CERN/FSG/14
June 26, 1961

EUROPEAN STUDY GROUP ON FUSION

Seventh Meeting

Rome (Frascati) - 6, 7 and 8 April, 1961

NOTES

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NOTES

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B.P. No 6
Gif-sur-Yvette (S. et O.)

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Linhart, J.G.
Magistrelli, F.
Maisonnier, C.
Martellucci, S.
Martone, M.
Nation, J.A.
Segrè, S.E.
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Other delegates

Auer, P.L.
General Electric Laboratory
Schenectady

Frieman, E.A.
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1. WELCOME BY THE ROME GROUP

Brunelli extended his welcome to all participants on behalf of the Rome Group.

2. VISITS TO LABORATORIES

The participants were taken round the laboratories to see the experimental facilities. The main devices are:

1. Fast orthogonal pinch (CARIDDI).
2. Small orthogonal pinch.
3. Hollow dynamic pinch (MIRAPI).
4. Magnetic field intensification (MAFIN).
5. Sheath experiment 1.
6. Sheath experiment 2.
7. Initial magnetic field for CARIDDI (H_0).
8. Schlieren experiments.
9. Interferometry.

3. WORK AT JÜLICH

Fucks gave an overall talk on the new Plasma Institute at Jülich.

Jordan summarized the experiments being set up or already performed:

A. High Density Plasma Experiments

a) 5 kJ fast compression. A combination of bias B_z field, preionization and preheating has been used; essential data have been given at previous meetings.

b) The 5 kJ experiment has paved the way for a larger experiment. A 250-500 kJ condenser bank is now under construction; longer coils and larger volumes will be used. Main difficulties are switching, safety, collectors and timing.

c) A plasma gun of the Marshall type has been constructed. It is provided with an asymmetric compression coil, preheating, B_z guide field and fast valve. This experiment will be extended.

d) A fast opening valve (10-100 μs) is under construction.

e) Studies of optimal coil shape are being made.

f) A new plasma gun is being developed to investigate injection, trapping and interactions with magnetic fields.

B. Diagnostic Experiments

a) Probes.

b) Spectroscopy (from visible to vacuum ultra-violet).

c) Coaxial sliding spark source.

d) Microwave interferometry (8 + 4 mm).

e) Time-resolved photography.

f) Mach-Zehnder interferometer for high densities.

g) Ion spectrometer operating on plasma gun.

h) Match of RF plasma to the compression coil and to the stabilized pinch.

C. Theory

a) Compression with internal magnetic field (Kever).

b) Stability theory (Schindler).

4. WORK IN STUTTGART

Kluge gave an overall review of the work performed at Stuttgart where the Institute for the Study of High Temperatures is mainly engaged in research on ohmic heating of plasmas. In this work, approximately two thirds of the capacity of the theoretical group and almost the total of the experimental staff are used. Other aspects of the work, partly of a more preparatory nature, are fundamental problems of kinetic theory, hydromagnetic shock waves, azimuthal pinch configurations and electromagnetic waves in a plasma. Several papers on these subjects will be presented at the forthcoming conferences in Munich and Salzbourg, and more detailed information is available in the form of theses presented at the "Technische Hochschule Stuttgart".

In investigating the ohmic heating of plasmas with relatively high density, it was decided to use an experimentally simple gas, namely nitrogen, for the initial phase of work. The investigation of a hydrogen plasma has also been started, but these experiments have not yet progressed sufficiently to warrant a comprehensive report at present.

The heating of plasmas to very high temperatures is generally associated with short-time phenomena. In order to limit the experimental equipment and, thus, the financial expenditure, it was decided to use condenser discharges in the microsecond range where small energy capacities still yield sufficiently high electric power output. This required an extensive development of techniques and equipment for short-time measurements which have their own difficulties.

At present, time intervals of about 10^{-7} seconds are used, both with image converters and mechanical as well as electronic shutters for spectrographs.

In the case of the nitrogen discharge, a geometrically and thermally well defined plasma is obtained for the duration of a current half-period. This plasma is of high density and has a relatively high temperature.

The diagnostic methods developed for the nitrogen discharge are being applied now to the hydrogen discharge. Theoretical methods consecutively developed permit numerical calculations of such discharges as well as a satisfactory interpretation of the experimental results.

Kaeppeler reported in more detail on ohmic heating of high density plasmas (10^{17}-10^{18} particles/cm^3):

A. Experimental Procedures

In addition to the short-time technique mentioned above, the experiments were characterized by the use of a predischarge, so that the condensers are discharged over a preionized plasma column. The preionization reduces the breakdown voltage of the condenser discharge.

The essential requirements for such a predischarge are well defined geometry, spectral purity, a near to 100 o/o degree of ionization and possibilities for visual observations. Furthermore, the preionization should be reproducible with reasonable technical expenditure. Various possibilities can be used for obtaining preionization: ion beams, electron beams, γ-rays, shock waves, electromagnetic waves (RF heating), exploding wires, free-burning discharge arcs, wall-stabilized arcs, rotating arcs, vortex-stabilized arcs, etc.

Preionization by electron beams, by rotating arcs and by vortex-stabilized arcs was tested. In the last case satisfactory results were achieved. Spectroscopic measurements under moderately forced operating conditions showed temperatures between 12 and 15 000 ^{o}K near the axis, corresponding to degrees of ionization between 16 and 56 o/o. This type of arc was also used to preionize a hydrogen plasma where temperatures exceeding 20 000 ^{o}K were measured. For practical purposes such a plasma may be considered as fully ionized.

Over the plasma column thus generated, a condenser bank is discharged and this achieves the actual heating of the plasma.

To develop diagnostic methods, several small impulse discharge sets were constructed. In most cases these sets were equipped with one condenser $C = 7.7\ \mu F$ and $U_o = 18$ kV. The characteristic data of the discharge are $I_{max} = 140$ kA and rise time $t_A = 1.5\ \mu s$.

B. Diagnostic Methods and Theoretical Analysis

The optical observation of the impulse discharge was performed using an image converter with effective exposure times of 2 to 3 x 10^{-7} seconds. The photographs obtained with the aid of the image converter showed geometrically well defined columns of approximately 1.5 mm radius, taken from the initiation of the pulse discharge up to the maximum current.

No instability during the duration of the experiment was observed. A theoretical investigation was then attempted, based on a separate treatment of a viscous gas envelope and a rotation of a plasma cylinder with gas envelope. These studies showed that the presence of a gas envelope as such does not provide full stability, but the viscosity of this envelope results in a reduction of the velocity of instability growth. Considering inertia and viscosity of the gas envelope, the theory yields a minimum time constant of 2 x 10^{-7} seconds for the instabilities in the experimental arrangement considered. The life-time of the plasma geometry in this arrangement should, according to theory, be appreciably larger than that of pinch experiments; it should at least be equivalent to a quarter-period of the current oscillation.

In the case of a rotating gas envelope (vortex), there exists a current limit below which the plasma configuration is stable. In the experiments considered, the current is below the limit in the predischarge but above the limit in the impulse discharge. In the case of nitrogen, the cylindrical plasma is therefore stable during the predischarge (stability due to envelope rotation), but it is unstable for the impulse currents used. It may, however, be considered as quasi-stable for the duration of the experiment (damping by viscosity of the envelope).

For further investigations, knowledge of the current density profile in the plasma was essential and this was determined by probe measurements. With the probe measurements as a basis, the ohmic heating process was calculated, including ionizations as non-equilibrium phenomena. The calculations show that while the electron temperature is somewhat higher than the ion temperature during the first 10^{-7} seconds, the particle density soon establishes practically full thermal equilibrium. Furthermore, it was found that the degree of ionization deviates less than about 30 o/o from its prevailing equilibrium value. At the initiation of the pulse discharge, the plasma radius increases slightly, remains almost constant in the neighbourhood of the current maximum, and later increases due to the magnetic pressure decreasing with current.

The calculation also yields the distribution of energy among the various loss mechanisms. Radiation loss is by far dominant because of the nearness of the black-body regime.

Finally, it should be mentioned that to carry out time-resolved spectroscopic investigations of the discharge, a mechanical shutter with effective exposure times of the order of 10^{-7} seconds has been constructed.

5. WORK IN MUNICH

Eckhartt reported on work in Munich:

A. H. Schlüter's Experiment

In this experiment (described during the last session), much emphasis has been put upon an understanding of the mechanism of the discharge. A powerful RF excited discharge is maintained in a quartz tube under very clean conditions and a static magnetic field forming a magnetic bottle is superimposed on the discharge. Temperature and density measurements have been made using Langmuir probes, microwaves and spectroscopic data. The probe measurements reveal the existence of hot electrons of about 40 000 ^{o}K. The spectroscopic determinations from the slope of the continuum radiation of the Balmer series and from an absolute measurement in the continuum gave an electron temperature of about 2 000 ^{o}K. The density was measured using the shift of the series limit, from line profiles, and from the absolute measurements mentioned above; it is found to be in good agreement with the results of microwave measurements. It is now believed that the bunch of electrons of high temperature and low density is responsible for the ionization processes which are balanced by radiative recombination of the slow electrons of high density. Following these ideas, a modified "Corona Formula" can be used which reasonably well describes the behaviour of the discharge, i.e. the degree of ionization.

B. Eieruhr

This is a pulsed discharge at He-pressures of 20-40 mm Hg, and thermal equilibrium should be achieved at these conditions. The voltage along the straight portion of the discharge tube as well as the current have been measured and the temperature and radial temperature profile were determined spectroscopically at the end of the observations. Temperatures range from 27 000 to 35 000 °K and, using these data, the resistivity of the plasma has been computed; within the experimental errors there is agreement with Spitzer's formula.

C. Cabinet

With this experiment, some fundamental features of a plasma in a magnetic field like oscillations and diffusion across the magnetic field will be studied. The experimental apparatus consists of a glass tube, 20 cm in diameter and 120 cm in length, with a magnetic field parallel to its axis. At one end of the tube, plasma is produced by a "duoplasmatron" plasma source. At the other end, the gas which leaks through the plasma source is pumped off by a 8 000 litres per second pump. The duoplasmatron, which was originally conceived as a strong ion source, consists essentially of a low voltage arc burning through a nozzle and a strongly inhomogeneous magnetic field. Plasma and fast electrons leave the source along the magnetic lines of force, forming a beam of about 2 cm in diameter in the long glass tube. Preliminary measurements of potential and density distributions in the tube with hydrogen at pressures of 10^{-3} and 10^{-5} mm Hg have been made using Langmuir probes and microwaves. Pressure conditions in the tube seem to govern the composition and the temperature of the beam of plasma leaving the source. At the higher pressures, the density of the plasma is relatively high in the central part of the beam, the degree of ionization being estimated to about 50 o/o. The radial distribution of the floating potential of a Langmuir probe shows a characteristic dependence on pressure and magnetic field strength. With Langmuir probes of different shapes it is attempted to determine the radial density distribution and hence the diffusion across the magnetic field, together with simultaneous measurements of the noise in the microwave region.

D. UV-Intensity Standard

In the spectroscopic group (Boldt), an intensity standard has been developed for the vacuum ultra-violet which is useful for the calibration of detectors in this spectral region. This standard consists of a cascade arc burning in argon at atmospheric pressure. A second gas, hydrogen in this case, is admitted at a certain point along the discharge in such a manner that it is confined to the column of the arc. In the vacuum UV region and in the vicinity of its resonant lines, the intensity emitted by the hydrogen gas is equal to that of a black body having the temperature of the arc. This temperature can be determined by measurements in the visible region. The observation of the UV radiation produced in that way is made through a narrow channel in the cathode which opens only for the central and homogeneous part of the column. This light source is connected to the vacuum spectrograph by means of a movable valve which opens during 10 seconds for observations. Measurements have been made using the Lyman α-line 1216 Ångström units at an arc temperature of 11 900 °K. It is planned to extend this method to other regions of the vacuum UV by the introduction of other gases.

6. THEORETICAL WORK IN MUNICH AND GARCHING

Hain reported on theoretical work in Munich and Garching:

A. Bineau (Euratom)

The stability of an axially symmetric torus has been investigated, and a necessary and sufficient stability criterion has been found by generalization of Newcomb's criterion for a cylinder. This work will be supplemented by numerical calculations as well as an attempt to generalize the results to cases without symmetry.

B. Canobio, Croci (Euratom)

A modulated point ion beam is being studied by treating the problem as an electromagnetic disturbance which acts on the plasma. The energy dissipation of the beam into the plasma is being investigated.

C. Fisser, K. Hain, G. Hain

An implicit code for the numerical solution of the fully ionized pinch collapse has been developed and a few computations have been completed. The code can be used for conventional z-pinches as well as for fast θ-pinches. A substantial part of this work has been done in collaboration with the Naval Research Laboratory and the National Bureau of Standards, Washington. The results will be compared with the experiments performed by Kolb at Los Alamos and by Fünfer and his group at Garching. Fisser is working on a comparison with experiments (z-pinch) carried out in Aachen.

D. Hagenow

The correlation function of a one-dimensional plasma model has been computed numerically by a Monte Carlo method, and it was found that the Debye theory holds good in all cases where the number of particles within a Debye volume is not too small (about three or more).

E. Knorr

The one-dimensional Vlasov equation for one kind of particles has been solved numerically. The main purpose is to investigate the non-linear behaviour of the time-dependent distribution function for several sets of initial conditions, especially non-linear Landau damping and the stability of the non-linear solutions as found by Bernstein, Green and Kruskal.

F. Lüst, Martensen

The numerical work on the stability of a torus possessing axial symmetry and surface currents has been generalized.

G. Pfirsch

The microscopic dispersion relations have been expressed by moments of the distribution function by expanding the undisturbed function into a series of Hermitean polynomials. This form of the dispersion relation will be studied by means of numerical calculations and the influence of runaways will be investigated.

H. Trefftz

Ionization cross-sections for OV - OVI and similar configurations are being computed.

