in the other transverse direction. Due to its geometry, and according to the theory in the low resistivity limit [1], the sheet should exhibit unstable "tearing" modes. The growing time of these modes should be 0,1 μs.

However, the destruction of the sheet appears only when a time of 1 μs has elapsed, during which a given amount of plasma flows out. The magnetic energy localized on each side of the sheet disappears then in a time of 0,2 μs, during which a component of the magnetic field normal to the plane of the sheet appears. We may identify this configuration with a Tearing mode but we have to explain why the stability of such a mode does not depend only on the geometry of the sheet as the theory [1] predicts. We do this taking account of the actual values of the resistivity and the viscosity of the plasma.

[1] H.FURTH, J.KILLEEN, M.ROSENBLUTH, Phys.Fluids 6, 459 (1963)
P.H.REBUT, J.Nuclear Energy, pt C, 4, 159 (1962)

# Experimental Studies of Collisionless Shock Waves

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The nature of a shock transition in a magnetized, highly ionized plasma is considered. A distinction is made between transitions in which normal coulomb collisions dominate and those in which "collisionless" processes, such as collective interactions, must occur.

The results of a number of experiments and observations on collisionless shocks are described with more detailed reference to the Tarantula experiment at Culham. The structure of the transition in density, electric and magnetic field are described together with the initial and final plasma conditions. The results are analysed and discussed in relation to various models, mechanisms and theories.

The kinetic theory model is introduced with an effective collision frequency to represent the transport of momentum by "collisionless" processes. Solutions of the kinetic equations through the shock do not exist for all conditions. Above a critical Alfven Mach number $M_A^* \sim 3$ non-viscous shocks cannot exist. The experimental results for $M_A < 3$ are combined with the kinetic equations to form a self consistent description of a resistive shock. The resistivity is provided by collective interactions derived from electron-ion drift instabilities. A change of shock structure is observed at $M_A^*$ but the viscous mechanism required for higher $M_A$ is not clearly understood.

The experimental results are also discussed in terms of the single particle model and a combination of this with the kinetic model. The predictions of other published theories are compared with experiment.

# CHARGE EXCHANGE LOSSES ANALYSIS IN DECA II.

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Previous measurements on a plasma of deuterium confined in the magnetic well of DECA II have shown that the lifetime limitation by charge exchange should require a local pressure higher than the measured base pressure.

The charge exchange plasma losses have been investigated by the analysis of fast neutrals of fixed energy (between 0.7 and 3.5 keV).

The maximum of the neutral flux is reached 50 μs after the maximum of the plasma density. Its decrease becomes purely exponential 150 μs later.

The neutral flux evolution has been registered for different base pressures of deuterium ( $2\ 10^{-7}$ to $1.2\ 10^{-5}$ torr ). The instantaneous flux varies linearily with the pressure and the total number of neutrals produced is constant.

The injection of helium gas up to $2\ 10^{-5}$ torr does not modify the neutral flux signal.

All these measurements suggest that the plasma is lost by charge exchange on both atomic and molecular deuterium components. Their density increases respectively up to $10^{11}$ and $4\ 10^{11} cm^{-3}$, in agreement with the observed variation of the decay time as a function of the neutral energy.

If other phenomena which limit the lifetime exist in the plasma, these are not modified by the value of the base pressure ( up to $10^{-5}$ torr ).

# ION CYCLOTRON OSCILLATIONS IN DECA II

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A plasma of deuterium is confined in the magnetic well of DECA II. For these measurements, the plasma density is $2.10^{10} cm^{-3}$ ; the decay-time of the fast neutral particles signal is 200 μs ; the diameter of the plasma is 3 cm and its length 10 cm.

Oscillations of the plasma surface potential are observed with probes capacitively coupled to the plasma. Radio-frequency activity occurs during 50 to 70 μs , when the plasma density is maximum.

By using four probes located in different positions, it is shown that this radio-frequency activity affects the whole plasma.

Two frequencies are detected, corresponding to the deuteron gyro-frequency and to its first harmonic. The spatial variations of these frequencies may result from the calculated variation of the magnetic field. This spatial variation of the frequency makes difficult the study of azimuthal and longitudinal correlations.

The total number of fast neutral particles emitted by the plasma during 600 μs is inversely proportional to the intensity of these oscillations.

Theoretical sufficient criteria for drift cyclotron instabilities [1] [2], are satisfied. The cyclotron double distribution [3] instability is also a possible candidate.

[1] MIKHAILOVSKI, TIMOFEEV, Soviet Phys.JETP 17, 626 (1963)

[2] POST, ROSENBLUTH, Phys.Fluids 9, 730 (1966)

[3] HALL, HECKROTTE, KAMMASH, Phys.Rev. 139 , 1117 (1965)

# THE BILLE-EN-TETE B EXPERIMENTS RESULTS

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The Bille-en-Tête B experiment is designed to study plasma injections into open magnetic configurations and further evolution of this plasma. Experiments are now conducted in a simple magnetic bottle and in a homogeneous central field configuration, in order to prepare for the future injection into a deep magnetic well. Several ways of trapping the plasma between the two-end magnetic mirrors are investigated. Among these, the collision of two plasma puffs (created and accelerated by two electrodeless plasma guns, 666 cm apart) , and the heating of ions using a fast discharge ( $T \approx 1 \mu s$ , $B_{\sim} \leq 1$ kgauss) into a coil wound around the vacuum vessel and located between the two mirrors. It seems that when the heating field $B_{\sim}$ is larger than the static initial field $B_o$ and $\omega_{\sim} > \omega_{ci}$ , essentially electrons are heated. For $B_{\sim} < B_o$ the plasma appear to be mainly axially accelerated and the heating effects appear to be larger when $\omega_{\sim} \simeq \omega_{ci}$ .

So far, two main difficulties have been encountered : the tendency of the puffs during the injection procedure to drift away from the axis of the experiment, and the incomplete separation of the plasma which is inside the magnetic bottle from that which remains outside. The first one was solved by careful compensation of parasitic external magnetic fields and screening of the electric field at the slot of each accelerating gun coil.

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## Characteristics of Micro-Instabilities and Stabilisation Experiments in Simple Mirror and Magnetic Well Geometry

by

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Micro instabilities in the Phoenix experiments are characterised by R.F. emission corresponding to ion-cyclotron frequency and its harmonics.

Experiments are described in which the frequency and polarisation of the radiation is measured along with energy spreading of the trapped protons.

In the case of simple mirror geometry the dominant mode corresponds to azimuthal currents which are accompanied by energy spreading of the trapped 20 keV protons to energies greater than 100 keV. Experiments will be described in which this instability has been suppressed by introducing energy spread into the injected proton distribution by the application of high frequency electric fields.

Emission from a plasma formed in magnetic well geometry is more complicated, is predominantly due to axial currents and the observed spreading of the proton distribution is less than that in a simple mirror. Some features of the R.F. emission from the plasma, are indicative that some degree of plasma trapping of the injected beam is taking place.

# INVESTIGATION ON THE COMPRESSION AND THE CONTAINMENT OF A PLASMA IN CUSP-GEOMETRY

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ASSOCIATION EURATOM-KFA

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ABSTRACT

Discharging a 10 kJoule/25 kV capacitor bank on a pair of coils in such a way, that the electric currents in the two coils have opposite directions, a cusp-shaped plasma (electron densities of about $10^{17}$ $cm^{-3}$, electron temperature up to 100 eV) is produced. The maximum magnetic field was 75 kGauss at the line and point cusps, the half-period was 3.6 $\mu$sec.

Due to this short half-period the plasma could be contained no longer than 2.5 $\mu$sec. With a crowbar system (time-constant 20 $\mu$sec) the containment of the plasma was strongly improved.

Using streak-camera and spectroscopical methods, the space- and time-dependence of the electron density and an estimate of the electron temperature is obtained.

# High β Injection Experiments

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Two field-free ($\beta = 1$) plasma spears[1] having directed energies of 250-500 eV have been injected along magnetic guide fields of 3-4 kG and collided in a spindle-cusp magnetic bottle. Plasma is lost from the trap through a hole which is roughly an ion gyro-diameter wide at the ring cusp, but extensive electric field measurements at the ring cusp have given no evidence of "wall-shorting", or plasma rotation. The relevance of this experimental observation to published high-β cusp containment experiments[2] is discussed.

The interaction between two colliding spears in cusp, mirror and uniform magnetic guide fields will also be compared.

References

1. T. K. Allen et al. 7th Int. Conf. Ionized Gases, Belgrade 1965.
2. T. K. Allen et al. To be published in Physics of Fluids, July 1966.

# MEASUREMENTS ON A PLASMA FORMED BY INJECTION OF ENERGETIC IONS INTO A MAGNETIC QUADRUPOLE FIELD

by

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A. Vis, and H. de Kluiver

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ABSTRACT

In Jutphaas measurements on the experiment of ion injection into a magnetic cusp field as described in Culham (CN 21-124) have been consolidated and new diagnostics have been used.

Measurements with probes and microwave interferometry show that the densities of charged particles are in the range of $10^8$/cc. Particle energies show a wide spread, a greater part of electrons and ions have a few hundreds electron volts. When applying high electric retarding voltages to the grid probe in order to select only ions with higher energies, the simultaneous presence of the high magnetic field caused extremely weak spurious discharges to interfere with the ion collection.

Results of measurements with gridded probes, Langmuir probes, 8 mm microwave interferometry, decimeter waves using the vacuum vessel as resonant cavity and open photomultipliers are compared and discussed in view of machine parameters.

