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CERN STUDY GROUP ON FUSION

Fifth Meeting

Munich - 26, 27 and 28 November, 1959

NOTES

Chairman:	J.B. Adams		
Attendance:	H. Luc	Labor. Elec. Gén. Université de Bruxelles	Belgium
	C.F. Wandel	Risö Research Establishment	Denmark
	R. Aymar	C.E.N., Fontenay-aux-Roses	France
	C. Mercier	" "	"
	P.H. Rebut	" "	"
	F. Waelbroeck	" "	"
	A. Septier	Labor. d'Electronique, Fontenay-aux-Roses	"
	M.Y. Bernard	C.E.A., Saclay	"
	T. Consoli	" "	"
	C. Manus	" "	"
	E. Fünfer	Max-Planck-Institut, Munich	Germany
	G. v. Gierke	" "	"
	M. Kruskal	" " (Princeton, USA)	"
	R. Lüst	" "	"
	D. Pfirsch	" "	"
	A. Schlüter	" "	"
	C. Wharton	" " (UCRL, Livermore, USA)	"
	W. Fucks	Phys. Inst. Techn. Hochschule, Aachen	"
	D. Dorn	Inst. für Kernfusion, Aachen	"
	H. Jordan	" " " "	"
	G. Lehr	Bundesministerium für Atomkernenergie und Wasserwirtschaft, Bad Godesberg	"
	W. Kluge	Technische Hochschule, Stuttgart	"
	A. Michel	Forschungslaboratorium Siemens-Schuckert-Werke, Erlangen	"
	H. Zwicker	Phys. Inst. Techn. Hochschule, Hannover	"

J.E. Allen	C.N.R.N., Lab. Gas Ionizzati, Rome	Italy
B. Brunelli	" " " " "	"
C.M. Braams	F.O.M., Jutphaas	Netherlands
H. Brinkman	Natuurk. Lab., Groningen	"
H.C. Brinkman	T.N.O.-F.O.M., The Hague	"
J. Kistemaker	Lab. v. Massaspectrografie, Amsterdam	"
J.C. Terlouw	F.O.M., Utrecht	"
K. Johnsen	Norwegian Techn. University (and CERN)	Norway
S. Berglund	Inst. of Physics, Uppsala	Sweden
St. Herlitz	" " " "	"
N.R. Nilsson	" " " "	"
B. Agdur	Royal Inst. of Technology, Stockholm	"
A. Dattner	" " " " "	"
H. Knoepfel	Phys. Inst. E.T.H., Zürich	Switzerland
A.N. Dellis	A.E.R.E., Harwell	United Kingdom
R.S. Pease	" "	" "
T.E. Stringer	" "	" "
W.B. Thompson	" "	" "
B. Wieder	" "	" "
A. Folkierski	Imperial College, London	" "
J.B. Adams	CERN, Geneva	
J.G. Linhart	" "	
Ch. Maisonnier	" "	
E. Regenstreif	" "	
A. Schoch	" "	
D. Palumbo	EURATOM, Brussels	

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1. WELCOME BY THE MUNICH GROUP

v. Gierke extended his welcome to all participants on behalf of the Munich Group.

2. VISITS TO LABORATORIES

Special sessions were arranged to take the visitors round the laboratories of the M.P.I. at Munich and Dr. Fünfer's establishment at Garching; opportunity was provided for them to see in detail the work on fusion going on there.

3. EXPERIMENTS AND FACILITIES AT THE M.P.I. MUNICH

T 1 , toroidal discharge ($r/R = 2.5$ cm/50 cm).

Extensive screening having considerably reduced the perturbations, useful measurements can start now. At present spectroscopic investigations as well as X-ray intensity measurements are under way. Probe measurements are in preparation.

Mimikry, toroidal discharge ($r/R = 12$ cm/50 cm).

Construction is finished, first measurements have started. Arc discharges to the aluminium walls have been observed. Aluminium oxyde liner segments tightened together could not completely suppress the discharges, cementing the liner segments together suppresses however the wall currents. 45 kA have been obtained as yet. Preliminary spectroscopic and probe measurements are under way.

Wendelstein, stellarator type torus ($r/R \approx 3$ cm/35 cm, race track shape).

Construction is finished. At present measurements of the electric field are being carried out by means of an electron beam.

Eieruhr, linear high density discharge, involving very high magnetic fields.

With a small model constant magnetic fields of about 30 000 Gauss have been reached for 3 ms. The final condenser bank should allow to obtain 300 000 Gauss. The set is used for spectroscopic investigations of plasma in thermal equilibrium and to study the optical Faraday effect.

RF discharges in magnetic fields

In a quartz tube cleaned by ultra high vacuum techniques a hydrogen plasma is excited by means of RF discharges of about 10 kW, 3-30 Mc/s. Measurements of the discharge have been carried out in hydrogen and deuterium plasma as a function of magnetic field, density and transmitter power. Furthermore, spectroscopic records of the Balmer series and of the continuous part have been made. Other quantitative records will be made for interpretation.

Microwaves

A 8 mm fringe shift interferometer has been built with which measurements will be made soon on the RF discharge and on the machines. A small PIG discharge is under construction to have a test discharge for microwave measurements.

Magnetic probes

In addition to the conventional induction probes, Hall probes have been used for measuring magnetic fields in plasma. Experiments carried out so far are encouraging; they show that for many experiments Hall probes should be preferred.

Electric probes

In a low voltage gas discharge measurements are being carried out by means of Langmuir probes; the plasma potential is being investigated as a function of radius, density and magnetic field.

Ultra high vacuum techniques

Various pumps, measuring instruments and components are being tested to check the possibilities of using them in ultra high vacuum. Oil free pump stands with water jet and mercury pumps have been constructed, as well as oil pump stands with copper and ceramics traps. Metal-metal joints have been tested. Investigation of residual gases has been carried out by means of an Omegatron.

Cathode sputtering

Preliminary results have been obtained with a small accelerator, giving accelerating voltages up to 150 kV; the currents (protons) were of the order of 1 mA. The apparatus is now being improved.

4. EXPERIMENTS AND FACILITIES AT THE TECHNICAL PHYSICS LABORATORY (DR. FÜNFER), GARCHING

Linear pinch

30 kJ condenser bank. Probe measurements of B_z-field, microwave measurements, Kerr cell photography.

Stabilized linear pinch

120 kJ condenser bank. Runaway electrons (X-rays). Neutron measurements.

Induction pinch

Ignition, preionization, X-rays, smear camera, Kerr cells, light measurements.

5. STATUS REPORTS

Pease reported on the status of experimental research at Harwell.

a) Zeta

The Zeta apparatus is functioning with a 3 MJ capacitor bank, and gas currents of up to 900 kA have been obtained. Most studies have so far been conducted in the 5-600 kA range. The main purpose of the surveys now being carried out is to study the discharge properties as a function of the line density N. So far a minimum resistance (maximum energy containment time) has been found in the region $N \approx 10^{18}$ cm^{-1}. At this line density, the average ion temperature equals the drift velocity of the electrons $w_e \approx (k\bar{T}/m)^{1/2}$. At higher densities, energy loss by impurity radiation, particularly from the C (IV) 1550 Å line, appears to cool the discharge. At lower densities, this form of energy does not occur. There is, so far, no strong evidence of greatly enhanced electron or ion temperature. Neutron yields appear to be enhanced to 10^8 neutron/pulse for $N < 10^{18}$ particles per cm. Other experiments on Zeta currently in hand include Whistler mode microwave propagation (Gallet, Wieder), ion containment times from spectral data (Wilson), absolute measurements of intensities (Mc Whirter), neutron energy measurements (Ward), power loss measurements (Gibson), and experiments on mass motion (Ramsden).

Zeta is now in pieces, but will be reassembled soon. Many of the electrical and mechanical problems associated with the large gas currents seem to be solvable by using a stainless steel liner construction.

b) ICSE

Design studies of the ICSE experiments continue. Two important problems still unsolved are the provision of clamping switches (100 kV hold off, 10 kV switch, 1 ms), and the methods for preheating the gas to the required degree of ionization and temperature without injection of prohibited impurity concentrations. The experiments will be carried out at the new establishment at Culham, of which J.B. Adams will be the Director. The first half of the 14 MJ capacitor bank will be installed in the first half of 1961.

c) Pinch-unpinch experiments

In these experiments (Reynolds and Aitkin), the disturbances responsible for unrepeatibility of magnetic probe signals have been shown, in the unpinch case, to be propagated from the cathode with approximately the Alfvén velocity. Both this and other observations indicate the importance of end effects in these experiments.

d) Alfvén waves

In these experiments, the apparent difference of velocity between waves travelling parallel and anti-parallel to the heating current has been shown to be due to the experimental technique originally used, i.e. one probe measurements. With the wave velocity timed between two search probes the difference disappears. To eliminate the effects due to toroidal geometry, straight tubes (2 m long, 10 cm bore, for example) will be used in future experiments.

e) Other small-scale experiments

Shock heated toroidal pinch: no real progress.

Small straight tube to demonstrate collision-free shocks (Adlam): under way.

Miller's machine: just started to work again.

RF containment: no progress.

f) Aldermaston

Sceptre IV has just started working.

Thompson reported on theoretical progress at Harwell.

