THE DESIGN AND CHARACTERISTICS OF HIGHLY IONIZED HYDROGENOUS LABORATORY PLASMA SOURCES

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Summary

The design and construction of two highly ionized hydrogenous plasma sources are described. Details are also given of the measurements that have been made to investigate the formation, density distribution, and decay of plasmas.

I. Introduction

Our plasma physics research program is directed towards three objectives: (*a*) studies of methods of formation of highly ionized plasmas in the laboratory, (*b*) studies of plasma waves including possible heating effects near ion cyclotron frequency, (*c*) the development of diagnostic methods which enable the characteristics of the plasma to be measured.

For this work we have designed and constructed two sources known as Supper I (Sydney University Plasma Physics Experimental Rig 1) and Supper II. Supper I was designed primarily for the development of diagnostics; Supper II as a wave study machine.

II. Supper I (see Fig. 1)

This machine consists of:

2·1. A cylindrical copper vacuum vessel of diameter 6 in. and length $2\frac{1}{2}$ ft, complete with quartz or "Pyrex" end plates and 12 radial diagnostic ports. A pair of 2-in. oil diffusion pumps with a Freon-refrigerated baffle provides a background pressure of 2×10^{-5} mm. The copper cylinder can be replaced by a Pyrex tube for pulsed magnetic field operation. The quartz end plates have been fitted with 2-in. diameter molybdenum electrodes to enable plasma preparation with either an axial or a radial discharge current.

The hydrogen gas is introduced through a palladium filter; the machine is operated on a continuous flow basis at the rate of 10 000 litre microns per minute. As shots are fired once every minute this enables complete replacement of the gas between discharges.

2·2. A d.c. axial magnetic field of up to 10 000 G which is provided by 28 coils wound in pancake form of internal diameter $9\frac{1}{2}$ in. and external diameter $24\frac{1}{2}$ in. Each pancake consists of two layers each of 16 turns of $\frac{7}{16}$-in. square copper conductor with a $\frac{1}{4}$ in. cylindrical hole for water cooling. Electrical insulation and mechanical stability of the coils have been achieved by vacuum epoxy resin impregnation after fitting with a 9-mil glass stocking and winding with 7-mil glass tape.

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The d.c. supply for the magnetic field coils is furnished by 120 diesel-engine starting batteries capable of delivering 5000 A. The rise time of the current in the coils is half a second and it remains essentially constant for several seconds thereafter.

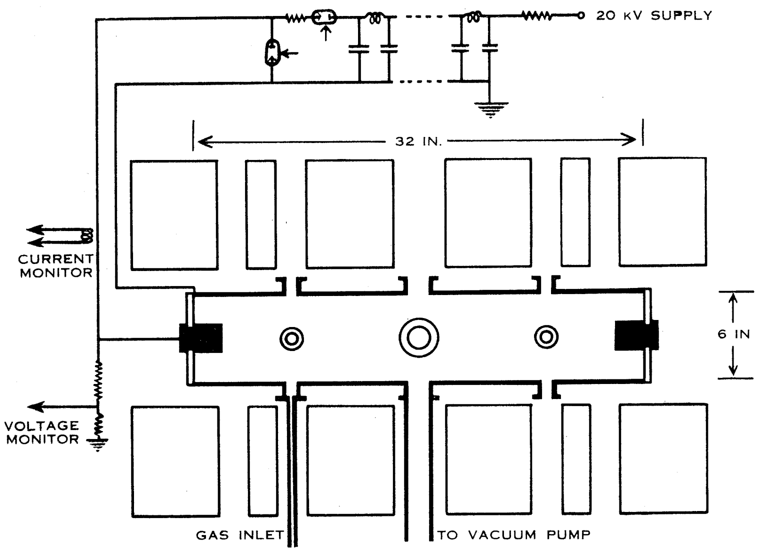

Fig. 1.—Schematic drawing of Supper I showing copper tube with diagnostic ports and end electrodes together with magnet coils and plasma preparation condenser bank.

Delay circuit arrangements are such that the plasma preparation condensers are fired 1 s after the batteries are switched on; the batteries are switched off $\frac{1}{2}$ s later; "switch off" transients are reduced by floating a reverse voltage rectifier across the coils.