7. WORK IN ERLANGEN

Michel reported on the use of Hall probes in fast, high current pulse discharges:

The experiments were carried out by means of a big condenser bank of the Siemens Laboratory at Erlangen. Data of the bank are 1030 μF, 15 kV, 116 kJ, 4 nH. The condenser can be discharged through a glass or quartz vessel of 38 cm inner diameter and 45 cm length by means of 36 spark gaps.

In measuring space and time distribution of the current density, a high sensitivity, high resonance frequency and high signal to noise ratio can be obtained by means of Hall probes.

The principle of the Hall effect is well known. In applying this effect to practical measurements, care must be taken to reduce the galvanomagnetic effect, namely the increase of the resistance in the direction of the control-current with increasing magnetic field. By inserting a high resistance into the circuit, the change in control-current can be kept sufficiently small. The temperature dependence of the Hall coefficient limits however the applicability of the Hall method because the control-current heats up the semiconducting plate. As a remedy to this, the control-current can be pulsed; much higher values can then be used than is permitted in the stationary case. Following this idea, a pulse generator has been built which consists essentially of two thyratrons, one of them switching on the control-current and the second cutting it off after some delay. The pulse generator delivers rectangular pulses between 3 and 20 A up to 15 μs, the total rise time being 40 ns.

A predetermined overall sensitivity of a given Hall probe can be reached either by low Hall-sensitivity (i.e. low control-current) and high amplification or high sensitivity and low amplification. When the Hall probe is inserted in a fast linear pulse discharge, a high-frequency noise is observed, especially at low pressure, low Hall-sensitivity and high amplification; but no noise can be seen at all if the probe sensitivity is high (e.g. 2×10^{-3} Volt/Gauss, control-current 20 A) and the amplification gain small. It should be mentioned that it is unnecessary to shield the probe by a metallic screen.

As long as axial symmetry is conserved, the magnetic field in the chamber wall can be correlated to the discharge current. Thus, by comparing the integrated Rogowski-coil signal with the output of a Hall probe located in the chamber wall, the axial symmetry can be checked.

To measure the space variation of the current onset in the discharge, a Hall probe of 6×10^{-3} Volt/Gauss sensitivity and 240 Mc/s resonance frequency was used. The amplification could be adjusted so that an overall sensitivity of 168 Gauss per cm deflection on the oscilloscope could be reached. By inserting this probe into the discharge, the current onset was measured at various distances from the axis; it turns out that at a distance of 5 cm from the axis a magnetic field of about 40 Gauss appears at the moment of breakdown. This field rises slowly with time until the contracting current layer reaches the probe.

In conclusion it can be said that in comparison with induction probes the pulsed Hall probe is not only adequate to measure strong magnetic fields inside a high current discharge but can also be used to measure very weak fields on account of its high sensitivity, high resonance frequency and high signal to noise ratio.

<u>Motschmann</u> reported on optical experiments with high current pulse discharges:

At the Research Laboratory of the Siemens-Schuckertwerke in Erlangen a group of physicists is studying the behaviour of high current pulse discharges of the linear pinch type. A small condenser bank together with a cylindrical tube have been developed (Schindler) and measurements have been made with magnetic probes. Data of the apparatus are: capacity 30 µF, load voltage up to 15 kV, stored energy about 3 kJ, external inductivity 62 mµH. The condenser is connected coaxially via a single triggered spark gap to the electrodes, the discharge tube (of Duran-glass) between them having a length of 50 cm and a diameter of about 20 cm. The time-dependent current behaviour and the voltage between the electrodes have been measured by means of Rogowski coils and low inductance voltage dividers respectively. The optical instruments are all located at 3 m distance and work synchronously. The discharge tube is surrounded by 16 conductors, 8 mm in diameter, enabling the discharge to be viewed from the side. Streak photographs of a cross-section of the discharge diaphragmed out by a 3 mm slit were taken with a drum camera (film speed 100 m/s, focal distance of the objective glass 10 mm, aperture 1.8). The time resolving power was 0.1 µs. On the opposite side, a photoelectric cell picks up the light emitted along the diameter. From the double beam oscillograms of the photoelectric signal and the change of current accurate time relations could be obtained between the electric and the optical records. For spectrographic work a time resolving spectrograph has been built consisting of a cross-slit, 1 mm high, a prism, an achromatizer, and drum camera. The time resolutions used were 0.3×10^{-6} seconds with glass optics and 0.7×10^{-6} seconds with quartz optics.

Typical streak photographs of hydrogen discharges at initial pressures from 0.03 up to 3 mm Hg show that while the details may vary widely with pressure, discharges at the same pressure are not essentially different. At the beginning of the discharge a faint luminosity has been observed, followed by a reduced light emission. It may be assumed that at this time the light is emitted especially in the vicinity of the walls, so that no luminous layer of great thickness is to be seen from outside in the observing direction. Film density measurements make this assumption probable. The luminous sheath detaches itself from the walls and is rapidly accelerated, whereas the velocity of the compression seems to be roughly constant afterwards. The time of contraction decreases if the initial pressure is reduced. At highest pressure the region of strong light emission is small during the pinch. A glow over the whole cross-section visible in all pictures appears at the time of completed first contraction. At later times these phenomena reduce probably to gas oscillations. If the initial pressure is low, the discharge is turbulent after the first contraction.

Time-resolved spectra show that at the times of the various contractions, a strong continuous radiation is emitted in the visible and ultraviolet region. The Balmer lines are observed with different Stark broadening.

The results of magnetic probe measurements made it possible to plot on the radius-time plane lines of equal value of the circular magnetic field as well as of the current density. Maximum values of the current density have been found to be in agreement with the radiation intensity in the luminous front.

From the intensity distribution of the radiation in the observing direction $I(x)$ the radial intensity distribution $i(r)$ has been derived by solving Abel's integral equation.

Results of investigations performed with image converters will be presented later on.

8. WORK IN HANNOVER

Zwicker reported on work performed in Hannover:

This work is essentially concentrated on four devices: dynamic Z-pinches, O-pinches, plasma-jets and Z-pinches in preformed high pressure plasmas produced by exploding wires.

On the Z-pinch, spectroscopic measurements were systematically performed to provide a base for the spectroscopic examination of the pinch at various initial conditions. Four different methods were combined for that purpose:

a) absolute photoelectric intensity measurements;

b) absolute photographic time-resolved measurements of intensity;

c) a method which gives 20 spectra from one shot with a time distance of 0.8 seconds, every spectrum giving the spectral distribution over the whole cross-section of the discharge.

d) the direct measurement of the optical thickness.

Photoelectric measurements of the absolute intensity distribution at the moment of the pinch in helium for various initial pressures indicate that the intensity increases rapidly towards the shorter wavelengths. It has been found that already at 4 000 Å the optical thickness of the continuum is greater than 2. This strong reabsorption complicates on one hand the correlation between the state variables in the pinch and the measured intensities; on the other hand, however, it opens the possibility to take into account the strong influence of the radial temperature distribution and therefore to give more than qualitative results of the state variables at the axis of the pinch column. This evaluation is under way.

Examples of photographically measured smear spectra were given for xenon, the pressure increasing from 6×10^{-2} to 1 mm Hg. This absolute method gives the possibility of measuring line shapes and intensity ratios of different lines during the contraction and can give further information. The spectra for rather high pressures show a great number of self-reversed lines short before the pinch, and each of these lines allows a temperature measurement. The comparison at different lines can answer the question whether there exists a uniform excitation temperature or not.

In order to find out something about the radial distribution of the spectrum at different phases of the discharge and to measure the geometrical thickness of the pinch continuum, a special method has been developed, the results of which were shown in a slide where 18 succeeding spectra of one helium discharge at 2 mm Hg could be observed. The time sequence of the spectra was 0.8 seconds.

Until now the optical thickness was directly measured only at 4 000 Å. In agreement with the spectral distribution of the continuum, a value of about 2.8 was found. Because of this large value the measurements are rather difficult in the visible and are now continued in the UV.

In addition to the spectroscopic investigation, the time correlation between contraction, spectral intensity, current and voltage has been determined for various initial conditions. It was found, for example, that xenon-pinches at 0.1 mm Hg and higher are not accompanied by a kink in the current, while helium-pinches with the same time-scale have a strong kink. This implies that the current distributions are different in both discharges. To clear this and other questions, the following measurements have been started on the Z-pinch device:

magnetic probe measurements

piezo-electric measurements of the pressure

absolute measurements in the UV range

X-ray measurements.

The 0-pinches in rare gases up to 20 mm Hg were at first investigated for different coils by a simple smear-technique in a 20 kJ device. After some unsatisfying preheating experiments with Z-pinches and exploding wires, the upper electrode was opened up in another 20 kJ Z-pinch and the plasma jet was observed shooting into the tube above the pinch vessel at the moment of the pinch. This device will be combined with 0-pinches to study preheated 0-pinches.

The phenomena of confinement in a Z-pinch, preheated by an exploding wire, are being further investigated with the new 200 kJ bank. The influence of the stored energy on the contraction is being looked for, the methods of observation being similar to those used in the case of the dynamic pinch.

Finally, a series of spectra were shown in a slide of an argon discharge at 0.5 atm.

9. WORK IN ROME

Allen reported on some aspects of the work being carried out in Rome:

A. Large Condenser Bank

The large condenser bank (144 kJ) for the Cariddi experiment is under construction. One third of the condensers have been connected so far.

B. Small Condenser Bank

This will be used to excite low-frequency discharges in a 1 m long, 30 cm diameter tube.

C. Experiments

a) Rapid compression of a plasma; compression velocity comparable to Alfvén velocity in plasma.

b) Space charge sheath surrounding a low temperature plasma.

c) Plasmoids of RF type.

d) Refractive index experiments (Ascoli).

e) Hydromagnetic shock waves.

D. Diagnostic Techniques

Magnetic probes, rotating mirrors, image converters, framing and streak cameras, interferometry; the possibility of using Schlieren photography is being studied.

E. Theoretical Work (Gratton)

Dynamics of a collision-free plasma in the absence of a magnetic field.

Numerical integration of Vlasov's equation.

Hydromagnetic stability in a torus.

Linhart reported on unconfined plasma configurations:

A high-temperature, high-density plasma which is either unconfined or marginally confined may be typically specified by its mean density n, temperature T and the period of its existence τ as follows:

$$n > 10^{20} \text{ el/cm}^3 , \quad T > 10^7 \, {}^{\circ}\text{K} , \quad \tau < 10^{-7} \text{ s}$$

Three methods of production of such plasmas are being investigated.

The first is based on the acceleration by a magnetic field of a thin cylindrical layer of plasma (a typical line-density is 10^{19} deuterons/cm). This should result in a shock produced near the axis, generating a region of thermalized high-density plasma within a radius r_o whose temperature is T_o and whose mean life-time is $\tau = 2 r_o / \sqrt{2 k T_o / M}$. The total neutron flux from such a shock is

$$\nu = 0.9 \times 10^{-21} \frac{N^2}{r_o} \frac{F(T_o)}{\sqrt{T_o}} \quad \text{(neutrons/cm)}$$

where $$T_o = 0.25 \times 10^{26} \frac{W}{N} \quad ({}^{\circ}\text{K, kJ/cm, deuterons/cm})$$

$$F(T_o) = 0.37 \times 10^{17} < \sigma_n W >_{DD}$$

and W is the available input energy per cm length of the discharge. Similar formulae can be obtained for a 50/50 mixture of a DT plasma. For this, a reactor condition can be written as

$$W > \frac{3 \times 10^4 \, r_o}{x \; Q} \quad \text{(kJ/cm)}$$

provided $T_o = T_{opt} \approx 0.85 \times 10^8$ (°K). Here Q is a factor representing the quality of recuperation of the plasma energy into the electrical energy of the condenser bank and x is a factor expressing the quality of confinement and can be written as

$$\varkappa = \frac{\sqrt{2\,k\,T_0/M}}{v_{ex}}$$

where v_{ex} is the mean speed with which the plasma expands from r_0 to $2\,r_0$.

The experiment designed to test these phenomena is called MIRAPI, i.e. the Minimum Radius Pinch.

The second method for the production of high-density, high-temperature plasma follows naturally from the first in trying to confine the high-temperature plasma core for a time superior to $\tau = 2\,r_0/\sqrt{2\,k\,T_0/M}$. In other words, one tries to obtain $\varkappa > 1$.

If this is to be done by means of a magnetic field, the strength of such a field must correspond to at least 10 MGauss. Such fields were produced by imploding cylindrical metallic liners at Los Alamos. In the Rome arrangement such a liner can be driven either by a magnetic field or by chemical explosives. In either case it compresses a B_φ field which in turn compresses, heats and confines a central column of plasma. The confinement resembles the inertial confinement used by putting tempers around bomb-assemblies. The experiments embodying these ideas were called MAFIN 1 and 2, standing for Magnetic Field Intensification.

The third method, studied so far only theoretically, is that of spherical shock waves. The efficiency η of converging shocks in transferring, e.g., explosive energy located originally outside a radius R into a much smaller volume of radius r_0 has been calculated to be

$$\eta \sim \left(\frac{r_0}{R}\right)^2$$

This poor energy transfer seems to eliminate the converging shocks as a possible mechanism for reactors.

10. WORK IN HOLLAND

Braams gave a short review of work performed in the Netherlands:

The new Jutphaas laboratory is now finished and a few experiments are being set up.

A. Pinch Experiment

Techniques are being developed and the trapping of B_z as a function of preionization is studied.

B. Alternating Pinch

Theoretical work on stability.

Primary currents about 90° out of phase during 1½ cycle.

C. Duoplasmatron

50 mA unanalyzed at 20 keV.

D. Radial Plasma Gun

A ring of plasma is contracted by a B_θ field. 1 μs, ¼ period. Estimated velocity from I(t) and V(t) is $3\text{-}4 \times 10^7$ cm/s.

E. RF Confinement

Most proposals have met with great technical difficulties. A simple experiment is now being designed, based on single particle confinement.