I. Stable Configurations

Since the last meeting the theoretical effort has mainly been concentrated on a study of methods of producing a slow magnetohydrodynamically stable pinch, in support of the ICSE programme. The questions to be asked here pertain to the existence and production of such a configuration.

a) Existence of a stable magnetohydrodynamic configuration

i) Stability in a cylinder

Several stability criteria have been derived for a confined cylindrical plasma. The validity of these and the relations between them are under study. It appears that whereas Suydam's criterion is necessary but not sufficient, the criterion given by Rosenbluth is both necessary and sufficient for the case of a plasma cylinder contained by a thin current layer (Tayler, Laing, Whiteman).

ii) Configurations satisfying these criteria

A study is being made of configurations satisfying these conditions. A class of particular solutions satisfying the Suydam condition has been considered and configurations have been discovered differing only slightly, one stable and the other unstable. It appears that the Rosenbluth condition will require reversed axial fields and probably reversed axial currents (Tayler, Jukes).

iii) External regions

One object of the ICSE experiment is to avoid electron runaway associated with magnetohydrodynamic instability by working at such high densities that $e E \lambda \ll k T$ (E axial electric field, λ mean free path, T electron temperature), a condition that there be few runaways. This, however, is only possible inside the confined plasma; it appears inevitable that this region be surrounded by a pressureless plasma of very low density. Unless the fields in this are vacuum fields, $\bar{j} \parallel \bar{B}$ and the drift velocity w associated with the current is $w_{-} \gg \sqrt{\frac{kT}{m}}$, runaways will occur. To obtain vacuum fields, the applied fields must be carefully programmed (Roberts, Thompson).

iv) Transition to the torus

Existing stability analysis is concerned with the cylinder. However, the experiments are to be performed in a torus and this geometry must be studied. A technique has therefore been developed for discovering the toroidal analogues of a given cylindrical configuration. This is done by writing the magnetic potential $\psi(r)$ and observing that on transformation to a torus, the flux tube ψ is displaced in position, losing its symmetry about the centre of the toroidal tube; thus $r(\psi) \rightarrow X(r, \theta', \psi)$, where X represents the curve in the cross-section of the tube now occupied by $\psi = \text{const.}$ If we replace $\psi(r)$ by $\psi(\bar{X})$ in the equilibrium equation $\bar{\nabla} p + \bar{j} \times \bar{B} = 0$ and expand in inverse powers of the aspect ratio $\varepsilon = R\ \text{minor}/R\ \text{major}$, we have $X = r + \varepsilon f(r,\theta) + \text{etc.}$ and X may be specified. If the configuration has no toroidal analogue, X becomes infinite for some ψ (Whiteman).

b) Production of a stable configuration

i) From a preionized plasma filling a tube

This question may be discussed in two ways: for some part of the collapse dissipative processes may be negligible and the plasma may be compressed approximately reversibly. This has the advantage that a calculation can start from the final configuration, and the field programme as well as the required initial conditions can be determined; on the other hand, during the reversible processes flux is trapped; hence only by considering dissipative, irreversible effects can the techniques for producing the desired initial trapped flux configuration be discovered.

α) Reversible programming

For this case one has as constants of motion

$$\psi\left[R\,(t)\right] = \int_0^{R(t)} B_z\, r\, d\, r \quad ; \quad \mu\left[R\,(t)\right] = \frac{B_\Theta}{r\, B_z}$$

$$M\left[R\,(t)\right] = \int_0^{R(t)} \rho\, r\, d\, r \quad ; \quad S\left[R\,(t)\right] = p\, \rho$$

where $R\,(t)$ is an arbitrary streamline.

Introducing $x = \frac{1}{2} R^2\,(t)$ and the initial position $x_o = \frac{1}{2} R^2\,(0)$ and using the equilibrium condition, one obtains a second order differential equation for $x(x_o)$, the boundary conditions $x(0)$ and $\left.\frac{dx}{d\,x_o}\right|_o$ being given. A computer programme has been written for this, but it can be shown analytically that vacuum fields cannot be maintained during the collapse of a pressureless plasma and that an approximate analytic solution can be written out for a thin surface layer at moderate β-values.

β) Irreversible programming

The equations of motion with resistivity $\eta\,(T)$ and thermal conductivity $K\,(T)$ have been programmed for the 704. Since the equations become unstable if the computational step is too large $(\Delta t > \Delta x/v_s)$, the programme is best suited to rapid collapse and a von Neumann pressure term (artificial viscosity depending on computational step length) has been introduced to deal with shocks. For slow collapse it is preferable to omit the inertial terms replacing the equation of fluid motion by pressure balance (equilibrium) (Roberts, Hain).

ii) From an unionized gas

α) Ionization in the Θ-pinch

A study has been made of breakdown in the thetatron and the essential rôle of the electric field in the early stages established. Since this is determined, at least in part, by charges on the external conductor, the apparent axial symmetry of the system is spurious, the feed point playing an essential rôle (Roberts).

β) Ionization in toroidal z-pinches

In heating a device which is intended to produce a stabilized pinch, the large initial B_z makes heating by radial collapse unattractive; it suggests that heating by a z-current is preferable. This must be kept below the Kruskal limit, energy must therefore be added rather slowly and the time to complete ionization is long. Hence, the preionizing must occur in a stable, confined configuration. Moreover, if ionization is to be uniform, the electric field must lie in the range $50 \text{ V} < E\lambda < 200 \text{ V}$, since otherwise the ionization rate varies exponentially rapidly with electron field, and in a torus E cannot be uniform (Roberts).

γ) Ionization and screening

As the gas in a large system is ionized, the conductivity increases and the electric fields are screened out, so that the ionization rate is decreased. An analysis of this is being carried out, using a simplified picture of gas kinetics (mean free time for ionization and collision assumed constant). Computation has shown that an earlier result based on asymptotic representation of the fields seriously overestimated the ionization rate.

II. Pure Theory

a) Kinetic theory

i) The small Larmor radius expansion has been used in an attempt to produce magnetohydrodynamic-like equations. If the symmetry along the field lines is sufficiently high, adiabatic magnetohydrodynamics with $\gamma = 2$ is produced in zero order, while in first order thermal conductivity and resistivity appear, the heat flux and pressure tensor being identical in form to the high field limits of those given by conventional methods (e.g. Chapman and Cowling). There is, however, no true electrical resistivity, neither is the fluid a perfect conductor; instead the electric field satisfies the equation $E + v_- \times B = 0$, where v_- is the mean drift velocity of the electrons, which differs from that of the ions by terms of order r_L .

If the flow is not uniform along field lines, no purely local representation has been found and dissipative processes such as Landau damping occur (Thompson).

ii) The relationship between the r_L expansion and the exact solution of the Vlasov equation which can be found if the symmetry is high is being explored (Thompson, Laing).

b) Comparison of magnetohydrodynamic models

A comparison has been made of the propagation of Alfvén waves for several possible magnetohydrodynamic models: 1) normal magnetohydrodynamics, 2) double adiabatic magnetohydrodynamics, 3) magnetohydrodynamics with collisional dissipation, 4) magnetohydrodynamics using the strong field no-collision limit of the Chapman-Cowling transport coefficients.

c) The Vlasov equation

It is found that where the constraints prevent motion, Landau damping occurs (Thompson).

d) Basis of the Fokker-Planck equation

By expressing the diffusion coefficient in terms of the fluctuating microfield, using the Nyquist theorem to calculate the fluctuating microfield $\mathcal{E} = \langle E^2 \;(k,\omega)\rangle \simeq R \;(k,\omega)\; k\, T$ and the Vlasov equation to calculate $R\;(k,\omega)$ (an effect of Landau damping), the results of Spitzer and Chandrasekhar have been recovered without the introduction of a screening length (Thompson).

e) Stability of an RF confined plasma

The spherical confined plasma of Knox has been shown to be unstable (Whipple).

f) Growth rate of electrostatic instabilities

For a monoenergetic beam this is determined by the Landau term. For a beam with a Maxwellian distribution the growth rate is considerably reduced (Thompson, Stringer).

g) Mirror coil design

A programme has been written for the accurate design of mirror field coils (Roberts, Laing).

Consoli reported on the general lines of work at Saclay.

During the last months the Saclay group has been concerned with the general equipment of the laboratories and development of apparatus already mentioned during the last meeting in connection with a number of new experiments. Work has been devoted to ionization studies, preliminary design of cross-section apparatus, measurements concerning "diffusion drain" mechanisms, experiments with diagnostic tools and RF confinement.

With respect to ionization studies, the experiments on high frequency plasmoïds have been pursued and checks of the resonance mechanism between the plasma and the external high frequency field have been extended up to 100 Mc/s. Equality between ω and ω_p is still observed considering the possible errors existing in these measurements.

A PIG source of 90 cm has been built. The electron density is higher than 1.6×10^{13} el/cm^3, neutral pressure is 10^{-4} mm Hg. The source is operated on pulsed cycles of 100 μs duration, repeated every 1/50 of a second. Further work is planned to obtain good operating conditions at lower neutral pressures combined with compression equipment in the central part of the discharge, so as to allow the investigation of the influence of pre-ionization on the compression phenomena.

Regarding cross-section measurements, the interest is centred on interactions of ionic molecular hydrogen with charged particles. The construction of the apparatus is at its very beginning.

Diffusion measurements transverse to magnetic fields have been taken up recently. A critical magnetic field has been observed, below which the diffusion obeys the theoretical law of binary collisions. For higher values a kind of "diffusion drain" mechanism appears and this agrees with Lehnert's measurements. A critical value has also been observed when the diffusion parameter is pressure. The measurements have been carried out on weakly ionized gases and the critical values are associated with build-up of oscillations; the latter are under investigation at present.

The construction of a device in order to study the compression effect of an RF confining field on a plasma is in preparation.

<ins>Waelbroeck</ins> reported in more detail on progress at Saclay.

a) Theoretical studies

The theoretical group has particularly been interested in two problems, namely the magnetohydrodynamic stability of equilibrium configurations possessing axial symmetry and electron cyclotron radiation.

The stability of equilibrium configurations possessing axial symmetry has been investigated at first for those cases where the azimuthal component B_Θ of the magnetic field was zero. Various analytical solutions of the equilibrium equations with lines of force closed upon themselves inside the plasma have been studied. They have all been found to be unstable. The stability of similar equilibria with a finite azimuthal component of the magnetic field is being studied.

