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EUROPEAN STUDY GROUP ON FUSION

Sixth Meeting

Paris (Fontenay-aux-Roses) - 23, 24 and 25 June, 1960

NOTES

Chairman:	J.B. Adams	
Attendance:	D.W. Allan	(Imp. College, London)
	J.E. Allen	(Rome)
	K.W. Allen	(AWRE, Aldermaston)
	Ashby	(AERE, Harwell)
	M.Y. Bernard	(CEA, France)
	R.J. Bickerton	(AERE, Harwell)
	L. Biermann	(Munich)
	A. Bishop	(AEC)
	Block	(Royal Inst., Sweden)
	C.M. Braams	(Netherlands)
	H.C. Brinkman	(Netherlands)
	B. Brunelli	(Rome)
	D.R. Chick	(AEI, Aldermaston)
	Cole	(AERE, Harwell)
	T. Consoli	(CEA, France)
	J.L. Delcroix	(Fac. Sciences, Paris)
	A. Folkierski	(Imp. College, London)
	E. Fünfer	(Munich)
	G. von Gierke	(Munich)
	J. Guéron	(Euratom)
	Gratton	(Rome)
	K. Hain	(Munich)
	Hintz	(Aachen)
	L. Högberg	(Uppsala)
	P. Hubert	(CEA, France)
	K. Johnsen	(CERN)
	H.L. Jordan	(Aachen)
	J. Kistemaker	(Amsterdam)
	H. Knoepfel	(Zurich)
	R. Latham	(Imp. College, London)
	Lehner	(Munich)
	J. Linhart	(Frascati)

R. Lüst	(Munich)
Ch. Maisonnier	(CERN)
C. Mercier	(CEA, France)
G.B.F. Niblett	(AWRE, Aldermaston)
D. Palumbo	(Euratom)
F. Prévôt	(CEA, France)
E. Regenstreif	(CERN)
Roderick	(UNESCO)
A. Schlüter	(Munich)
A. Schoch	(CERN)
J. Taillet	(CEA, France)
Tchen	(Munich)
W.B. Thompson	(AERE, Harwell)
M.G. Trocheris	(CEA, France)
G. Vendryès	(CEA, France)
Vogel	(Uppsala)
F. Waelbroeck	(Euratom-CEA, France)
C.F. Wandel	(Risö, Denmark)
Wienecke	(Munich)
S. Winter	(CEA, France
J. Yvon	(CEA, France)
Zabusky	(Munich)
H. Zwicker	(Hannover)

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1. WELCOME BY THE PARIS GROUP

Dr. Yvon extended his welcome to all participants on behalf of the Association EURATOM-CEA.

2. VISITS TO LABORATORIES

As in the past, special sessions were arranged to take the visitors round the laboratories and show them in detail the work on plasma physics.

3. EXPERIMENTS ON ZETA

Cole reported briefly on experiments performed with the new chamber:

a) looking at X-rays

b) absorption measurements and energy of electrons producing X-rays

c) spectroscopy.

A tube protruding inside the torus contains a detector (phosphor, light guide, photomultiplier). The particles reach the detector by passing through a pinhole and a grid device. While the variable potential of the grid allows energy discrimination, the orientation of the pinhole enables one to take spectra in various directions.

4. WORK AT THE M.P.I., MUNICH

v. Gierke reported on experiments at Munich.

a) Mimikry

Standard experiments of the usual kind have been started. Studies have been made to diminish the currents in the walls which were very high (thousands of amps) at the beginning. Finally pure plasma currents were obtained.

b) Resistance curves

Defining the specific resistance distributed between all sections of the tube as the ratio of voltage at peak over the peak current, curves of this specific resistance versus B_z have been plotted for toroidal devices with i) ceramic walls, ii) metal walls. Various devices such as Zeta, Sceptre, TA 2000 and Mimikry have been compared with respect to specific resistance, but no satisfactory understanding of the discrepancies is available as yet.

c) High vacua

Very clean conditions are necessary in linear discharges. Ultra-high vacua of 4×10^{-10} mm Hg have been obtained over 2 m length.

d) Wendelstein

Some measurements have been performed to determine the magnetic field distribution and the toroidal transform. A shift in the position of the magnetic axis was observed which is not explained as yet. The measurements are being continued.

e) Toroidal discharge

X-ray measurements show a large peak at the moment of the discharge.

f) H. Schlüter's experiments

These experiments were carried out on an RF apparatus in a static magnetic field and involved spectroscopic investigations as well as a study of matching the RF to the plasma.

The discharge vessel was a quartz tube of 6 cm diameter and 50 cm long.

Efforts have been made to keep clean discharge conditions, to reduce the wall effects and to maintain a sufficiently powerful electrodeless discharge.

Vacua of 10^{-10} mm Hg have been obtained in the discharge vessel, approaching slowly 10^{-8} after a number of discharges.

To reduce the influence of the walls during the discharge, two coils have been used parallel to the RF source coil. These two coils are capable to accept 40 kW and produce the static magnetic field of a magnetic bottle.

The transmitter was able to feed about 10 kW maximum into the discharge.

Under these operating conditions a Balmer series with an extremely high degree of purity could be observed (quantum number up to 26, which could only be observed in the stars before).

More generally, the clean operating conditions make it possible to determine spectroscopically the characteristic parameters of the plasma and compare them to results obtained by other methods (probes, microwaves, etc.). They also allow to check how well ionization formulae are applicable to non-thermodynamic equilibria.

Another purpose of the apparatus was to examine the conditions of matching of the RF to the plasma. Good matching was found for static magnetic fields for which the geometric mean ν_o of the ion and electron gyrofrequency is of the order of magnitude of the transmitter frequency f.

$$\nu_o = \frac{1}{2\pi} \frac{Z\,e\,H}{\sqrt{m_i\,m_e}}$$

(where H is the magnetic field, Z the charge number, m_i the ion mass and m_e the electron mass) plays an important rôle in the theoretical work of Körper on resonances with RF heating. For $\gamma/\nu_o \ll 1$ (γ = collisional frequency) resonances may occur for $\nu_o = f$. For $\gamma/\nu_o \gg 1$ damping mis-tuning occurs and $\nu_o = f$ goes over into $\nu_o \sim \sqrt{f\,\gamma}$. Whereas the theory is concerned with the refractive index for RF waves, the experiments were devoted to study a related quantity, namely the ohmic resistance of the discharge. The experimental points found follow well the square root law.

More measurements will be done on a new apparatus being built.

5. WORK AT ROME

J.E. Allen gave a review of the work carried out at Rome:

a) Plasma-sheath transition in a magnetic field

Experiments have been carried out using a low pressure mercury-arc discharge tube in which an azimuthal or "pinch-type" magnetic field could be applied. The magnetic field, which was of the order of one gauss, was produced by a current-carrying wire situated at the axis of the tube.

Measurements have been made using Langmuir probes both with and without the applied magnetic field, the direction of the latter being reversible.