F. Stimulated Emission

An experiment is being designed to study the interaction of electron beams of anisotropic and non-Maxwellian distribution with radiation fields.

G. Diagnostics

Rotating mirror camera, 50 frames of 5 μs each.

Image converter.

Microwave interferometer (8 mm).

Time-resolved neutron spectrometer.

H. Work at Kema-Laboratories

A linear discharge tube for high-current arcs in hydrogen and deuterium is under construction. Length of the tube 181 cm, inner diameter 30 cm. The tube is composed of seven elements (aluminium bronze), separated by porcelain rings; it has a double pumping system.

The generators of the Kema short-circuit laboratory provide intensities of up to 150 kA at 50 c/s. At the operating frequency, the heating of the gas will be mainly ohmic. The behaviour of the arc and its temperature will be studied as a function of gas pressure for various axial magnetic field configurations.

11. WORK IN BRUSSELS

Baudoux introduced the work.

Vanhauwermeiren summarized the experiments being carried out at Brussels University:

Work on T-tube shocks is in progress, but no results are available as yet.

Linear pinch experiments were performed with a condenser bank of 60 µF, 10 kV. The external inductance was 170 mµH. A pyrex tube 430 mm long and 200 mm in diameter was used at pressures between 0.3 and 1 torr.

An attempt was made to check the Leontovich-Osovetz model. For that purpose, the Leontovich-Osovetz equation was integrated by means of electronic and analogue computers for various initial conditions and several values of the parameters. On the other hand, the experimentally observed law of current was inserted into the equation. Consequently, the law giving the radius as a function of time could be found theoretically as well as experimentally. The curves fit more or less according to the values of the parameters.

Optical measurements were carried out, using the image converter technique on the tube described above and on another one, somewhat smaller

(67 mm diameter). The presence of a very luminous thread was observed in the middle of the discharge some tenths of a microsecond before the pinch. This phenomenon was particularly important in the smaller tube.

Comparisons between optical and electric measurements gave an indication as to the values of the resistance and the resistivity of the plasma. From electric measurements it is possible indeed to calculate the radius of the discharge as a function of time, the resistance of the plasma being neglected. The actual law being optically obtained, the discrepancy between the first (approximate) result and the second provides a means of determining the resistance. The figures obtained were 4 x 10^{-2} ohm after 1 µs and 4 x 10^{-3} ohm after 4 µs (pinch).

Spectroscopic measurements indicated that the emission of silicon from the walls - revealed by the intensity of the silicon lines vs. time - takes place together with the instability of the plasma column, which was otherwise observed with the image converter. The instability appeared well to be like an explosion of the plasma column in many luminous balls.

The distribution of the magnetic field inside the discharge will be measured next.

12. WORK IN STOCKHOLM

Alfvén gave an overall review of the work being carried out at the Royal Institute of Technology:

A. Confinement and Energy Balance of a Magnetized Plasma (Lehnert and Bonnevier)

It has been suggested (Lehnert 1958; Colgate 1959) to confine a plasma in the magnetic field of a current loop, the heating of the plasma being provided, e.g., by a transverse electric field which sets the plasma into rotation around the axis of symmetry (Lehnert 1959). A study of the motion of an individual particle has shown that under certain conditions particles get completely trapped inside a "bag" of magnetic field lines which is "sealed" by the centrifugal force (Bonnevier and Lehnert, 1959). In the case where the electric and magnetic fields are perpendicular all over the confinement region, it can be shown that the angular velocity of rotation becomes constant along a field line. The situation resembles that of a planetary atmosphere, where the particles are trapped by a gravitation field, provided that their thermal velocity falls below the escape velocity. To determine the situation completely, the relation between the centrifugal force and the thermal energy of the plasma has to be derived from the energy balance.

For this purpose, a macroscopic theory was established where conservation of mass, charge, momentum and energy is taken into account as well as interactions between all particles being involved. The theory was derived for a three-fluid model consisting of an ion and an electron gas moving in a neutral gas, the latter being essentially at rest. For an axially symmetric plasma the angular velocity is again found to be constant along a magnetic field line to a high degree of approximation. Two special cases can be treated in detail, one with vanishing heat conductivity and one with infinite heat conductivity in the direction along the magnetic field lines. Due to the relatively high thermal conductivity along the field in a high temperature plasma, the latter case is more likely to occur and the energy loss by escaping particles has been studied in detail for this case. The results of the calculation seem to be applicable up to a temperature of about 10^7 ^{o}K. Above this value the confinement is impaired by charge exchange collisions and elastic scattering of neutrals which enter the plasma region. The theory predicts that the energy loss by escaping particles should be several orders of magnitude less in the field of a current loop than in homopolar machines.

Experiments to check this theory and to study the confinement of electrons in different types of magnetic "bottles" have been carried out by Bonnevier. A cathode was placed inside the confinement region and the electron current to the surrounding walls was measured as a function of the magnetic field strength. Toroidal and mirror-shaped fields were examined as well as the field generated by a circular loop. The experiments indicate that the latter field can be used to trap particles in all directions. Further, it has been found that the suppression of the total electron current is controlled only by the poloidal part of the magnetic field, as predicted by theory. The experiments are being continued.

B. Plasma Resonance (Dattner)

The interaction between an ionized gas column and an electromagnetic wave in a waveguide was studied experimentally, special attention being given to the subsidiary resonance peaks. These were investigated as a function of frequency in the interval 2-4 Mc/s, and as a function of the plasma column diameter. It was found that the number of resonance peaks decreases with frequency and plasma diameter, that the spacing between the resonance densities corresponding to different peaks increases with decreasing plasma diameter, that the plasma resonance spectrum possesses a definite series limit (i.e. a plasma density under which no resonance occurs) and that the densities corresponding to both the resonance peaks and the series limits are linear functions of ω^2.

C. Amplification of the Poloidal Magnetic Flux in a Plasma (Lindberg, Jacobsen, Angerth, Witalis and Wilner)

The purpose of this experiment was to produce rings of magnetized plasma.

In the experiment, a magnetized plasma is produced by a high current discharge between coaxial electrodes and is shot out of them. Before it leaves the electrodes it has to pass a radial magnetic field between a magnetic N-pole in the inner electrode and a ring-shaped S-pole in the outer electrode. When the plasma passes this field it takes the lines of force with it, provided the conductivity and the density of the plasma are sufficiently high. The lines of force will be stretched out and finally they can be expected to "break" so that a free plasma ring is produced which moves on.

One would expect that the ring-shaped plasma passing the static magnetic field at the nozzle of the gun would conserve the magnetic flux through the central electrode of the gun as a "poloidal" flux through the centre of the plasma ring. The experiments, however, often show that the flux carried by the plasma is several times larger than the static flux. This phenomenon seems to be due to an instability of the pinched current path in the plasma which turns to a helix, so that the azimuthal flux in the plasma, originally set up by the discharge current, is transformed to a poloidal flux.

D. Experiments with Plasma Moving through Neutral Gas (Fahleson, Block, Lundgren, Malmgren and Nilsson)

A rotating plasma machine has been used to study the effects that appear when a low density plasma is moving through a neutral gas. The experiment indicates that the plasma interacts very little with the neutral gas as long as the relative velocity is less than a certain limit, characteristic for each gas. Above this limit a strong interaction appears, which brakes the plasma motion and ionizes the gas. The ion energy corresponding to this critical velocity is found to be equal to the ionization energy of the gas atoms. It seems difficult to explain this phenomenon from the theory of binary collisions. Detailed investigations on the influence of the geometrical configuration of the electrodes and insulators are in progress.

E. Toroidal High Pressure Discharge Experiment (Smårs, Johansson, Wilner and Lindberg)

In all experiments carried out during recent years with the aim of heating a plasma to thermonuclear temperatures and confining it in a magnetic field, one has been working on the principle of having the plasma surrounded by vacuum in order to avoid heat conduction to the walls. It has, however, been suggested (Alfvén, Smårs) that there may be some advantages in insulating the plasma from the walls not by vacuum but by a high pressure gas. Fälthammar has shown that the power lost by heat conduction in a strong magnetic field is not very high. Calculations made by Murty show that instabilities grow at a slower rate in the case of a plasma surrounded by a neutral medium. By concentrating the hot plasma and the heating currents from the beginning to the central region and surrounding them by gas of high density, impurities ought to be kept out of the plasma much more efficiently than if a discharge current starts at the walls and a vacuum is left outside the plasma during the compression.

The purpose of the experiment was to carry out a preliminary study of the behaviour of a plasma in a high current discharge surrounded by gas of high density. The observations show that it is possible to create a circular electrodeless discharge at high gas pressure with the characteristics of a conventional arc. They also give some indication that the stability increases with increasing pressure. Spectrograms give clear evidence that in the experiment the plasma has a much higher degree of purity at high pressures than at low pressures.

F. Diffusion Processes in a Plasma Column in a Longitudinal Magnetic Field (Hoh and Lehnert)

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

Agdur reported on plasma work at the Microwave Department of the Royal Institute of Technology:

An efficient mechanism for transferring energy from fast particles in a plasma to waves in the microwave region and capable of being radiated away from the plasma has been studied theoretically and experimentally. The transfer of energy from the fast particles to the waves in the plasma is effected by an electromagnetic coupling between the particles and the waves having about the same velocity as the particles. When these slow waves, which are amplified, penetrate into an inhomogeneous region of the plasma which has a proper composition, they can be transformed into fast waves radiating away from the plasma.

Experimentally, this effect has been studied in an apparatus where an electron beam (energy 100-1000 eV, current 1-100 mA, diameter about 4 mm) is shot through a circular waveguide filled with argon at a pressure of about 10^{-3} mm Hg. The electron beam thereby creates a plasma which can be of quite high density ($\omega_p \sim 10\ 000$ Mc/s). The beam and the plasma are focused by a magnetic field from a solenoid surrounding the waveguide. The magnetic field directed along the axis of the plasma column has a constant value along a certain length of the column (where the waves are slow) and decreases after this region, thereby transforming the slow waves into fast waves. The power radiated from the system is of the order of 100 mV, and the frequency was in this particular case centred around 3 000 Mc/s.

To measure density and collision damping, the plasma was introduced in a cylindrical microwave cavity resonating in the TM_{010}-mode. Using this mode, one can measure plasma frequencies at least ten times higher than the frequency of the signal used for the measurements (in the case where the radius of the plasma column is much smaller than the radius of the cylindrical cavity).

To study plasma characteristics, the cavity method was also applied to other modes of a cylindrical cavity, particularly to the dipole-mode. New information was obtained on the well known but unexplained splitting of the dipole resonances in a cylindrical cavity.

13. WORK AT UPPSALA

Svennerstedt reported on work performed at the Institute of Physics, University of Uppsala:

The plasma physics group at the Institute of Physics, Uppsala, is working on four projects: plasma gun, small torus, larger torus and spectroscopy.

A. Plasma Gun

The experiments with the electrodeless plasma gun are continued with a pulsed gas inlet.

B. Small Torus

During the last year, equipment for automatic operation of high current discharges has been constructed and tested. Special attention has been paid to the design of low inductance components. In particular, a small low pressure spark gap has been developed (inductance 5 mμH) that can switch 2 kJ satisfactorily, with a ringing frequency of 4 kc/c. At higher frequencies the energy can be increased. The jitter time is approximately ± 0.1 μs for switching voltages from 50 to 35 kV, with a trigger energy of 0.1 J. The operating equipment is now being tested further on a small toroidal pinch apparatus (one discharge per minute; maximum energy 50 kJ) where experiments with magnetohydrodynamic waves, temperature measurements and runaway phenomena have been started.

C. Larger Torus

This device is mainly devoted to stability experiments with a toroidal pinch discharge. The torus is made of porcelain, major diameter 102 cm and minor diameter 22 cm. The primary system is divided into three parts giving (1) a weak axial field, (2) the main gas current, and (3) a pulsed strong axial field with reversed direction to the weak field.

Under certain experimental conditions without the reversed field, the discharge is stable for 20 μs, the length of the first half-period is

100 μs and the amplitude 70 kA. Spectroscopic investigations show no wall impurities and the highest ionization stages are CIV and OV.

In corresponding experiments with the reversed axial field, delayed 15 μs with respect to the gas current, it has been found that the discharge is stable for a longer time and that the outward drift is reduced.

In a new series of experiments, it has been possible to vary the gas current within a wider range by means of an improved preionization. It has now been possible to obtain a stable discharge of low energy, and a careful study of the instability mechanism of a toroidal pinch will be made.

D. Spectroscopy

A stigmatic spectrograph can be used for studying the distribution of photon emitters in a symmetric plasma. The intensity variation along a spectral line gives the projected intensities at various distances from the centre. From this observed projected intensity, the radial distribution of the photon emitters can be calculated. A new method for carrying out these calculations, more accurate and more rapid than previously published methods, has been developed by K. Bockasten.

A 3-meter grazing incidence vacuum spectrograph and monochromator for the region 50-800 Å is being built for the group by Manne Siegbahn (The Nobel Institute of Physics, Stockholm). By means of a toroidal mirror in front of the slit, this instrument will be made stigmatic for one wavelength.

14. WORK AT RISØ

Wandel reported on the activity of the Danish Group:

Much time has been devoted to the International Summer Course in Plasma Physics held in August 1960 and to the subsequent publication of the lectures. The plasma physics group, which now consists of five experimental and two theoretical physicists, has furthermore studied the properties of discharges in the shock generating device described during the previous meeting.

A. Experimental Work

Observation of the shock motion has been performed with a rotating mirror camera, magnetic probes and light probes. Recently, spectroscopic measurements have been initiated.

The conjecture, supported by simple theoretical considerations, that the dependence of the shock motion on E , M , p (E = initial field strength, M = molecular weight of filling gas, p= initial pressure of filling gas) is only through the parameter combination $E/\sqrt{Mp}$ has been tested experimentally by measuring the travel times of the shock front over a fixed distance for a large number of different values of E , M and p . The results indicate that over a wide range of pressures ($40\ \mu$ Hg $< p <$ 4 mm Hg) the expected dependence is essentially borne out by the experiments. However, when approaching the lower end of the pressure range, the points start to scatter when the ionization becomes complete. The reason for this behaviour is not yet clear.