With respect to electron cyclotron radiation an attempt was made to clarify some points in the calculation of Trubnikov. This calculation can be criticized for frequency components lower than the plasma frequency ($\omega_n = n \cdot \omega_c < \omega_p$), but seems to be correct for the higher harmonics. Unfortunately, in the Trubnikov calculations the energy radiated by the first harmonic is almost entirely reabsorbed, and it contributes little to the radiation losses. Consequently, it appears that the order of magnitude of the result still holds for the very high temperature necessary for the DD reaction.

The correlations between the electrons might affect the intensity of this radiation and lead to some reduction of the emitted power at the higher frequencies. This problem is being studied at present.

b) Pinch-Group activity

In the experiments reported at Uppsala, TA 2000 was fired with a 40 kJ condenser bank. A study of the breakdown conditions has led to the use of 0.3 volt/cm predischarge for a working pressure of 10^{-4} mm Hg. X-rays from runaway electrons have been observed as the ionization increased. The collapse of the configuration with decreasing current has been followed by means of magnetic probes of low pass band.

A new condenser bank of 204 µF, 35 kV, 120 kJ is ready for use.

A spectroscopic study of the rate and degree of ionization is planned, using hydrogen-like atoms from gaseous components.

It has been observed that the intensity of the carbon line fluctuates rapidly whereas the hydrogen line emission remains rather smooth. This phenomenon will be investigated looking for arcing or turbulence as a cause. Large band integrators are ready to provide better measurements of magnetic configurations for various B_z , pressure and currents.

At the same time a more fundamental approach to the stability problem is planned:

i) Cyclotronic instabilities produced by high energy electrons will be investigated using a $n = 10^{11}$ dense plasma from an ordinary discharge.

ii) Stable configurations in cylindrical geometry will be looked for and investigated through magnetic probing and particle analysis. New information on the turbulence and the energy balance are expected from particle diagnostics and the validity of the linear relation $a\ B_z + b\ r\ B_\theta + c = 0$ developed by Rebut will be checked.

iii) Experiments with the Equator torus are devoted to the study of the radiation losses from conventional stabilized pinch discharges. Spectroscopic measurements with time and wavelength resolution are planned.

c) Rapid compression of a plasma in a mirror configuration

These experiments (performed in a spherical vessel, surrounded by a single loop coil) have been described at Uppsala. New measurements of the magnetic field have been obtained by means of a single turn probe of large area, directly introduced into the plasma. The results confirm the previous conclusions: the configuration turns rapidly into an unstable toroidal pinch, disappearing after a short time. Attempts to measure the density by the transmission and absorption of a microwave beam are in progress; the pick-up problem seems however difficult.

d) Electrodeless plasma gun

Experiments are being started on an electrodeless plasma gun. A discharge is induced in hydrogen at an adequate pressure (10^{-3} mm Hg). The configuration is that of a toroidal pinch, stabilized by an externally generated longitudinal magnetic field. One side of the torus is opened, and the plasma is accelerated through this opening. The experiment is designed to use a low amount of energy, in order to be repeatable at a sufficiently rapid rate. In that case a practically continuous injection of neutral gas at one end of the apparatus might lead to the formation at the other end of a succession of highly ionized puffs of high velocity.

e) Other experiments

The experimental apparatus for two other injection experiments is being completed; plasma guns with electrodes will be discharged into pre-established magnetic fields. The aim is to produce an irreversible phenomenon in order to trap the ions in the configuration.

In the first experiment, the ions will be injected longitudinally into a mirror configuration. In the other, two plasma guns will be fired simultaneously, sending "colliding" plasma puffs perpendicularly to a uniform magnetic field. It is planned to measure the velocity and momentum in various directions. Provisions are also being made to measure the density and energy by the absorption and transmission of 3 cm microwave beams, and by the variation of the load of a low power oscillator (a few watts) which would excite the plasma at a frequency close to the ion cyclotron frequency.

Another experiment is centred around a plasma gun similar to the one presented by J. Marshall at the Geneva Conference 1958. Various parameters of the beam, in particular its velocity and momentum, have been studied with electric probes, with photomultipliers at various points along the plasma path, with streak photographs and with a ballistic pendulum. Difficulties arise in interpreting the results, most probably because of the luminous phenomena occurring when the plasma strikes the sides of the tube. Attempts are being made to confine the plasma beam away from the walls by means of a longitudinal magnetic field.

f) Injection of fast ions into a mirror configuration

The technological aspect of this experiment and its design are progressing. The problems which have been worked on during recent months are:

i) Magnetic field of the mirror

A model of the coils giving a magnetic field with a mirror configuration has been built. Measurements of the magnetic field have been carried out for various geometries of these windings and the influence of the iron envelope on the field configuration in the injection region has been studied. This makes possible a preliminary choice of the solenoid characteristics leading to favourable conditions for injection and confinement.

ii) Orbit studies

By means of a digital computer the ion trajectories have been calculated for various initial velocities and directions. One finds that there are two types of trajectories: paths of single traversal, passing once through the centre and escaping afterwards, and multiple traversal orbits passing 10 times or more through the axis of the mirror. This means that dissociation of low efficiency could possibly be remedied by suitable injection conditions.

iii) Dissociation studies

Investigations have been carried out on the possibility of placing on the axis of the mirror a plasma column containing hydrogen or deuterium. This column should be sufficiently dense for the dissociation of the molecular ions to be efficient; practically, the column must be fully ionized to avoid charge exchange losses. A long oscillating electron discharge, associated with differential pumping seems to be a reasonable approach and such an apparatus is now being built for preliminary tests. Considerations pertaining to the cooling effect of the plasma column on the injected ions lead to the design of a programmed plasma column varying in density with time.

Jordan reported on work carried out by the Aachen group.

At the moment the main interest there is focused on the compression experiment. A plasma is compressed by a fast rising external magnetic field in a linear tube. A simple geometry is used, without mirrors or additional complications. A 5 kJ 25 kV capacitor bank is used, the coefficient of self-induction being 2×10^{-9} H at the bank. Current rates are of the order of 10^{13} A/s in a coil 16 cm long and having a diameter of 4 cm. The peak field is 50 kGauss, the initial electric field 1.5 kV/cm.

The discharge appears to be fully ionized at the first few compressions. The lines of the filling gas disappear early and appear again around the third or fourth compression of the plasma. The impurity lines show up at the fourth compression. A rather large neutron pulse is observed at the second compression, decreasing at subsequent ones.

Probe measurements show that a considerable amount of the magnetic field existing before the discharge is penetrating into the plasma, trapped and compressed.

A study is now being carried out to find correlations between the neutron appearance and the values of the temperature in the regions of trapped magnetic field. Similar observations have been made by the Los Alamos group on Scylla and by Kolb.

There are two possible interpretations. The Los Alamos interpretation is consistent with the assumption that the neutron production is due to a thermal plasma, where the ion energies are of the order of a few keV. Breakdown would occur in the first half-cycle; the plasma would then be heated to intermediate temperatures by shock heating, put into ordered motion by the rapidly rising magnetic field and adiabatically compressed to a few keV during the second cycle. The second interpretation, put forward by Kolb, assumes that the production of neutrons and the heating of the gas are intimately connected with the magnetic field trapped inside the plasma, the energy stored in the magnetic field being transferred by antiparallel field interdiffusion to the plasma. If this is true, one must have trapping to get neutrons and the nuclear reactions would depend critically on the amount of magnetic field penetrating into the plasma.

Observations carried out after the Uppsala Conference have shown that in all cases where a high RF pulse (100 kV, 100 μs) was applied to the plasma, the large neutron pulse in the second cycle disappeared. Kolb has made similar observations and if this proves to be true, serious doubts would be cast on the relevance of the shock heating and plasma compression experiment.

Other experiments are under way. Measurements of the magnetic field distribution inside a plasma are being prepared, using larger volumes. The effect of RF production of plasma is being investigated by matching the RF to the coils and measuring the electron density. A Marshall type experiment is also under construction. Very small magnetic probes possessing high signal/noise ratios have been developed and used for these measurements as well as for determining the field distribution in a stabilized linear pinch. In this latter experiment B_z and B_θ have been plotted as a function of radius and time, the current distribution has been calculated and the stability conditions have been established parallel and transverse to the magnetic field. The results obtained are in good agreement with theoretical predictions.

<u>Brinkman</u> reported on the graphical representation of the Suydam stability criterion

$$\frac{r}{4}\,\frac{1}{\mu}\left(\frac{d\mu}{dr}\right)^2 + \frac{8r}{B_z^2}\,\frac{dp}{dr} \geqslant 0 \qquad \text{where} \quad \mu = \frac{B_\theta}{r\,B_z}$$

Expressing the pressure gradient in terms of the magnetic field components, which is possible under equilibrium conditions, one gets three variables

$$\phi = \frac{d \log B_{\theta}^{2}}{d \log r}$$

$$Z = \frac{d \log B_{z}^{2}}{d \log r}$$

$$\lambda = \frac{B_{\theta}^{2}}{B_{z}^{2}}$$

Plotting Z versus ϕ for various values of λ, considered as a parameter, one obtains a parabola tangent to $\phi = -2$. Inside the parabola there is no stability, to the left of $\phi = -2$ there is absolute stability, and in the intermediate region there is conditional stability, depending on the field components.

Braams mentioned briefly the work of his group.

Buildings are finished now, the construction of a new laboratory has been started and facilities are being built up.

Coils have been ordered to produce quadrupole magnetic fields. The fields will be used: a) For injection of charged particles and checking of the capture process by non conservation of momentum. b) For constructing a plasma based on leaks; equalization of the leaks may be possible by changing the position of the coils.