An extended form of the Bohm criterion has been derived, which reads

$$\frac{kT_1}{2\ e_2\ V_o} = \frac{1}{\alpha^2} \left(1 + \frac{\bar{v}\ H}{c\ E_s}\right)$$

where kT_1 is the electron energy, $2\ e_2\ V_o$ the energy of the ions leaving the sheath, $\bar{v}$ the drift velocity of the electrons, E_s the radial electrostatic field at the plasma boundary and α a quantity of the order of unity. Quantitatively the results are in agreement with this equation; the variation of E_s with arc current, however, is not what one would expect. In the experiments this field was of the order of several volts/cm.

b) Spectroscopy

The measurements of the refractive index of a plasma in the optical region have been continued. These experiments, as reported at the last meeting, were designed to demonstrate the effect of the free electrons. Such measurements, therefore, provide a new method of determining the electron density in a plasma. The method has the following advantages when compared with microwave techniques:

i) magnetic field effects are negligible

ii) the method can be used to measure high electron densities

iii) spatial resolution can be obtained.

The recent experimental work, which has been carried out using an electrodeless RF discharge, was in relation with iii). Radial distributions of electron and neutral gas density have been obtained. The distribution of electron density has a complicated form showing several maxima; this may be due to the non-uniformity of the discharge in the axial direction, since the measurements refer to the mean electron density averaged over the length of the tube.

In these experiments the electron density is about 10^{15} cm^{-3}.

c) Orthogonal pinch experiment (11 μF, 25 kV condenser bank)

Recently a study has been made of the frequency response of the magnetic probes used in these experiments. It was found that there is an optimum value for the impedance of the recording circuit given by

$$R = R_o / \sqrt{2 - r^2/R_o^2} \simeq R_o \sqrt{2}$$

where $R_o = \sqrt{L/C}$ and r is the resistance of the coil. When this impedance is used, the flattest frequency response is obtained. In the present case typical figures are: $L = 1.14$ μH, $C = 15.5$ pF, $r = 21$ ohm, and $R_o = 271$ ohm. With this probe a response curve flat (to within 1 o/o) up to 20 Mc/s is obtained and a signal of 2 V is recorded when $dB/dt =$ 1 kGauss/μsec.

d) Orthogonal pinch experiment (Cariddi)

This apparatus is under construction. It includes a multi-sector device which enables one to obtain an effective voltage/turn which is greater than the charging voltage of the condensers. Six sectors are used in the present case, but the inductance of the condensers and cables reduces the effective voltage/turn to about three times the charging voltage.

At the present time the device is operating with 4 condensers per sector charged to 20 kV. The spark-gaps are of the 4-electrode type, similar to those used in Scylla.

In the future 30 condensers per sector will be used, charged to 40 kV. Tests on spark-gaps pressurized to 2 atmospheres are in progress; these spark-gaps are designed for 40 kV.

6. WORK AT A.W.R.E., ALDERMASTON

Niblett reported on work carried out at A.W.R.E., Aldermaston:

The equipment comprises mainly 3 condenser banks of 40 kV (to be brought up to 80 kV) and the experiments are aimed at studying

i) preionization processes

ii) radiation of discharge

iii) rapid compression and shock waves

iv) confinement in mirror geometry.

One experiment was reported in detail, namely the rapid compression of a deuterium plasma by an axial magnetic field. The experimental equipment comprises a copper coil 21 cm wide surrounding a quartz tube of 8 cm internal diameter; the coil is connected by a single spark-gap switch to a bank of capacitors supplying 3.5 kJ at 24 kV. The total circuit inductance is 0.14 μH, of which the coil contributes about 0.02 μH. A magnetic probe at the centre of the coil measures the field on the axis of the tube.

Discharges in deuterium at initial pressures in the range 50-200 microns have been photographed axially using two high-speed rotating mirror cameras. A typical streak photograph was shown, displaying clearly the outer edge of the imploding luminous sheath; this is interpreted as the boundary between magnetic field and plasma and has a constant inward acceleration of 5×10^{12} cm/sec^2 lasting for about a microsecond. The inner boundary of the sheath is taken to be a shock wave. A typical framing camera picture of a discharge was then shown; the cylindrical implosion could clearly be seen and the plasma was concentrated in a cylindrical annulus with an inner core of trapped axial magnetic field.

Irregularities in the plasma cylinder develop during the implosion phase and these subsequently become well-defined on the outer surface of the plasma and are believed to be instabilities of the Rayleigh-Taylor type. The irregular inner surface of the quartz discharge tube provides non-uniform starting conditions and these perturbations grow in response to the inertial forces produced by the inward acceleration of the interface between plasma and magnetic field. The growth time of the instability is a fraction of a microsecond, and the wavelength of "maximum instability" is about 1.5 cm. Various estimates indicate that the temperature is of order 6×10^4 °K and the particle density of order 10^{17} cm^{-3}.

The instability of an accelerated fluid interface was first studied by Rayleigh and the theory subsequently developed by Taylor. Experimentally, observations on liquid-liquid interfaces have been made by Lewis and others. If ρ_1 and ρ_2 are the densities of the lighter and heavier fluids respectively and a is an acceleration applied normally to the interface, then an initial disturbance of amplitude A_o and wave number k $(k = 2\pi/\lambda$, where λ is the wavelength) is amplified in the form

$$A = A_o e^{nt}$$

where

$$n = \left[a\, k \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \right]^{1/2}$$

The growth rate would therefore increase indefinitely with increasing wave number.

Kruskal and Schwarzschild were the first to discuss Rayleigh-Taylor instabilities on an accelerated interface. They showed that though the magnetic field produces the plasma motion, the gross nature of the instability and its growth rate are the same as for ordinary fluids.

The application of Taylor's theory to the experiment under consideration can only be approximate since this theory is applicable in principle only to an incompressible fluid of infinite extent. Regarding the magnetic field as a fluid of zero density, the above equation becomes

$$n = (ak)^{1/2} = (2\pi\ a/\lambda)^{1/2}$$

In the experiment λ was 1.5 cm and $a = 5x10^{12}$ cm/sec^2. The characteristic growth time is therefore $2x10^{-7}$ sec, which is of the order of the observed value.

Taylor's theory ignores effects such as surface tension and viscosity which act as damping terms and produce a wave number k_m of "maximum instability". Subsequent investigators have considered these effects. The inertial, viscous and resistive contributions to the growth rate n can be written

Inertial term	$(ak)^{1/2}$
Viscous term	$\eta\ k^2$
Resistive term	$\frac{k^2}{4\pi\sigma}$

where η is the kinematic viscosity and σ the electrical conductivity of the plasma. The relative importance of viscosity and resistivity as damping processes is given by the dimensionless parameter

$$P = 4\pi\sigma\eta = \frac{R_m}{R_h} ,$$

P being the ratio of the diffusivities of momentum and magnetic field and also the ratio of hydromagnetic to hydrodynamic Reynolds number. Inserting numerical values gives

$$P = \frac{3.2x10^{-5}}{n} T^4$$

showing that $\dot{P}$ is very sensitive to temperature. At the estimated temperature of the experiment under consideration ($6x10^4$ °K) it is resistivity that determines the wavelength of greatest instability.

Equating the inertial and resistive terms in the growth rate gives

$$\lambda_m = \left(\frac{\pi}{2}\right)^{1/3} a^{-1/3} \sigma^{-2/3}$$

showing that λ_m is insensitive to a .