## The Polytron: A Toroidal device for the containment of a hot moving plasma.

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An experimental apparatus has recently been set up to examine the containment of a moving plasma in toroidal geometry. Preliminary results will be presented at the meeting.

The general principles of the Polytron are as follows. A toroidal discharge is set up to thread through superposed multiple cusp magnetic field. The cusp fields give rise to two essential and novel effects. Firstly, the radial magnetic field components interact with the axial currents to produce an axial acceleration of the plasma through the intermediary azimuthal Hall currents. Secondly, when the acceleration has taken place, the ions are now the main current carriers and, if their flow is supersonic the favourable stability properties of the cusp fields can be employed with minimum plasma leakage through the annular loss cones. In its centre-of-mass frame the plasma sees a travelling cusp magnetic field moving faster than the mean ion thermal speed, and the plasma is unable to escape. The centrifugal force is balanced by the cusp field gradients, and the wave length of the fluctuating cusp fields is less than the ion Larmor radius but much greater than the electron Larmor radius.

The experimental conditions chosen are 4cm bore 50cm major diameter torus, 10 KG cusp fields, from 36 independent coils, initial pressure about 1 micron hydrogen or deuterium

and 200 volts/cm accelerating axial electric field. The 36 cusp field coils are energised by a 100KJ, 5KV condenser bank and the axial induction coils by a 64 KJ 40KV condenser bank. The breakdown behaviour has caused difficulties but an initial axial guide field is now being used in conjunction with a plasma gun.

The earlier Hall acceleration theory has been extended to time varying electric and magnetic fields, and computor results in a regime close to the experimental conditions will be presented.

# COAXIAL GUN WITH ANNULAR PREIONIZATION SYSTEM. CHARACTERISTICS OF THE PLASMA PRODUCED IN THE HIGH DENSITY MODE.

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A coaxial gun with annular preionization system is operated in the high density mode. The gun is located in an axial magnetic field $B_c$. An investigation of the acceleration process is made by using high speed photography and by measuring the voltage and current of the main discharge. The characteristics of the discharge are found to be strongly related to the value of $B_c$.

The plasma is injected into a longitudinal magnetic field $B_z$. The mass and energy spectra of the ions are determined with an electrostatic analyser located in a zero field region. The influence of the broadening of the ion beam under the space charge effect is studied. The energy spectrum of the protons is determined by using entrance holes of different diameters. The total number of ions collected at the output of the analyser is compared with the number of incident ions in order to check the possible loss of particles in the analyser. The spectrum is also determined with a Faraday cup and a gridded analyser located either in the $B_z$ field or outside the $B_z$ field. The results obtained by those different methods are compared.

# ACCELERATION AND CONFINEMENT OF PLASMA IN A THREE-STAGE PLASMA GUN

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A b s t r a c t

Earlier experiments have shown that plasma can be accelerated by a gun consisting of two solenoids for the generation of a cusp field and a single turn coil which provides for a Θ-pinch in the ring cusp region. Combining two or more stages of the same type a step by step acceleration is possible. In this way hydrogen plasma was accelerated up to 21 keV. This arrangement of several identical stages may be regarded not only as a multi-stage plasma gun but also as a confining system, consisting of axial and cusp fields alternately. This magnetic field configuration provides for macroscopic stability. The losses in the ring cusp region are reduced by the plasma compression which takes place when the single turn coils are triggered. In a device of this type plasma is compressed, emitted, and injected into the cusp of the next stage where another cycle begins. The last stage can be operated in such a manner that the plasma at least is partially reflected, thus reducing axial losses. This behaviour of the plasma in a three-stage arrangement was ascertained by optical and probe measurements.

# DRIFTS OF A PLASMOID INJECTED INTO A CURVILINEAR MAGNETIC FIELD. APPLICATION TO THE PURIFICATION OF THE PLASMA.

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The hydrogen plasma produced by a coaxial gun using annular preionization system is injected parallel to the axis of a magnetic field. This field has two identical oppositely curved sections, each extending over 1/8 of circumference (radius of curvature 1 meter). Most of the experimental work reported here is made by using a magnetic field of 3 kgauss strength. The mean velocity of the plasma is of the order of $10^8 cm.s^{-1}$ and the density is in the range of $10^{13} cm^{-3}$. The drifts of the plasma stream are deduced from measurements made with Faraday cups.

The electrical drift of the plasma was not present in the experiments reported previously [17]. It was shown that the plasma was submitted only to the centrifugal drift according to the guiding center approximation and the removal of heavy ions by using this property was evidenced. In the present set up, the electrical drift can be detected and the experimental conditions can be easily changed in order to act on it. It is shown that the electrical drift is cancelled if the polarization field is shorted out. The possibilities of eliminating the slow plasma and neutrals are discussed.

[17] D.VERON, J.Nuclear Energy, pt.C, 8, 283 (1966)

## The Injection of Tenuous Plasma into a Magnetic Guide Field

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A burst of plasma from a thetatron gun is allowed to expand freely as it passes along a drift tube; an aperture limiter selects a central beam of the plasma which then flows axially into the field of a solenoid. The ions are moving parallel to the magnetic axis as they enter the field. The ion energy is centred about 800 eV and the maximum ion density is typically $3 \times 10^{11}$ cm$^{-3}$. The solenoid is suspended in a large vacuum chamber so that the "wall-shorting" effect described by Ashby and Avis*, in connection with a similar experiment, is inhibited. A removable conducting cylinder at the solenoid entrance allows a direct comparison to be made between the case when a radial space charge electric field exists and when it is "short-circuited". Measurement shows that the diamagnetic current is carried predominantly by electrons if a radial electric field exists and by ions in the absence of a field; in both cases the radius of the plasma column is about $2R_{ci}$ although simple theory predicts that in the latter case the radius should be nearer $\sqrt{R_{ci}R_{ce}}$. The increased radius in this case is believed to result from an electrostatic instability.

*D.E.T.F. Ashby and B.E. Avis. Jour. of Nuc. Energy. Pt.C. 8, p.1, 1966.

# THE HARMONICA EXPERIMENT

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According to Mercier's M.H.D. treatment of a toroïdal plasma of general form, in which the effects of the curvature of the magnetic axis are included, lack of equilibrium should occur at certain discrete values of the rotational transform, which are related to the shape of the magnetic axis.

As a first test of Mercier's theory, the plasma equilibrium is to be compared in two plane toroïdal machines, which differ in the shape of their magnetic axis but are otherwise similar. The first is circular with radius $1/a_o$ = 43 cm, whilst the second has a magnetic axis whose radius of curvature R(s) is given by the equation

$$\frac{1}{R(s)} = a_o \left( 1 + 2\cos\frac{4\pi s}{L} \right)$$

where s is the curvilinear abscissa and L the length of the axis. For the first machine, the predicted lack of equilibrium at K (rotational transform) = 0, corresponds to the well known case. For the second machine the lack of equilibrium should occur at K=0 and 2 .

Preliminary results concerning the formation, stability and equilibrium of hydrogen plasma in these two machines, are presented.

* On leave of absence from Culham Laboratory.

# RESISTIVE DIFFUSION OF CESIUM PLASMA IN A STELLARATOR

by

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## A b s t r a c t

At the Culham conference we reported on measurements of particle losses from cesium plasmas produced by contact ionization in our WENDELSTEIN stellarator, which was equipped with helical stabilizing windings of type $\ell = 2$ [1] We found particle loss rates to be much less than the anomalously high pump-out losses usually encountered in stellarators. Moreover, the relationship observed between ion input flux and the resultant particle density distribution was in agreement with calculations which assumed resistive diffusion across the magnetic confining field and recombination on the insulating surfaces of the supports of the plasma source, the latter constituting the predominant loss process.

In recent experiments, which will be described in this paper, surface recombination losses within the plasma volume could be made negligibly small. This was done by suspending the plasma source from a very thin wire and heating it by bombardment with a beam of energetic electrons. In this way it was possible to show that the radial transport of the cesium plasma is governed by resistive diffusion.

1) D. Eckhartt, G. v.Gierke, G. Grieger, Proceedings of the IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Culham (U.K.), Vol. II, 719 (1966)

# EFFECT OF ION-NEUTRAL COLLISIONS ON THE ION DENSITY IN A Q-MACHINE

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A b s t r a c t

The conditions of a Q-machine can be significantly changed if the ion temperature is reduced below the electron temperature. Cooling of the ions is achieved by collisions with noble gas atoms which are introduced into the plasma column. This causes among other effects an increase in plasma density and a change in sheath conditions. Langmuir probe density measurements have been made as a function of neutral gas pressure under various sheath conditions. Theoretical predictions based on the "equilibrium model" are compared with experiment.

* Guest from the USA.

## CRITICAL VOLTAGE OF A ROTATING PLASMA

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The accessible voltage levels, and the corresponding velocity, have been studied for a rotating plasma device:
(i) There exists a sharply defined critical voltage, and a corresponding velocity limit, which cannot be exceeded when the power input is being gradually increased.

(ii) The critical voltage increases with the mean radial ratio $r_o/r_w$ in the plasma. This ratio is defined by a magnetic field line which intersects the mid-plane of the device at the radial distance $r_o$ from the axis of symmetry and cuts the end insulator at the corresponding distance $r_w$.

(iii) The results can be explained by an interaction between the plasma and a neutral gas layer at the insulator surface. The plasma velocity at the insulator is then limited to the value $v_c = (2e\phi_i/m_i)^{1/2}$ which corresponds to the ionization potential $\phi_i$. As a consequence of the iso-rotation law, the velocity limit becomes $(r_o/r_w)v_c$ in the mid-plane of the device.