Table 1

SUPPER I MAGNETIC FIELD

Field	Hall Measurement	Theoretical
1. On axis at centre of machine	$2\cdot05\pm0\cdot02$ G/A	$2\cdot098$
2. Field variation along central axis	$\pm2\cdot8\pm0\cdot09\%$	$\pm3\%$
3. Field variation along axis $0\cdot25$ in. from vacuum wall	$\pm4\cdot5\pm0\cdot9\%$	
4. Field at centre port at vacuum wall	$1\cdot98\pm0\cdot02$ G/A	

The magnetic field has been calibrated with a Hall probe; comparison with theoretical figures computed on the electronic computer, SILLIAC, are given in Table 1.

2·3. A plasma preparation condenser bank consisting of a selectable number of 8·5 μF, 25 kV, 160 kc/s self-ringing frequency condensers. The condensers can be connected in parallel or in the form of an artificial line. We have used two such lines of impedances of 0·7 and 1 ohm and of pulse lengths up to 80 μs. The impedance of the plasma can be matched to that of the line by the use of a series variable stainless steel resistor. To facilitate electrical break-down at low pressures a 0·1 μF condenser charged to 15 000 V is discharged through a small "spark gap" electrode in the centre of the main electrode.

2·4. Delay and switching circuitry which comprises:

(*a*) Multivibrator delay units, which provide 100 V pulses of rise time about $\frac{1}{10}$ μs and an adjustable delay between 0·2 and 10 000 μs.

(*b*) The ignitron firing units, which are similar to those described by Wilcox *et al.* (1961), use a 15-kV thyratron and a step-down pulse transformer in order to provide a sharply rising pulse to the ignitron to thus reduce jitter to less than $\frac{1}{10}$ μs.

III. Supper II (see Fig. 2)

This machine is similar to Supper I with the following differences:

3·1. The vacuum vessel, because of the use of a pulsed magnetic field, is manufactured from stainless steel of thickness 0·06 in. It consists of four sections of lengths 1, $3\frac{1}{2}$, $3\frac{1}{2}$, and 1 ft to give a total length of 9 ft of diameter 8·5 in. The volume of the magnetic field is fixed by the energy of the condenser bank (ultimately 900 000 J) used to pulse the magnetic field to 20 000 G. The actual dimensions of the vacuum vessel result from a compromise between the need for a large axial length to facilitate attenuation and other propagation measurements and the need for a large diameter to minimize the role of boundary conditions in determining attenuation coefficients, particularly for higher modes of hydromagnetic waves. While only part of our electrolytic bank is commissioned, we have omitted one of the $3\frac{1}{2}$-ft sections of the machine.

We are at present using one 6-in. diffusion pump with chevron baffle and Freon refrigeration and have achieved a background pressure of 1×10^{-6} mm. A "Vacion" pump is used over week-ends.

3·2. *Magnetic Field*

The coils for the magnetic field have been constructed on a similar module basis to Supper I except that in this case each module consists of 14 turns of $\frac{7}{16}$-in. square conductor spiralled on an inner diameter of $12\frac{1}{2}$ in. Thirty-six modules in all have been manufactured and can be connected to provide various magnetic field configurations (Brennan and Lehane 1962).

The initial experiments require a uniform field which has been examined theoretically and experimentally with a Hall probe fluxmeter. Characteristics of the field are:

On axis

Average axial field $1\cdot12\pm0\cdot02$ G/A

At vacuum wall

Average axial field $1 \cdot 02 \pm 0 \cdot 04$ G/A

Drop in field from axis to wall

At a module coil 4%

At a diagnostic port 14%.

These figures apply except in the volume in the vicinity of the diffusion pump at one end of the machine.