At higher temperatures where viscosity provides the damping one should expect

$$\lambda_m = 2\pi a^{-1/3} \eta^{2/3}$$

so that λ_m is again insensitive to the acceleration, but since η varies as $T_i^{5/2}$, λ_m should vary as $T_i^{5/3}$, increasing rapidly with temperature.

7. WORK IN AACHEN

Jordan gave a review of the work in Aachen:

Various experiments on RF preionization, plasma acceleration and diagnostic methods such as probes, microwave inteferometers, spectroscopy in the visible UV and vacuum UV, Kerr cell and image converter photographs are in progress.

The experiment made by Hintz and Fay on the rapid compression of plasma was reported in some detail. Progress has been made by using an additional heater discharge over the compression coil. The main discharge can now be switched with a precision of $5x10^{-8}$ sec at any time and magnetic field polarity of the preheater discharge. One can therefore control the initial conditions of the main compression such as degree of ionization, temperature, amount and polarity of the trapped internal B_z-field.

The preheater gives an oscillating B_z-field with a 1.5 μsec period on which a 10 Mc/sec high frequency oscillation of the collector plate-coil resonant circuit is superimposed. When the gas breaks down, this high frequency oscillation is rapidly damped out, the energy being used for the ionization and preheating of the plasma. The plasma is then held by the oscillating B_z-field. Probe measurements show a trapped internal field which indicates that the conductivity is around 50 mhos. Spectroscopic analysis shows full ionization and a high purity of the discharge when the tube has been cleaned by about 40 previous discharges.

For the purpose of magnetic field measurements a very small probe coil shielded by a 1 mm total diameter stainless steel tube has been newly developed. With this probe field distributions in space and time have been measured in the preheater and in the main discharge. The latter shows a good separation of field and plasma with a β of 60 o/o.

CIII lines appear in the predischarge, when C is added, CIV and CV lines in the main discharge successively. Electron temperature is between 50 and 100 eV.

A space resolved spectrum shows that CV appears only in the region of compressed plasma. The CV lines are broadened at low pressure (0.1 mm Hg) and are sharp in a high pressure (1 mm Hg) discharge. A strong continuum appears in the centre of the discharge at high pressure, while CIV and other lines are strongly broadened at high pressure. This is an indication that the CV line broadening at low pressure is Doppler broadening. The mean ion energy following from this is about 1 keV.

X-rays appear when the gas breaks down in the predischarge at lower pressures, neutrons appear in the main discharge when the internal B_z-field has opposite polarity, even in the first half-cycle.

Circuit components such as capacitors and multiple spark-gap switches are being developed and tested for a several hundred kJ bank, which seems to work reliably. Progress has also been made on a plasma gun experiment with a similar coil and fast bank as in the magnetic compression experiment.

8. WORK OF THE DANISH GROUP

Wandel described the activity of the Danish group:

a) History

The Danish group was created in 1958 and worked at the beginning on the theory of energy balance in a reacting thermonuclear plasma. Most of this work has now been published in a series of Risö internal reports as well as in the open literature.

In early 1959 it was decided to go into experimental plasma physics, on a small scale, by building a device for the production of EM-driven shocks. The staff presently consists of five people.

b) Experimental work (Vagn Jensen, Sillesen and Vinther)

The work is centred on a small apparatus consisting of two plane parallel electrodes which together with insulation and windows form a discharge chamber in which the pressure can be controlled. When a voltage is applied at one end of the plates, a discharge starts at this end since this is the path of lowest inductance. Once started, the discharge is driven towards the centre of the apparatus by the magnetic field. A simultaneous discharge from the other end can be arranged for and thus the motion, development and collision of EM-driven shocks can be studied in a relatively simple geometry.

Data:

Dimensions of apparatus	: 3 x 20 x 50 cm
Condenser bank units	: 16 x 2500 Joule
Each unit consists of	: 1 spark-gap, 8 condensers (25 kV, 1 μF per condenser)
Ringing frequency incl. leads	: 180 kc/s

Diagnostic tools:

Rotating mirror camera AVCO MC300

Oscilloscopes for el., magn. and light probes

1 Tektr. 517, 2 Tektr. 551 + 1 Tektr. 555

Quartz spectr. Zeiss Q24

Monochromator Zeiss M4Q II

Image converter RCA C73435 B

c) Theoretical work (T. Hesselberg Jensen and C. Wandel)

A crude phenomenological theory has been developed for the dynamics of an electromagnetically driven shock in a simple one-dimensional device fed by a finite power bank. It incorporates several possibilities of interaction between the advancing front and the particles of the gas. Among them are the "snow-plough model", a "perfect mirror" and "immediate loss of particles".

Apart from the two parameters characterizing the model of interaction, only one further parameter is required; this is essentially the value of $V/\sqrt{Mp}$ (V = initial voltage, M = molecular weight of filling gas, p = initial pressure of gas). Furthermore, a very characteristic difference in behaviour is found depending on the degree of loss of particles from the front. When the containment is good, the velocity of propagation stays constant while the current reverses; this is not so when particle losses dominate, since the lack of inertia behind the shock makes it reduce its speed each time the current reverses.

d) Programme

The present programme includes an investigation of how satisfactory a description one can get using only the parameter combination $V/\sqrt{Mp}$, seeking both quantitative and qualitative agreement with theory. Furthermore, an investigation of the inertia-effect will be made and used as a stepping stone for further investigation of the shock mechanism and structure at different pressures. For this purpose one hopes to benefit from the possibility of firing simultaneous shocks in order to investigate the collision of two shocks.

9. PROGRESS AT FONTENAY-AUX-ROSES

Hubert reviewed the experimental work carried out at Fontenay-aux-Roses:

a) Pinch programme

i) Metal torus TA 2000

This device has been used for spectroscopic measurements (Breton) using mixtures of hydrogen, helium and methane. Although the interpretation of data is not complete, it indicates that an elaborate theory would be necessary to explain the observations.

TA 2000 has been dismantled in order to move it into a new building. This circumstance has been taken advantage of to improve several experimental facilities and place a new liner.

ii) Tubular pinch

A versatile device for the study of triax and unpinch configurations has been built by Ginot who hopes to avoid, by means of a peculiar shape of electrodes, some of the difficulties associated with end effects.

iii) Equateur

Absorption spectroscopy is attempted with a Lyman tube, the development of which has turned out to be a major effort in the experiment. First results have now been obtained by Sternberg.

b) Plasma injection programme

i) Button sources

Bostick and coaxial types are being investigated. Probe measurements seem to indicate the existence of two groups of particles, a slow and a fast one. The slow group is expected to be titanium ions and the fast group would be deuterium. Alidières is carrying out experiments to investigate this situation and possibly make use of it.

ii) Micropinch

This device (Samain) is an induction plasma gun, the primary of which is a U shaped single turn coil, the sides of the U being parallel to the axis.

Recent investigations have revealed several properties:

First, removing the bottom of the U results in a slower plasma; this shows that the propulsion is not a trivial thermal expansion effect.

Second, a radial field in the proper direction increases the speed.

Finally, projected plasma can go through a narrow annular slot and this gives some hope to operate the device with differential pumping.

iii) Marshall gun

Waelbroeck has performed a series of experiments with this.