Another experiment contemplated now is aiming to produce in a toroidal tube a plasma column confined by a rotating magnetic field. This would involve 10 kW, 3 Mc/s and it is believed that plasma can be confined during several cycles.

According to a remark by Allen, Tayler has predicted instabilities in a rotating magnetic field of simple geometry; finite conductivity may however improve the situation.

Dattner mentioned an experiment where a concentric type of plasma gun, fed by a condenser bank, is provided with an outside electric field. In its motion the gas discharge interacts with the magnetic field and moves outwards. The acceleration process is being studied. Photographic and spectroscopic techniques as well as magnetic probe observations are used. Of particular interest is the fine structure of the current distribution and that of the light in front of the current.

A homopolar machine has been working for some time and a bigger machine of this type is being built.

Allen reported on work carried out at the Rome Laboratory for Ionized Gases.

Four experiments are in progress there, one of which is on a larger scale.

a) Sheath transition

This experiment is connected with investigations pertaining to the influence of a magnetic field on the energy of positive ions accelerated towards a plasma boundary. Experiments of a preliminary nature have been carried out using a low pressure arc. An azimuthal or "pinch-type" magnetic field was produced by a current carrying wire situated at the axis of the tube. Measurements were made with Langmuir probes while a d.c. current was passed through the wire, the direction of the current being reversible. Present evidence supports the assumption that plasma-sheath transition can be affected by the presence of a magnetic field.

b) Theta pinch

Orthogonal pinch experiments have been carried out, the term orthogonal referring to the situation where an inwardly directed magnetic force results from the interaction between azimuthal plasma currents and an axial magnetic field. A 11 µF 25 kV condenser bank was used, and probe measurements have been made of the spatial and time variation of the magnetic field strength within the plasma.

c) A larger apparatus of the same type is being built, including a multi-sector coil which should develop a large voltage per turn.

This work was reported during the previous sessions of the Study Group as well as at the Uppsala Conference.

d) Refractive index measurements

The refractive index of an electron gas in the optical region can be represented by the dispersion relation

$$n - 1 = - \frac{2 \pi N_e e^2}{m \omega^2} .$$

For free electrons $n - 1$ is negative and considerably larger than for noble gases, for instance, in the visible region. These circumstances suggest the possibility of measuring the electron density in a plasma by observing the behaviour of the refractive index when the gas is electrically excited. The application of this principle to radio frequency and microwaves is well-known.

Experiments on an argon plasma excited by an RF field have been carried out by Ascoli. Light from a high-pressure mercury arc formed interference fringes through a Jamin interferometer giving a 2 cm separation between the beams; the fringes were focused on the wide slit of a small spectrograph. One of the beams passed through the discharge tube, the other through an open, air filled tube whose function was to prevent strong thermal convection currents being formed in the vicinity of the heated discharge tube. The fringe shift due to the refractive index difference between the low-pressure argon in the discharge tube and the air at atmospheric pressure in the side tube was compensated by adjusting the interferometer plates, so that fringes of orders near zero appeared through the spectrum. The discharge was excited by placing the tube coaxially with a coil of 8 cm diameter and 20 cm length, consisting of 6 turns of wire and operated by a 20 Mc/s oscillator. At an anode potential of 3000 V the circuit delivered about 1 kW RF power output. To perform quantitative measurements, the fringe system was adjusted so that the reference line fell in the centre of an intensity maximum. A photograph with a 0.5-1 s exposure was taken with the discharge off, and about 2 s later a similar exposure was taken by simultaneously turning on the discharge. The fringe shift between the two exposures was measured by scanning the plates under a microphotometer. The appearance of the discharge was found to be sensitive to small changes in RF excitation.

Observed fringe shifts ranged from - 0.03 to - 0.06 fringes. The latter figure corresponds to an electron density of $N_e = 7.6 \times 10^{14}$. Assuming equality of the refractivities of argon ions and atoms, this would indicate that 4 o/o of the argon atoms had been ionized. The assumption is certainly not true, but the result is insensitive to the differences to be expected, owing to the large effect of an electron compared with a neutral atom and an ion.

The measurement of refractive indices may afford a valuable diagnostic tool in plasma studies, as the measurements do not affect the plasma and the method is unaffected by the strong electric and magnetic fields in which the plasma is often produced. The main shortcoming at present is the low sensitivity.

Folkierski reported on plasma studies at the Imperial College, London.

a) Instabilities of the linear pinch discharge

Kerr cell photographs have shown the presence of a particular type of instability, occurring as soon as the first compression is over and having the appearance of ripples on the surface of the column. The ripples are concave outwards and join each other in cusps.

Experiments are in progress to measure the rate of growth of this instability under various conditions.

There is no unique wavelength, and both the length and the depth of the ripples are being analyzed statistically.

The appearance of the ripples is similar to that of the Rayleigh-Taylor instability in hydrodynamics. It is intended to test whether the theory of this instability can be used in the interpretation of the observed data.

The appearance and growth of the ripples was demonstrated on a sequence of photographs taken in a low-pressure argon discharge. The discharge conditions were:

energy of condenser bank	6 kJ
maximum current	60 kA
pressure	180 μ
discharge tube	pyrex, 20" long, 6" int. dia.
exposure time	5 μs

b) Experiments with a longitudinal field

A pulsed B_z was applied to the discharge. The time of application of the field could be varied at will, but the rise time of the field was rather slow, with a quarter-period of some 20 μs.

Kerr cell photographs show that while the ripples are still there, they are not so pronounced as without B_z. It is however too early to draw conclusions as the results have not been properly analyzed as yet.

The conditions were adjusted so that the maximum value of B_z could be made larger or smaller than that of the B_θ at the surface of the column at the time of appearance of ripples.

c) Comparison of Kerr cell and image converter photographs

The same discharge was photographed simultaneously with equal exposure times by the two cameras. The photograph taken with the image converter camera shows a discharge column diameter greater than that obtained with the Kerr cell camera; it is thought that this is due to different wavelengths of light.

d) Copper liner for the discharge tube

It has been observed in several laboratories that material coming from the walls of the tube can form a second collapsing sheath. In an attempt to prevent or modify this effect, a form of copper liner has been constructed at Harwell and tested at the Imperial College.

The liner is 10" long and has an internal diameter of 4.5". It consists of 175 copper rings, each of which is divided into eight segments. The elements of the assembly are insulated from one another by alumina washers, and the whole fits into a glass discharge tube.

The liner was tested at 5 keV with 25 kJ in hydrogen at 100 microns. The only signs of breakdown between the elements occurred on the first few rings nearest to the anode.

Schlüter summarized the theoretical work being carried out at the M.P.I.

I. Pure Theory

a) Stability (v. Hagenow)

Attempts have been made to obtain simple derivations of hydromagnetic equilibrium and stability criteria. The applicability of Suydam's criterion has also been investigated.

b) Connection between microscopic and macroscopic equations (Hertweck)

The aim here is to derive the macroscopic (magneto-hydrodynamic) behaviour from the microscopic (Boltzmann or Fokker-Plank) equation; extension of the validity range to the case where collisions are not frequent is investigated.

This study is based on the assumption that there are definite relations between velocity momenta of a certain order and momenta of higher order.

c) Discussion of the validity of Boltzmann's equation

This represents one step further with respect to b). It is essentially a n particle problem equivalent to the application of Liouville's theorem to the plasma as a whole. Mathematically the problem becomes solvable by connecting a 1-particle distribution to a 2-particle distribution, a 2-particle distribution to a 3-particle distribution, etc.

d) Stability (Lüst)

Stability conditions of a homogeneous plasma in a homogeneous magnetic field described by hydrodynamic equations; generalization to anisotropic pressures.

II. Applied Theory

a) Pinch calculations (Hain)

To determine the dynamic behaviour of a pinch-compressed plasma, numerical computations are being performed. The problem is to solve the relevant partial differential equations as a function of time by taking into account finite heat conductivity and finite resistivity; the assumption of cylindrical symmetry has been maintained.

Also rotating magnetic fields have been investigated as well as the way in which time varying magnetic fields penetrate into the plasma. The basic question is of course: "can one find arrangements not necessarily unstable?".

b) Toroidal geometry (Lüst)

Stability conditions have been investigated taking explicitly into account toroidal geometry. It has been found that in the limiting case where the major radius of the torus tends towards infinity, the stability behaviour of the torus does not become equivalent to that of an infinitely long cylinder, at least not for the largest λ's.

c) Modulated ion beams (Kippenhahn, de Vries)

The modulation-dependent energy loss of an ion beam in a plasma has been found less than hoped for; a big loss would indeed destroy adiabaticity.

d) Parameters (Fisser)

The problem here is to find the best parameters for a device intermediate between a stellarator and a Scylla-type machine.

6. MICROINSTABILITIES

Pfirsch reported on microinstabilities and particle diffusion.

The problem of microinstabilities arises mainly in connection with the fact that in several experiments a strong particle diffusion in a plasma across the magnetic field has been observed. One may wonder whether one should expect quite generally strong particle diffusion, independent of special causes such as runaway electrons.

The well-known formula of the diffusion time is

$$t = \frac{d^2 \sigma_m}{\beta}$$

where d is the plasma diameter, σ_m the electric conductivity and β the ratio of plasma pressure to magnetic pressure. This formula expresses the motion of plasma particles under the joint influence of the magnetic field B and the thermal fluctuations of the charge density in stochastic form. It is a special case of the more general formula

$$t = \frac{\omega B^2}{c^2 E^2} d^2$$

where E is a general statistical electric field possessing a main fluctuation frequency ω. In the case of thermal fluctuations ω is the electron plasma frequency ω_p, and E^2 corresponds to a charge fluctuation in a Debye volume. The first formula then follows.