B. Comparison with Theory

The absolute values of the measured shock velocities check reasonably well with those predicted from a simple snow-plough model in the high pressure region. At the lower pressures, the measured values are lower. This may be due to increased interaction with the walls, contamination of the shock by wall material and phenomena connected with the increased ionization mentioned above.

Comparisons have also been made with theory to investigate the shock velocity as a function of the condenser bank capacity. Although the predicted trend is reproduced by the experiments, the agreement in absolute value is only satisfactory at high pressures (above 1 mm).

C. Magnetic Probe Measurements

These measurements, which have been recently initiated, show an initial leak of magnetic field to the region in front of the shock wave. Also a few μs after the break-down, a stationary, current carrying, luminous region forms behind the shock, preventing the full magnetic field pressure from acting on the shock. This luminous region is spectroscopically shown to be contaminated with heavy ions (Al, Si and Fe). The luminosity disappears at current reversal and a second shock is then formed.

D. Future Experiments

The main advantage of the apparatus, apart from simple geometry, is the possibility of observing colliding shocks. When the main features of the single shock have been investigated and understood, an experimental program to study the collision of shocks will be started.

15. ULTRA-FAST PINCH EXPERIMENT

Adlam reported on an ultra-fast pinch experiment at Harwell:

This experiment, which has been delayed by technical difficulties in producing spark gaps, involves basically a current flow in the axial direction and on the outside of a plasma cylinder. The cylinder thus collapses radially inwards and within the plasma there exists a magnetic field in the axial direction. The purpose of the experiment was to feed as much energy per particle into the plasma as possible (≈ 1 keV).

If V is the voltage applied to the system comprising the plasma cylinder and the return conductor and I the current flowing, then $V = d\,{}^{(LI)}/_{dt} = L\,{}^{dI}/_{dt} + I\,{}^{dL}/_{dt}$. If the current rises to a steady value in a time considerably less than the length of the pulse, $dI/dt = 0$ and $V/I = dL/dt$. In order to arrive at a numerical value for the impedance defined in this way, it was assumed that the current flows only in a thin skin of the plasma while the plasma contracts. Under these conditions $dL/dt = \frac{2\ell}{r}\,\frac{dr}{dt}\,10^{-9}$ ohm, ℓ being the length of the plasma cylinder and r its radius. Further $\frac{dr}{dt} = \frac{I\alpha}{20\,\pi\,r}\sqrt{\frac{\pi}{\rho}}$, where ρ is the plasma density and $\alpha = 2$ for the snow-plough model, $\alpha = \sqrt{3/2}$ for the shock wave model and $\alpha = 1$ for a collision-free model of the plasma (the effect of B_z is neglected). For $I = 50$ kA, $r_o = 1.5$ cm, $\rho = 10^{-9}$ g/cm^3 (5 μ D_2

initial pressure) one finds $dr/dt = 3.7 \times 10^7$ cm/s . If the plasma boundary is allowed to collapse half-way to the axis at a velocity of 3.7×10^7 cm/s, the time needed is 20 μs. The current should be built up in a small fraction of this time. If the length of the plasma column is 10 cm, $V/I = \frac{2\ell}{r} \frac{dr}{dt} \times 10^{-9} = 0.44$ ohm.

It was decided to use a modified form of the coaxial line circuit due to Blumlein. Initially the inner conductors of the cables and the load are charged to a voltage V_c and a number of spark gaps are then used to short the ends of the cables which are attached to one electrode of the discharge tube. Current waves are sent along the cables and when these reach the discharge tube, voltages appear across the tube. If the load impedance is made twice the characteristic impedance of all the cables in parallel, then voltages of $+ V_c/2$ and $- V_c/2$ appear across the load for a time corresponding to transmission along twice the length of the cables. At the end of the pulse, the cables are discharged and all the energy has been transferred to the load.

If the impedance of the cable attached to each spark gap is Z_c and the inductance of each spark gap is L_s , then there is a time constant L_s/Z_c associated with the rise of current in the spark gap. Further, if there is an inductance L_T associated with the discharge tube, and assuming that a step function wave form of current is applied to the discharge tube, there would be a time constant of $L_T/2\ Z_D$ associated with the rise of current through the discharge tube, Z_D being the characteristic impedance of all the cables in parallel attached to the discharge tube. In practice, the rate of rise of current is predominantly limited by the inductance of the spark gaps. By making Z_c equal to 2 ohm, L_s/Z_c is about 4.5 ns, and nine spark gaps in parallel are required to match the expected impedance of the load. The 2 ohm cable was effectively produced by using seven 14 ohm cables in parallel.

The coil producing the B_z field in the discharge has been shaped so that B_z is uniform to within 5 o/o between the discharge tube electrodes. The B_z field is pulsed and fields up to 9 000 Gauss can be produced.

Preionization is produced by a discharge between the electrodes, which is started when the B_z field reaches its maximum value. The preionization current is obtained by discharging a condenser using a thyratron. The preionization current is such that the B_z field prevents collapsing of the plasma under pinch force effects. The fast pulse voltages are applied 1 μs after the preionization current has stopped. With this system it is possible to preionize hydrogen gas at an initial pressure of 5 μ.

So far the variation with time of the current through the tube, the voltage across the tube and the B_z field on the axis have been measured, the latter by means of a magnetic probe.

The experimental results show that the main effect of varying the preheat current is that the maximum value of the B_z field measured by the probe increases as the preheat current is increased, and at the same time the time to reach the maximum B_z field decreases.

The time for the hydromagnetic disturbance to propagate across the B_z field from the wall to the axis of the tube gives a measure of the average velocity of the disturbance. If it is assumed that this velocity is given by $V_a = H_{max}/4 \pi \rho$, then an estimate can be obtained for ρ . One finds that this is equal to the density of the gas before ionization to within an accuracy of 30 o/o.

The experiments show that for the first 10 ns the assumption that the current flows in a thin skin on the surface of the plasma is not correct. Integrating $V = \frac{d}{dt} (LI)$, one has $L = \int V \, dt/I$. On the other hand, $L = 2 \, \ell \log_e r_o/r$. Thus, from a measure of the voltage and current it is possible to obtain the variation of L and r with time. When this is done, it is found that dr/dt rises to a maximum value of about 10^8 cm/s after 5 ns. This would mean that the kinetic energy in the plasma was far greater than the electrical energy fed into the system.

Further, the maximum B_θ field produced by the current I is about 6 000 Gauss. Thus, when the initial B_z field is 8 000 Gauss, the B_θ field is insufficient to push the plasma away from the wall. Under these conditions the current I should rise to the value corresponding to a short-circuit on the tube that is V_c/Z_D. The current does not do this; however, an appreciable disturbance is sent across the B_z field.

A rough explanation of these results can be made if it is assumed that the voltage across the tube during the first 10 ns is due to current flowing through a resistive plasma. Electrostatic instabilities may cause the plasma to have this comparatively high resistance (1.5 ohm/cm).

16. PRECURSOR RADIATION IN SHOCK TUBES

Green reported on precursor radiation ionization observed at the A.W.R.E., Aldermaston:

Several authors (Kolb, Griem, etc.) have pointed out the existence of precursor radiation (ahead of shocks), mainly in electromagnetically driven devices. In particular, Kolb has shown that the data are consistent with shock theory only if it is assumed that there is some extra internal energy in the gas ahead of the shock.

Some evidence has been obtained at the Aldermaston laboratories, showing that the gas ahead of the shock is ionized. These results were obtained during some preliminary studies concerned with the development of microwave diagnostic techniques.

Axial shocks were generated using inductive coupling to a condenser discharge. The shocks travelled at velocities between 10^4 and 10^6 cm/s depending on the gas and were observed using streak-camera photography and microwave reflection. Comparison of velocities observed from the Doppler shift of the reflected microwaves and from the photographs showed discrepancies. However, the most important discrepancy was between the estimated velocities and electron number densities behind the shock. The latter was estimated at the time at which the plasma no longer reflected the microwaves and from measurements of transmission normal to the shock. The densities were appreciably higher than those calculated from the standard shock equation -

as observed by Kolb. The data would only appear to be consistent with the existence of internal energy ahead of the shock wave, and this possibility is borne out by the observation of light ahead of the shock.

Further studies of microwave transmission showed that there was some modification of the transmission before the shock arrived and this can only be ascribed to ionization of the gas.

Observations of the transmission at various points suggest that (a) there is structure on the precursor intensity which correlates with bank oscillation, (b) the effect appears to be diffusive and to decrease in intensity. Velocities of 7×10^7 cm/s have been estimated.

17. PLASMA FLOW THROUGH A MAGNETIC FIELD

Pain reported on experiments performed at the Imperial College, London, in relation to the generation of shock waves in a plasma moving through a magnetic field:

When a fast moving plasma of velocity $\underline{u}$ passes through a magnetic field $\underline{B}$, the induced electric field $\underline{u} \times \underline{B}$ may generate a current of density $j = \sigma u B$, where σ is the plasma electrical conductivity. If a path is provided for the current to flow, a retarding force $\underline{j} \times \underline{B}$ is experienced by the plasma.

The behaviour of the plasma depends on its flow conditions on entering the magnetic field region and on the strength of interaction. If its flow is subsonic, the plasma will increase its speed to a limit approaching the speed of sound appropriate to the plasma temperature. When the flow is initially supersonic, it will be slowed down until it reaches the speed of sound. The flow is then said to be "choked".

If the retarding force is strong enough, then the supersonic flow will become subsonic, but it can do this only through a shock wave. When the retarding force is slightly in excess of that required to produce a "choked flow", then a standing shock wave will exist in the interacting field region. An increase of the retarding force will then cause a reflected shock wave, the front of which will move back against the direction of plasma flow.

The theory of this problem in a form applicable to shock tube geometries was first developed by Lin (Cornell University) and later modified by de Leeuw (University of Toronto). Both used the conservation equations of mass, momentum and energy across the shock front with an extra pressure term $\underline{j} \times \underline{B}$ per unit length in the momentum equation.

Lin assumes that the degree of ionization remains constant across the interaction region, i.e. this region is very small, but de Leeuw modifies the enthalpy contribution in the energy equation to allow for a change in ionization.

The solutions to the conservation equation are found by means of a computer program where initial flow conditions are fed in and the parameters characterizing the final flow are found by trial and error methods. In this way, de Leeuw was able to calculate the final flow for a whole range of initial flow conditions and interaction forces. In particular, he derived the values of the choking force required to produce a standing shock wave in the magnetic field region for each set of initial conditions.

The experiments performed at the Imperial College were designed to produce standing and reflected shock waves in such an interaction. The plasma is produced in a pressure driven shock tube and consists of a cylindrical slug of argon of number density 10^{18} per c.c., at a temperature of about 14 000 ^{o}K, 50 cm long, 5 cm in diameter and 25 o/o ionized, moving at 5×10^{5} cm/s through a field of 10 000 Gauss transverse to its flow. The current path is provided by a brass ring electrode set in the glass walls of the shock tube at the centre of the interaction region. The electrode, which is 2 mm wide, is in contact with the plasma at the inner wall of the tube over two lengths of arc of the tube circumference, each arc of one third the total circumference having its centre point at the end of a common diameter. These arcs thus form a pair of opposite facing electrodes and the induced current is free to flow around the ring electrode. The narrow width of the electrode meets Lin's requirement for "frozen ionization". The development of standing and reflected shock waves was observed for a wide range of initial flow conditions and interaction field values, and although experimental results were highly reproducible, the forces required for a standing wave were found to be consistently greater than those predicted by the theory. However, experimental results matched the theoretically predicted values for the maximum velocity of the reflected shock front. As the interaction force was increased, this velocity tended to a limit determined by the initial flow conditions and in no case was the theoretical limit exceeded.

18. MAGNETIC COMPRESSION OF A COLLISION-FREE PLASMA

Auer discussed the results of machine calculations on the propagation of strong magnetic compressional disturbances in a cold collision-free plasma (work performed in collaboration with H. Hurwitz, Jr. and R.W. Kilb at the General Electric Research Laboratories in Schenectady, New York):

The principal motivation for this computational program is the existence of several theta-pinch or orthogonal pinch experiments. The system of equations treated are those described at the 1958 Geneva Conference by Adlam and Allen.

The starting conditions are those corresponding to a uniform cold plasma contained between two infinite plane conductors. There is an initial magnetic field pointing in the z-direction and the plasma is distributed among a set of infinite plane sheets, uniformly placed along the x-direction. The net charge on each sheet is zero, but a net current is allowed to flow in the transverse y-direction. Initially all sheets are at rest and all currents are zero. At time zero, an electric field is applied in the y-direction at the interface between plasma and conductor. As the electric field propagates into the plasma, the induced current and magnetic field provide a compressional force which drives the plasma sheets towards the centre axis. On account of the symmetry of the model it is necessary to account only for the movement of the sheets located in one half-plane. In most of the runs, 1 500 sheets were used. The external electric field was applied either as a step function or as a slowly rising asymptotically constant amplitude field. The calculations were performed in terms of appropriate dimensionless variables and contain one adjustable parameter which specifies the strength of the disturbance. This parameter is the Alfvén-Mach number that one would obtain for a classical magnetohydrodynamic shock in which the plasme acts as a gas with $\gamma = 2$. This allows comparisons with the predictions of elementary Hugoniot theory for a hydrodynamic fluid with $\gamma = 2$.

A. Mach Number Less Than 2

In the case of weak disturbances propagating in the form of coherent waves with $1 < M < 2$, the motion is seen to be quite coherent and there is no orbit crossing of sheets. Looking at magnetic field behaviour, one can notice waves being launched at intervals from the interface between plasma and vacuum (called piston). The wave peaks correspond to the compression ridges of the sheet motion, and the series of waves takes the form of a dispersion train with strong resemblance to the linearized solution of this problem given by Gardner. At later times, strong non-linear effects appear and the solutions no longer resemble the dispersion train but the isolated pulse solution of Adlam and Allen.