(iv) The plasma is heavily disturbed even by a very small obstacle which is introduced in the equatorial plane.

(v) As compared to earlier plasma devices, the stability is not influenced by the fact that the confinement region surrounds a ring-shaped coil which is suspended by a single rod. Most of the field lines will then pass freely around the coil, and do not end upon an insulator surface.

# CHARACTERISTICS OF AN $\bar{E} \times \bar{B}$ DISCHARGE[+)]

by

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Abstract

In rotating plasma experiments internal short-circuiting along B-field lines occurs often at very early times in the discharge even with puffed gas input.

In an attempt to avoid this effect it was found that:

1. elongation of the magnetic field lines results in a delay of the internal crowbar, and
2. pyrex cylinders, placed where field lines cross the outer electrode, suppress the crowbar completely.

However, marked differences in the discharge with or without pyrex are observed. Without pyrex the current distribution in the outer electrode shows a dependence on Larmor radius. The plasma energy density in this case is proportional to $E^2 B^{-3}$ for Larmor radii $< 0.5$ cm.

With pyrex the current enters the outer electrode in a small annular area at the midplane of the magnetic bottle.

The burning voltage is not proportional to B as is expected from the Alven velocity limit, but to $B^2$. This suggests a voltage limiting process connected with Larmor radius, which for the electrode constituents is about half the electrode distance at burning voltage.

The thermal energy density decays at a constant rate of 80 μsecs. The rotational energy density change on external crowbar has the same decay as the energy content determined from the back delivered current, allowing to estimate the plasma volume. The time constant for this decay starts with 20 μsecs and gradually approaches the thermal energy decay time constant.

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[+)] Association contract EURATOM-FOM

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# INSTABILITY IN A ROTATING PLASMA[+)]

by

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Abstract

Gravitational instabilities can be studied in an E x B - configuration where a radial electric field is applied independently from the magnetic field. This makes it possible to vary the parameter of the rotational velocity by intention and to study its influence on the growth-rate of instabilities.

The discharge is formed in a dc magnetic field between the negative central electrodes and the outer cylindrical electrode. Fast gas injection helps to avoid internal short-circuiting.

The ionization starts near the central electrodes and a plasma is formed near the axis which slowly expands in radial direction and seems to undergo an m = 1 instability with a moderate growth rate. Measurements of the local radial electric field and optical observation show that after the expansion the plasma becomes centered around the axis again, and stays away from the wall electrode.

Out of small perturbations of the plasma surface a fast growing instability of higher mode ($m \approx 8$) develops after the current maximum. The measured growth rates depend on the local rotational velocity which agrees with the theory of gravitational instabilities. The influence of Larmor stabilization or resistive effects can be neglected. Small growth rates of disturbances with a low mode number can be understood by the charge separation out of phase which is produced by the Coriolis force.

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# EXPERIMENTAL RESULTS ON THE STRUCTURE OF HYDROMAGNETIC SHOCKWAVES IN A COLLISON-FREE PLASMA

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ASSOCIATION EURATOM-KFA

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ABSTRACT

Radially converging hydromagnetic shockwaves are generated by means of a fast theta-pinch in a large diameter discharge tube. The initial plasma is nearly fully ionized and particle densities range from about $10^{13}$ $cm^{-3}$ to a few times $10^{14}$ $cm^{-3}$. The direction of shock propagation is almost perpendicular to the magnetic field. In most cases plasma conditions are such that the shock is collision-free. The shock structure is investigated mainly by means of small probes. Machnumber and initial $\beta$ ($\beta$ is the ratio of kinetic pressure to magnetic pressure) are chosen so that resistive shocks are obtained.

Under certain conditions steady state shocks are observed with high reproducibility so that the radial magnetic field profiles can be determined as a function of time. The driving f ield may be parallel or antiparallel to the initial magnetic field.

The mechanisms responsible for the formation of the shockwaves are discussed.

# NUMERICAL AND EXPERIMENTAL INVESTIGATIONS ON COLLISIONFREE COMPRESSION OF A PLASMA WITH ANOMALOUS FRICTION

by

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Abstract

Friction of electrons moving under the action of an induced electric field in a dilute collisionless plasma was investigated by comparison of numerical calculations with experimental results. Calculations were made for a cylindrical plasma in an axial time-varying magnetic field. The behaviour of the plasma was treated by two-fluid equations including a friction term for the electron component as was used by Adlam, Holmes and Bardotti, Cavaliere, Engelmann to describe in a phenomenological way the action of a two-stream instability on electron motion. This term forces the electron velocity to stay under a critical value and simultaneously describe the conversion of energy of directed motion in energy of unordered motion. Free parameters in this friction term were to be determined by experiment.

The investigations were made in a density regime ($2 \cdot 10^{11}$ - $5 \cdot 10^{12}$ $cm^{-3}$) where the characteristic length $c/\omega_{pe}$ for the structure of magnetic field, density etc. is comparable to or larger than the radius of the plasma. In this case there are no limitations on the strength of the induced field, which are imposed in the other case by an unadmissible steepening of the front of the compression wave.

Calculated current distributions are compared with probe measurements of magnetic fields.

# DRIFT WAVES EXCITATION IN ALKALI-HALOGEN PLASMAS

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ABSTRACT - The drift wave universal instability, arising when a density gradient is present in a magnetically confined plasma, is studied in the hydrodynamic limit in which the effect of resonant particles is neglected. The marginal stability condition is given for the general case of arbitrary Larmor radius and arbitrary ratio between positive and negative ion masses. In the limit of small Larmor radius both the real and the imaginary part of the oscillation frequency are explicitely found. The relevance of these results in connection with alkali-halogen plasma experiments in Q-machines* is pointed out.

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*S. von Goeler, T. Ohe and N. D'Angelo, J. Appl. Phys. 37, 2519 (1966).

# Radiation From a Plasma Stimulated by Two Short Microwave Pulses at the Gyrofrequency and its Second Harmonic +)

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A magneto-plasma excited by two short microwave pulses is considered in the single particle approach. The first pulse is assumed to be at the electron gyrofrequency and the second at the second harmonic thereof, the time separation of the two pulses being $\tau$ . At a time $\tau$ after the second pulse there arises a radiation peak at the electron gyrofrequency, coming from the plasma. This radiation peak is due to the nonlinear interaction between the second pulse and the plasma. If other nonlinearities (energy dependent gyrofrequency or collision cross-section) are taken into account, further radiation maxima arise at times $3\tau$ , $5\tau$ etc after the second pulse.

+) Work done at the California Institute of Technology, Pasadena, Calif. and sponsored by the U.S. Navy, Office of Naval Research.

# INVESTIGATION OF MICROWAVE SCATTERING FROM ALKALI PLASMAS

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ABSTRACT - An experimental investigation has been carried out on microwave scattering by ion waves in alkali plasmas.

The dependence of the effect on various parameters such as the plasma density, the plasma length, the frequency and power if tge electromagnetic radiation has been studied.

The results are discussed.

# MICROWAVE RADIATION AND SCATTERING FROM A HOT ELECTRON PLASMA

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ABSTRACT NOT RECEIVED

# GENERATION OF HARMONICS OF HALF THE ELECTRON GYROMAGNETIC FREQUENCY IN A TWO-BEAM SYSTEM

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Some recent results are presented for the generation of harmonics of half the electron gyromagnetic frequency in a beam interaction experiment which has been described earlier[1][2]. The system consists of two electron beams of diameter 1 cm, energy 500 to 2000 eV and intensity 5 to 30 mA, counter-streaming parallel to a magnetic field of 50 to 300 gauss in a chamber 80 cm long. The properties of the fundamental ( $\omega = \frac{\omega_{ce}}{2}$ ) harmonic of the generated waves, such as the azimuthal wave number, the wavelength, the radial profile of the oscillating potential and the amplitude of the perturbations of potential, density and current, have been measured. It has been possible to establish from these results, the quasi-electrostatic character of these waves, by evaluating the ratio $\frac{|\nabla \wedge E|}{\nabla . E}$, which always remains less than unity. Measurements concerning the amplitude and width of the rays, and the growth rate of the first harmonics in the transient regime, have also been carried out. A theoretical calculation of the growth rate of the instabilities which can develop at harmonics of half the gyromagnetic frequency, shows that if the growth rate calculated in the linear approximation is sufficient to explain the generation of the first harmonics, it decreases too fast with the order n to explain the presence of high order harmonics ( $n \gtrsim 10$ ). Some observations are described which show the importance of non-linear wave interactions in this system, and which suggest an interpretation of the generation of high harmonics in terms of such interactions.

(1) C.ETIEVANT, J.OLIVAIN, M.PERULLI
Comptes Rendus, 261, 3310 (27 octobre 1965)

(2) J.OLIVAIN - Rapport CEA ( to appear ) -
Thèse 3e Cycle, Faculté des Sciences de Paris(Centre d'Orsay), Juin 1966

# RADIATION OF HARMONICS $n\omega_e$ AND $n\frac{\omega_e}{2}$ FROM A BEAM-GENERATED PLASMA

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A b s t r a c t

Radiation of harmonics of $\omega_e$ and $\frac{\omega_e}{2}$ ($\omega_e$ = electron cyclotron frequency) from an electron beam plasma is observed when a metal probe is introduced into the beam. Without the metal probe present in the beam, there is no radiation. Whether harmonics of $\omega_e$ or $\frac{\omega_e}{2}$ are radiated depends on the pressure and also on the homogeneity of the external B-field near the electron gun. The dependence of the radiation on gas pressure and on position and potential of the probe is discussed and interpreted.