In studying increased diffusion, one may look for overthermal electric field fluctuations. An overthermal E^2 could exist if the plasma is unstable in microscopic regions (of the order of a Debye length or of a radius of gyration). Such instabilities can be thought of if the plasma is not in a local thermodynamic equilibrium, e.g. if there is locally a deviation from a Maxwellian velocity distribution. In several recent papers, non-Maxwellian velocity distributions have been treated with the result that indeed such plasmas can be unstable, but the considered plasmas were always homogeneous in space.

Consider an inhomogeneous plasma, possessing the property of deviating in principle from local thermodynamical equilibrium, unless confined by a potential; one must then expect instabilities very generally. The influence of these instabilities on diffusion is given by their maximum value of E. In linear theory the growth rate is determined by damping (collision-like damping, damping by phase-mixing like Landau damping, and radiation damping). If these terms are large enough, the amplitudes will be small, but in the opposite case instabilities can exist and the amplitudes will be limited only by non-linear effects. Neglecting linear effects, the non-linear limiting condition may be written

$$k\,(f_1 + f_2 + \ldots) \ll \frac{\delta f_o}{\delta x}$$

k representing the wave vector of the perturbation, f_o the unperturbed distribution function, and f_1 , f_2 ... the perturbations. Multiplying by $mv^2/2$, integrating over v and applying the law of conservation of energy, one finds a macroscopic condition for E

$$\overline{E^2}/8\pi \ll \frac{1}{k}\;\frac{\delta}{\delta x}\;\left(\frac{3}{2}\,n\,k\,T\right)$$

Comparison with experimental results obtained by Gabor show good agreement, although this may be only incidental.

Two examples have been studied to some detail, although under restrictive conditions. The instabilities found are not exactly of the kind mentioned above, but seem to allow similar conclusions on the diffusion as those contained in the formula given above. Linearized theory has been used, i.e. unperturbed systems have been considered, described by a distribution function and by electric and magnetic fields, and the development in time of small perturbations has been followed. The two examples treated assume one-component plasmas; this is a strong restriction since, e.g., the two-stream instability does not exist if the mass of the ions is taken to be infinite.

The two examples are: i) one-component plasma involving a quasi-stationary one-dimensional density gradient with particle diffusion but without magnetic field; ii) one-component plasma confined by a magnetic field in one dimension, without particle diffusion.

In the first case, the dispersion relation can be found exactly and the result is that there are no instabilities, the plasma waves being damped slowly; this damping may be thought of as being due to differences in the drift velocities of the electrons leading to phase-mixing and consequently to Landau-type damping. In non-linear theory this phase-mixing may not exist, so that one cannot exclude a priori instabilities by diffusion.

In the second case, a plasma in a very strong magnetic field has been considered, $B^2/8\pi \gg n\,k\,T$, and a distribution function $n(x) = n_0\, e^{-\frac{\gamma}{1+\gamma}\frac{x^2}{r_g^2}}$ has been assumed, where r_g is the mean gyration radius and $0 < \gamma = \text{const.} \ll 1$. This leads to the equation

$$E_y^{(4)}(x) \approx -\frac{1}{A}\,\frac{\omega^2}{c^2}\, e^{\gamma \frac{x^2}{r_g^2}} \left[E_y^{(2)} + \frac{\omega^2}{c^2}\, E_y \right]$$

where $A = \frac{3}{2}\,(1+\gamma)^{1/2}\,\frac{1}{\alpha\, c^2}\,\frac{\omega^2\,\omega_{p_0}^2}{(\omega - \omega_c^2)\,(\omega^2 - 4\,\omega_c^2)}$,

E_y is the y-component of the electric field of the wave which propagates in the x-direction; the magnetic field B_0 is in the z-direction. The equation has two different pairs of solutions, one corresponding to transverse electromagnetic waves in a plasma without a magnetic field, and the other to longitudinal waves in such a plasma. In the first case, $E^{(4)}$ can be neglected, leaving $E_y^{(2)} + \frac{\omega^2}{c^2} E_y = 0$, i.e. $E_y \sim e^{\pm \frac{i\omega x}{c}}$ which, for ω real, represents a stable plane electromagnetic wave in vacuum. The second kind of waves is characterized by $\left| E_y^{(2)} \right| \gg \left| \frac{\omega^2}{c^2} E_y \right|$, $x \to \infty$, leading to $E_y^{(4)}(x) \approx - \frac{1}{A} \frac{\omega^2}{c^2} e^{\gamma \frac{x^2}{r_g^2}} E_y^{(2)}$. For this to represent finite waves for $x \to \infty$, $\frac{\omega^2}{A}$ must be real and greater than zero. It follows $(\omega - \omega_c^2)(\omega^2 - 4\,\omega_c^2) > 0$, and unstable solutions will exist for $\omega^2 < 0$. The wavelengths corresponding to these solutions are $\lambda/2\pi < (3/8)^{1/2} (1+\gamma)^{1/4} r_g \frac{\omega_{p_o}}{\omega_c} e^{-\frac{1}{2}\gamma \frac{x^2}{r_g^2}}$ and the validity conditions are $\frac{\omega_c^2}{\omega_{p_o}^2} e^{\gamma \frac{x^2}{r_g^2}} \ll 1$, $\frac{1}{A} e^{\gamma \frac{x^2}{r_g^2}} \gg 1$, the latter being satisfied if the temperature is sufficiently low. There is therefore an instability where the wavelength is determined by a microscopic quantity, the radius of gyration, and this is essentially the characterizing feature of a microinstability. Because the ion radius of gyration may be much larger than the wavelength of the unstable solutions, one could define a frequency $\omega \approx v_{ion}.k$ and the diffusion time becomes then $t \gg \frac{1}{\beta} \frac{k^2 v_{ion} d^3}{c^2}$.

More special causes for increased particle diffusion are anisotropic velocity distribution, runaways and two-stream instability. In the latter case, the wavelength may be quite macroscopic and the instabilities can be derived in a pure macroscopic theory, if one takes into account certain inertial convection terms; however, the macroscopic theory fails to describe these instabilities in a correct manner if the relative velocity between ions and electrons is smaller than or of the order of the thermal electron velocity. The reason for this is that the phase velocity of the unstable waves is of the order of $v_{ph} \approx \left(\frac{\omega_i}{\omega_e}\right)^{2/3} u$, where ω_i and ω_e are the ion and electron plasma frequencies respectively, and u is the mean relative velocity between the ions and the electrons. Consequently, the phase velocity is smaller than u , and if the phase velocity is smaller than or of the order of the thermal velocity, large Landau damping occurs, so that these waves are stable instead of being unstable. There exists therefore a critical velocity u , below which the waves are unstable. The problem has been considered recently in a paper by Buneman and in an unpublished paper by Bernstein, Frieman, Kulsrud and Rosenbluth.*) Different conclusions are drawn in the two papers. Buneman is mainly concerned with the problem of plasma heating and he finds that the main part of the electrons which would run away by standard theory give up their energies to the plasma waves in about 100 plasma oscillations, which means a very effective heating of the electrons in a plasma. Bernstein, Frieman, Kulsrud and Rosenbluth point out that their results show a mechanism by which pump-out in the stellarator B-3 could possibly be explained; by this the diffusion appears to be caused by ohmic heating. They also give a necessary and sufficient criterion for two-stream instability if $T_i \approx 0$.

Finally, Rosenbluth considers a slightly inhomogeneous plasma where, on account of a magnetic field gradient perpendicular to B , a motion of the electrons and ions exists with velocities $v_{D\,e,i} = \frac{1}{B} \frac{dB}{dx} \frac{v_{e,i}^2}{\omega_{c\,e,i}}$. He points out that when the phase velocity $\frac{\omega}{k}$ is about v_D , trapping of particles in longitudinal plasma waves which propagate perpendicularly to B is possible, and by this an instability may arise. He finds growing plasma waves in the region of the ion cyclotron frequency with growth rates which are slower than $\omega_{c,i}$ by several orders of magnitude. The wavelengths are given by relations involving the radius of gyration, and therefore these instabilities can be considered as microinstabilities. Rosenbluth suggests effects of these instabilities on resistivity and diffusion.

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*) See Matt 23, Nov. 1959.

7. MICROWAVES

Wharton gave a review of microwave plasma diagnostics.

I. Coupling Resonances

In the vicinity of certain critical frequencies or resonances a strong coupling between waves and plasma can be expected, and the plasma properties are highly dispersive. The Tonks-Langmuir formula

$$f_p = \frac{\omega_p}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{ne^2}{\varepsilon_o m}}$$

shows that for plasma densities of interest, i.e. $n = 10^{12} - 10^{15}$ particles/cm^3, f_p is in the range 9000 - 300 000 Mc/s, which is in the millimetre and microwave region. Another strong resonance occurs at the electron gyrofrequency

$$f_c = \frac{\omega_c}{2\pi} = \frac{e}{2\pi m} B \quad .$$

For fields between 3000 and 100 000 Gauss, one finds frequencies in the same range as above.

II. Propagation Properties

From the theory of Margenau, combined with calculations for gyro effects and propagation characteristics, one can infer some approximate properties of the plasma as a function of the frequency of a wave incident upon a semi-infinite slab of plasma for example. The range of measurable electron densities can then be established; it is bounded on one side by a line (whose position is a function of the effective thickness of the plasma slab) representing the minimum density at which some measurable effect (phase shift) occurs, and on the other side by a line representing plasma cut-off due to $K \longrightarrow 0$ at the plasma frequency. Taking into account complex conductivities and plotting the propagation characteristics as a function of frequency one finds two regions in which transmission occurs, one in the vicinity of gyro-resonance (the so-called "Whistler mode") and one at frequencies above the plasma frequency.

a) B = 0

At frequencies above plasma resonance, the required frequencies are in the cm and mm wavelength part of the spectrum. Besides E.M. waves, several other types of waves may propagate here, such as Alfvén waves, space charge waves, etc.