The gun is of the induction type with a conical coil. The d.c. guiding magnetic field has been put into operation, showing a spectacular confinement in the transverse direction. Measurements with magnetic coils and photomultipliers have revealed some characteristics of the plasma jet.

Preionization seems to improve considerably the performance at high voltage.

iv) DECA

This is a slow mirror experiment being prepared (Bariaud) for studies of adiabatic compression. Design parameters of the coils are $\phi_1 = 21$ cm, $\phi_2 = 31.5$ cm, L = 28 cm. The energy available from the condenser bank will be 300 kJ. Injection will use the plasma sources mentioned above.

c) Fast ion injection programme

Some progress has been made in relation with the theory of the machine being built by Prévôt.

Prévôt's calculations on the cooling of injected ions by the deuterium plasma column show that pulsed operation of the arc is unavoidable if burnout is expected to occur. Other calculations made by Gourdon show that rather long trajectories can be obtained before dissociation in the contemplated hybrid geometry (mirror field with an external cusp).

A model is being built to observe the trajectories of injected electrons when their length makes computations unreliable.

The annular ion source has been operated up to 400 mA, this figure being limited only by the power supply. A new one is being prepared with a magnetron type discharge in the arc volume. It is expected to work at a still lower pressure.

The deuterium plasma column is being assembled while diagnostic techniques are prepared by Papoulard.

d) Miscellaneous experiments

Capel is a device in which one hopes to trap electrons in a magnetic mirror bottle with periodic perturbations. Electrostatic perturbations are tried instead of magnetic ones as demonstrated by Sinelnikov. This would have the advantage to allow a rapid pulsation transforming temporary trapping into a quasi-permanent state. In fact the experiment has turned out to be a gas discharge experiment since breakdown occurs at the lowest pressure obtainable (10^{-8} mm Hg).

The work on the transverse pinch has consisted, since Uppsala, in the application and study of preheating.

Concerning beam-plasma interactions, Etievant tries to shoot a 10 kV - 1 Amp beam into a plasma with a longitudinal magnetic field. The device is expected to be a better approximation to plane wave theory than other devices previously described in the literature. The plasma gun and the plasma source (PIG discharge) have been tested independently. They are now being put together.

Various types of spark-gaps of the air or vacuum version have been developed to satisfy the needs of the experimenters. Taquet and André are continuously improving their first models.

10. STABILIZED PINCH CONFIGURATIONS

Fünfer reported on stabilized pinch configurations:

a) Linear pinch

The following measurements were carried out on 2 pinch arrangements with energies of 30 kJ and 120 kJ and stabilized B_z-fields up to 6500 Gauss: current and voltage, magnetic fields with pick-ups, Kerr cells and smear-camera pictures, microwaves, impurities by means of spectroscopic measurements, γ-waves and neutrons.

The study of the pinch dynamics reveals the following results:

i) In the field of stable pinch oscillations the measured compression times are in good agreement with calculations based on a simple plasma model. The pinch times are independent of the strength of the B_z-field also in the later compressions.

ii) During the compression of the B_z-field azimuthal electric fields appear. In these fields runaway electrons of high energy (400 kV) are formed which produce a γ-radiation just before the first plasma compression.

In small magnetic fields the electric field is too weak to produce γ-waves, in high magnetic fields the number of electron circulations is diminished. There is also a maximum of γ-radiation for a certain B_z-field depending on pressure.

iii) The measurement, by means of magnetic probes, of the captured magnetic field in a sufficiently preionized gas shows the existence of magnetodynamic shock waves. Here, the captured B_z-field is proportional to the density of the charged particles. The results of photographs are in good agreement with Hain's magneto-hydrodynamic theory.

iv) The stabilizing effect of the B_z-field has been investigated by Kerr cell pictures and measurements of the field variations. Up to B_z-fields of 500 Gauss the m=0 instability is predominating. In B_z-fields over 500 Gauss m=0 disappears. With the appearance of the m=1 instability at low B_z-fields the longitudinal magnetic flux rises suddenly to a high value. With increasing B_z-field the growth rate of m=1 diminishes.

b) Azimuthal pinch

A battery of 40 kV and 300 kJ was used. The discharge tube had a diameter of 5 cm and a length of 8-16 cm without mirrors. Mainly problems of plasma ignition and pinch dynamics were studied.

In the oscillograms of the discharge neutrons, γ-waves and light could be seen. The ignition occurred rather exactly at the maximum of dI/dt. The neutron emission took place in the second half-wave after the ignition with a maximum of 10^5 n/discharge. The neutron impulse started at the end of the radial plasma oscillation and its duration was probably limited by the diffusion of plasma out of the coil. The γ-emission appeared predominantly at pressures lower than 10^{-2} mm Hg. It was often formed in the first half-wave about 10^{-7} sec after ignition, but also in later half-waves.

c) Ignition problems

The ignition and the formation of a well conducting plasma layer occurs 0.2 or 0.3 μs after the current has changed its direction. The captured field is then about 5000 Gauss and the radial compression is limited to r/r_0 = 1/3 to 1/4. This is in good agreement with Kerr cell pictures.

Several methods of preionization were tried to change the ignition time either to place it in an earlier maximum of dI/dt, at the beginning of the discharge, or as near as possible to the point of no current to reduce the captured field. The displacement of the ignition time towards the early stages of the discharge can easily be obtained by means of a preionization fed by oscillations of a coaxial cable. The oscillations are brought to electrodes on the outer sides of the tube ends. The ionization is about $5x10^{-6}$ (10^{10} ions). The same effect can be obtained by a weak axial discharge. However, a displacement of the ignition time to the point of zero current could not be obtained.

Theoretical estimations show that ionization during ignition is only possible up to a critical magnetic field. An estimate of the charged particles produced and their accumulation over several half-waves yields the half-waves of ignition, and this is in good agreement with measurements of the ion density produced by the preionization.

d) Instabilities

In the Kerr cell pictures one can notice non-reproducible motions of the plasma in the second half-wave after ignition. These motions occur accidentally in the first half-wave in the presence of impurities.

Mainly with preionization a very strong light emission occurs in the third or fourth half-wave; this may be due to the glass walls.

11. WORK AT UPPSALA

Högberg gave a short review of work carried out at Uppsala:

Three experimental set-ups are at present in operation: two toroids and a small plasma gun. The smaller of the toroids has a main diameter of 60 cm, the inner diameter of the tube being 8 cm. A typical primary current in present experiments is 30 kA with a half-period of 140 μs. The main diameter of the second toroid is 130 cm, the inner diameter of the tube being 25 cm. Typical gas currents are about 100 kA with a half-period of 100 μs.

The investigations with the toroids comprise the development of various diagnostic techniques, such as probe measurements and spectroscopy. On the small toroid a hydromagnetic wave experiment has just been started.

A study of the performance of a small electrodeless plasma gun has just been finished. The driving circuit consists of a low inductance capacitor feeding a single 65 mm diameter primary turn, which is placed behind one end wall of a 120 mm diameter pyrex tube filled with deuterium of 75-400 μ pressure. The maximum primary current is 65 kA with a rise time of 0.35 μs. The discharges have been studied electrically, spectroscopically, and with a Kerr cell camera. Plasma rings of comparatively high purity and with velocities up to 5 cm/μs have been produced. By means of a longitudinal magnetic field the burst of plasma has been contracted to the centre of the tube.