Looking at the variation of piston velocity and vacuum magnetic field as a function of time, one notices that at late times the piston oscillates sinusoidally about a constant mean velocity, whereas the magnetic field shows a small drift. In the vicinity of the piston the motion is quasi-stationary and the agreement with elementary Hugoniot theory is remarkably good in spite of the fact that no shock is observed. A tentative explanation of this may run as follows. In the ordinary shock, the disturbance is confined to a single region. In the present case, one may assume a two-region model for the disturbance. In the vicinity of the piston and far from the disturbance front, there is a quiescent and cold plasma which differs from the initial state only in that it is compressed and moving uniformly with the piston velocity. This region is joined onto the undisturbed plasma by a transition region from which Adlam Allen pulses radiate. The strong repulsion between pulses causes them to accelerate until the spacing between them is several times their characteristic width. At these distances, the repulsive force becomes very weak and a nearly uniform set of pulses result which traverse the undisturbed plasma region with nearly constant speed.

To Adlam Allen pulses one can readily ascribe particle-like properties with respect to the undisturbed plasma they traverse, i.e. these pulses carry excess mass, linear momentum and energy; these quantities can be computed and related to the pulse Mach number. In this manner, one can establish mass, momentum, and energy conservation relations for the two-region disturbance model and arrive at a set of relations which resemble the familiar Hugoniot relations. This two-region model can be made to fit the observed calculations quite well.

B. Mach Number Greater than 2

The sheet model lends itself to describing events in which orbit crossings occur. It is necessary in this case to have two labels on each sheet, one which specifies its serial ordering at a given instant and one which designates its initial serial ordering. As one knows from the theory of Adlam and Allen, orbit crossings are to be expected when the pulse Mach number exceeds two, and this is borne out by the calculations. In order to explore the effect of orbit crossing events, a model was adopted initially in which electrons and ions were treated as if they had equal mass. Within the framework of the Adlam Allen equations, this leads to a completely self-consistent model in which the longitudinal electric field due to space charge is identically zero. Physically, this means that a given ion-electron pair which initially occupied some given portion of space remain together during the entire history of motion. In terms of the model, a given electron-ion pair remain on the sheets of their origin even if sheets overtake each other.

Under conditions where the Mach number from elementary theory corresponds to about 6, one observes that the sheet trajectories become rather entangled during orbit crossing events and tend to return to their original ordering upon reaching the piston, which in turn moves well behind the disturbance front. Looking at the magnetic field profile after a sufficiently long time and averaging over the fluctuations, one would obtain a sort of picture book shock with excellent agreement between calculation and the elementary Hugoniot theory based on a $\gamma=2$ plasma. The region that corresponds to the shocked plasma has been taken and histograms of the velocity groups have been plotted. The envelope is a Maxwellian fit to the number of particles (i.e. sheets) used in the calculation and the temperature given by elementary Hugoniot theory. The agreement is rather good. Furthermore, the calculations indicate that the degree of spatial averaging (i.e. coarse graining) necessary to produce a thermalized distribution decreases as one moves away from the shock front towards the piston. The transition region, or shock width, one infers by this method is of the order of the ion gyration radius if one treats electrons and ions as particles of equal mass. Equipartition is obtained to a fairly high degree in the two degrees of freedom allowed, but nothing can be said of the third degree, which is not included in the model.

A test has been made to find the relation between the described model and the Vlasov equation; this equation describes a continuum with an infinite number of particles rather than a finite set. The test was quite satisfying, and presumably it would be better if the number of sheets per unit interval were increased. In order to answer this and related questions, a more powerful computing machine will be used.

C. Adiabatic Electron Model

To investigate the situation in which the ion to electron mass ratio is not unity but very large, the electrons were encouraged to remain in the vicinity of the magnetic field lines on which they were initially created. Thus, a model was investigated in which neighbouring electrons were not allowed to overtake each other and change ion partners whenever an orbit crossing event takes place.

This results in a sort of adiabatic electron model which is sometimes called the guiding centre fluid approximation. On account of these restrictions, such a model precludes the thermalization of electrons and initially cold electrons remain cold. Another consequence of the model is that the electron mass does not disappear from the problem and the equations become singular in the limit of zero electron mass. For purposes of machine calculations it is necessary to maintain a finite ion to electron mass ratio, and the best one can do on the IBM 704 at present available is to use a mass ratio of 100. More realistic mass ratios must await the opportunity of placing the calculations on larger machines.

19. CONVERGING SHOCK WAVES IN PLASMA

Linhart reported on some theoretical work performed in Rome on the possibility of producing fusion energy in the focus of a spherical converging shock:

The neutron output from such a shock in a D, T mixture of specific density ρ_o is given by

$$\nu = \int_{-T}^{-\tau/2} \int_{R}^{r_o} \pi\, n^2 \langle \sigma_n\, w \rangle r\, dr\, dt + \int_{\tau/2}^{T'} \int_{r_o}^{R} \pi\, n^2 \langle \sigma_n\, w \rangle r\, dr\, dt$$

$$+ \tfrac{1}{4} N\, n \langle \sigma_n\, w \rangle \tau$$

where $\tau = \dfrac{2\, r_o}{\sqrt{2kT_o/M}}$, $T_o = W_o/3Nk$, $N \approx 40\, \dfrac{\rho_o\, r_o^3}{M}$

The third term corresponds to the neutron emission from the thermalized core produced by the reflection of the converging shock on the axis. As the temperature of this core is higher than that found in the converging and diverging shock, one may neglect the two integrals and write upon putting

$$\langle \sigma_n\, w \rangle_{DT} = 10^{-15}\, F\, (T_o)$$

$$\vartheta \approx 1.5 \times 10^{31} \rho_o^{\,2} \; r_o^{\,4} \; \frac{F(T_o)}{\sqrt{T_o}}$$

$$T_o \approx \frac{1}{4} \; 10^{-9} \; \frac{W_o}{\rho_o \, r_o^{\,3}}$$

These equations have been solved graphically in a $(r_o \; T_o \; W_o)$ nomogram. From this it appears that the fusion output $W_F = \vartheta \times 17.6 \times 10^6$ eV is equal to W_o when $W_o \approx 1$ MJ and $r_o = 0.025$ cm, $T_o \approx 10^8$ °K.

In order to find the initial energy W_1 of a converging shock for W_o being transmitted into a spherical focus of radius $2\,r_o = 0.05$ cm, one may define the efficiency of the energy transfer by

$$\eta = \frac{W_o}{W_1} = 4\,\pi \int_{r_o}^{2r_o} w_o \, r^2 \, dr / W_1$$

where w_o is the energy density. Using Guderley's solution for converging shocks (transformed by Aitken to apply to plasma), one gets

$$\eta \approx \left(\frac{r_o}{R}\right)^2 \quad \text{and therefore} \quad W_1 \approx \left(\frac{R}{r_o}\right)^2 \; W_o$$

If W_1 can be stored in a shell R, 2R as the energy of chemical explosives, then $W_{1ex} = 3 \times 10^{12} R^3$. Putting $W_1 = W_{1ex}$ and taking the $W_o = W_f$ condition (i.e. $2\,r_o = 1/20$ cm, $W_o \approx 1$ MJ) one finds $r_1 = \frac{4}{3} \times 10^3$ cm.

This poor energy transfer seems to eliminate the converging shocks as a possible mechanism for reactors.

20. TOROIDAL THETA-PINCH

Remy reported on a preliminary investigation of a toroidal theta-pinch at the Max-Planck Institute:

The drift time of a plasma from the centre to the wall of a torus has been calculated with a simple hydromagnetic model and the results of the calculations have been compared to those of the experiments. The observations were made with the aid of smear-camera pictures and the compression of the plasma to the centre of the torus as well as the subsequent drift to the walls were investigated. The drift time was measured as a function of the line density by changing the pressure and the filling gas (noble gases, H_2). In order to reach at least approximately a state of equilibrium of the plasma in the torus and consequently to extend the drift time, a torus with an "M + S" configuration and one with a figure of eight configuration are in preparation.

21. CALCULATIONS IN RELATION WITH A FAST Θ-PINCH

Hain reported on calculations performed for a fast Θ-pinch:

This work consists in solving numerically the complete set of magnetohydrodynamic equations and investigating the effect of various initial (homogeneous) magnetic fields B_z. The basic assumptions are:

Validity of magnetohydrodynamics.

Fully ionized plasma.

Charge neutrality, two-fluid model.

Cylindrical symmetry.

Initially, there is a cylinder of radius R in which a plasma of homogeneous density ρ_0 is placed. The initial field is B_{zo} and the plasma has the initial temperatures T_{eo} and T_{io}. To this plasma a ring voltage V_0 is applied by discharging a condenser bank of capacity C. The outer inductance is L and the streaming velocity in the r direction is v.

Starting from these parameters, the equations of continuity and of momentum and energy conservation have been written out explicitly and solved by numerical procedures. Some difficulties have been encountered. First, the fact that the density is very low compared with the inner regions of the pinch gives rise to very high Alfvén velocities (10^3 cm/μs). The calculations show some rather violent oscillations in this region. In order to compute through this stage, which appears after a bounce together with outward motion, a suitable smoothing procedure has been used, resulting in the elimination of the fluctuations. A more serious difficulty is to get the right relative heating of ions and electrons. An estimation has been made of the relative heating for strong shock waves where the sound speed can be neglected against the Alfvén speed. One finds that only relatively strong shocks can produce a very high ion temperature compared to the electron temperature.

The following table shows a typical result of the computations; the parameters were $R = 4.25$ cm, $L = 4.78$ mμH, $C = 3.3 \times 10^3$ μF, $V_0 = 30$ kV.

B_{zo} kGauss	Compression time μs	B_z (R) kGauss	B_z (0) kGauss	T_e (R) eV	T_i (R) eV
-5	0.54	13.1	-21	290	250
0	0.39	13.0	0.06	320	210
5	0.28	13.2	23.7	200	190

The electron temperatures in the first two cases are about the same. In the second case, a heat wave of electrons runs in front of the shock wave because in a zero magnetic field region the heat conductivity of electrons is rather high. The high electron temperature is due to a very high compression factor (about 8). The difference in the compression times comes from the fact that with a reverse field the ring voltage has first to overcome the initial field and this takes some time.

22. HYDROMAGNETIC SHOCK WAVES

Köppendorfer reported on hydromagnetic shock waves in linear and tubular pinch discharges.

23. MAGNETIC FIELD MEASUREMENTS

Hintz reported on magnetic field measurements at Jülich:

These measurements were made on a fast magnetic compression experiment (of a preheated deuterium plasma) described in some detail at a previous meeting.

The experimental set-up comprises a closely fitted quartz tube of 60 cm length placed inside a single turn cylindrical coil of 15 cm length and 4 cm inner diameter. The coil is connected to two separate capacitor banks, which can be fired with an arbitrary delay with respect to each other. The gas inside the quartz tube is preionized by a 500 Watt, 10 Mc/s RF generator. By discharging the preheater bank, an alternating magnetic field with a frequency of 900 kc/s and a maximum amplitude of 5 000 Gauss is generated. The preionized gas breaks down, an electrodeless ring discharge starts, and within 2-3 µs a plasma is built up. The electron temperature of the plasma is about 20 000 ^{0}K, the degree of ionization is about 80 o/o, the impurity content is low and determined only by the leak rate of the vacuum system. The development of the plasma properties is reproducible in time. The main bank, consisting of 30 0.5 µF capacitors charged up to 24 kV, can be fired after an arbitrary delay with respect to the preheating discharge. The maximum field of the compression pulse is about 46 500 Gauss, the rise time to maximum amplitude about 0.9 µs, and the maximum E_{θ} about 1.5 kV/cm.

The magnetic field measurements are being made with probes of 1 mm total diameter. The pick-up coil of 0.5 mm length and 0.4 mm diameter is separated from the plasma by a steel tube of 1 mm diameter and 0.13 mm wall thickness. The penetration time for a magnetic field into the steel tube is about 3 x 10^{-8} seconds, which gives an estimate of the time resolution. Space resolution in a non-moving plasma is about 1 mm. In a plasma moving with velocity v , the space resolution is $v \Delta t$, where Δt denotes the time resolution of the probe. The probe can be moved along a diameter of the compression coil.

A streak-camera with a resolution of 10^{-8} seconds is used to observe the variation of the plasma radius with time.

The initial pressure was 250 μ deuterium and the delay between preheater and discharge was about 3 μs. Under these conditions the minimum diameter of the plasma is about 8 mm. The magnetic probe signals were reproducible within 5 o/o.

During the adiabatic phase of the compression, the time and space resolution of the probe is sufficient to measure the radial distribution of the magnetic field. Possible cooling effects of the probe on the plasma were examined by comparing streak-camera photos with and without probe.

A strong damping effect of the plasma cylinder was observed when 1 o/o CH_4 was added to the deuterium.

Under the assumption that the flux is constant during one oscillation period and that the radial flow velocity of the plasma is proportional to r/a, the magnetic field on the axis should be proportional to $1/r^2$. This relation has been checked experimentally and was found to hold with a remarkable accuracy.

Oscillation periods with and without probe also showed good agreement, demonstrating that the plasma cannot be largely contaminated by Fe-ions from the probe. At current maximum, the measured oscillation period agrees with the calculated values so that end losses turn out to be unimportant, at least up to this time.

At current maximum, the distribution of the magnetic field in a cross-section of the coil 2 cm off the centre plane of the coil has been measured. The plasma radius obtained from this measurement agrees with the radius determined from a densitometer plot of the streak photo.

The β of the plasma in the vicinity of the axis is higher than 0.8. Pressure balance gives an estimate of the ion temperature which leads to 2 x 10^6 °K at a density of 3 x $10^{17}/cm^3$. Comparison of this result with theoretical calculations (Kever) based on the snow-plough model, with the additional assumption of an initial magnetic field, shows again good agreement and leads to the conclusion that the plasma is predominantly heated up by the first shock.