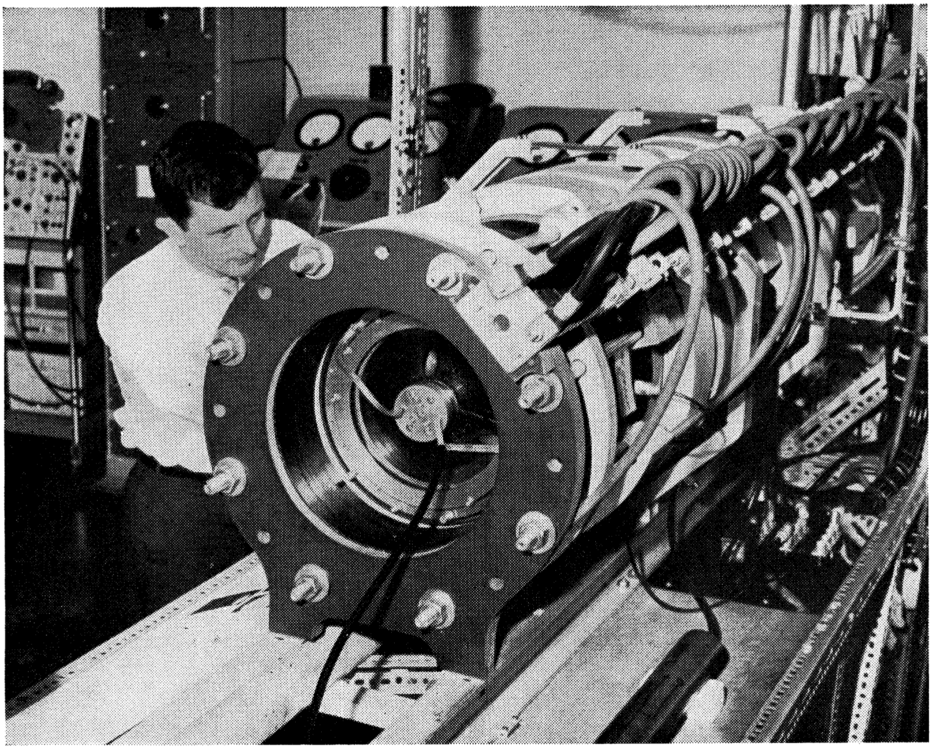

Fig. 2.—Sydney University Plasma Physics Experimental Rig II (Supper II). The epoxy-impregnated coils, wooden spacers, and water cooling tubing are clearly visible. The stainless steel vacuum vessel (with insulating end plate and central electrode) is independently supported inside the coil system. The waveguide used in the 8-mm interferometer can be seen entering the machine through the middle diagnostic ports. Control equipment and power supplies are grouped in the rear and the vacuum pumping equipment is located under the aluminium frame on which the machine stands.

In the case of Supper II an electrolytic condenser bank similar to that described by Wilcox *et al.* (1961) has been used to supply the energy to the magnetic field. The electrolytic condensers, which are a very generous gift by the Ducon Condenser Company, are of capacity 850 μF, 450 V d.c. working. They are arranged in trays of 168 condensers connected in series-parallel to provide a capacity of 1 mF at $5 \cdot 4$ kV.

A 1-ohm nichrome wire is used to provide the charging current between equipotential condensers and to limit the current from other condensers in the event of one condenser developing a short. It has been found convenient to identify such a short circuit by the discoloration of white paint on the nichrome wire. The condensers are charged from a 5·4 kV 3 A three-phase rectifier with diode isolation for each pair of trays each containing 168 condensers. Each pair of trays is connected to a type 5550 ignition, which in turn is fired by a master ignition. At present 12 trays (175 000 J) have been commissioned; these provide a peak current of 10 000 A and a magnetic field rising to 10 kG in 8 ms. At the current peak the coils are shorted