Consider a simple slab geometry with plasma of thickness d , taken as a Lorentzian gas, $B = 0$, and a small-magnitude microwave electric field acting perpendicularly to density gradients. The phase coefficient, contained in the reactive component of the complex propagation constant γ , plotted as a function of electron density (for several spatial distributions) shows that at a density above critical (propagation frequency below plasma frequency) the phase term goes to zero, leading to infinite phase velocity as in a waveguide at cut-off. In the absence of power-absorbing particle collisions, the wave suffers total reflection from the plasma plane whose density is at cut-off. If absorption (due to collisions or other high temperature effects) is present, the wave may penetrate a distance δ , which is reciprocally related to the absorption coefficient α ,and the amount of reflected energy is diminished by an exponential 2α .

b) Propagation along the magnetic field lines

A wave travelling through a uniform B-field region in a plasma slab finds itself decomposed into two waves, oppositely circularly polarized and having different velocities. An initially linearly polarized wave which travels some distance in the plasma and which is then picked up by a linearly polarized antenna will have its angle of polarization rotated by an amount depending on the difference of propagation velocity of the two contra-rotating waves (Faraday effect). Calculations have been made and indicate qualitatively the effects of high temperature in broadening out the resonances.

c) Propagation across field lines, $E_{RF} \perp B$

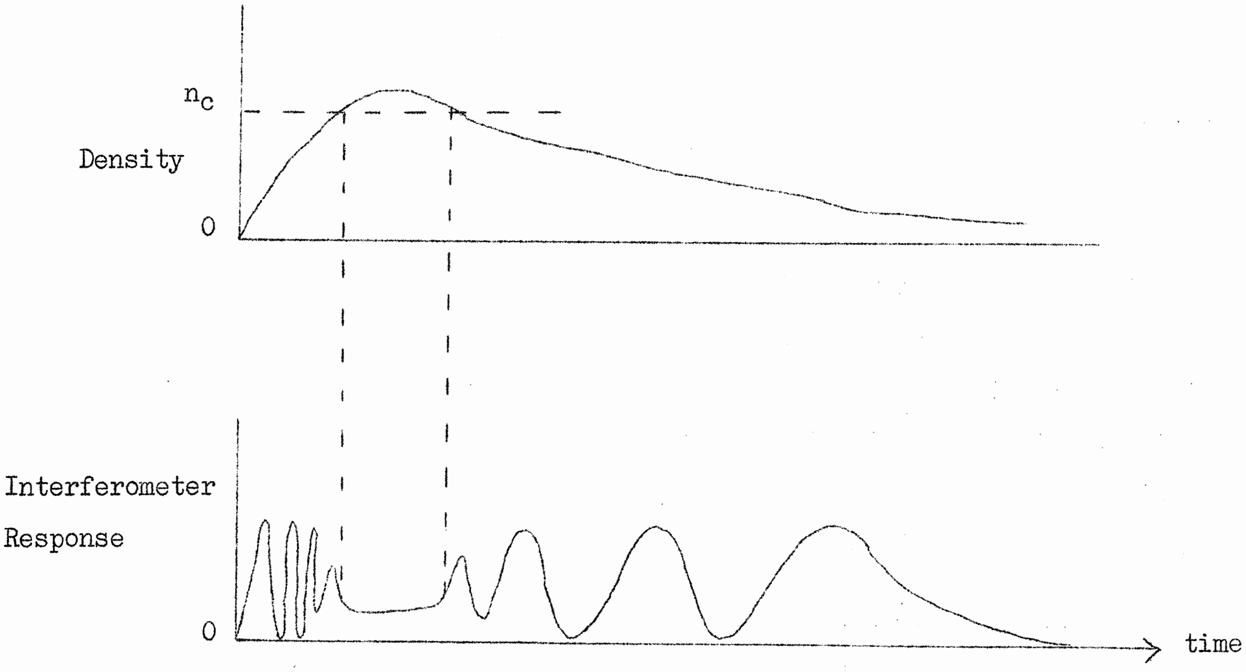
This case also exhibits anomalous dispersion but is more complicated. Certain "pass-bands" of propagation occur at high field strength in a plasma which would normally be cut off.

d) Propagation across field lines, $E_{RF} \parallel B$

At low electron temperatures, this case gives propagation properties which are identical to the no-field case. However, when the electron random velocities are high, some coupling to the rotating component can occur and mild cyclotron resonances at high densities result.

III. Experimental Techniques

Since most plasmas generated in controlled fusion studies are transient in nature, it is convenient to compare the propagation characteristics of an empty transmission path with those of the same path containing plasma. A microwave bridge or interferometer can then be used to measure the change in phase due to inserting plasma into the transmission path. To measure transmission loss, the "null path" is removed and the changes in the transmission signal are viewed.



The figure shows a typical transient plasma density event, the density rising rapidly to a value slightly above cut-off ($n_o \geqslant n_c$, for case II a), and then decaying away slowly. An equivalent path length of 4 wavelengths is assumed. If the bridge is initially balanced (zero output) for n•

plasma, its response, using a square law (silicon crystal detector), will be as sketched. The decrease in amplitude of the envelope of the interference "fringes" (so called by analogy to optical interferometry) is due to a combination of scattering and absorption. When the density is so high that the plasma path is cut off, the detector output rests at 1/4 of its peak value, corresponding to half-signal strength.

Other kinds of data presentation permit simplified read-out and up to $n_0 \lesssim 0.5\ n_c$ give an output proportional to density. In the "fringe-shift" or "zebra-stripe" presentation, the vertical shift of the bars is directly proportional to phase shift.

The antenna systems ordinarily used have a small aperture and wide separation, so that geometrical optics can be used to a fair approximation. Since small aperture antennas have a wide angle of radiation, the interior of the discharge vessel should be made as reflection free as possible to avoid stray paths between the horns.

IV. Radiation from Plasma

a) Bremsstrahlung

The incoherent or thermal radiation emanating from a plasma bears in principle some relationship to the electron kinetic temperature. For a tenuous plasma the bremsstrahlung is easily calculated, and the total radiation will be approximately the number of radiators times the intensity of each radiator, since there is little internal absorption. The total radiation density in the microwave region is some 10^{-4} times that of a black body for a plasma of a hundred eV temperature.

b) Black body radiation

When the plasma region is strongly absorbing (e.g. when the collision rate is very high) and when the electron energy distribution is Maxwellian, the radiation characteristics are similar to those of a black body. Planck's radiation law then applies and the radiation power density is proportional to electron temperature. In order for a plasma to appear black, it must have smooth gradients and be several wavelengths thick. Otherwise some reflections will occur and the region will have incomplete absorption. The absorption and radiation will be maximum in the vicinity of cut-off ($n \approx n_c$) since α reaches a maximum there. At densities below n_c the plasma is transparent, and when the density is well above n_c the plasma is highly reflecting.

c) Gyrofrequency radiation

In the vicinity of the gyrofrequency and its harmonics the plasma has both a real and imaginary index, leading to large absorption. It is to be expected, therefore, that a certain plasma region will be black and will radiate strongly at these frequencies; in fact, the intensity will approach the black body intensity even for an otherwise tenuous plasma. The large gyro-effect can be demonstrated experimentally. In a particular absorption-radiation experiment, a klystron transmitter was used, modulated by random noise to produce a spectrum about 200 Mc/s wide, centred at 24 kMc/s. The signal was transmitted from a circularly polarized horn into the end of a cylindrical plasma chamber; the chamber was surrounded by a pulsed solenoid, producing a time-varying mirror field. A 24 kMc/s superhet receiver was coupled to a circularly polarized horn placed at the other end of the chamber. Approximately 100 db of attenuation was placed in the receiver antenna line to absorb plasma radiation and to adjust the level of transmitted signal to a convenient background level when no plasma was present. When plasma was injected into the chamber from a plasma source a strong absorption was seen to occur in the vicinity of gyro-resonance, even when the density was below the normal cut-off. When the 100 db pad was removed and the transmitter turned off, peaks of radiation were seen to occur at the times when absorption previously occurred. The noise temperatures found checked fairly well with a direct energy analysis of escaping electrons.

The gyrofrequency effect was also apparent in measurements on the ion magnetron experiment. In this measurement the discharge was left burning steadily and the field was varied. The antenna was a linearly polarized horn looking into one end of the chamber through a window. The noise temperature was within 50 o/o of the temperature estimated from neutron yields.

c) Coherent radiation

If any mechanism can occur causing electrons to move coherently, a plasma region can radiate more power than a black body and the radiation intensity no longer has an understandable dependence on temperature. Such coherent effects may be excited by violent instabilities or by sheath oscillations. Great care must be exercised in a radiation experiment to be certain that cooperative effects are not present.

V. Composite Experiments

The "Little Pig" experiment was devised for the purpose of correlating microwave measurements with other measurements. Characteristics of this experiment are: helium gas at 50 microns Hg pressure, peak current density 50 mA/cm^2, peak electron density 10^{13}/cm^2, collision rate 10^{18}/s, electron temperature 5-10 eV, with small high velocity component at 100-200 eV. The electron temperature could be inferred from a single, biased Langmuir probe and from microwave radiation intensity. The plasma absorption coefficient was determined from absorption and reflection measurements. 1 P 21 photomultiplier tubes attached to a pair of optical monochromators viewed respectively the He^+ 4686 Å and the He^o 5015 Å line. The relative intensities of these two lines can be related to the degree of ionization and thus to the electron temperature of the discharge. After taking metastable transitions into account, the calculated temperature is between 2 and 4 eV, which compares well with the microwave noise temperature of 5 eV and the Langmuir saturation temperature of 5 to 10 eV.