# STUDY OF A PLASMA BEAM CREATED BY A RIGHT HAND CIRCULAR WAVE IN A DECREASING STEADY MAGNETIC FIELD AT THE ELECTRON CYCLOTRON RESONANCE

by

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Abstract

The use of the whistler mode in a decreasing magnetic field permits to get a dense plasma beam which density is higher than the cut off density corresponding to the incident wave. We have used a X bande 300 Watts C W generator.

In the case where the plasma is created in a guide, at a pressure of $10^{-3}$ torr of argon, microwave unterferometric measurement indicated a plasma density one order greater that the cut off density.

With helium, we have only got $\omega p = \omega HF$ because the pumping system was not suffident. The second important characteristic is that if the electrons have a great tranverse energy, the ions have only an axial velocity. This speed was deduced from the measurement of the Doppler shift of the 4806 A ray of ionised argon.

Ref. - Proceedings of VII th International Conference on Phenomena in ionised gases (1965, Belgrad).

- C. R. Acad. Sciences PARIS t 262 - page 929-932

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# REALIZATION OF A RADIOMETER FOR ELECTRONIC DOPPLER SHIFT MEASUREMENTS IN PLASMAS

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Abstract

This apparatus enables the measurements of the diffusion coefficient $\sigma$ of electromagnetic waves in plasmas and the determination of the electronic Doppler shift $\Delta f$ . The knowledge of $\sigma$ and $\Delta f$ permits then to deduce the electron density and the electron and ion temperatures. (Ref. 1 - 2).

The scattered energy and the Doppler shift being both small in the usual laboratory plasmas the apparatus is supposed to solve two contradictory effects :

1) To have a sensitivity of the same order than the usual radiometers (Dicke type).

2) To be able to measure a frequency shift of $\Delta f \leqslant 10$ kc/s around an incident frequency of $f_o \sim 35\,000$ MHz.

The apparatus is constituted by two main parts :

1) The generator which is a 1 watt klystron in the Ka band with a squarewave 30 Hz amplitude modulation.

2) The special receiver using a quadruple frequency mixer (by four heterodynes) followed by a synchroneous detector.

The principle of operation is the following :

A fraction of the incident power is frequency changed by the local oscillator which simultaneously mixes the microwave signal scattered by the plasma. By this way one obtains a reference voltage which is now mixed with the signal in an electronic wideband mixer. In this case, whatever are the drifts of the generator and the local oscillator, the output frequency of the wide band mixer represents exactly the Doppler shift

The measurements obtained with a plasma simulator give the following characteristics

Sensitivity $S \sim 10^{-15}$ watts

Frequency resolution $\Delta f \sim 10$ KHz

REF. 1 : FEJER J. A. : Jour. Geoph. Res. 65, Sept. 1960.

REF. 2 : BOGHOSSIAN A. : Cornell University Research Report EE501

## Evolution of cold plasma resonances as a function of magnetic field

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A plasma cylinder exhibits one or two (if an axial magnetic field $\bar{B}_0$ is present) main resonances when an electromagnetic wave (with $\bar{E}$ perpendicular to the axis and $\bar{B}$ parallel to the axis) is shone on it. Cold plasma theory predicts the following behaviour of the resonances as a function of $B_0$ :

$$\omega^2 = \frac{\overline{\omega_e}^2}{2} \left(1 \pm \beta\right)^{-1} \qquad (1)$$

where $\omega$ is the applied angular frequency, $\sqrt{\overline{\omega_e}^2}$ the average electron plasma frequency and $\beta = \omega_c/\omega$ ($\omega_c$ : cyclotron frequency). If the plasma is enclosed within a glass wall, the factor $\frac{1}{2}$ is modified by the permittivity of the wall [1].

Experimental measurements carried out both in the positive column of a Hg discharge and in an afterglow plasma show that formula (1) describes the phenomenon precisely only for rather low values of $\beta$. When $\beta > 1$, there remains a single resonance - as predicted by (1) - but a saturation phenomenon appears instead of the linear dependance on $\beta$. The plasma electron density is measured independently by the cavity perturbation method using a TM mode.

The combined effects of non-uniformity of the plasma density and of non-zero electron temperature in the presence of $B_0$ are investigated theoretically.

1. P.E. Vandenplas and A.M. Messiaen, Nucl. Fusion, 5, 47 (1965).

# INVESTIGATION OF ALFVEN WAVES IN A PLASMA-FILLED WAVE GUIDE.

By
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## Abstract.

In a magneto-active plasma two different modes propagate in the frequency region $\omega < \omega_{ci}$. If the plasma is surrounded by conducting walls, the boundary conditions lead to a cut-off for the fast mode. The dispersion relation of the slow mode is not altered. The propagation velocity of the slow mode is the Alfvén velocity. The wave is of a torsional or shearing Alfvén wave type with its magnetic field perpendicular to the static magnetic field. The experimental investigations concern the propagation of this type in a rectangular plasma filled wave guide.

A hydrogen plasma is produced by an arc discharge with a current of 0.5 up to 3 kA supplied by a capacitor bank for a duration of 250 $\mu$sec. The range of the initial gas pressure is 0.05 to 1 mm Hg. The longitudinal quasi-static magnetic field is of the order of a few kGauss. Smear camera and probe measurements showed ranges of stable and unstable plasma behavior. Wave propagation was studied in the stable range. The wave was generated by a fast discharge of a capacitor. The frequency of this discharge was in the range of 1 Mcps. The wave was detected by small magnetic probes combined with light guides. This combination permits a simultaneous measurement of light intensity and magnetic field at a specific point in the plasma.

# HIGH FREQUENCY INSTABILITIES IN A PIG-DISCHARGE

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A b s t r a c t

High and low frequency instabilities in a cold cathode PIG-discharge has been studied. The experimental work has mainly been concentrated on studies of instabilities in the frequency range 500 - 3000 MHz.

After a brief description of the discharge tubes used in the experiment some of the characteristic features of the instabilities will be presented and discussed.

It can e.g. be mentioned that as much as 35 % of the d.c. power put into the discharge may be transformed into r.f. energy in the frequency range 500 - 3000 MHz and that the r.f. field under these conditions are so strong that they have a dominant influence upon the behaviour of the discnarge.

# OBLIQUELY PROPAGATING LARGE-AMPLITUDE WAVES IN A LOW-DENSITY PLASMA

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ABSTRACT NOT RECEIVED

# NON-LINEAR EFFECTS IN A BEAM PLASMA SYSTEM[+)]

by

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Abstract

Investigation of the electron-plasma instability, in a d.c. beam-plasma experiment, reveals two types of non-linear behaviour

As a function of time, the amplitude of the instability is pulsed, the pulses coming at random.
Spatially, the amplitude shows an interference pattern, with a wavelength decreasing monotonously if the instability is scanned at a fixed frequency from the gun to the collector.

It is attempted to give an explanation for the latter effect, by stressing the difference between waves propagating parallel and anti-parallel with the beam. Due to the electron beam, the dielectric tensor is anisotropic, and waves in opposite direction propagate at different speeds.

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[+)] Association contract EURATOM-CEA

[++)] formerly: FOM Laboratory for Mass Separation

# LOW FREQUENCY WAVES IN A BEAM-PLASMA SYSTEM[+)]

by

T.Matitti, A.Vermeer, H.Hopman, J.Cabral and J.Kistemaker
FOM-Instituut voor Atoom- en Molceluufysica, Amsterdam, The Netherlands[++)]

Abstract

The interactions between a thin unmodulated elelctron beam and its own created plasma, in the presence of a longitudinal B-field, are studied.

For not very high values of the B-field (less than 8oo gauss), a clear instability occurs in the surroundings of the ion-plasma frequency.

On the basis of the theory for a wave-guide filled with a homogeneous plasma and electron beam, this instability is identified as the interaction between the slow cyclotron wave on the beam and the plasma wave. From measurements of wavelengths it appears that the unstable wave propagation is confined to a cone between $85^{o}$ and $9o^{o}$ with respect to the B-field.

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[+)] Association contract EURATOM-CEA

[++)] formerly: FOM Laboratory for Mass Separation

# NON-LINEAR PROCESSES IN BEAM-PLASMA SYSTEMS

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Using a perturbation method for processes which are weakly non-linear, we have calculated the rate of generation of a secondary longitudinal wave due to the resonant interaction of longitudinal waves in beam-plasma systems immersed in an external magnetic field. The interaction matrix takes the form :

$$M(k_2\,\omega_2 \mid k_1\,\omega_1) = -\sum_j \frac{4\pi q_j n_{oj}}{k_3^2(\omega_3 - k_{z3}V_{oj})} \left[ \frac{\vec{k_2}\cdot\overline{\overline{\sigma}}^{j}_{k_2\omega_2}\cdot\vec{k_2}}{\omega_2 - k_{z2}V_{oj}}\,\vec{k_3} - \right.$$

$$\left. - \frac{i m_j}{q_j}\,\vec{k_1}\cdot\overline{\overline{\sigma}}^{j}_{k_2\,\omega_2}\cdot\vec{k_2}\,\vec{k_3}\cdot\overline{\overline{\sigma}}^{j}_{k_3\,\omega_3} \right] \cdot\overline{\overline{\sigma}}^{j}_{k_1\,\omega_1}\cdot\vec{k_1}$$

where : $\omega_1 + \omega_2 = \omega_3$ , $k_1 + k_2 = k_3$ ( resonant conditions ).