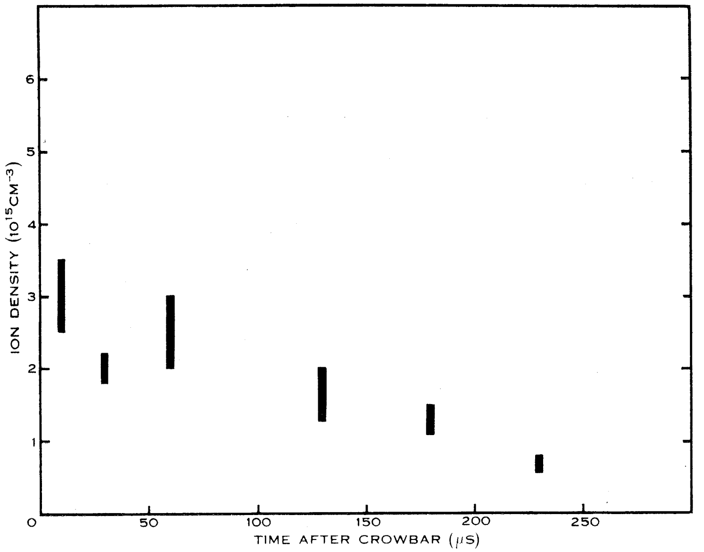

Fig. 3.—Ion density as a function of time derived from Stark broadening of the Hβ line, observed in Supper I with hydrogen filling at a pressure of 100 microns, magnetic field of 5 kG, and axial plasma preparation current of peak value 45 kA.

by an ignitron and the magnetic field decays with a time constant of 15 ms. As a further protection against reversal of voltage on the condensers a second voltage-sensitive shorting circuit is provided.

3·3. The plasma preparation condenser bank, together with its delay and switching circuitry, is similar to that of Supper I.

IV. Plasma Preparation

We have used two methods of plasma preparation:

4·1. An *axial* mode where the condenser bank is discharged along the axis of the tube and the current is returned via the tube walls.

With Supper I at a pressure of 100 microns, and a magnetic field of 5000 G, the resistive component of the plasma impedance fell from 100 mΩ at 5 kA to 20 mΩ at 50 kA. With this method of plasma preparation at pressures of the order of

100 microns very high currents have to be used to supply sufficient energy to ionize the plasma and, moreover, the ionizing current is confined to the centre of the tube, resulting in a pronounced radial density gradient.

Stark broadening measurements described in Section 5·2 of this paper are given in Figure 3 and show an ion density of 3×10^{15} cm^{-3} decaying to 1×10^{15} in 200 μs. These results were taken with an axial magnetic field of 5000 G and a neutral pressure of 100 microns of hydrogen.

4·2. A *transverse* mode of preparation pioneered by Wilcox *et al.* (1961, 1962). In this method of plasma preparation a radial voltage is applied between the central electrode and the outer cylinder. The high radial electric field causes an electrical breakdown of the gas and a radial current flows. The cross product of this radial current and the applied axial magnetic field results in an azimuthal force which causes the plasma to rotate. A well-defined ionization front travels down the cylindrical tube at a velocity dependent upon plasma and magnetic field characteristics.

Based on a number of simplifying assumptions, Kunkel and Gross (1961) derive a velocity for such an ionization front given by:

$$V^2 = \frac{16}{9}e_0\left[-1+\left(1+\frac{9B_0^2b_\perp^2}{16\mu_0^2\rho^2e_0^2}\right)^{\frac{1}{2}}\right] \mathrm{m}^2\mathrm{s}^{-2}, \tag{1}$$

where V = velocity of the ionization front,
e_0 = total energy of dissociation and ionization of the gas per unit mass,
B_0 = applied axial magnetic field in teslas,
$b_\perp$ = transverse magnetic field of ionization front,
ρ = gas density in kg m^{-3},
$\mu_0 = 4\pi\times10^{-7}$ henry m^{-1}.

Relations are also derived for the density and electric field behind the front.

We have undertaken an extensive series of observations with hydrogen, deuterium, and helium gases to determine the effect of gas enthalpy, pressure, ionizing current, and magnetic field on the velocity of the ionizing front and on the plasma impedance (Brennan *et al.* 1962).

For the purpose of our present paper we are mainly concerned with:

(*a*) the ionization front velocity so that we can arrange the length of the pulse to be sufficient for the front to reach the end of the cylinder,

(*b*) the impedance so that we can choose the characteristic impedance of the artificial line and so insure that sufficient energy is fed to the plasma to fully ionize the gas at the operating pressure.

For velocity measurements we have used three techniques.

(*a*) We have measured the radial current from the shock front by using current buttons of one square centimeter area coplanar with and electrically isolated from the cylinder wall and then connected to the adjacent wall coaxially through a non-inductive resistance of one ohm.