Radiation probe measurements have been made on the "Little Pig" discharge. The probe was made by electroforming copper and nickel on a tapered piece of a high dielectric constant material (mycalex 500, $\varepsilon = 13$). The open end had a diameter of only 0.4 mm for 25 kMc/s, the other end joining normal RG - 53/V waveguide. The probe, which had a radiation pattern essentially the same as a very short dipole, is coated with a ceramics enamel down to the end, leaving about 1-2 mm of bare metal to act as a Langmuir probe. The whole assembly floated electrically, the wave being coupled out through insulated choke joints. The exit waveguide was soldered into a movable vacuum seal which allowed both rotation, to change the plane of polarization, and motion along itself, to vary the depth of penetration into the plasma. Using this probe it was found that the radiation seemed to have a maximum at a particular radius. The position for this maximum was a function of both frequency and peak density and, within experimental accuracy, was near the radius at which plasma cut-off occurred. The probe, however, perturbed the discharge. A monitor receiver which viewed the general region showed an increase in noise radiation of as much as 50 o/o when the probe was inserted.

Dellis reported on microwave work at Harwell.

Before the Geneva Conference the 8.6 mm radiation from micron pressure discharge in argon and hydrogen had been measured at currents of several kA in a 14 inch bore torus. The first attempts to do measurements like this on Zeta gave rough answers for the electron temperature in the range 0 - 5×10^5 °K. The transmission of 4 mm radiation across a diameter of the bore of Zeta was then looked at and cut-off was observed for varying lengths of time according to the gas current used. The results suggested electron densities greater than $7\times10^{13}/\text{cm}^3$ during cut-off; the length of time for which cut-off exists at low currents depends sensitively on how clean the discharge is.

After Geneva further observations were made of microwave radiation from Zeta at pressures of $1/4\ \mu$, $1/2\ \mu$ and $1\ \mu$, using a horn aerial outside the main plasma column in a recess in the liner.

Different types of radiation pulses were observed for $\lambda = 8.6$ mm and $p = 1/4\ \mu$. At low voltages a single short pulse, much shorter than the 3 ms current pulse, could be observed, reproducible from shot to shot. When the condenser voltage was increased, a second quite unreproducible peak appeared in the pulse.

Looking at the gas current pulse, one observes a practically linear rise free from hash, followed by a break at which large fluctuations appear.

For low condenser voltages the single first peak occurs during this initial linear current rise; at higher voltages the noise pulse is longer but still ends before the current pulse does.

Since the microwave noise is reproducible from shot to shot during the time that the current pulse is free from hash, this initial period is presumably one in which the configuration of the plasma is the same for each shot. The lack of reproducibility of the second noise peak suggests that the main plasma or some outer layer does not have the same configuration from pulse to pulse.

Changing from $1/4\ \mu$ to $1/2\ \mu$, the characteristics of the second noise pulse spread to the whole pulse. At $1\ \mu$ pressure very little noise is seen, indicating that the electron density is too high to give 8.6 mm radiation.

The results are consistent with a plasma which emits thermal noise. The difficulty in understanding how such thermal noise can be emitted arises because, if one takes into account electron-ion collisions, the attenuation of these frequencies in the plasma should be very low, of the order of c/ν , where ν is the collision frequency, unless the index of the plasma is very near to zero.

If the noise is emitted because of current flowing or runaways, one would expect to observe plane polarization of the microwave noise; it has been possible, however, to show that the radiation is either randomly or circularly polarized.

Measurements of electron density near the wall show that quite high densities can exist near the wall during the current pulse, so the observed noise must be attenuated if it comes from the centre of the discharge. For $1/4\ \mu$ pressure of deuterium, the electron density would be $2\times10^{13}/\text{cm}^3$ for no pinch and complete ionization.

In addition to the observations on Zeta, some measurements have been done on the afterglow of a discharge in argon, to compare microwave measurements of density and temperature with Langmuir double probe results. The very good agreement is probably better than the accuracy of the double probe plots would warrant.

On passing through the plasma, the 8.6 mm radiation is strongly absorbed. The absorption for two different pressures has been plotted as a function of electron density as calculated from the interferometer results. The fact that both pressures give the same absorption suggests that the loss is not due to electron-neutral collisions. Such unexpectedly large absorption is particularly interesting when considering that the difficulty in explaining thermal noise from a low pressure plasma is due to the smallness of the theoretically predicted attenuation.

The results quoted so far have been obtained with microwave horns inside the plasma. Other experiments have been performed with the horns placed outside the torus glass walls. Similar attenuation has been found in this case, and the attenuation is the same with the electric vector of the microwaves either along or across the discharge channel. This shows that there are none of the effects present such as those concerned with reflection from meteor trails, in agreement with the fact that the plasma diameter is much greater than the free space wavelength of microwaves.

By noting the detuning and damping of a resonant circuit wound on the glass torus, a rough measurement of the electron collision frequency has been made. The figure 2×10^{7} s^{-1} determined in this way as an average over the first millisecond after the afterglow is in good agreement with the theoretical value.

Experimentally it has been found necessary to use aerials which are nearer together than their Raigleigh distance a^2/λ , a being the physical aperture.

Further observations on radiated microwave noise revealed that at 8.6 mm wavelength where a level of about 2000° K could have been seen, no radiated noise could be detected. Using 4 mm equipment, about 5000° K worth of noise can be seen. It is then interesting to note that the noise pulse corresponds to a much lower temperature than that given by the double probe and appears to follow the current pulse. This suggests that the noise may be a function of the current rather than of the temperature and that it may somehow be generated by the flowing current.

The Appleton-Hartree formula for the propagation of electromagnetic waves in a magneto-ionic plasma contains implicitely the possibility of propagating waves through a dense plasma below the electron cyclotron frequency. In the hope of seeing such propagation, a straight discharge tube having a longitudinal magnetic field of 5000 Gauss has been built. Matching to the plasma, which has high dielectric constant in this region, and receiver sensitivity are important here.

Further experiments on high frequency propagation in straight tubes will be carried out, both along and across the magnetic field lines, and observations will be made to detect the Doppler shift in the reflection from a contracting plasma in the presence of a reduced axial magnetic field.

Other immediate plans include a time resolved study of the microwave radiation from a 14 inch bore torus and the apparatus is ready for this. Of particular interest here is the correlation of the microwave noise emitted with the current pulse and with the time resolved electron temperatures as deduced from Langmuir double probe plots. This should help to understand better the diagnostic results obtained from Zeta and similar devices.

Wieder reported on observations of Whistler mode wave propagation in Zeta discharges.

Transmission experiments were carried out with 10 cm wavelength in a plasma whose frequency was 150 kMc/s.

Three interesting results were found:

a) The refractive index was very large (around 100).

b) The energy of the radiation was confined to a very small cone about the lines of magnetic force.

c) The medium was highly dispersive.

Consoli reported on the Faraday effect in plasmas.

The use of ultra-high frequency electromagnetic fields for measuring electron densities in plasma diagnostics has the advantage of not perturbing the plasma. In the experimental application of this technique, it is natural to start with interferometric and reflection devices.

At Saclay 8 mm equipment has been used for making electron density measurements, and the intention is to use 4-2 mm equipment to cover a density band from 10^{12} to 10^{14} particles/cm^3. However, the density bands covered by these wavelengths are too narrow and do not permit overlapping; another method has therefore been looked for which does not have this disadvantage.

One conventional method that can be used is to measure the frequency shift of a resonant cavity containing the plasma. This method has been described by the Sanborn-Brown group at M.I.T. Wharton has now presented another interesting method for measuring varying densities. Still another way of attack, at present worked on by the Saclay group, attempts to make use of the Faraday effect, discovered in 1845 and observed in the ionized gas of the ionosphere in 1931 by Appleton.

The Faraday effect in plasma has been studied by several authors, such as Suhl and Goldstein, USA, 1954, and Roubine, France, 1955. In Great Britain, Brown and Evans used it in 1956 to measure the average electron density in the ionosphere by sending a radar signal to the moon. In more recent days the method has been used with rockets and satellites as transmitting stations. However, it did not seem possible to find in the literature a description or study applied to density measurements in laboratory plasma machines. Theoretical studies have therefore been started at Saclay in parallel with the construction of an experimental set-up representing a first step towards the application of the principle to density measurements.

The interpretation of the Faraday effect is based on the decomposition of a linearly polarized E.M. wave into two circular waves of equal amplitudes which rotate in opposite directions. These two E.M. waves propagate in the medium with different velocities and one can write for the rotation angle of the resultant wave

$$\varphi = \frac{f}{2c} \int_0^{\ell} (N_e - N_o)\, dz$$

φ being the number of complete rotations, N_e and N_o the refractive indices, f the frequency of the probing E.M. wave and c the velocity of light.

If the medium is equally transparent to the circularly polarized waves, the resultant wave will be linearly polarized and its angle of rotation with respect to the incident wave is φ. If the medium is dichroic, the wave becomes elliptical, with its major axis in the rotated direction.

Considering the high frequency behaviour of a plasma, one has, in order to describe the wave propagation properties of such a medium, to determine the refraction index and the conductivity. In the special case considered, the waves are linearly polarized and propagation takes place in the direction of the magnetic field. If one does not take into account the influence of the temperature, one can write

$$N_{o,e} = \text{real part of } \left[1 - X \left(\frac{1}{1 \pm Y_e + jZ_e} + \frac{m_e}{m_i} \, \frac{1}{1 \mp Y_i + jZ_i} \right) \right]^{1/2}$$

where $X = \omega_p^2/\omega^2$, $Y_e = \omega_{ce}/\omega$, $Z_e = \nu_e/\omega$, $Y_i = \omega_{ci}/\omega$, $Z_i = \nu_i/\omega$.

In the absence of a magnetic field the plasma is isotropic for E.M. wave propagation, but if it is placed in a magnetic field, the medium is no longer isotropic. It behaves as an uniaxial crystal.