The consequences of resonant conditions in several particular systems (plasma, beam, beam-plasma) are discussed in detail, with the help of a geometric construction. This discussion brings to light the existence of allowed and forbidden bands for the generation of waves by non-linear effects.

In the case of a plasma this wave generation has been observed experimentally for the two situations: $\omega_p \ll \omega_{ce}$ and $\omega_{ce} \ll \omega_{pe}$ . We have verified that the frequencies generated satisfy the relation : $\omega_1 + \omega_2 = \omega_3$ , and are situated in the frequency bands allowed by the linear dispersion relation.

# STUDY OF THE "ELECTROSTATIC" CHARACTER OF ION CYCLOTRON OSCILLATIONS

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The "electrostatic" character of microinstabilities observed in the EOS apparatus (1) is studied and an attempt is made to determine the extent to which the quasi-electrostatic approximation is justified by the experiment. A cylindrical ion beam (r = 1 to 3cm) is extracted from a penning source and injected parallel to the lines of force of a uniform magnetic field (Bo $\leq 10^4$ Gauss). The beam (I = 1 to 5mA) consists of approximately 60% $H_2^+$ ions, 10 to 20% $H^+$ ions, and of higher mass impurity ions. $E_{||}$, the parallel beam energy varies from 0,4 to 2,5 KeV and the transverse energy is about a quarter of the parallel energy. On these conditions, large amplitude oscillations develop in the beam, with frequencies equal to the cyclotron frequency of the $H_2^+$ ions and its harmonics. By mapping the electromagnetic field of these waves, inside and outside the beam, it has been possible to evaluate the wavelength, the azimuthal wave number, the sense of wave rotation, the amplitude of the oscillating potential and also to determine an upper limit for the amplitude of the magnetic field. From these measurements it is found that the electric field is essentially irrotational ( $\frac{|\bar{\nabla} \times \bar{E}|}{\bar{\nabla}.\bar{E}} < 5.10^{-6}$), which fully justifies the use of the quasi-electrostatic hypothesis ($\bar{E} = -\bar{\nabla}\phi$ ), in the theoretical description of this type of instability.

(1) M. PERULLI, C. ETIEVANT, J. OLIVAIN
Comptes Rendus 262 B, 181 - 17 Jan. 1966 .

# CREATION OF A SYNTHESIZED PLASMA BEAM AND APPLICATION TO THE STUDY OF A TWO BEAMS-PLASMA INSTABILITY

by

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Abstract

We first describe the creation of a synthetic plasma : a pulsed ion beam is neutralised either by injection of thermonic electrons or by ionisation of the residual gas.

We obtain a plasma, the main characteristics of which are the following : the electron density varies from $10^7$ to $10^8$ $cm^{-3}$ and the electron distribution function can be taken as Maxwellian ; the longitudinal electric field is negligible in the plasma and no external magnetic field is applied ; Collisions are negligible at the very low background pressures used (around $10^{-6}$ mmHg) and at the plasma densities quoted above ; furthermore the plasma is stable.

Due to the technique used for the creation of this plasma, we can modify each parameters independently i. e. without changing the other characteristics.

In particular we can create a longitudinal electric field in the plasma by applying a positive voltage on a grid : the plasma adjusts itself to the grid potential and electrons emitted by the neutraliser are accelerated and oscillate inside the potential well, thus created.

The measurements of the characteristics of the perturbed medium show the creation of a two beams-plasma instability.

# EXCITATION OF ELECTRON PLASMA OSCILLATIONS BY THE INTERACTION OF AN ION BEAM WITH A PLASMA

by

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Abstract

The interaction of an infinite homogeneous monochromatic ion beam with an infinite homogeneous cold plasma without a magnetic field leads theoretically to the excitation of waves at the electron plasma frequency. In the experiment a beam of either $H^+$, $H_2^+$, or $H_3^+$ penetrates a chamber filled with hydrogen gas with a pressure between $5 \cdot 10^{-5}$ and $2 \cdot 10^{-3}$ torr. The beam ionizes the neutral gas and creates a plasma with which it can interact. A probe near the end of the chamber detects waves whose frequencies increase linearly with the pressure. Under the assumption of homogeneous plasma density in the region of the beam and a logarithmic radial density profile cavity measurements give a density and a plasma frequency in the beam region, which corresponds to the detected frequencies.

# EXPERIMENTAL STUDY OF A STRONG BEAM-PLASMA DISCHARGE

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The use of electron beams to heat plasma has been stimulated recently by the existence of a strong beam retardation mechanism which transfers an important part of the beam energy to the plasma [1,2,3]. Preliminary results are presented here for a plasma in which a strong interaction with an electron beam produces ionization and heats a fraction of the plasma electrons. The hydrogen plasma with electron density in the range of $10^{12}$ $cm^{-3}$ is obtained in a simple mirror magnetic configuration with a mirror ratio variable between 2 and 7,8. The maximum magnetic field can be maintained up to 4 kgauss. The surrounding neutral gas pressure is in the range of several $10^{-5}$ to several $10^{-4}$ torr. For these conditions, X-rays with energies exceeding 200 to 300 keV have been observed for beam intensities between 0.5 and 4 amperes and applied voltages between 4 and 10 kV. The electron temperature, measured by the slope of the X-ray spectrum, recorded on a multichannel analyser is 20 to 40 keV. An additional check with X-ray absorption technique supports this result. The X-ray flux, constant during the discharge, goes to zero with a decay time of a few tens of milliseconds after the accelerating voltage is switched off. Decay time increases when surrounding neutral gas pressure is lowered.

(1) ALEXEFF I., JONES W.D., NEIDIGH R.V., PEED W.F. and STIRLING W.L., Culham Conference Proc. II, 781 (1965)

(2) SMULLIN L.D. and GETTY W.D.,Culham Conference Proc. II, 815 (1965)

(3) NEZLIN M.V. and SOLNTSEV A.M., 7th Int.Conf.Phen.Ion.Gases, Belgrade (1965) - ( in press) -.

# The Application of Hamilton-Jacobi-Theory to Vlasov's Equation

by D. Pfirsch

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Abstract:

Solutions of Vlasov's equation are given in terms of the Hamilton-Jacobi-function S for the characteristics of this equation. Such solutions are appropriate in order to calculate macroscopic quantities like the current density or charge density; one must sacrifice, however, knowledge about the distribution functions in $\underline{x},\underline{v}$-space. Upon use of these quantities one can derive nonlinear equations for the electric and magnetic fields, which are of special importance in plasma turbulence theory. One essential point in this kind of theory is that one need not develop the, in general, difficult elimination procedure which is necessary to find the motion of a particle. This means one need not know really the characteristics of the Vlasov equation. A second essential point consists in that the Hamilton-Jacobi-theory allows a rather simple and straight forward nonsecular perturbation theory. As an example a one-dimensional plasma is treated. Upon use of an equation similar to the Hamilton-Jacobi-equation, namely $\partial S/\partial t = H(\underline{p}, \partial S/\partial \underline{x}, t)$ , it is possible to derive expressions for the spatially homogeneous part of the distribution functions. Some preliminary results of this theory will be discussed.

## Hamiltonian Formulation of Magnetic Field Equations

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Abstract

The analogy between the action integral, $K = \oint pdq$, for a mechanical system and the flux integral, $\Phi = \iint B.dS$, for a stationary magnetic field suggests that the equations for the motion of magnetic field lines may be put in Hamiltonian form. The Hamiltonian equations are found explicitly for a magnetic field given in any curvilinear coordinate system. In cartesian coordinates xyz the Hamiltonian is simply $H = \int^{y} B_x dy - \int^{x} By^* dx + f(z)$, where the integrals are the variable part of the indefinite integrals. $By^*$ is the part of By independent of y, and f is arbitrary. The corresponding canonical variables are, $p \equiv \int^{y} B_z dy$, $q \equiv x$, $t \equiv z$. The advantage of the canonical formulation is that all the mathematical tools of classical mechanics are immediately available. It can be shown for example, that when $B^i$ is large compared with the other field components, which are also periodic in $x^i$, that magnetic surfaces are defined by a quantity similar to the adiabatic invariant of the Hamiltonian system. The solution of the equation for the surfaces is easily found to third order in the expansion. The stability of these surfaces and surfaces in helically symmetric fields and multipole fields is readily examined in the canonical formalism.

# EXPLODING LIQUID JETS AND THEIR USE FOR PERIODICALLY WORKING HIGH TEMPERATURE DEVICES

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A b s t r a c t

By analogy with the electrical explosion of thin metal wires we have 'exploded' thin liquid jets, ejected from narrow nozzles, by short-circuiting a charged condensor bank over the jet. It is possible to make the appearance and the running of the explosion quite analogous to the explosion of metal wires. Using appropriate liquids containing deuterium enables us to heat deuterium in a new manner, which has not yet been investigated. The initial state is restored by itself, and so periodic working is possible.