(*b*) We have measured the radial, azimuthal, and axial magnetic fields associated with the shock and the rotating plasma.

Here we have used three mutually orthogonal loops each consisting of 10 turns of diameter 2 mm wound on a polystyrene former and electrostatically shielded with a slotted stainless steel cylinder. The magnetic coil assembly is inserted to a given radius through a Pyrex glass tube. The magnetic loops have been previously calibrated in a known field.

(*c*) We have looked at the emitted light with the aid of photomultiplier tubes at radial diagnostic ports.

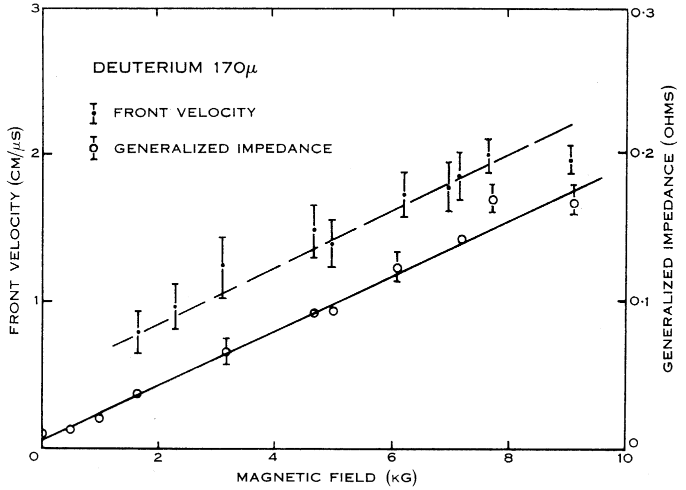

Fig. 4.—Variation of the velocity of the ionizing front and of the plasma impedance with axial magnetic field. The curves shown are not theoretical curves but are included to emphasize the almost-linear dependence on magnetic field of velocity and impedance.

Typical curves showing the variation of velocity and impedance with axial magnetic field at a pressure of 170 microns of deuterium and a driving current of 15 kA are given in Figure 4. Just before the shock front reaches the end of the tube the ionizing current is shorted out ("crowbarred") with an ignitron switch. This stops the energy flow from the pulse line of the tube and also abruptly halts the rotation of the plasma. The kinetic energy of rotation is recovered electrically in the form of a reversed current flow shown in Figure 5, where typical voltage and current traces for the transverse plasma preparation are displayed.

V. Plasma Measurements

We have examined with a number of diagnostic methods the properties of our plasma sources when prepared by a transverse mode:

5·1. Ionizing current and voltage measurements yielded plasma impedance.

5·2. *Stark Broadening*

In a plasma the radiating atoms are being continually perturbed by the electric Coulomb fields of neighbouring ions and electrons. The resultant Stark broadening of a spectral line is roughly proportional to the two-thirds power of the ion density.

Detailed calculations of the line shape have been made by Griem, Kolb, and Shen (1959, 1962). The addition of electronic effects introduces a weak dependence on temperature to the line shapes; however, only a very rough knowledge of the temperature is required to allow the curves to be used for ion density measurements.

We have measured the ion densities with the aid of a diffraction grating monochromator with a resolution of 0·56 Å. A photomultiplier at the exit slit monitored the light intensity and fed the signal via a suitable cathode follower to a recording oscilloscope. Our observations were with the Dβ line at two of the radial diagnostic ports.

Several shots were taken at each wavelength with a repeatability within a few per cent. At selected times we then plotted amplitude against wavelength and obtained densities by fitting to the theoretical curves of Griem, Kolb, and Shen (1962). An example is given in Figure 6. The time variation of densities at the two radial ports is given in Figure 7 for Supper II.