24. SPECTROSCOPIC MEASUREMENTS ON A COMPRESSION EXPERIMENT

Bogen reported on spectroscopic measurements carried out at Jülich (Bogen, El-Khalafawy):

The electron and ion temperatures of a plasma produced by a fast magnetic compression were estimated by spectroscopic means. A pulsed electrodeless discharge was used as a preheater and the temperature of this discharge was measured by the Fowler-Milne method. At a pressure of 50 μ H_2 + 0.1 o/o CH_4, temperatures between 20 000 and 30 000 °K were obtained. By comparing photomultiplier traces of CII and CIII spectral lines with magnetic field measurements, it was inferred that the plasma is heated essentially by intermixing of parallel and antiparallel magnetic fields.

The relaxation times of the ionization at an electron density of $n_e = 10^{16}/cm^3$ and $kT_e = 1.5$ eV were estimated to be 25 μs for the ionization of hydrogen in one step from the ground state, and 1 μs for the ionization from the ground state via the resonance level.

In the fast magnetic compression experiment with a 5 kJ capacitor bank, the lines of CIII-CIV-CV were observed successively. From the appearance of CV, an electron temperature of $kT_e = 25$ eV would be expected using the Saha equation. The true T_e is estimated to be considerably higher, as there exists no thermal equilibrium in the ionization processes. To obtain the ion temperature, the line broadening of the CV line $\lambda = 2271$ Å was measured. The influence of Stark broadening by microfields of electrons and ions, the

Zeeman effect and the reabsorption of radiation in the plasma were estimated to be considerably lower than the observed line width. Therefore, the line broadening was interpreted as caused by Doppler effect. From time integrated spectra a width of 1.8 Å was obtained end-on and side-on at a pressure of 100 μ. This value corresponds to a radial and axial mean velocity of 1.2 x 10^7 cm/s. If the line broadening is interpreted as a Doppler-effect caused by thermal motion, a value of 1.3 keV follows from the ion temperature.

25. ELECTRODELESS PLASMA GUN

Leloup reported on electrodeless plasma gun experiments carried out at Fontenay-aux-Roses (Evrard, Leloup, Mousay, Poffé, Waelbroek):

The electrodeless plasma gun which was shown at the last meeting has been considerably modified to suppress a few drawbacks and improve the overall reproducibility.

The apparatus consists of a 10 cm diameter glass tube normally evacuated to 10^{-7} mm Hg. A hammer blow on a quick acting valve triggers the injection of a small amount of deuterium inside the tube. This gas is slightly preionized by a 20 Mc/s 200 W generator. A short time after the opening of the valve, a 10 μF capacitor bank is discharged through a single loop coil. The voltage of the bank can be varied between 6 and 25 kV. The vacuum inductance of the coil is about 60 mμH. A crowbar switch has been developed for this gun (André) and tested successfully on a mock-up model. The crowbar effect can be produced at any time of the cycle. A solenoid around the axis of the tube produces a slowly pulsed magnetic field. The timing is set so that the gun, which has a period of about 6 μs, is fired a few μs before the first maximum of the guiding field. This field is essentially constant in time as the plasma goes through it and homogeneous over a length of 45 cm. The use of an ignitron to switch the guiding field allows to vary the intensity of this field from 300 to 2 400 Gauss.

Diagnostic tools include time integrated photography, balistic pendula, teflon plate darkening and magnetic loops. These loops, placed outside the tube, give some indication on the longitudinal shape of the plasmoid. Velocity measurements with photomultipliers and microwave techniques agree with the results obtained by means of the magnetic loops. The plasma purity has been checked spectroscopically.

At present, it seems that at least for certain experimental conditions the plasma behaves properly and reproducibly. Most of the differences could be attributed to the manual charging of the condenser bank. A fully automatic system, setting these potentials within a fraction of a percent, has just been put into operation.

Observation of the signals produced by the magnetic loops shows that under normal conditions the plasma is ejected during the second half-cycle. When no preionization is used, ejection at the third, fourth or even fifth half-cycle is observed.

The mutual orientation of the gun magnetic field and of the guiding magnetic field at the moment of plasma ejection is an important parameter. In particular when the guiding magnetic field is large ($\sim$ 2 400 Gauss), a large peak is observed, originating from the second half-cycle when the two fields form a mirror configuration at that time; the third half-cycle, which is a cusp, is not seen. Conversely, when the second half-cycle is a cusp and the third a mirror, the only peak observed is due to the third half-cycle.

For low guiding fields and otherwise unchanged experimental conditions, second and third half-cycle ejections are observed simultaneously, whatever the initial orientation of the two fields may be. Several explanations can be brought forward to interpret this effect.

A parameter which turns out to be essential for the interpretation of the results obtained with guns using quick acting valves is the delay between the opening of the valve and the firing of the gun.

26. STRUCTURE AND STABILITY OF THIN CURRENT SHEATHS

Dungey reported on theoretical work at the A.W.R.E., Aldermaston in connection with thin current sheaths:

In cusp machines, and possibly theta-pinches, one expects to have a thin current sheath separating plasma and magnetic field. The situation resembles the Rosenbluth sheath in that both the field on the plasma side and the plasma density on the field side should tend to zero at large distances from the sheath, but differs in that the velocity distribution in the plasma can be taken as maxwellian. There are two types of particle trajectories in the neighbourhood of the sheath. Particles coming from the main body of the plasma,in which the field is negligible, are reflected from the sheath and return to the main body. The other type of trajectory is confined between two planes parallel to the sheath, and such particles may be described as "trapped". Trapped particles tend to thicken the sheath by their pressure, but in the relevant machines trapped particles are likely to escape along the lines of force and through the mirrors or cusps. The collision time was supposed to be long compared with the time of reflection of a particle in the sheath, but short compared to the time of an experiment, so that the mirror effect is not enough to keep the trapped particles from escaping. Their escape makes then the sheath thinner, and the thinnest possible sheath contains no trapped particles; a sheath of this kind was thought to be a convenient extreme case to study.

For carrying out the calculations, a plane sheath was assumed, $\underline{B}$ was taken in the z-direction, $\underline{j}$ in the y-direction, and spatial variation was assumed only in the x-direction. A magnetic vector potential $\underline{A}$ in the y-direction and an electrostatic potential ϕ were introduced, both of which were taken as zero in the main body of the plasma $(x \rightarrow -\infty)$. From the equations of motion of a particle with velocity components u and v (w being ignorable), one finds the condition separating the main body from trapped particles

$$u^2 - 2\,e\,A\,v/mc > (eA/mc)^2 - 2\,e\,\phi/m \qquad (1)$$

The main body particles lie therefore outside a parabola in the u,v space. Investigating the possibility of a sheath with no trapped particles,Liouville's theorem can be applied and the velocity distribution can be written down in the form of a step function

$$f = \frac{n_0 \quad m}{2 \pi k T} \exp \left\{ - m \left[(u^2 + v^2) + 2 e \phi \right] /2 k T \right\} \quad \text{when (1) is satisfied}$$

$$f = 0 \quad \text{when (1) is not satisfied}$$

The structure of the sheath is then determined by the consistency of the charge and current density with the fields.

The problem of the stability of sheath models in which the field vanishes on one side is awesome, because one should integrate the Liouville equation along the unperturbed trajectories. It was therefore thought worthwhile to try some crude approximation running on the following lines.

The general perturbation will go like $f(x) \exp i \left[(ky + \ell z + \omega t) \right]$, where k and ℓ are real and ω is complex. To examine waves on the border between growth and decay, one may take ω real. Due to the large separation of the mean velocities of electrons and ions deep in the sheath, electrostatic instabilities are expected. Applying the theory of this type of stability in uniform plasmas, it is expected that the growing wave will tend to travel in the y-direction with a speed no greater than the thermal velocity of the ions. This suggests that one might start taking ℓ and ω as zero and neglect magnetic effects. Finally, the integral of the motion has been retained for the special case $k = 0$ and a perturbation in ϕ, e.g. $\varphi(x)$, has been assumed. One then gets from Poisson's equation, and for sufficiently low values of A,

$$\varphi \approx \sqrt{x} \quad \begin{matrix} \sin \\ \cos \end{matrix} \left[\left(\frac{80 \sqrt{2\pi}}{\beta} \quad \frac{m_e c^2}{kT} \right)^{1/2} \log x \right]$$

Now the stability problem is an eigenvalue problem for ω in which φ has to satisfy boundary conditions. This has not been done, but the result obtained suggests instability, although conditional stability might perhaps be obtained by sufficiently rounding off the step function represented by (2). Anyhow, it seems likely that this kind of instability controls the diffusion of particles from the main body into trapped orbits, from which they escape along the lines of force.

27. WORK AT FONTENAY-AUX-ROSES

Hubert gave an overall review of the work at Fontenay-aux-Roses:

During the last six months the work at C.E.N.F.A.R. consisted mainly in operating existing experiments and in continuing to set up those already under way.

A. Pinch Program

a) T.A. 2000

The reassembly after removal is now finished and tests have been started. Discharges at 170 kA are currently obtained. Microwave experiments have confirmed previous spectroscopic estimations of the ionization level during preionization. Spectroscopic work goes on with a vacuum ultra-violet spectrograph equipped with photomultipliers.

b) Tubular pinch

This pinch has the following characteristics: length 120 cm, $\phi_1 = 25$ cm, $\phi_2 = 4$ cm, pressure 10^{-2} torr hydrogen, unpinch condenser bank 7 kJ, 125 kA, 4 kV, theta-pinch condenser bank 6 kJ, 125 kA, 3 kV, half-period 70 µs.

Magnetic probing reveals a stable period of 16 µs at the beginning of the first half-cycle and another one lasting about 20 µs at the end. The estimated β is 0.4.

B. Plasma Injection Program

a) The induction gun has been described by Leloup. An important result is the blocking of plasma when shooting into a high longitudinal magnetic field in a cusped geometry.

b) DECA (adiabatic compression device) works with DC fields only. Propagation and trapping of plasma is studied with the usual diagnostic tools.

c) In the micropinch gun experiments, the results agree with the theoretical predictions concerning matching of electric and magnetic field. This matching allows the same amount of energy to be put into ohmic heating and into ordered motion acceleration.

d) A study of longitudinal propagation has been made with a Bostick type button source firing into converging lines of force. Some evidence has been obtained about a division of the plasma into droplets when entering into the field.

e) A transverse propagation study shows the E.M.F, but the impedance was too high to be measured. A slowing down of the plasma occurs when it penetrates into the field.

f) A time-of-flight mass spectrometer has been developed for analyzing the material ejected by the plasma guns.

C. Ion Injection Program

a) The preparation of Prévôt's machine makes good progress. The main coils have been delivered and the flywheel generator feeding them is being installed.

b) Experiments have been made with an electron model for testing the temporary trapping of particles injected into the configuration. Observations have revealed a few tens of revolutions of the electrons. This limit is imposed by technical difficulties in the detection device which will, it is hoped, be overcome soon.

c) The hydrogen arc has been tested with 3 pumping sections (total length 2.7 m). Present results are $p_{neutral} = 3 \times 10^{-5}$ torr, $n_i \geqslant 10^{12}$ (Langmuir probe measurements), $T_e = 15$ eV. A critical field has been observed above which enhanced diffusion takes place.

Spectroscopy has not revealed any metal impurity.

d) The annular ion source gave some trouble when an attempt was made to use it in a pulsed fashion because of breakdown occurring in a localized area. Modifications are being contemplated to improve this situation. Another type of source based on the magnetron discharge principle has been tested on a small model. A current of ions of 20 mA has easily been obtained with a very simple construction.

e) An elaborate theory about build-up, developed by Prévôt, takes into account neutral density inside and outside the plasma and a large variety of phenomena. Numerical applications with electronic computers have given results for practical cases.

D. Plasma Beam Interaction Experiment

Experiments show that instabilities are greatly enhanced when $\omega_{ce} > \omega_p$.

E. Spectroscopy

A new diagnostic tool has been set up for time resolution of line broadening. This is made with an Ebert type monochromator equipped with a glass fiber optic system, splitting the light into ten channels. Resolution is 0.19 Å per channel.

Trocheris reported on theoretical work at Fontenay:

A. Hydromagnetic Stability

Generalizing the method used in the case of axial symmetry, Mercier has obtained a new "local" criterion for stability of toroidal equilibria in the absence of any particular symmetry. In this work, the pressure is assumed to be scalar and the constant pressure surfaces are a family of closed surfaces of the same topology as toruses, enclosing one another and all enclosing the magnetic axis. The criterion is derived by using the energy principle and by considering special displacements localized around (i.e. vanishing outside the neighbourhood of) a particular constant pressure surface on which the lines of force are closed. By considering the limiting case of a line of force which closes on itself after a large number of turns, a criterion is obtained in the form of a necessary condition for stability to be fulfilled on every constant pressure surface S :

$$\frac{1}{4\int_S B^2 \dfrac{dS}{|\mathrm{grad}\ p|^3}} \left[\left(\frac{d\Psi}{dp}\right)^2 \frac{d\,\frac{i}{2\pi}}{dp} - 2 \int_S \vec{j} \cdot \vec{B} \frac{dS}{|\mathrm{grad}\ p|^3} \right]$$

$$- 2 \int_S \left(\vec{j} \times \vec{B}\right) \cdot \left(\vec{B}\,\nabla\right) \vec{n} \frac{dS}{|\mathrm{grad}\ p|^3} > 0$$

where p is the pressure, Ψ the stream function, S a surface of constant p and Ψ, $\vec{B}$ the magnetic field, $\vec{j}$ the current density, $\vec{n}$ the unit vector perpendicular to S, and i the rotational transform angle on S.