# EXPLODING FOILS AS LINERS

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ABSTRACT - When a magnetic flux (or a plasma) is compressed by a moving conducting liner, the energy density of the field (or of the plasma) at the moment of maximum compression is comparable with the initial kinetic energy density ( $1/2\ \rho_0 v_0^2$ ) of the liner. In order to obtain high final energy densities, $\rho_0$ and $v_0$ have to be large. A solid liner ($\rho_0 \simeq 10$ g/cm$^3$) can be driven by chemical explosives to velocities of not more than $5.10^5$ cm/sec. A plasma liner can be driven by pinch forces to substantially higher velocities ($5.10^7$ cm/sec), and could then be of interest if very high initial plasma densities could be obtained. To try to realize such a high initial density an experiment has been designed in which a thin (10 - 100 Å) cylindrical metallic layer is first electrically exploded by means of a rectangular current pulse of 100 nsec duration, and then driven towards the axis by the discharge of the main condenser bank. Experimental results on the dynamics of this hollow pinch and on its ability to compress and axial magnetic field are presented.

# DIFFUSION DUE TO ION-ION COLLISIONS IN A MULTICOMPONENT PLASMA

by

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In a fully ionized plasma consisting of electrons and one kind of ions, Coulomb-collisions between electrons and ions produce diffusion. Collisions between ions produce only higher order effects. If, however, two or more ion species are present, collisions between these will be important. The diffusion for such a multicomponent plasma transverse to a magnetic field has earlier been treated by SPITZER (1952), LONGMIRE and ROSENBLUTH (1956) and POST (1959) in presence of pressure gradients. In the present paper, diffusion due to a strong centrifugal force is considered. Application to diffusion of impurities in rotating plasmas is discussed.

# ABOUT SOME MEASUREMENTS OF PARTICLE FLOW, DIFFUSION COEFFICIENT, AND NOISE IN 'DAPHNIS' EXPERIMENT

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Abstract

In the experiment DAPHNIS the gas is ionized in a cylindrical source, then diffuses along the magnetic lines into a 1.5 meter tube. We measured the longitudinal flow of particles by using the "plasma eater" device described by Alexeff and Jones. From the knowledge of the variations of this flow along the magnetic field we can obtain the perpendicular diffusion coefficient. We show that the particle loss is essentially longitudinal : this is in good agreement with the results obtained by measuring the decay-time of the plasma by means of interferometry or with the "plasma eater" ifself. The variations of the perpendicular diffusion coefficient with respect to the magnetic field are compared to the classical collisionnal theory and to Bohm's values, as well as to the variations of the mean quadratic value of noise emitted by the plasma column.

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# OHMIC HEATING OF A HYPERSONIC DEUTERIUM JET

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ABSTRACT - As basic experimental study on hypersonic gas injection in order to get a unconfined ionized gas structure for a dynamic pinch, a high-density deuterium jet of a velocity of 8 Mach is studied in low density medium.

The ionization and the ohmic heating of the 5 mm medium diameter jet is obtained by a current pulse of about $10^6$ A.

An electron beam preionization is prepared.

# RESEARCH ON NON-LINEAR INTERACTIONS BETWEEN A PLASMA FLOW AND A MAGNETIC FIELD

by

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Methods of solving numerically the non-linear system of the MGD basic equations, which describe the interaction between a plasma flow and a magnetic field are given.

For the one-dimensional, unsteady, indeal MGD basic equations a variational mechanism is presented leading to a closed analytical approximate solution. A variational functfonal for which a non-linear differential equation for a potential function describing the behaviour of the plasma may be derived as the Euler-Lagrange equation can be given. The variational integral is numerically evaluated by means of the RITZ method.

In the case of finite electric conductivity, a numerical method developed for the solution of the one-dimensional MGD basic equations is used to calculate the acceleration of a plasma by a travelling magnetic field. In order to achieve a reasonable computer time this problem has been calculated in low- approximation. This is physically reasonable as the initial velocity of the plasma is assumed to be due to a magnetically driven shock. The acceleration is investigated for various magnetic Reynolds numbers.

Two-dimensional magnetogasdynamic flow of small magnetic Reynolds number are investigated with regard to ($\underline{j} \times \underline{B}$)-accelerators. The restriction to two-dimensional flows and the assumption of small magnetic Reynolds number permit a decomposition of the system of equations into the electrodynamic basic equations for which solutions valid independently of the flow quantities can be found, and into equations corresponding to the flow, energy and continuity equations of ordinary gas dynamics which, however, will now contain inhomogeneity terms of electrodynamic origin. This system of four non-linear partial differential equations is solved by a numerical method based on the theory of characteristics.

# EXPERIMENTAL DEVICES "BOGEN" AND "EIERUHR" FOR THE PRODUCTION OF HIGH DENSITY STEADY STATE PLASMA IN THE TEMPERATURE RANGE ABOVE 10 eV

by

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Abstract

The maximum temperature that can be obtained in steady state high pressure arc discharges is limited by the radial heat conduction losses. The application of a strong axial magnetic field to such discharges reduces thermal conductivity of the plasma provided $\omega\tau > 1$. As a result of this, the temperature of the plasma increases appreciably over the value that corresponds to zero magnetic field, even though the power input required per unit length of the discharge column remains the same or decreases. Furthermore, the magnetic field causes a radial pressure increase towards the axis of the discharge column.

The effects of the magnetic have been investigated in two different experiments. In the first experiment ("Bogen") an arc discharge has been maintained for a few seconds a hydrogen flow at total current values up to 3 kA and magnetic induction field strengths up to 30 kΓ. In the second experiment ("Eieruhr"), an impulse discharge of 1 msec duration is produced in a closed vessel filled with hydrogen or helium. In this the total current and the magnetic induction could be varied up to 5 kA and 80 kΓ, respectively.

In both experiments, the plasma is clearly separated from the wall and is free from impurities. Temperatures up to $4.10^5$ °K and particle densities up to $2.10^{16}$ $cm^{-3}$ have been measured.

# SPECTROSCOPIC TEMPERATURE DETERMINATION IN THE "BOGEN" AND "EIERUHR" EXPERIMENTS

by

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Abstract

As a result of the applied magnetic field and the related reduction of the heat transfer, large temperature gradients are present both in the arc experiments and in the "Eieruhr" experiments. Hence the population density of the ground state of both the neutral and the single ionized helium atoms decreases rapidly in the direction from the boundary towards the axis of the plasma column. Thus line radiation caused by transitions to the ground level is emitted by optically thick layers at the boundaries whereas it is emitted by optically thin layers in the plasma zone. It is investigated how the determination of the temperature is affected under these conditions. Three cases are considered: 1. temperature determination based on the relative intensities of two lines corresponding to different ionization states, 2. determination of the temperature based on the relative intensities of the line and continuum radiation, and 3. determination of the temperature based on the continuum intensity and the density of free electrons. Experimental results are presented.

# MEASUREMENTS OF THE RADIAL DEPENDENCE OF THE NUMBER DENSITY OF FREE ELECTRONS AND ELECTRON TEMPERATURE IN AN "EIERUHR" PLASMA

by

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Abstract

In a linear device called "Eieruhr" the radial dependence of the number density of free electrons and the continuum intensity have been measured by means of Faraday rotation of ruby laser light and spectroscopic measurements respectively.

The maximum temperature in a He plasma is 400 000 °K. The pressure on the axis of a Helium plasma is about 1 atm, whereas the pressure off the axis is less than 1/10 atm; this has been found also by O. Klüber by quite different measurements. This pressure rise comes about essentially due to two different effects. The first one occurs in the boundary of the plasma column and is based on the fact that ionized particles diffuse outward while neutral particles diffuse more inward. The second one is known as the Nernst-Ettingshausen effect, which states that an electric current can flow perpendicular to both a magnetic field and a temperature gradient. In plasma physics up to now little importance has been attached to the latter effect. The azimuthal current $j_s$ which is caused by both effects together with the external magnetic field strength $B_z$ yields a pressure gradient.

# INVESTIGATIONS ON THE PRESSURE DISTRIBUTION INSIDE THE "EIERUHR" BY MEANS OF DIAMAGNETIC SIGNALS

by

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Abstract

"Eieruhr" is a linear, stationary discharge in the field of a cylindrical coil. The difference of the pressures at the axis of the plasma column and in the surrounding neutral gas is about one atmosphere. There are two contributions to this compression: the pinch effect (force between the discharge current and its own magnetic field) and the force between ring currents in the plasma and the meridional field induced by the coil currents and the plasma ring currents. The discharge is surrounded by pickup coils to measure the magnetic flux of the meridional field. Using a difference method the contributions $\phi_c$ and $\phi_p$ of the coil and the plasma currents are measured separately. ($\phi_p \approx 10^{-3} \phi_c$). By a quantitative relation between $\phi_p$ and the plasma ring currents the contribution of these currents to the pressure rise is determined. This contribution is found to exceed the pinch effect for the part of the plasma inside the coil. It is shown that in this region the plasma ring currents are caused primarily by two effects: the amibipolar diffusion and a thermomagnetic effect, the so-called Nernst effect.

# MEASUREMENTS OF ELECTRIC FIELDS AND PLASMA VELOCITIES IN THE "BOGEN"

by

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Abstract

Calculations concerning the energy balance in a steady state arc show a relation between temperature and electric power input at a given magnetic field. To confirm this relation experimentally in addition to the arc current, the axial electric field must be known.

The latter was obtained from potential probes being swept across the "Bogen". The results agree with calorimetric measurements of the radial heat loss.

The measurements revealed the existence of radial electric fields up to 200 V/cm, the axial field being only in the order of 3 V/cm. The radial electric field is explained by e.m.f. forces due to a rotation of the arc. This yields azimuthal velocities between $10^5$ and $10^6$ cm/sec, confirmed by the Doppler shift of spectral lines. The probe causes an electric perturbation which travels downstream the arc and is noticed as a small drop in the arc voltage. The assumption that the velocity was verified by an additional measurement: A small plasma volume was followed photoelectrically.