12. WORK AT IMPERIAL COLLEGE, LONDON

Latham reported on work carried out at the Imperial College:

The Kerr cell work on the linear pinch apparatus has been extended to cover a wide range of parameters, taking sequences of pictures at progressively later times in the development of the discharge, each on a separate discharge.

Typical sequences were taken with 0.4 μs exposure time and at 1 μs intervals. The slides show the pre-pinch axial filament, the expansion of the filament as the shell collapses and the rebouncing with growth of surface ripple.

To obtain more quantitative results a crude statistical approach was made by tracing profiles, measuring many diameters at intervals along the length and taking means; rough wavelengths were obtained in this manner.

The results seem to be consistent with the Rayleigh-Taylor mechanism of growth although there are many inaccuracies in drawing profiles and obtaining scaling factors.

The instability which a column of steady diameter would have was not taken into account at early stages in the growth of instabilities. This is because they are local disturbances without cylindrical symmetry, so that there is no increase of B_θ for a local decrease in r and vice versa; the surface should therefore be in neutral equilibrium.

A slide was projected where an accelerated pair of immiscible liquids was compared to a bit of plasma surface. The boundary conditions showed good similarity.

The attempts to influence surface instabilities by putting on axial magnetic fields after the first pinch are temporarily in abeyance while a current-clamping arrangement is being made.

Some shock tube work has been done on magneto-hydrodynamic interactions. A shock tube was used with O_2H_2 explosion to burst a diaphragm and produce a "slug" of plasma (argon) at 20 000 ^oK, 25 cm long and 5 cm in diameter. This passes at 10^5cm/s into a transverse magnetic field of 30 kG where a ring electrode system can be used to abstract energy. Powers of 0.3 MW for 100 μs have been obtained. This came rather as a surprise as one would expect boundary layer phenomena to reduce the conductivity to values appropriate to ionic motions. There is no evidence of this; conductivity is that of the electrons and it can be concluded that at large currents to the electrodes the boundary layers do not form. An appreciable fraction (30-50 o/o) of plasma energy is being extracted and dissipated in a resistive load.

An attempt will be made to improve the quantitative side of the observations on growth of instabilities and to investigate the effect of putting probes into the discharge on the discharge profile.

13. INTERPRETATION OF INSTABILITIES

Allan (Imperial College) made a few remarks on the interpretation of photographic observations of a B_θ pinch:

Since fast pinches involve overall oscillations of large amplitude, the interpretation may well be carried out in terms of the Rayleigh-Taylor theory of instabilities of accelerated fluids. On the other hand, the mean free path remaining quite small, it seems quite reasonable to use the simplest forms of hydromagnetic stability theory.

Three observational tests which might distinguish which theory is the most appropriate to the fast pinch are: the rate of growth of instabilities and its correlation with overall motion, the shape of the instabilities when grown moderately large (i.e. into the non-linear regime as regards the governing equations), and their wavelength as a function of time.

a) Rates of growth

The information on rates of growth in cylindrical confinement available from equilibrium theory is extensive. This theory is unfortunately limited to the linear regime, and therefore soon becomes inapplicable to experimental observations. As for the Rayleigh-Taylor theory, the plane hydrodynamic case is well worked out and there is some information on the non-linear regime as well. If there are no dissipative forces, the exponential growth rate when the instabilities are small in amplitude is given by

$$\omega^2 = \frac{2\pi g}{\lambda} = g\,k$$

whilst during the non-linear regime "bubbles" of magnetic field should rise into the plasma with a constant velocity U , where $U \propto \sqrt{g\lambda}$.

The analysis made at the Imperial College has revelaed the correlation with acceleration to be expected on the basis of the Rayleigh-Taylor theory. The rate of growth deduced seems to be about half that given by the simple formula above, but this may be a result of the cylindrical geometry or a consequence of dissipative effects coming into play.

b) Shape of instabilities

The photographs taken at the Imperial College of the instabilities of the pinch when they have grown moderately large reveal the characteristic Rayleigh-Taylor structures of "scallops" and "spikes" which have been observed in Lewis and Taylor's experiments with accelerated fluids. In spite of a number of theoretical papers on this subject it is necessary to rely on the comparison with hydrodynamic experiments, for the theory contains some unresolved subtleties.

c) Dominant wavelength of instabilities

Another fundamental question in determining the mechanism responsible for the observed instabilities is whether a dominant wavelength will arise from a "noise" spectrum of initial disturbances and, if so, how this should change with time. The simplest Rayleigh-Taylor theory predicts an infinite growth rate at zero wavelength, which merely means that the linear analysis breaks down there. When viscosity is introduced into the linear theory (Chandrasekhar and Hide) a more sensible relation between growth rate and wavelength is obtained. For the wavelength which should grow at the maximum rate and therefore become dominant one has $\lambda_m \propto T^{5/3}$, i.e. instabilities ought to be damped out with increasing temperature.

Once the amplitude of the instabilities is large enough for the "asymptotic" theory of rising bubbles to apply, the larger ones will outpace the smaller ones, contrary to the tendency in linear theory, so that something like a dominant wavelength may develop even in the conservative case with no viscosity. Frieman has combined the linear and non-linear theories in a rough way and finds this to be so, and that the dominant wavelength would increase with time. In the theory of stability of equilibrium, Tayler has shown that the singularity at $\lambda=0$ is similarly cured by introducing viscosity.

The experiments at the Imperial College suggest a dominant wavelength in early stages of instability growth, and this increases with time. The theoretical value of the wavelength from Hide's formula turns out to be larger than that observed, but one may well be overestimating the viscosity.

d) Conclusion

The analysis of observations made at the Imperial College on the B_θ pinch is rather favourable to the hypothesis that the Rayleigh-Taylor mechanism is the fundamental cause of instability. One can then conclude that the pinch will become more stable at higher temperatures. There is, however, a need for further theoretical and experimental work in this field, such as

i) some treatment of the non-linear regime in the development of instabilities

ii) an estimate of the effect of the cylindrical geometry on the Rayleigh-Taylor theory

iii) simple experiments with viscous fluids to check the theory of a dominant wavelength, and to ascertain how the non-linear behaviour is affected by viscosity.