This criterion was applied by Mercier and Cotsaftis to a general toroidal equilibrium in the neighbourhood of the magnetic axis, and a necessary condition for stability was derived. This condition depends on the shape of the magnetic axis, particularly on the integrated torsion or geometric rotational transform angle and on the values of the magnetic field and current density on the axis. The result applies directly to the case of the figure eight stellarator without correcting windings which is found to be unstable. In the presence of correcting windings, the application of the criterion is difficult as it requires the knowledge of the exact magnetic axis.

Cotsaftis has found a convenient Lagrangian formulation of the hydromagnetic equations and is using it to discuss the stability of dynamic equilibria.

Vuillemain is working on the stability of equilibria in a mirror geometry by using the CGL approximation. In the presence of conducting walls intersecting the lines of force, it is possible to find various sufficient conditions for stability.

B. Microinstabilities

Rébut has studied in detail the microinstabilities due to pressure anisotropy. In particular, the case was considered where one species, ions or electrons, is assumed to be cold and the distribution function of the other species has the form of a Gaussian curve for both components of the velocity parallel and perpendicular to the magnetic field. In this case, a departure from isotropy, however small, always leads to instability with respect to a definite type of wave propagating along the magnetic field and circularly polarized. The discussion is made by considering the order of magnitude of the growth rates and the results can be summarized by the following necessary condition for stability

$$\beta_{\perp} \lesssim \left(\frac{T_{\parallel}}{T_{\perp}} \right)^2 \quad \frac{1}{\alpha^2}$$

where $\beta_{\perp}$ is the ratio of perpendicular kinetic pressure to magnetic pressure, $T_{\parallel}$ and $T_{\perp}$ are the parallel and perpendicular "temperatures" and α is a number of order unity which depends on the acceptable growth rate.

C. Propagation of Plasmoids in a Magnetic Field

Theoretical investigations are being carried out by Lafleur in connection with the experimental work on the injection of plasma into a magnetic configuration.

D. Statistical Mechanics

Possible definitions of entropy in a plasma have been considered and particular problems have been discussed by Engelmann, Feix, Minardi and Oxenius in an attempt to understand phenomena like the thermalization or randomization of waves without collisions.

E. Spectroscopy

Fidone has been working on spectroscopy and in particular on Stark effect in close connection with the experimental effect on diagnostics by optical measurements.

28. WORK AT SACLAY

Taillet reported on work carried out at Saclay:

A. Cross-section Measurements

Dissociation, dissociation plus ionization, and charge exchange cross-sections for H_2^+ collisions on hydrogen, helium, nitrogen and argon have been measured from 100 kV up to 250 kV. The analyzing process involves individual counting of secondary particles by crystals and photomultipliers. Amplitude or time selection (coincidence) of the output pulses give results consistent within a few percent. The measurements will be extended to energies of the order of a few tens of kV. Cross-section measurements for inelastic collisions of H_2^+ on H_1^+ and on plasma are now in preparation. The crossed-beam method will be used in the early stages.

B. Enhanced Diffusion and Microinstabilities

(See also the Notes of the Sixth Meeting)

In weakly ionized plasmas, measurements of enhanced diffusion transverse to the magnetic field, in correlation with LF and UHF noise emission by the discharge, have been performed in a large range of pressures and magnetic fields. Decrease of diffusion and noise emission have been found when the magnetic field is increased well above the critical value. The influence of pressure, which below the critical field tends to increase diffusion and above the critical field tends to reduce diffusion, has been pointed out. The value of the magnetic field corresponding to maximum diffusion increases when the pressure is higher.

Density gradients seem to have but little action on the value of the critical field.

Along with the experimental work, a theory is being worked out by Brifford and Manus; enhanced diffusion is assumed to be due to electromagnetic instability, the latter resulting from amplification of electromagnetic perturbations (in some large frequency range) occurring when the velocity distribution is anisotropic.

The anisotropic velocity distribution has been computed, starting from the Boltzmann equation and the Maxwell equations; a linearized perturbation method applied to Vlasov's equation gives a dispersion equation from which the conditions for oscillations to be set up have been derived. In a future step, the influence of collisions and of the static electric field on the perturbation will be taken into account.

In future the same experiments will be attempted in highly ionized plasmas (more than 5 o/o ionization) along with mathematical developments using the Fokker-Planck equation. A highly ionized P.I.G. plasma source and a low pressure hollow cathode argon arc have been built and are now in operation in order to carry out such measurements.

C. Magnetic Compression

To study the effects of preionization and preheating of a plasma prior to magnetic compression, a small compression device (theta-pinch type), with a 5 kJ bank in a preliminary set-up, has been built. The initial plasma given by a hot cathode reflex plasma source is highly ionized, with a density of 10^{13}- 10^{14} e/cm^3, an ion temperature of about 20 000 $^{\circ}$K (measured by Doppler broadening with a Perrot-Fabry interferometer) and an electron temperature of about 50 000 $^{\circ}$K. Collisional and cyclotron heating can also be provided. Magnetic compression is then applied to this quasi-static plasma, the parameters of which are well reproducible, including a trapped magnetic field. This arrangement may turn out to be of considerable help in understanding the compression mechanism.

D. RF Confinement

Experiments on plasma confinement in a resonant cavity have been started. To avoid large frequency shifts and detuning, the plasma is present in the resonant cavity before the application of the RF field. For this purpose, the cavity is built around the central portion of a P.I.G. plasma source, giving a plasma density of 10^{13} e/cm^3. At the working frequency of about 1 200 MHz this plasma acts as a conductor.

E. Diagnostics; 2 mm Wavelength Interferometry

A wide variety of optical devices for 2 mm wavelength (lenses, mirrors) have been developed and are used in connection with CSF backward wave tubes to obtain well focused microwave beams.

29. WORK AT HARWELL

Adlam reported on work carried out by Bickerton's group at Harwell:

A. Straight Tube (Ashby)

A straight tube with preionized gas is used, an initial axial magnetic field existing within the plasma. In the main discharge, current from condensers is made to flow on the surface of the cylinder of ionized plasma in an axial direction. The purpose of the experiment is to compare the results obtained practically with theoretical calculations by Roberts. These calculations are similar to those which have been described by Hain and Roberts in work already published. The practical measurements used for this comparison are measurements of the magnetic field (B_θ and B_z) made using magnetic probes. The characteristics of the experiment are: working pressure 14 μ, bank voltage 11 kV, total capacity 40 μF, tube length 60 cm, tube bore 24 cm, initial B_z 800 Gauss, maximum current 140 kA. The preionization is produced by discharging a condenser between the same electrodes as are to be used for the main discharge. A half-size wave of current is used of 8 μs duration and 40 kA peak current. During this discharge, the energy fed into the discharge per particle is 50 to 100 eV. It is believed that at the end of the half-size wave of preheat current, the highly ionized plasma produced is supported by a layer of dense and comparatively poorly ionized gas at the walls of the discharge tube.

Calculations have been made first assuming that just before the main pulse is applied, the gas in the tube is completely ionized and of uniform density. Further, it was assumed that as the main body of plasma contracts under pinch effect forces, fresh plasma is given off at the walls the density of which is much less than the initial density of plasma within the tube. Using these assumptions, the agreement with experiment was qualitative only.

Calculations have then been made assuming that the plasma given off at the walls is of comparable density to the plasma already within the tube, and the agreement between theory and experiment is then better.

Experiments have been made to see if there is a low density plasma at the walls of the discharge tube at any time. These experiments used 8 mm microwaves and time and space resolved spectroscopy. It was found that at no time would 8 mm waves propagate in the plasma near the wall, and that at all times during the preheat and the main discharge some impurity light was emitted from the plasma near the wall.

B. Plasma Velocity and Decay Length (Jephcott in conjunction with Stocker and Woods)

An experiment has been made to measure the phase velocity and decay length of Alfvén waves. In the experiment, a plasma is first formed by a discharge between electrodes at either end of a cylinder, there being an axial magnetic field up to 15 kGauss. The waves are then launched by discharging a condenser between two concentric rings at one end of the discharge. The discharge is oscillatory and produces a wave train. A theory has been developed which takes into account finite conductivity and collisions with neutrals. It has been found possible to obtain very good agreement with theory, and to measure the resistance of the plasma and the collision frequency with neutral particles.

C. Plasma Compression (T.K. Allen)

An ionized plasma is compressed by a magnetic field with a cusp-shaped geometry. Before the compression with the cusp field can be applied, the gas must be fully ionized. Further, the experiment demands that the temperature should be at least 10 eV and that there should be no magnetic field within the plasma.

The initial ionization and heating are produced by electrically driven shock waves. The apparatus consists of a cylinder containing the gas which is 60 cm long and 20 cm in diameter. At either end of the tube there are cone-shaped conductors and current is made to flow round these conductors by switching charged condensers. The current produces a magnetic field which is predominantly in the axial direction and the gas is driven from each end towards the centre.

The filling pressure is 25-50 μ and the observed shock wave velocity 5-8 x 10^6 cm/s. The shock velocity decreases as the shock travels towards the centre of the apparatus. The shock wave cannot be described as one which is driven by a constant velocity piston, which would produce a constant shock velocity, nor as a blast wave produced by an explosion, which would produce a shock of rapidly decreasing velocity. The experimental results are between these two extremes.

Spectroscopic measurements have recently been made to estimate the electron temperature produced from measurements on the Balmer continuum.

D. Pinch Experiment (Adlam)

This is a straight tube pinch experiment in which, as in Ashby's experiment, preionization is used to produce a cylinder of plasma with a B_z field inside. Then the main discharge sends currents in an axial direction on the surface of the plasma. The experiment has been designed so that the energy per particle fed into the plasma is large ($\geqslant$ 1 keV) and this has been achieved by making the voltage gradient along the length of the cylinder large. The shock velocity is then larger than 3 x 10^7 cm/s. The tube is 10.5 cm long and 3 cm in diameter. The effect of high shock velocity and small diameter is to make the time for the shock wave to cross the tube small. The total length of the current and voltage pulses is made 25 x 10^{-9} seconds. The power supply consists of charged coaxial lines, and it is arranged that the voltage rises in about 5 x 10^{-9} seconds.

The most significant result of this experiment is that the plasma appears to have a higher electrical resistance than expected. This may be due to the appearance of electrostatic instabilities of the type suggested by Bunneman.

E. Theoretical Investigations (Stocker)

A collision-free plasma without magnetic field is considered and a numerical analysis is made of the problem in which a diaphragm separating two cylinders of collision-free plasma or a collision-free plasma and a vacuum is suddenly ruptured.

The equations to be solved are Boltzmann's equation and Poisson's equation. The dependent variables are the electron density and the ion density in phase space. The independent variables are distance, velocity and time.

The only case so far considered is the case where a diaphragm between a plasma and a vacuum is suddenly burst. Initially, the distribution in velocity space is taken as Maxwellian for both electrons and ions. In order to simplify the numerical problem, ions are taken which have just 16 times the mass of the electron. As would be expected, changes take place in a time of the order of a period at the plasma frequency, and sheaths form the dimensions of which are of the order of the Debye length.

Gibson reported on progress on Zeta.

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

Green reported on work at A.W.R.E., Aldermaston:

The experimental program of the A.W.R.E. has been devoted in the past year to investigations on the behaviour of the theta-pinch in the condition in which it breaks down on the second half-cycle; in this condition it is likely to trap reversed field. The experimental techniques used have been photography with both streak and framing cameras and also magnetic probing. The latter is a novel technique, which has been developed to derive data concerning the plasma current without probing into the plasma.

Two probes are used. One is mounted outside the discharge coil and measures a fraction of the total flux passing outside, and hence inside, the coil. The other is mounted between the primary discharge coil and the insulating wall of the discharge tube and measures the density of flux within the coil but external to the plasma. The two probes are arranged in series to give zero signal when there is no plasma within the tube. Consequently, an out of balance signal arises when there is plasma, which depends on the flux depression caused by the plasma. As the gas becomes diamagnetic, the signal varies from zero to some point where it implodes and changes its gradient. Subsequently, the plasma oscillates radially and the signal also shows oscillations. Implosion criteria and plasma oscillations have been investigated.

A. Implosion Criteria

An estimate has been made of the plasma resistance at the time of the implosion. It was assumed that the signal obtained up to this time is derived solely from the build-up of current in the plasma and not from any dynamic effects, and that the plasma forms at the wall of the tube. It is then possible to estimate the current from the integral of the signal and the voltage from the signal, so that the resistance can be derived. The results show that the resistance is very low at the higher pressures but increases rapidly as the pressure decreases below 100 μ. This can be interpreted in terms of the trapping of parallel and antiparallel fields within the plasma. At the low pressures like field is trapped and the driving magnetic field is always greater than the trapped field. If the resistance is high, however, the field diffuses through the plasma rather than causing it to move. Lundquist and Allen have derived a condition for the plasma to become dynamic, which is that

$$\frac{B}{RC^2} \left(\frac{2\pi\mu}{c}\right)^{1/2} \gg 1$$

As the pressure is decreased, more field is trapped, so that B increases; consequently the value of the resistance at which the plasma becomes dynamic increases as observed.

At the higher pressures a different criterion holds, and it is assumed that antiparallel field is trapped. In this case, the plasma is not driven inwards until the external field pressure is greater than the trapped field pressure, so that at the time of the implosion the two fields are equal in magnitude but opposite in directions. Assuming that the plasma is again formed in a thin skin close to the wall, the signal can be integrated to give a measure of the difference between the two fields, i.e. twice either in magnitude. In this way, the strength of the trapped field has been derived. Data obtained from framing camera photographs corroborate this variation of the trapped field strength and sign with pressure.

B. Plasma Oscillations

The oscillations have previously been shown to arise from the bouncing of the plasma against the trapped magnetic field and to have a period τ given by the equation $\tau = \sqrt{M/B^2}$, where M is the mass of plasma per unit length and B the confining field strength. The experiment under consideration showed that $M_c = (\tau B)^2$ varies considerably. At high pressures M_c was observed to increase with time, the amount of increase varying with pressure. The trapped field is then reversed in direction. This observation is interpreted as the axial contraction of plasma which takes place when the reversed field forms closed loops around the plasma. At low pressures M_c is found to be constant or to decrease with time. It is thought that like field is then trapped within the plasma, and that the variation of M_c depends only on the plasma containment. Experimental results are being analyzed in terms of medium β plasma models (Roberts), which indicate that the loss rate of plasma depends on its temperature and on the amount of field mixed within the plasma since the latter controls the dimensions of the hole through which the plasma can escape.