Using a computing machine, a family of curves of φ has been drawn for various values of f , H , n_e . Using this family, one can deduce, for a given magnetic field, the frequency which gives the largest frequency band for a given number of rotations. Two examples have been examined for the case $\nu \ll \omega$:

Case	Operating Conditions	Physical Conditions	Angle of rotation in radians
I	$\omega_p \ll \omega < \omega_{ce}$	Plasma of low density and high magnetic field	$2.4 \times 10^{-11} \int_0^{\ell} \frac{n(z)}{H(z)} \, dz$
II	$\omega_{ce} \ll \omega_p \ll \omega$	High density and high magnetic field, or low density and low field.	$2.9 \times 10^{-2} \, f^{-2} \int_0^{\ell} n(z) H(z) \, dz$

Taking as a specific example the OGRA machine, one has $n_e = 10^{16}$ e/m^3 (low density), $B = 12$ W/m^2 (high intensity field), length = 12 m. Applying the result of the first case, one finds $\varphi = 3$ radians or $\frac{1}{2}$ a complete rotation for any frequency that is greater than the plasma frequency. Following the variation of density from 10^{16} to 10^{18} e/m^3, the number of complete rotations is 50.

Three slides were then given, showing the layout of the experimental apparatus which has been constructed by Dagat to measure φ, as well as an interferogramme obtained with the 8 mm set and the interpretation of the density curve versus pressure.

8. MISCELLANEOUS

Linhart reported on the theory of fusion reactions in an unconfined plasma.

In order to derive a net power gain from thermonuclear reactions in plasma, a large number of proposals have been put forward during the last ten years, aiming at the achievement of long-term confinement in a given volume of plasma. None of these proposals appear to be adequate owing to the instability of confinement and to the large radiation losses. Several lines of approach have been suggested to overcome these drawbacks in the future.

In the case of a long-term confinement not being discovered or such confinement leading to a technically useless apparatus, a solution to the liberation of fusion energy can be sought in systems exhibiting only marginal confinement or even no confinement. A small version of an unconfined plasma reactor whose power output can be absorbed by laboratory apparatus is considered here.

Consider an infinitely long plasma column of radius r_0 in which the plasma density and temperature are initially uniform. The plasma is composed of equal parts of deuterons and tritons and a corresponding number of neutralizing electrons. In the absence of any constraining forces the column will expand radially. However, the electron gas is spatially coupled to the positive ion gas by electric fields and is, therefore, constrained in its expansion by the inertia of the positive ion gas. At the same time the collisions between electrons and positive ions cause the difference in temperature between the two gases to be small as compared with the average plasma temperature. It follows that the random velocities of the particles in the plasma are steadily converted into the energy of radial plasma flow away from the axis. This behaviour can approximately be expressed by an equation of state

$$\frac{T}{T_o} = \left(\frac{r_o}{r}\right)^{4/3} \quad , \text{ where } \quad T_e = T_p = T$$

and an equation of motion

$$N\,M\,\ddot{r} = 2\,\pi\,r\,k\,T\,n\,.$$

It can then be shown that after an expansion of the column to $r = 4\,r_o$, the velocity of the radial flow reaches about 90 o/o of the maximum attainable value. The original step distribution of plasma density will diffuse during the expansion into a more gradual one; this is neglected in the simplified model, but does not alter the main conclusions about the expansion process.

The fusion energy output during the expansion can be written formally as

$$W_F = \tfrac{1}{2}\,N\,P\,Q_{DT}$$

where $Q \approx 2.8\mathrm{x}10^{-5}$ erg is the Q-value of the DT reaction and P is the probability that a deuteron will be involved in a reaction. P can be determined under certain simplifying assumptions and one finds

$$W_F = 0.24\mathrm{x}10^{-29}\,\frac{N^2}{r_o}\ \mathrm{erg}\,.$$

The loss of energy per unit length W_L is readily computed if one assumes that the expansion results in a complete loss of all the kinetic and thermal energy of electrons and positive ions. Thus

$$W_L = 3\,N\,k\,T_o = 4.5\mathrm{x}10^{-7}\,N\,.$$

The condition for a net energy gain is $W_F > W_L$ or

$$\frac{N}{r_o} > 2x10^{23} .$$

Thus if the linear density is large enough, an energy gain can be expected from a completely unconfined plasma configuration.

The requirement of a large N becomes difficult to satisfy technically owing to the enormous stored energy per unit length. Considering the inequality as an equation, one gets for the stored energy of a zero-gain reactor

$$W_S = W_L = 10^{10} r_o \text{ Joules.}$$

Comparing this with the energy liberated in an explosion of one ton of TNT, which is about 10^{10} Joules. one can see that this type of reactor is somewhere between a large rocket engine and a small atom bomb.

There are at least three ways to minimize the requirement for such high stored energies. First, one should make an attempt to decrease r_o as much as possible. Second, one should try to decrease the expansion speed below that of free expansion and this implies the use of some confinement mechanism. Third (and this is connected with the second method), one may try to recuperate the energy of the radial plasma flow during the expansion of the plasma column. All three objectives may be accomplished by using a magnetic field to drive a hollow plasma shell.

A simple model of such a configuration is a cylindrical shell of plasma of effective thickness d, driven towards the axis of symmetry with an acceleration $\ddot{r} = B_\varphi^2/8 \pi d n M$, where $d n M$ is the plasma mass per cm^2 of the surface of the shell. The thickness d can be very small; if, e.g., $\dot{r}$ approaches $2x10^8$ cm/s near the axis and if the radial distance over which the collapse occurs is 50 cm, then $\ddot{r} = 4x10^{14}$ cm/s^2. If at the same time T is about 10^6 °K, the thickness d becomes $d \approx 0.08$ cm. The formation of the plasma on the axis of the system occurs as a result of collisions within the hollow shell which for $r < d$ is collapsing on itself. Restricting to the case of such large plasma densities that the nuclei in the inter-shocking plasma become nearly thermalized, one finds under simplifying assumptions

$$\frac{N}{d} > 2.6\mathrm{x}10^{22} .$$

It follows that a system whose N/d is an order of magnitude lower than required for a zero-energy gain reactor will already produce a nearly thermalized nuclear gas column in the axial region, in accordance with the fact that the DT reaction cross-section is an order of magnitude smaller than the Coulomb cross-section of large angle scattering at 100 keV.

In the case of no collisions, the minimum radius of the plasma column r_o is $d/2$, whereas in the shock generated by collisions the minimum radius r_o is $d/(2 \sqrt{6})$, giving $N/d > 0.4\mathrm{x}10^{23}$ for the zero-energy gain reactor.

After the collapse to a minimum radius, the plasma will expand and encounter a decelerating force of the pinching magnetic field B_φ ; the energy of the expanding shell will be transformed back into the magnetic field B_φ and through this into the stored electric energy of the plasma source. The efficiency of such a recuperation mechanism can be estimated only by means of an experiment, but neglecting radiation losses and loss in solid conductors, the efficiency can be made as high as desired, provided the expansion ratio is made correspondingly large. The radiation losses are probably small owing to the rapidly decreasing electron temperature.

As an example, let $d = 0.1$ cm , $Q = 20$. Then $N > 6\mathrm{x}10^{20}$ and the stored energy in the column is $W_S = 3\ k\ T\ N = 2.5\mathrm{x}10^7$ Joules/cm. The energy dissipated during the half-cycle becomes $W_L = 4$ MJ/cm. The absorption of such an amount of energy by a reactor chamber seems to be within the scope of present day engineering.

In practice it may be necessary to use a toroidal system rather than a cylindrical one, and the requirement of very large stored energy may lead to the use of hydromagnetic capacitors rather than conventional ones.

Rebut summarized some theoretical investigations of a collision-free plasma in a cylindrical geometry.

Starting from the equations of motion and Maxwell's equations, the behaviour of the electric and magnetic parameters have been followed and a first integral has been obtained for the motion of a particle in a general field configuration.

The equations of motion have then been integrated in the case of a static axially symmetric configuration, where the magnetic field possesses only the components $B_z(r)$ and $B_\theta(r)$, and the electric field the component $E_r(r)$. The condition of confinement can then be written down in phase space.

Next, stationary states of a collision-free plasma in a cylindrical geometry have been looked for, starting from Boltzmann's equation and assuming isotropy of the distribution functions around a macroscopic velocity.

The assumption of no collisions is justified if one is interested in the instantaneous plasma configuration (not in its evolution) and if a) the time during which the collision takes place is much smaller than the time elapsing between two consecutive collisions, b) the characteristic length L corresponding to the various gradients in the plasma does not exceed considerably the mean free path. The assumption of stationary state is valid if the variation of the magnetic fields is negligible in a time L/v, v being the average speed of the particle. The isotropy is a first approximation for a distribution function.

With the preceding assumptions one can show that in an axially symmetric configuration there exists a linear relation between B_z and rB_θ, that the longitudinal current is proportional to $r\,n(r)$.

Numerical values have been worked out with the help of a digital computer and the results have been checked against those obtained by Tuck on Columbus 4 and by Colgate on a similar device.

Finally, the results have been extended to helicoidal geometries and stability criteria have been established in this case.

9. ORGANIZATIONAL PROBLEMS

After discussion it was agreed that the Chairman should ask the CERN Council to continue its sponsorship. In case CERN did not want to do so, it was decided to declare the Fusion Study Group as a new Society and seek for recognition by leading scientists in the various countries (Cockcroft, Heisenberg, Perrin, etc.).

10. E/CEA AGREEMENT

On behalf of Palumbo, Waelbroeck announced the signature of a Euratom/Saclay contract. A mixed team of research has been created, led by Vendryes.

Various scholarships have been granted by Euratom for Saclay and Munich.

11. DATE OF NEXT MEETING

The next meeting will take place on 9 and 10 June, 1960 at Fontenay-aux-Roses.

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