14. SPUTTERING EXPERIMENTS

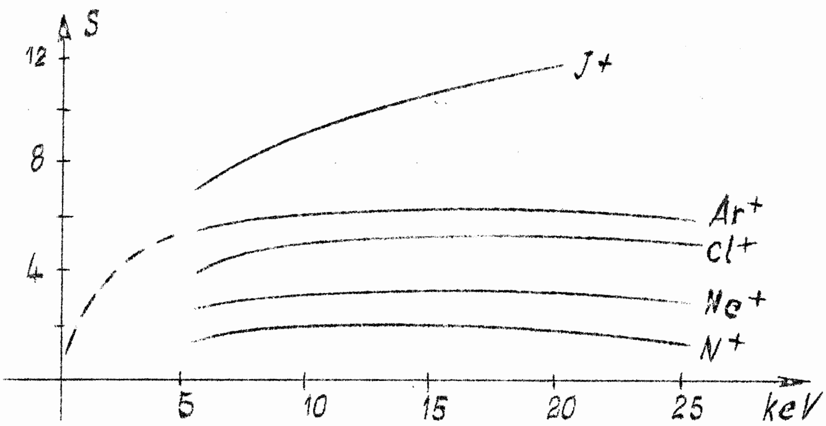
Kistemaker reported on sputtering experiments carried out at Amsterdam by himself, Rol and Fluit:

a) General description

In the usual experimental work on sputtering processes different target materials are used with bombarding ions of only one or a few elements. By changing the target materials, however, many more parameters are altered than by using ions of different elements making the interpretation of the results very difficult. For this reason only copper was used as a target material in the experiments reported here. The targets were of electrolytic copper and their dimensions were 90 x 20 x 1 mm. They were mounted at the place of the receiver of separated isotopes in an electromagnetic isotope separator. On the backside of the targets small strips were soldered to clamp the targets on a water cooled tube. The maximum temperature of a target never exceeded 125°C. In order to measure the sputtering ratio for different angles of incidence, the target was clamped in different positions on the tube. The sputtering ratio, i.e. the number of atoms released per impinging ion was determined from the total charge of the ions reaching the target and the loss in weight. The detection of sputtered material in different directions was done by condensation of the copper atoms on small glass plates surrounding the target.

b) Results for polycrystalline copper

The sputtering ratio was measured for copper bombarded with single charged ions of He, Li, C, N, O, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Cu, Zn, Sr, Zr, Cd, J., Hg and Tl. In the case of the elements which form very stable oxydes, i.e. Mg, Al, Ca, Sr and Zr, a layer was built on the target which could resist sputtering and decrease considerably the sputtering ratio. The ratio was also very low in the case of bombardment with C^+ ions, where a very hard layer of a carbon-copper mixture was found on the surface. In the case of other elements, the figure shows typical curves for the sputtering ratio as a function of energy.



Bombarding copper with Ar^+ and Tl^+ ions, the sputtering ratio was measured as a function of the angle of incidence at 20 keV. Very high ratios were measured here for Tl^+ ions at oblique incidence. At lower energies the increase was however less pronounced.

According to the measurements performed by Seeliger and Sommermayer, the angular distribution of the sputtered material can be described by a cosine function. The results reported here indicate, however, that the distribution was gaussian rather than following a cosine law; moreover, even for oblique incidence the distribution was symmetrical with respect to the normal on the target surface.

c) Results for monocrystalline copper

The sputtering ratio of copper monocrystals was measured by bombarding them with Ar^+ ions at 20 keV. The sputtering ratio at normal incidence was 8.2 for a 111 crystale plane, 3.2 for a 100 surface and 2.8 for a 110 surface, while 6.3 was measured for polycrystalline copper under the same conditions. It appears that even at these high energies the monocrystalline structure of the surface exists after a bombardment time long enough to remove 10 μ layers by sputtering. Also with respect to the angle of incidence, the difference with the results for polycrystalline copper is considerable, the sputtering coefficient depending now heavily on the axis around which the crystal is rotated.

The angular distribution of the sputtered material was measured with a hollow glass balloon, the beam reaching the target through holes in the balloon.

d) Comparison with theoretical predictions

The agreement of the experimental results with existing theories is remarkably poor. In any case, it is likely that only those collisions which take place near the surface are responsible for sputtering. Particles released deep under the surface will have very little chance to reach the surface and be sputtered. The probability that an ion will have a collision near the surface is inversely proportional to the mean free path λ for elastic collisions. The energy transferred in this first collision is proportional to

$$\frac{M_1 M_2}{(M_1 + M_2)^2} \quad E \ ,$$

where M_1 and M_2 are the mass numbers of the ion and target atom respectively and E is the energy of the ion. In a first approximation one can assume

$$S = \frac{K}{\lambda\ (E)\ \cos\ \varphi} \quad \frac{M_1\ M_2}{(M_1 + M_2)^2} \quad E$$

φ being the angle of incidence. The collision radius R for the rigid sphere model can then be calculated according to Bohr and λ derived from it by $\lambda = 1/\pi R^2 n_o$, n_o being the number of lattice atoms per unit volume.

The discrepancy one finds between the values thus calculated and the experimental results can only partly be understood from the approximation made in the theoretical model.

More experiments will be performed with monocrystals to attempt a closer analysis of the sputtering mechanism.

15. WORK IN HANNOVER

Zwicker gave a short review of work carried out in Hannover:

The interest there is mainly centred around two problems: confinement of plasma by a dynamic pinch from 10^{-2} up to 20 mm Hg and confinement by a strong discharge through the plasma, for instance by exploding wires.

a) Confinement by a dynamic pinch

Two condenser banks are available, one of 10 kJ and the other of 45 kJ. A number of smaller capacitors also exist.

Attention is focused around a few particular problems:

i) Is the confinement necessarily connected with the current kink or is it due to shock waves or compression by magnetic lines?

ii) What is the absolute intensity in the pinch when the pressure rises? What is the optical thickness of the pinch?

iii) What happens during contraction?

Measurements show that at low pressure the pinch occurs at the kink of the current; at higher pressures it occurs at a different time and one then has rather shock waves fed by current sheaths.

With respect to optical thickness, from temperature measurements one would deduce a figure of about 3 or 4.

b) Exploding wires

A 10 kJ condenser bank is available for these experiments in which a 0.1 mm copper wire is exploded by an auxiliary wire. When the wire has extended to a diameter of 1 cm, the discharge is fired.

The pressure varies from 2 to 400 mm Hg.

16. THEORETICAL WORK AT THE M.P.I., MUNICH

Schlüter reported on the theoretical work at Munich:

a) Applied calculations

i) Attempt to describe as closely as possible the dynamic behaviour of a pinch discharge (in close collaboration with Harwell).

ii) Körper's work on the effect of ion-electron scattering on radial oscillations. Near the ion resonance of an infinite plasma cylinder in an axial magnetic field one may produce heating of the plasma. Results have been obtained giving the energy absorbed, the radiative energy penetrating the plasma cylinder, and the corresponding reactive output as functions of the plasma density, the temperature and the frequency, when the oscillator and the plasma are optimally matched. The agreement with H. Schlüter's experiments is surprisingly good.

iii) Kippenhahn's and de Vries' work on modulated beams. They have investigated a beam of ions penetrating a plasma perpendicular to a homogeneous magnetic field. The particle density of the beam is modulated by varying the intensity of the ion source with a certain frequency. The modulation of the beam produces oscillations of the plasma and the ions of the beam will lose energy; therefore it should be possible to trap the injected particles into the plasma. Furthermore, the kinetic energy of the trapped particles should be transformed into thermal energy of the plasma.