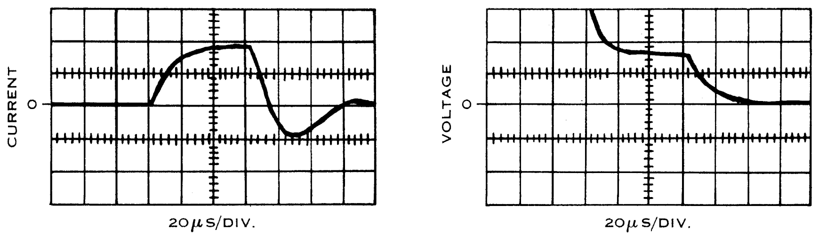

Fig. 5.—Typical current (7·8 kA/div.) and voltage (1 kV/div.) records obtained on Supper II with deuterium at 170 microns. The gas breaks down 60 μs after the scope is triggered and the electrode voltage is crowbarred after a further 60 μs.

It should be noted that the ionization front leaves behind it a plasma with an axial variation of density. We have found it useful to introduce a second electrode at the receiving end of the plasma source, terminating in a resistor, to provide an axial current to reduce this axial variation in ion density.

5·3. *Total Spectrum*

The total spectrum of the light from the machines has been examined by taking a number of shots with a Hilger spectrograph, recording photographically.

A plate showing the spectral lines at high and low pressure, with and without crowbar, is given in Figure 8. The impurity lines that have been identified are Si^{++}, Si^{+++}, Cr^{+}, Na^{+}, C^{++}, C^{+++}, O^{++}, Ca^{+}, Ca^{++}. These lines are associated with the electrode and insulating plates. The importance of crowbarring to prevent the rotating plasma removing impurities from the end insulating plate is graphically illustrated by these spectral photographs.

5·4. *Structure of Plasma*

The distribution of the light emitted by the plasma was investigated with a matrix of five photomultiplier tubes arranged to look at the receiving end plate with the central electrode removed.

Light pipes of 5-ft length were used to remove the Mumetal shielded photomultiplier tubes to a region of magnetic field of less than 10 G. Four of the photomultipliers were arranged symmetrically on a 2-in. radius and one at the centre. The photomultipliers were calibrated with an a.c. light source: the normalized results are given in Table 2 (p. 350).

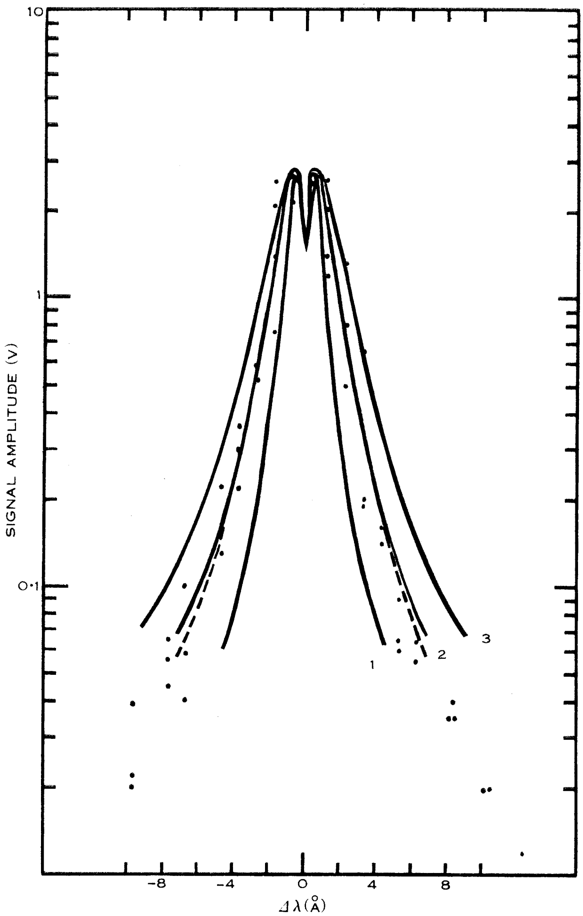

Fig. 6.—Profiles of the Dβ line as predicted by Griem, Kolb, and Shen (1959). The full curves correspond to ion densities of 1, 2, and 3×10^{15} ions cm^{-3} and 1×10^{4} °K. The broken curve is for 2×10^{15} cm^{-3} and 2×10^{4} °K. Typical experimental points are shown, all measured at the same time following plasma preparation.