# SCALING LAWS FOR COLD-GAS BLANKET CONFINEMENT

by

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ABSTRACT

We have studied the scaling laws for plasma containment devices in which the plasma pressure is balanced by a cold gas, and the heat conductivity is reduced by a strong magnetic field. For thermonuclear applications, the model of a plasma column in a uniform axial field leads to a large - but not an impossibly large - device. Admitting a weak azimuthal field, one obtains an important reduction of the size. Some aspects of this model will be discussed, and an outline of our experimental program will be presented.

# A new theory of the highly magnetised positive column and its experimental verification

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An investigation of a helium positive column at high axial magnetic fields, $B_c < B_z \lesssim 10\ B_c$, is described. $B_c$ is the critical magnetic field which marks the onset of a helical instability.

The results of a detailed study of discharge oscillations are given. It is shown that these results are not consistent with the requirements of either the turbulence theory of Kadomstev or the stable finite amplitude helix theory of Holter and Johnson.

It is proposed that the large amplitude helical oscillation, which is observed to dominate the discharge at all magnetic fields, is stable close to $B_c$ but becomes increasingly unstable as the field is raised.

The state of stability of such a helical relaxation oscillation is considered in a new analysis which is based on the Holter and Johnson theory. The assumptions of this analysis are checked experimentally. An analytic expression is derived for the mean radial density profile ($h_o(r)$) for the region $B_z > 2B_c$.

$$h_o(r) = \frac{1}{(1+s)}\left[4\,\frac{J_1(\beta r)}{\beta r}\left\{J_o(\beta r) - \frac{J_1(\beta r)}{\beta r}\right\} + sJ_o(\beta r)\right]$$

The values of s and $\beta$ are determined by fitting this function to the observed density profiles and these are introduced into the equations along with the experimental values of axial electric field, electron temperature and ionisation rate. The mean radial electron flux, axial wavenumber and rotational frequency are evaluated and are shown to agree with observed values. It is found that the calculated mean growth rate is zero for $B_z < 4B_c$, in support of the Holter and Johnson theory, but becomes finite for $B_z \gtrsim 4B_c$ and then increases with magnetic field.

# HARD CORE EXPERIMENTS AT FONTENAY-AUX-ROSES

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Our experimental program began after the second Geneva Conference. At that time a necessary stability condition, established by B.R.Suydam, gave some hope to obtain several stable configurations.

Among them we have chosen the hard core configuration because of its relatively simple practical realization, and also because the experimental work, begun on a straight (open) machine, could be continued on a closed hard core machine (Levitron).

The two first linear experiments, MEST and EPPE, allowed to show that in well defined experimental conditions the fluctuations of the magnetic field became very small and that the plasma lifetime increased appreciably.

In parallel to these experimental data, P.H.Rebut found a theoretical explanation for these instabilities :

in this theory based on the properties of the neighbouring equilibria, the plasma is not strongly tied to the magnetic field (as it is in the case in M.H.D.) and change of the topology can be possible.

Therefore, the domain of stability is seriously restricted.

In addition to the qualitative and quantitative verification of this theory the experiments on EPPE have shown that ohmic heating is incompatible with plasma stability,

and that the plasma lifetime was mainly limited, in the stable case, by the resistive diffusion of the magnetic fields in the plasma :

with electrodes the resistivity cannot be below a certain level because of the large thermal conductivity of the electrons which limits the electronic temperature.

At present, we are studying essentially two problems :

a) experiments on the closed machines : STATOR,

b) experiments on ion cyclotron heating.

From the experiments on STATOR we have deduced that the toroidal version of the hard core configuration does not present new instabilities : the radial profile of the $B_r$ probes always shows the characteristics of the "gross instabilities" described by P.H.Rebut.

In the stable cases the maximum lifetime of the plasma seems limited by the presence of a large quantity of neutral gas between the magnetic configuration and the pyrex tube and by heat losses to the rods supporting the hard core.

A perfectly toroidal configuration with levitated hard core is planned.

In the domain of radiofrequency plasma heating we have obtained the following results :

1) The addition of an electrostatic screen between the vacuum vessel and the heating coil has suppressed the abnormal absorption observed in the former experiments. At present, the absorption is observed only under particular conditions.

2) The radial profile of the wave, deduced from the magnetic probes, is in good agreement with the expected theoretical profile when the phase velocity of the wave is equal to the Alfven velocity.

3) The energy absorption is well correlated with the wave amplitude.

These experiments, made on EPPE, will be extended on the STATOR machine in the near future. Four oscillators of 8 MW each are under construction, to be used in these experiments.

# On the Energy Source of a Magnetically Driven Shock Tube

by

C. T. Chang

Research Establishment Risö

Danish Atomic Energy Commission

## Abstract

In order to study the effect of the variable load due to the motion of the current sheet on the driving current of a magnetically driven shock tube, it is demonstrated first that the usual snow plough model is adequate for the purpose.

On the basis of this model, it is shown theoretically that a shock moving at a constant speed can be obtained by using a constant voltage source.

Analytical solutions for the time history of the current and the position of the current sheet are obtained for two cases; namely when the characteristic impedence of the voltage source is negligible and when it is dominating.

The steady state current $I^*$, the voltage of the source $V_0$ and the initial gas pressure $p_1$ are related as $I^* \sim V_0^{1/2} p_1^{1/4}$ in the former case and as $I^* \sim V_0$ in the latter case. The steady state speed of the current sheet $u^*$ varies as $I^*/p_1^{1/2}$, does not depend on the characteristic impedence of the voltage source explicitly.

# DEVELOPMENT AND STRUCTURE OF A SHOCK WAVE IN A NOT FULLY IONIZED MAGNETO-PLASMA

By

B. Mayser, K. Eichert and H.J. Kaeppeler

Institut für Plasmaforschung
der Technischen Hochschule Stuttgart

## Abstract

In previous papers the influence of various dissipation mechanisms on the structure of shock waves was discussed. The influence of Ohmic dissipation and viscosity on MPD shocks and the dissipative influence of ionization reactions on gasdynamic flows and shocks was treated. In the paper presented here the influence of Ohmic dissipation, excitation and ionization reactions on the structure of MPD shockwaves in a partly ionized Hydrogen plasma is investigated.

A one-dimensional one-fluid theory is used with the flow velocity in x-direction, the electric field and current parallel to y-direction and the magnetic field in z-direction. The reactions are treated by means of a four level model for electron excitation of the atoms. Besides the ground state three levels for the excited states are used, the third of which is determined as the mean of the higher levels. For the excitation and ionization cross sections a polynomial approximation was chosen. By this way it is possible to use experimentally or theoretically determined cross sections. To avoid the difficulties appearing in the stationary treatment of shock structures due to the singular points of the system of differential equations, the corresponding time dependent partial differential equations are established. Development and structure of the shock is obtained by numerical solution of these equations. The results are discussed.

# Plasma Acceleration with an Electromagnetic Travelling Wave.

W. Bieger, F. Hoenen, A. Stampa, H. Tuczek

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The possibility of producing a continuous plasma beam by accelerating plasma with travelling electromagnetic waves is investigated. The efficiency of the acceleration mechanism has been determined in a single pulse device, while the initial conditions for continuous acceleration have been studied with a sinusodial wave consisting of several wave lengths.

In the device producing a single pulse only, a fully ionized initial plasma is accelerated by the inhomogeneous magnetic field in front of a travelling wave. A plasma with homogeneous radial density and velocity distributions is observed. Collisions between the ions are negligible. The acceleration mechanism of the ions in the plasma can be described by a free particle model in good agreement with the measurements. Particle losses during the acceleration process are studied by means of an ion-spectrometer and a microwave interferometer.

In the quasi-continuous apparatus the plasma is generated and accelerated by a sinusodial travelling wave. Under certain initial conditions an efficient generation of high velocity plasma beams seems to be possible, the length of which are substantially determined by the length of the wave train.

# HIGH POWER R.F. ACCELERATOR

by

P. Briand - T. Consoli - G. Mourier - L. Slama - P. Vial

C.E.A. - Centre d'Études Nucléaires de Saclay
Gif-sur-Yvette, France

Abstract

We give the principle of the "ICARE" machine which is the equivalent, inside a single resonant cavity, of two accelerating structures located on both ends of a region of confinement where $\nabla E^2$ is maximum.

We can operate either in pulsed regime at high RF power level (2 MW, 100 microseconds at 1250 Mcs) or in CW at a power level of 2, 5 KW.

We give the experimental results of the operation in acceleration and in confinement. Densities reached in the high power level regime are well above the cut off density ($\omega_p^2/\omega^2_{RF} > 300$). We have superposed both regimes where the plasma obtained in CW operation is used as preionisation of the pulsed operation. In that case the effect of the high power consist of an increase of the energy and current in the beam.

FIRST EUROPEAN CONFERENCE ON CONTROLLED FUSION
AND PLASMA PHYSICS

10th - 13th October 1966, Munich, Germany

List of Participants

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| | University of Michigan<br>Ann Arbor, Michigan 48104 | Dr.Terry KAMMASH |

# S o c i a l  E v e n t s

Tuesday , 11th Oct. 1966

6.30 p.m. R e c e p t i o n given by the Bavarian State Government, held at the "Schackgalerie", Prinzregentenstrasse 9, Munich 22

Evening dress not necessary. There is a local bus connection, line 53, along the Prinzregentenstrasse. Nearest stop to the "Dreier-Institut" : corner Theresien- Türkenstrasse ;see map.