The calculations show that under normal conditions the energy loss is very small and only in cases of resonance (ion velocity = Alfvén velocity) can measurable effects be expected. More refined calculations may lead, however, to somewhat different results.

iv) Aspect ratio and magnetic field ratio (Martensen). It has been found that in a torus of aspect ratio 1/3 (Mimikry, etc.) the ratio of the extreme field strengths across a diameter is as high as 9/1.

b) <u>More theoretical work</u>

i) Hydromagnetic description of plasma by means of particle distribution momenta. Starting from the Fokker-Plank approximation, Hertwick has calculated the ratio of electric conductivity along and across the magnetic field as well as the time development of runaways in a plasma subject to a constant electric field. Agreement has been found with Dreiser's results.

ii) Effect of non-linearities. Vlasov's equation appropriately describes a collisionfree one-constituent plasma; in linear approximation one then gets Landau damping. Knorr is trying to take into account non-linear terms.

c) Pure theory

Sophisticated calculations have shown that Debye's theory is a surprisingly good approximation.

17. THEORETICAL WORK AT HARWELL

Thompson reported on theoretical work at Harwell:

a) Collapse

In conjunction with Hain, programmes have been written to describe the collapse of a cylinder of plasma under an applied field.

b) Diagnostics

The idea is to use beams of charged particles as magnetic field probes in cylindrical symmetry.

c) Injection into mirror machines

It has been tried to increase the spinning time of particles by using modulated magnetic fields, i.e. by superimposing on the mirror field a sinusoidal ripple of about 3-4 o/o. If the wavelength of oscillation is correctly chosen for resonance between Larmor gyration and ripple periodicity, the particles will be trapped. Numerical computations have been carried out on the length of the trajectories, and at the same time programmes for designing fields have been produced.

d) Calculation of magnetic field

Magnetic fields in toroidal geometry can be calculated by means of Maxwell's equations.

e) Stability

Suydam's, Rosenbluth's and Newcomb's theories have been compared to each other and conditions found for circumstances where they are identical or not.

f) Generalisation of Newcomb's theory

Tayler is trying to generalize Newcomb's theory to arbitrary geometries.

g) Equivalent configurations

Laing is trying to establish a toroidal analogue to a cylindrical system.

h) Kinetic theory

Calculations show that one can use Landau's approximation to Fokker-Planck's equation and be sure that only dominant terms come into play.

18. THEORETICAL WORK AT FONTENAY-AUX-ROSES

Trocheris reported on theoretical work at Fontenay-aux-Roses:

a) Plasma waves

Non-linear and relativistic effects have been considered.

b) Collisionless theory

The most general self-consistent solution of Boltzmann's equation without collision terms has been looked for.

c) Equilibria in mirror configurations

Solutions with only two approximations have been looked for:

i) no collisions

ii) adiabatic approximation for the motion of particles.

d) Spectroscopy

In cooperation with experimental physics, plans for an experiment are being set up to test the techniques and the theories used in diagnostics by spectroscopic observations.

e) Magneto-hydrodynamic stability

The stability of a low pressure plasma in a strong magnetic field has been tackled in a particular way.

19. GENERALIZATION OF SUYDAM'S CRITERION

Starting from Bernstein's energy principle, Mercier showed that it is possible to generalize Suydam's criterion from cylindrical symmetry to any arbitrary axial symmetry. Applications were made to a magnetic axis and to a Hill vortex.

20. HYDROMAGNETIC STABILITY OF A TOROIDAL DISCHARGE

Lüst reported on theoretical work in connection with the hydromagnetic stability of a toroidal gas discharge. This work was first started in Göttingen by Lüst, Hain, Jörgens, Kippenhahn and Richtmyer. A method was devised to calculate the eigenvalues by a relaxation procedure, but the first calculations showed that the convergence was very slow. The main difficulty arose from the complicated boundary conditions of the plasma-vacuum interface. The work was then resumed at the New York University by Lüst, Richtmyer, Rotenberg, Suydam and Levy. The energy principle was used, so that this time the complicated boundary condition was avoided. The plasma was regarded as an ideal, perfectly conducting fluid of the shape of a torus and surrounded by a conductor. The pressure and density inside the plasma were taken to be constant and it was assumed that no electric currents were flowing except on the surface of the plasma. The conducting wall was supposed to have no effect on the equilibrium field. The cross-sections of the plasma surface and of the conducting wall were assumed to be circles lying on coordinate surfaces in a toroidal coordinate system, and they are therefore not quite concentric. With this assumption, the conductor is not placed on a line of force of the vacuum magnetic field as the equilibrium condition requires, but one may assume that the equilibrium field has enough time to penetrate the conductor and that the conductor acts only on the perturbed field.

The energy principle states that the necessary and sufficient condition for stability is that the change in energy δW for a given displacement $\vec{\xi}$ must be positive for all ξ's. Working this out for a toroidal configuration, one finds that the stability of this configuration depends on 4 parameters: the aspect ratio (large diameter/small diameter), the ratio of the radius of the conductor and the radius of the plasma, the ratio of inside magnetic field and outside magnetic field, and m .

As far as the dependence on m is concerned, one can show that for large m the configuration will become stable, since the contribution from the surface goes then to zero. From the numerical results one could see that if $m = 1$ was stable, $m = 0$ was always stable. In a few cases $m = 2$ was not quite stable, but so close to stability that only a slight shift in one of the parameters would have been sufficient to achieve stability.

The general results of the calculation obtained so far show that it is not possible to obtain a stable plasma in a toroidal gas discharge which has an aspect ratio larger than about 3 and a value large enough to compress the gas well away from the conducting walls. On the other hand, there are modes which have just one wavelength around the torus; this wavelength is always of the same order of magnitude as the curvature and therefore always feels the curvature. The stability of these perturbations is being investigated.

21. EXPERIMENTAL WORK AT HARWELL

Ashby reported on three experiments carried out at Harwell:

a) Long straight tube (Cockckroft)

A tube of 30 cm diameter and 6 m long, i.e. sufficiently long to avoid end effects, has been designed in order to study sheath formation. Actually it is used to investigate stability problems. A 126 µF, 20 kV capacitor bank is available, and the tube is provided with an outside coil producing a B_z-field. If B_z is sufficient, an instability associated with a current sheath develops at 5 µs.

b) Cusped geometry (Allen)

This device is made of a chamber 40 cm long and 20 cm in diameter; it is provided with 2 coils giving a maximum field of 30 kG. Rise time: 1.25 μs, stored energy 1 MJ. The device is intended to investigate shock waves.

c) Fast straight tube (Cole and Ashby)

Characteristics of the tube are: length 60 cm, diameter 24 cm. A 40 μF, 30 kV condenser bank is available. The external inductance is a few microhenries, the initial inductance 20 mμH.

22. THEORETICAL WORK AT THE F.O.M. INSTITUTE

Brinkman gave a survey of the theoretical work at the F.O.M. Institute for plasma physics. This work comprises:

a) Study of particle trajectories in a magnetic quadrupole field.

b) Hydromagnetic theory of rotating plasmas.

c) Stability of the alternating pinch.

Some details of c) were discussed.

An alternating pinch shows a longitudinal current and an azimuthal magnetic field, alternating in time (frequency ω) with a configuration consisting of an azimuthal current and a longitudinal magnetic field. Its stability was considered under the assumption that the plasma column is a cylinder (radius R) of infinitely high conductivity, carrying surface currents. Under these assumptions the electromagnetic field does not penetrate into the plasma.