These results were taken on Supper I with a field of 5000 G, and a pressure of 100 microns. Table 2 shows clear evidence of the low luminosity in the centre, which has been discussed by Wilcox *et al.* (1962).

We would expect the radial density gradient to be reduced by providing a small axial ionizing current along the centre of the machine and indeed we have found, at pressures of the order of 0·3 microns, using an 8-mm microwave interferometer, that it is possible to achieve greater radial uniformity of plasma density in this way.

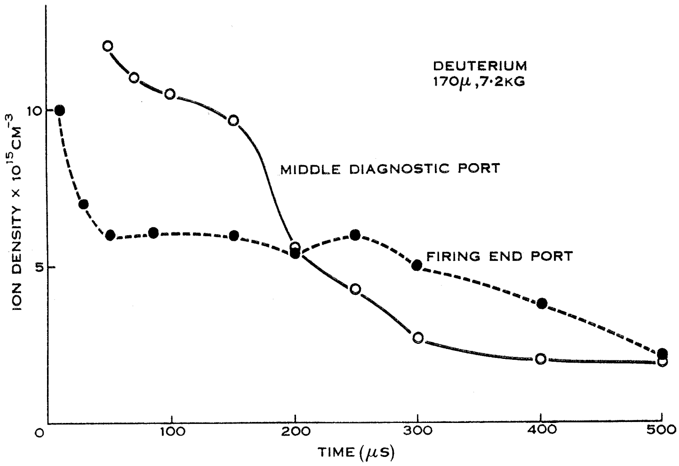

Fig. 7.—Ion density, as measured by Stark broadening of the Dβ line, as a function of time after plasma preparation. Observations were made at the two positions of the diagnostic ports along the length of Supper II.

It should also be noted that at low magnetic fields a radial density gradient will arise from the azimuthal current J_θ.

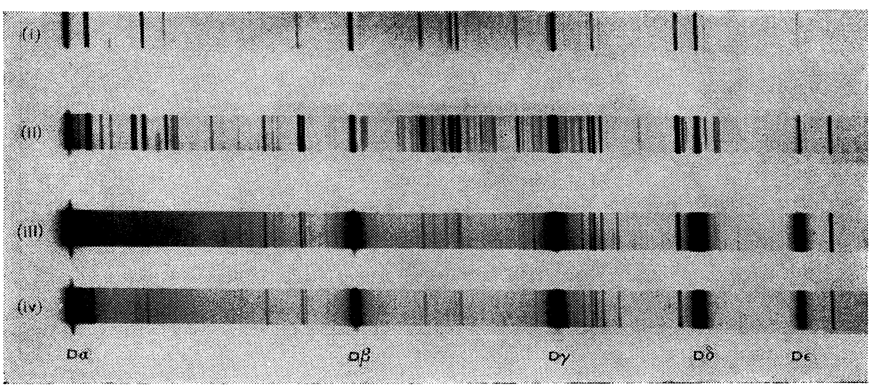

Fig. 8.—Spectra of deuterium plasma viewed from the end of Supper II using the transverse mode of plasma preparation with ionizing current of 15 kA and magnetic field 7·7 kG. Reading from top to bottom, the conditions were: (i) pressure 10 microns, current crowbarred before ionizing front hits end of tube; (ii) pressure 10 microns, no crowbar; (iii) pressure 100 microns, no crowbar; (iv) pressure 100 microns, current crowbarred before front reaches end of tube.

The equilibrium velocity of rotation v_θ of the plasma is given by

$$v_\theta = E/B_0 + mv_\theta^2/erB_0. \tag{2}$$

The last term is different for ions and electrons and leads to an azimuthal current, and the associated Lorentz force just balances that due to the centrifugal pressure of the plasma, that is,

$$\rho v_\theta^2/r = j_\theta \times B_0, \tag{3}$$

and from generalized Ohm's Law we get the radial velocity

$$\begin{aligned} v_r &= \eta j_\theta/B_0 \\ &= \eta\rho v_\theta^2/rB_0^2, \end{aligned} \tag{4}$$