Wednesday , 12th Oct. 1966

ca 7.00 p.m. O p e r a  P e r f o r m a n c e
Nationaltheater
Maximilianstrasse , Munich 22

Only a small number of tickets for "Karl V" , opera by the modern composer Ernst Krenek , will be available. Participants wishing to attend this opera performance are kindly requested to come to the conference bureau on Monday afternoon or on Tuesday during one of the breaks.

Thursday , 13th Oct. 1966

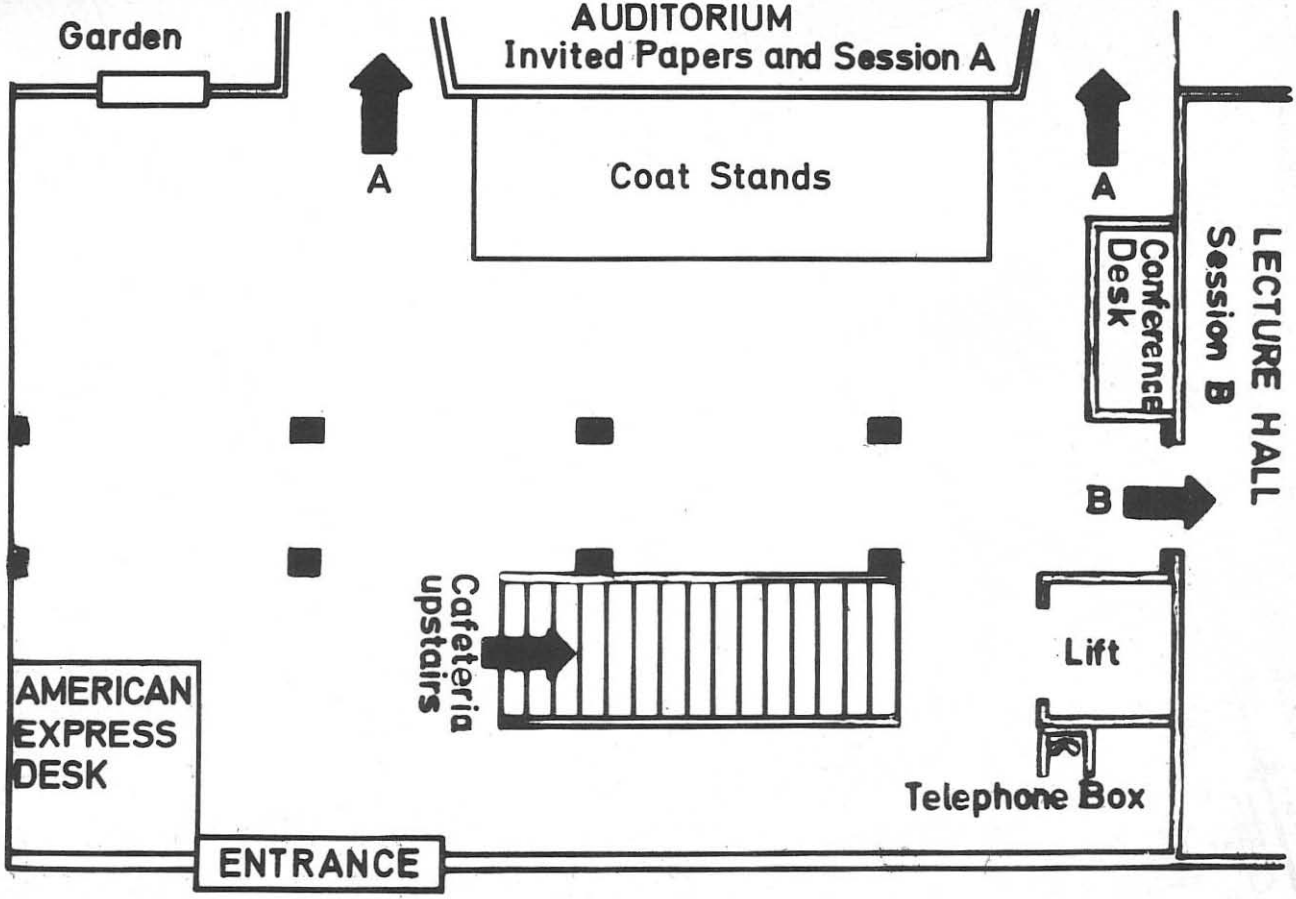
8.00 p.m. C o n f e r e n c e  D i n n e r
Künstlerhaus
Lenbachplatz 8 , Munich 2

The Institut für Plasmaphysik takes pleasure in inviting the participants of the conference and their wives to the official conference dinner held at the well-known "Künstlerhaus" in the center of Munich .

## Information for the Ladies

Please feel free to make use of our small bus for shopping , museum visits , tours to the surroundings , etc . The bus is there for this purpose only . We ask merely that you be at the conference bureau (Dreier-Institut , Schellingstrasse 2-8 , Munich 13) by 9.30 a.m. in order that we can help you plan your day .

C O N T E N T S


Garden
AUDITORIUM
Invited Papers and Session A
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Coat Stands
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Conference Desk
LECTURE HALL
Session B
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Cafeteria upstairs
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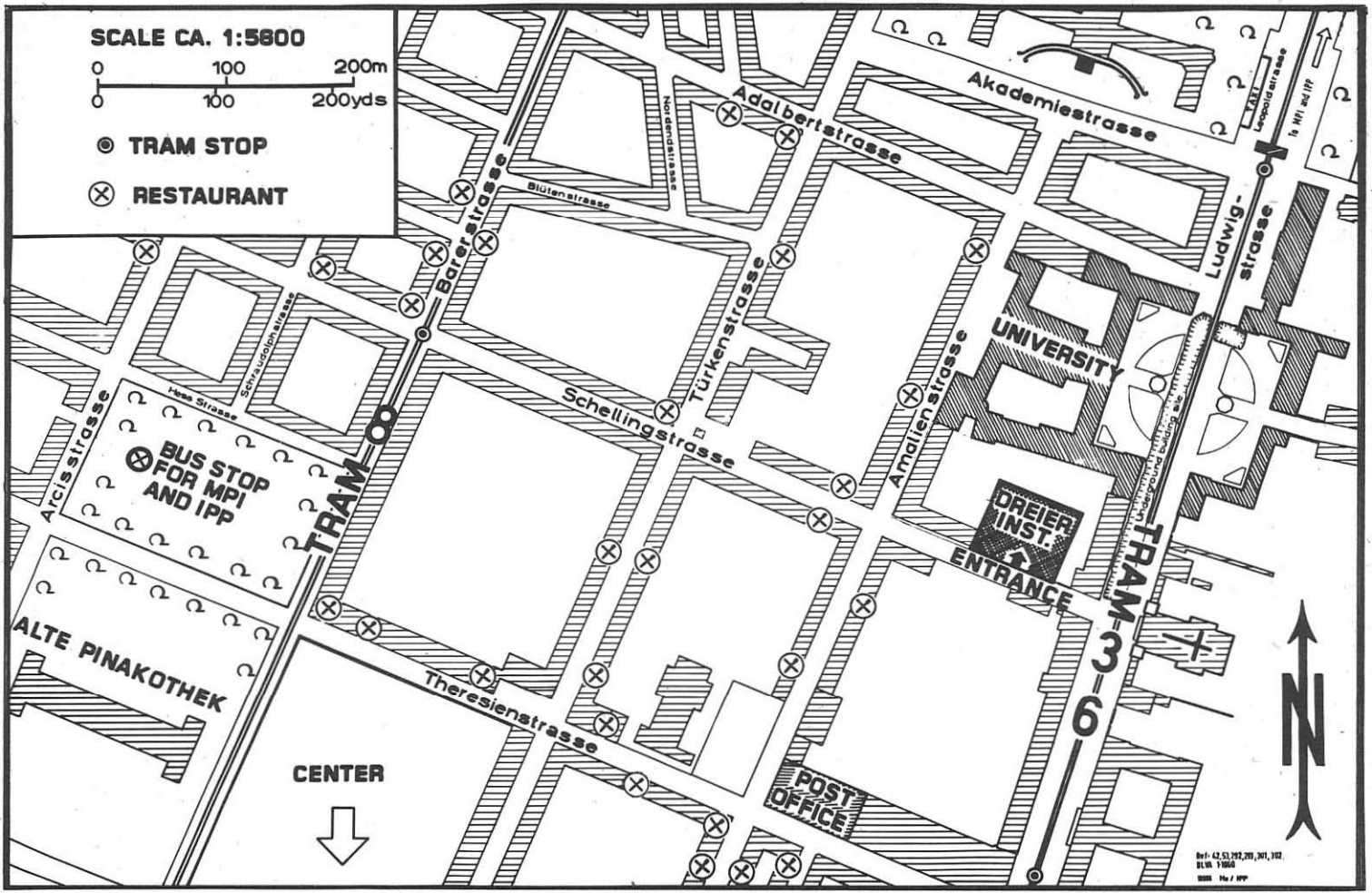
AMERICAN EXPRESS DESK
Telephone Box
ENTRANCE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Ludwig-strasse
Leopoldstrasse
UNIVERSITY
Underground building site
DREIER INST.
ENTRANCE
Arcisstrasse
Hess Strasse
Schraudolphstrasse
BUS STOP FOR MPI AND IPP
TRAM 28
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ALTE PINAKOTHEK
Theresienstrasse
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