The stability analysis, carried out in the normal way with a displacement of the plasma depending on z and φ as $\exp i\,(kz + m\varphi)$, leads to a boundary problem with a time dependent boundary condition:

a) $\omega \rightarrow \infty$. The only unstable modes are for $m = 0$ and $|kR| < 1.34$. This good stability is due to the fact that the magnetic field varies in direction with a very high frequency.

b) Incompressible plasma (velocity of sound $\rightarrow \infty$). In this case one is led to a Mathieu (or Hill) equation. For all values of m, kR and ω the result lies near the boundary between stable and unstable regions. The possibility of finding the solution for a compressible plasma by numerical methods is now being considered.

23. CALCULATIONS ON THE PINCH COLLAPSE

Hain reported on some calculations performed in collaboration with Harwell staff (L. and S. Roberts) on the pinch collapse:

Applying a longitudinal electric field to a fully ionized plasma in an infinite cylinder, the induced longitudinal current flow interacts with its own magnetic field and causes the gas to move inwards. Assuming the plasma sufficiently dense for the hydromagnetic approximation to be valid, the partial differential equations for the gas together with Maxwell's equation have been written out explicitly and solved numerically. Finite conductivity and ohmic heating depending on temperature, and heat conductivity depending on both temperature and magnetic field have been taken into account. It was shown that thermal conductivity is of great importance in the early stages of the pinch. It was also shown that a reversed B_z-field can be achieved by assuming an electric conductivity of the wall in the direction of some angle α.

Experiments were performed to check the theory, and slides were shown giving results obtained at 30 kV, 70 mμH.

24. STABILITY OF TUBULAR PINCH

Lehner reported on tubular pinch work:

Interest in the behaviour of magneto-hydrodynamic shock waves led to the study of the tubular pinch as a simple means to produce them.

A homogeneous plasma was considered to be imbedded in a homogeneous magnetic field, and a normal mode analysis was carried out. Dispersion formulae for a configuration consisting of a cylindrical plasma surface of radius r_o and a cylindrical metal wall of radius R_o were written out. The results of the calculation show that one cannot stabilize a tubular pinch without an outer conductor. This conductor has to be close to the plasma and does not give a limit for the compression rate.

25. STABILITY OF ACCELERATED LAYERS

Linhart reported on the stability of accelerated plasma layers:

The stability of a cylindrical layer of plasma driven by or compressing an azimuthal magnetic field can be analyzed either by the variational method or by the method of normal modes.

If one assumes that the temperature of the plasma is equal to zero, thermal and potential energy of an accelerated plasma layer is also equal to zero and the variational approach is equivalent to that of normal modes. However, as the latter implies the knowledge of the perturbed form of the equation of motion, it represents a more familiar analysis than the variational method.

In the analysis a small deformation R of the cylindrical shell was first postulated. Next, the magnetic field B corresponding to the perturbed surface was calculated, and finally the expressions for the perturbed R and B were substituted into the equation of motion of the shell. The analysis was restricted to small-amplitude perturbations and thus an appropriate superposition of solutions could represent the development of any deformation which is Fourier analysable in terms of elementary deformations.

In the case of sausage perturbations ($\ell = 0$, $k \neq 0$ in the usual terminology) it is found that a cylindrical shell compressing a B_φ-field oscillates with a frequency

$$\omega_{max} = \left(\frac{\ddot{R}}{R}\right)^{1/2}_{max}$$

and an amplitude given by the adiabatic theorem. In the case of an external B_φ-field, the perturbation is a growing one.

For flute perturbations ($\ell \neq 0$, $k=0$) the problem of finding the perturbed magnetic field is more complicated than that encountered for $\ell = 0$. One finds that the perturbation is never a growing one. The closest approach to instability is when $\ell = 1$ and B_φ is an external field; in that case the amplitude of the instability remains constant, but this was to be expected since the $\ell = 1$ perturbation transforms a circular cross-section into another circle.

In the case of helical perturbations ($\ell \neq 0$, $k \neq 0$) one finds that as the cylindrical plasma shell collapses towards its axis of symmetry, it passes radial positions at which the growth of higher order helical modes of perturbation becomes impossible. On the other hand, the $\ell = 1$ mode will grow at all radii except when $k \neq 0$.

The stability of the central column of plasma appears to be a more complex problem than the stability of the heavy and relatively thin shell of plasma, and the theory has not been advanced to a noticeable extent. The only help comes from experiments on fast pinches, where it is found that instability appears only after the first pinch.

26. WORK AT ORSAY

Delcroix mentioned that since last year there exists a small group working on experimental plasma physics at Orsay. The present programme involves cyclotron resonance in a weakly ionized gas and trapping of electrons in a mirror machine by means of electron cyclotron resonance. On the other hand, theoretical work on wave propagation in a plasma has been carried out by Delcroix and Denisse.

A simple problem was tackled aiming at a general graphical representation of various modes of propagation. For a plane wave and an indefinite medium the general case could be treated within the hydromagnetic theory, and dispersion curves were shown for the 4 modes of any propagation giving the square of the propagation index as a function of the ratio ω_p^2/ω^2 , where ω_p is the electron plasma frequency and ω the wave frequency. Various particular and limiting cases for these curves were considered.

27. WORK AT SACLAY

Taillet gave a review of the plasma physics work at Saclay:

a) Cross-section measurements

Dissociation cross-sections for H_2^+ collisions on hydrogen gas have been measured and the results are now being analyzed. The preliminary device which was used makes it possible to work in a range from a few tens of keV to 100 keV. The separation of the various possible reactions is carried out by individual counting of secondary particles on a cesium iodide target followed by a photomultiplier.

b) Microinstabilities

The diffusion of a weakly ionized plasma of a reflex discharge has been studied for a direction normal to the lines of force of the magnetic field. This diffusion is not ambipolar and leakage currents of ions diffusing in the symmetry plane of the discharge have been measured.

The results show that for magnetic fields smaller than a critical value B_c the measured currents can perfectly be explained by the laws of binary diffusion (leakage current proportional to $1/B^2$). For values exceeding B_c the leakage current changes completely its behaviour and increases even with increasing field. At the same time a strong white RF noise appears in the range of a few Mc/s and this is the consequence of an unstable regime in the plasma.

This behaviour does not depend on the discharge current and its feeding process. B_c depends on the pressure, and for a given value of B there corresponds a critical pressure p_c above which the unstable regime disappears.

The measurements will be extended to more highly ionized plasmas (50 o/o and more).

c) RF ionization and compression

A resonant cavity for RF confinement studies is being designed. The development of diagnostic equipment proceeds. A small device is used for rapid RF compression after reflex ionization. A condenser bank of 5 kJ provides compression of a plasma obtained by a reflex discharge.

d) Diagnostics

In addition to the development of interferometric devices for 8 mm and 4 mm wavelength for density measurements, a theoretical and experimental study of the Faraday effect in a plasma column has been performed. With $\lambda = 8$ mm, rotations of a few turns could be observed for a length of 60 cm; the longitudinal magnetic field was 500 Gauss.

28. NEXT MEETING

The Chairman expressed his thanks to the Association EURATOM-CEA and announced that the next meeting will be held in Rome, in April, 1961. Brunelli has accepted to carry out the detailed arrangements.

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E.R.

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