where η = resistivity perpendicular to B_0. v_θ is shown by Gross and Kunkel to be approximately equal to $\sqrt{(2e_0)}$ and hence for a shock front of velocity V the radial drift as a fraction of the radius r, in the transit time of the front along the machine, is given for a machine of length l by

$$\Delta r/r = 2\rho\eta e_0 l/B_0^2 V r^2. \tag{5}$$

TABLE 2

DISTRIBUTION OF LIGHT EMITTED BY THE PLASMA

Position of Photomultiplier	Normalized Intensity	
	50 μs	150 μs
Top left	$7\cdot1\pm1\cdot7$	$7\cdot6\pm0\cdot8$
Top right	$9\cdot9\pm0\cdot2$	$7\cdot5\pm2\cdot0$
Centre	$1\cdot2$	$2\cdot8$
Bottom left	$3\cdot4\pm0\cdot8$	$5\cdot1\pm1\cdot3$
Bottom right	$10\cdot8\pm2\cdot8$	$7\cdot0\pm0\cdot6$

The insertion of numbers into this relation shows that for a hydrogen plasma of pressure 100 microns and a magnetic field of 10 kG the radial drift will be about $\frac{1}{10}$ of a radius in Supper II. Evidence for such radial drifts has been observed in the form of "hash", which appears on voltage traces for magnetic fields below 2 kG.

5·5. *Alfven Wave Diagnostics*

Alfven waves of the TEM type (radial electric field, azimuthal magnetic field), of a frequency of 370 kc/s, have been produced by discharging a $0\cdot2$ μF condenser through an inductance with the aid of a type 5550A ignitron.

5·5·1. *Density Measurements*

In a highly ionized gas the velocity of an Alfven wave of frequency well below the ion cyclotron resonance is given by

$$V_A^2 = B_0^2/\mu_0\rho. \tag{6}$$

If the collision frequency between ions and neutrals is sufficiently high the neutrals will be strongly coupled to the ions and will participate in their motion; ρ is then the total mass density of ions and neutrals.

The impedance of a plasma-filled guide of inner and outer radii of a and b respectively is given by:

$$\begin{aligned} Z &= (\mu_0 V_A/2\pi)\ln(b/a) \text{ ohms} \\ &= \surd(\mu_0/\rho)(B_0/2\pi)\ln(b/a). \end{aligned} \tag{7}$$

The results of our observations of both velocity and impedance taken at a time immediately after crowbar, when the percentage ionization is very high, have shown a close correlation with ion density measurements obtained from Stark broadening results.

5·5·2. *Electron Temperature Measurements*

The attenuation constant ϵ for the principal mode of an Alfven wave is given by

$$\epsilon = \frac{\eta}{2\mu_0 V_A}\left(\frac{\omega^2}{V_A^2}+k_c^2\right)+\frac{1}{V_A}\cdot\frac{\omega^2}{\nu_{ni}}\frac{\rho_n}{\rho_0} \text{ m}^{-1}, \tag{8}$$

where the first term expresses the damping due to joule losses and the second arises from neutrals and can be neglected at high percentages of ionization.

$\epsilon = 1/L$, where L = distance for wave to damp by a factor e,

η = electrical resistivity which is given by the relation due to Spitzer (1956):

$$\begin{aligned} \eta &= 65\cdot 3 \ln \Lambda/T_e^{3/2} \text{ ohm m} \\ &= 400 T_e^{-3\cdot 2} \text{ ohm m, if we take } \ln \Lambda = 6, \end{aligned} \tag{9}$$

k_c = radial wave number defined by the boundary condition that at the outer radius b we have $J_1(k_c b) = 0$, where J_1 is the first-order Bessel function, giving in the case of Supper I $k_c = 51 \text{ m}^{-1}$, which is large compared with ω/V_A in equation (8).

In the first few hundred microseconds of plasma life the neutral damping term in equation (8) can be neglected and we can write

$$\epsilon = (\eta/2\mu_0 V_A)k_c^2 \text{ m}^{-1}, \tag{10}$$

which, taken with equation (9), can give an estimate of electron temperature.

Estimates obtained in this way have yielded an initial kinetic temperature of 1 V dropping to $\frac{1}{2}$ V in 250 μs.

VI. Acknowledgments

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