Sweetman reported on the mirror machine experiment (Phoenix) and on atomic cross-section work.

31. WORK AT A.E.I., ALDERMASTON

Chick reported on work carried out at the A.E.I., Aldermaston:

A. Sceptre IV

Doppler width measurements of the 0^{V} lines in Sceptre III indicated that ion temperatures of about 3×10^{6} °K were being obtained, and X-ray pin hole camera photographs showed that geometric irregularities in the torus (gap liners) and possibly regions of maximum B_{ϕ} inhomogeneity were the main sources of X-rays. It seemed a reasonable hypothesis that electrons spiralling back along the magnetic field lines, which were possibly anchored at geometric irregularities, were an appreciable source of energy loss, preventing the attainment of higher temperatures.

It was therefore decided to build another pinched toroidal discharge apparatus, Sceptre IV. This was characterized by its greatly improved B_{ϕ} field homogeneity and more nearly perfectly toroidal internal geometry. The vessel walls were made from oxygen-free copper, rather than aluminium with copper gap liners as was used for Sceptre III. The size of the apparatus was increased, the minor diameter being 12" and the major diameter 48". The stored energy of the condenser bank was increased to 1 MJ and the discharge time to 1 ms.

The homogeneity of the magnetic field near the axis was tested by shooting in an electron beam and observing its displacement after successive rotations. Cross fields were estimated to be less than 0.5 o/o of the B_{ϕ} vacuum fields when B_{ϕ} was 300 Gauss, and they were less than 0.1 o/o for B_{ϕ} of 1000 Gauss. The maximum value of $B_{\phi o}$ was 4500 Gauss, corresponding to a discharge energy of 750 kJ.

The torus was conditioned and preliminary discharges and measurements started on Sceptre IV in December 1959.

Ion "temperatures" were measured over the range of energy input of 100-700 kJ, and these were less than 2×10^{6} °K.

The Sceptre IV radial temperature distribution was unusual in that maximum temperatures were recorded, not near the axis of the discharge, but in regions some 6 cm from the axis, a subsidiary minimum occurring on the axis of the discharge. Plots of the plasma pressure derived from magnetic probe measurements showed a similar "double humped" characteristic, and $\delta p/\delta r$ changes sign about 8 cm from the wall.

Over the past year, most of the team's effort has been devoted to studying instabilities in the discharge. Fluctuations with frequency components at about 10^4 and 10^5 Hz, and with amplitudes about 20 o/o of the mean, are observed on the magnetic probe signals from the discharge and in the intensity of the 0^V light.

In Sceptre III, these fluctuations are more regular in that the component at about 10^4 Hz appears to be modulated with a smaller amplitude of higher harmonic, and consequently the pattern of the signals produced by the magnetic probes can be easily recognized. Thus, by using ten probes spaced 1.25 cm apart in the ϕ direction and parallel to the main axis of the torus, it was possible to observe phase lags between the signals from adjacent probes which can be interpreted as a motion of the instability in the ϕ direction. In Sceptre III, motion was always in the direction of positive ion motion and had a mean velocity of about 1.5×10^6 cm/s. Magnetic probes also indicated motion in the θ direction.

Observation in Sceptre III of similar fluctuations in the 0^V light intensity at two adjacent points in the ϕ direction again showed a phase shift which could be interpreted as corresponding to an instability velocity. The mean value of this velocity was about 4×10^6 cm/s in the direction of electron flow in the torus.

The probe measurements refer essentially to the outer regions of the torus, whereas the 0^V measurements refer to the central core.

All these measurements were repeated in the Sceptre IV apparatus, and very different results were obtained. The fluctuations in the magnetic probe signals were much less regular, i.e. the higher frequency components were relatively more important, and the signals from multiple probes showed an obvious correlation or recognizable pattern only in a limited number of cases (about 20 o/o). Where this occurred, it appeared that the instabilities could move in either direction, with velocity up to 2×10^{6} cm/s, with about equal probability, and that the average velocity was not a very critical function of plasma radius. The distance of the probes from the torus wall varied within the limits 2 cm to 9 cm.

Measurement of the fluctuations in the intensity of D_{β} lines at two positions in the outer region of the discharge corresponding to those occupied by the multiple probe confirmed that the fluctuations could move in either direction, and this spectroscopic confirmation was obtained with the probes both inserted into, and removed from, the discharge, suggesting that the probes were not seriously modifying the discharge conditions.

Measurements of fluctuations in 0^{V} intensity from the central region of the discharge indicated a velocity of $2\text{-}3 \times 10^{6}$ cm/s in the direction of electron flow. In this particular respect, Sceptre IV resembled Sceptre III.

Ware has suggested that the hydromagnetic instabilities will be trapped to the mean motion of the electrons and will, therefore, in general propagate around the torus. In the absence of mass motion, the propagation velocity will be positive or negative depending on whether the pitch of the helical current $\underline{j}$ is less than or greater than the pitch of the instability.

Ware claims that in Sceptre III the propagation velocities deduced from the probe results agree with the supposition of an $m = 1$ instability moving in the direction of ion motion. This holds for the radial range of 6 cm to 9 cm from the wall, but not for the range 2 cm to 6 cm. The motions in the central region of the discharge were deduced from the observations on the fluctuations of the 0^{V} light. Ware explains the behaviour of this central region of the Sceptre III discharge as being due to an instability parallel to the magnetic field giving rise to a propagation velocity antiparallel to the ion motion.

In the case of Sceptre IV a regular instability was more difficult to observe and the theoretical predictions could not be checked using the probe results. If the pressure distribution does in fact have a dip at the centre of the Sceptre IV discharge, $\delta p/\delta r$ near the centre is positive and the theory would predict a propagation velocity in the direction of ion motion, whereas the motion of the fluctuations in the O^V light was observed in Sceptre IV to be antiparallel to the ion motion.

O^V Doppler shift measurements in Sceptre III indicated a plasma mass motion. In Sceptre IV the demand for as nearly perfect geometry as possible prevented tangential viewing facilities from being provided, but measurement of the histograms of the emitted protons indicated a mean centre-of-mass velocity of $6 \pm 1 \times 10^7$ cm/s in Sceptre IV, compared to a value of $4 \pm 1 \times 10^7$ cm/s in Sceptre III.

By applying the hypothesis put forward by Hunt, that the fusing deuterons constitute the high energy tail of a general mass motion, it can be postulated that mass motion in the ϕ direction also occurs in Sceptre IV.

Proton plate results indicate a θ component of motion of the deuterons with the θ velocity about half of the ϕ velocity. It is thus suggested that the mass motion is in the form of a helix around the torus, following approximately the direction of lines of force. O^V Doppler shift measurements in the θ direction indicate that θ velocities of impurity ions at the centre of the discharge in Sceptre IV are less than 10^5 cm/s, whereas velocities of about 10^6 cm/s were measured in Sceptre III.

Experimental observations therefore indicate appreciable differences in the behaviour of Sceptre III and Sceptre IV, even under similar discharge conditions and similar θ values, but these are not the differences which were set out to be created in the design of Sceptre IV. In fact, by deliberately reducing the homogeneity of the magnetic fields by switching off the current in the bias and compensating windings, no appreciable change was noted in the behaviour of the Sceptre IV discharge.

B. The Levitron Experiment

In July 1959, the A.E.I. Research Laboratory proposed a toroidal Levitron experiment on the scale of Sceptre III. The principal features of the apparatus, using existing equipment, were decided in March 1960.

Because it was thought that any supports used would introduce effects similar to those of electrodes, it was required to levitate the toroidal hardcore to a central position, and it was shown that this can be done magnetically.

Once in the central position, a large current is induced in the ring, with small E_{ϕ} to prevent gas breakdown. When this current reaches its peak value, a preionizing pulse of RF is applied, followed by a "fast" rising B_{ϕ} field. When B_{ϕ} becomes greater than the azimuthal field at the walls, the discharge will pinch, trapping the B_{θ} field. The equilibrium position of the discharge is determined by the value of B_{θ} and the initial value of B_{θ} at the walls.

Rather than use a ceramic torus, or a thin metal liner as used by Colgate, the simplest engineering form of a thick walled torus with cuts in both θ and ϕ directions was chosen. For such a torus it is necessary to provide vacuum seals at right angles, and a satisfactory solution to this engineering problem has been achieved by using "Viton" gaskets.

During the experiment the hardcore will be in a state of free fall. Under gravity, an object starting from rest will take 30 ms to fall the first 0.5 cm. Since the duration of the proposed experiment will be of the order of 1 ms only, the requirement of free fall, in itself, presents no problem.

The torus has a 38" major and a 12" minor diameter. It consists of eight aluminium pressings, provided with a pumping port, six viewing ports and twelve probe ports. The gaps are insulated and made vacuum-tight by special rubber gaskets. They are shielded by copper overlaps. The hardcore is an aluminium tube of 4" outer diameter, weighing 32 pounds. The iron core used on the 64-sector torus has been modified to provide insulating gaps so that it is not a shorted turn to the θ field. The initial peak current in the hardcore will be 200 kA, and the peak B_{ϕ} field will be 9 000 Gauss.

Working pressures will be in the range 2 to 20 microns. The levitation pulse will last about 1.3 ms and the hardcore takes about 0.14 seconds to reach the centre of the torus. The ϕ current in the hardcore is started about 140 ms after the levitating impulse. The rise time of the current in the hardcore will be 0.5 ms and, in the absence of a discharge, will decay in 2.8 ms. The θ drive is connected as two separate circuits, each of 45 kJ and connected to 8-turn primaries.

In order to ensure that the B_θ field should be trapped, a relatively fast rise time of the θ circuit of 42 μs was chosen, and for an assumed electron temperature of 2×10^5 °K this ensures that the skin depth of the plasma is considerably smaller than the radial depth of the discharge region: for this assumed electron temperature, the θ circuit will decay in 160 μs. The B_ϕ rise time of 42 μs results in each of the gaps in the equatorial plane of the torus being stressed to about 900 V. Switching of the main ϕ, θ and catching banks will all be timed from the initiation of the levitation pulse. Hence, accurate knowledge of the levitation time is required.

All machining and welding of the components of the torus is complete. One half-turn of the vacuum system has been assembled and, using the specially developed rubber gaskets, a leak rate of better than 0.05 lusec has been achieved. At the gaps, the copper shields are to be fitted to protect the gaskets from the discharge, and also to prevent penetration of magnetic fields into the interior of the torus.

After the preliminary vacuum tests, the lower half of the torus was assembled with the hardcore and ϕ primary winding in position. Measurements were carried out to determine the leakage inductance between the ring and ϕ winding, so that an estimate could be made of the upward forces on the ring to be expected during the levitating pulse.

The sequence of switching in the ϕ circuit has been tested. The ring was first levitated by a current pulse from the first capacitor bank. An energy of some 6 kJ was required to levitate the ring to the centre of the torus. With the ring at the top of its trajectory, the second capacitor bank was discharged into the ϕ circuit to provide the initial B_θ field for the experiment. Finally, the pulse from the third capacitor bank has been used to diminish the impulse received by the ring on its fall onto the bottom of the torus. The crowbarring required for the first two pulses into the ϕ winding has operated satisfactorily. Testing of the θ circuit is proceeding, and the two fast capacitor banks, together with the four ignitron valves, have been installed and made ready for connection to the θ winding round the torus.

The complete torus will next be assembled for final vacuum testing, after which cables will be wound onto it for both the θ and ϕ primaries.

32. WORK AT THE IMPERIAL COLLEGE, LONDON

Pain reported on work carried out at the Imperial College, London:

The study of instabilities in the linear pinch has been continued. The small scale surface perturbations have been interpreted in terms of Rayleigh-Taylor instabilities and this work has been published (Proc. Roy. Soc. A, 257-286, 1960). Interest is now focused on the larger scale perturbations which develop after the pinch and continue throughout the history of the discharge.

The diagnostic technique is an array of three Kerr cell cameras, each capable of an exposure time of less than 0.5 μs. The intervals between the operation of these cameras are variable and the first camera operates at any chosen time during the discharge. An optical system arranges that each camera sees the discharge from two directions which are perpendicular to each other, so that circumferential symmetry may be observed. The images from each of these two directions are juxtaposed and may be directly compared.

Early study suggests that the large scale perturbations which result in the final break-up of the discharge are initiated at the electrode ends of the discharge and are propagated axially.

Experiments are in progress which are designed to stabilize the linear pinch and to prolong its duration, i.e. the time away from the vessel walls.

This is accomplished by applying a strong B_z field of 20 kGauss with a 30 µs rise time to a system which pinches in 50 µs. The timing of the applied B_z field is important and is an optimum just as the discharge is coming to the pinch. When the stabilizing field is applied too early, the pinch is inhibited by the resistance of the applied B_z to compression. When the applied B_z is at its maximum, a spark gap system short-circuits the field coils and B_z is clamped at its maximum with a characteristic decay time of twice the period of the discharge.

Long-term stability has been obtained and the pinched discharge has been kept from the walls for the complete current duration, the diameter of the pinch remaining approximately constant at 20 o/o of the tube diameter.

33. OTHER MATTERS

The Chairman announced that in order to avoid collision with the Munich-Salzbourg meeting, the six months periodicity will exceptionally be broken and the next meeting of the Group will be held at Jutphaas-Amsterdam during the week after Easter next year (1962).

To compensate for the loss, progress reports in written form should be sent before the end of the year to E. Regenstreif, Secretary of the Group (CERN, Geneva), who will arrange for circulation.

Finally, the Chairman expressed his appreciations to Professor Ippolito, Dr. Brunelli and the Laboràtorio Gas Ionizzati Staff for the success of the meeting.

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E.R.

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