PROPERTIES OF A LABORATORY PLASMA PREPARED WITH COMBINED TRANSVERSE AND LONGITUDINAL CURRENTS

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Summary

For some laboratory plasma physics experiments it is necessary to have a plasma of high fractional ionization that is confined in a relatively low magnetic field and for which the charged particle densities and kinetic temperatures do not change too rapidly in space or time. It has been found that a plasma prepared by a "hybrid" method with ionizing currents, both transverse and parallel to the steady magnetic field, has distinct advantages for such experiments.

This paper describes the hybrid method of preparation, giving results on the current distribution in the plasma and on the conditions limiting the use of this method. The gross behaviour of the plasma was studied with an image converter camera; particle densities were determined from Stark spectral observations and from laser interferometry; and electron temperatures were derived from spectral observations and from plasma electrical conductivity. Alfven waves were used to obtain information on total particle density, fractional ionization, and electron temperature.

I. Introduction

The $J \times B$ (radial current $\times$ axial magnetic field in a cylindrical geometry) method of preparing a laboratory plasma, pioneered by Wilcox *et al.* (1962), has interested a substantial group of workers throughout the world (e.g. De Silva 1961; Brennan, Brown, *et al.* 1963; Gross 1965; Millar and Watson-Munro 1965; Patrick and Pugh 1965; Taussig 1965). For some experiments we have found this method of plasma preparation inadequate, and this has led to the development of the method to be described here, a hybrid method in which both radial and longitudinal currents are used.

The hybrid method, in general, results in higher plasma densities and temperatures than obtained by the $J \times B$ method. It is a method particularly suitable when low magnetic fields are required, as, for example, in some recent giant Alfven-wave studies in our laboratory (Brown and Watson-Munro 1966), when it was necessary to have an almost fully ionized plasma in fields of the order of 3 kG. The normal $J \times B$ method in such cases is completely unsuitable owing to radial drifts and low percentage ionization. A further advantage of the hybrid method over the $J \times B$ method is that radial probes can be inserted into the plasma without grossly modifying the preparation.

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II. Description of Equipment

The measurements to be discussed were made using the SUPPER II machine, which has been described in detail by Brennan, Lehane, *et al.* (1963). This machine, which is shown schematically in Figure 1, continuously circulates palladium-purified hydrogen (in the present experiments at a pressure of 70 mtorr). It is provided with an axial magnetic field, variable up to 20 kG, which for any of the experiments to be described can be considered constant in space and time to within a few percent. One end of the machine is sealed with a quartz plate to which is attached a central molybdenum electrode of diameter 7·6 cm and length 7·6 cm; the other end of the cylinder is sealed with a Pyrex glass plate to which is attached, on the inside, a stainless steel wire mesh earthed to the vessel.

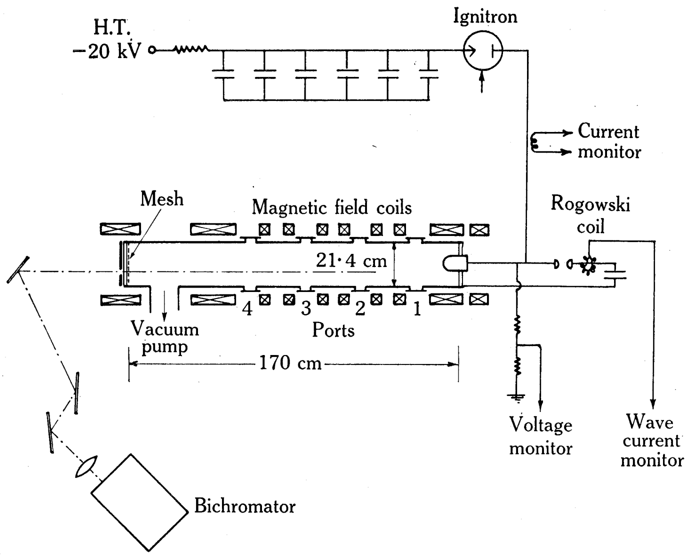

Fig. 1.—Schematic diagram of SUPPER II.

III. Preparation of Plasma

The energy source for plasma preparation consists of six 8·5 μF condensers each of internal inductance 0·1 μH. These can be charged positively or negatively to 20 kV and are connected together in the way appropriate to the method of plasma preparation being used. Associated with them is the usual time-controlled ignitron switching.

(*a*) *Normal* J $\times$ B *Preparation*

In this method the condensers are connected together by inductances to form a pulse line. This is charged positively and, with the aid of the series ignitron, discharged through a series resistance to the end electrode of the machine. Typically, the impedance of the line is 0·7 Ω, the charging voltage 17 kV, and the series resistance 1 Ω. After breakdown an essentially constant radial current flows; the interaction of this radial current with the axial magnetic field produces an azimuthal force ($J \times B$ force) which causes the plasma to rotate. The $J \times B$-produced rotation identifies itself by the large radial electric field resulting from the cross product of the plasma azimuthal velocity v_θ and the steady axial magnetic field B_0. At the same time a hydromagnetic ionizing shock front is driven down the tube with a velocity of the order of a few centimetres per microsecond. When the front reaches the end of the machine its radial electric field is "shorted" by the stainless steel mesh, removing the rotational energy. This "internal crowbar", first used by Wilcox *et al.* (1962), has the advantage of reducing turbulence by also shorting local azimuthal and radial electric fields. External "crowbar", which terminates the supply of energy from the plasma-preparation pulse line, is provided by firing a second ignitron.

TABLE 1

RESULTS FROM SUPPER II

Magnetic Field (kG)	Minimum Pressure for Negative $J \times B$ Front (mtorr)
5	7
8	25
10	45
13	60

(b) *Hybrid Plasma Preparation*

With this method the condensers are connected in parallel with noninductive straps and charged negatively. The maximum current is determined mainly by the inductance of the preparation leads and its decay by the total resistance of the circuit. For the measurements described here the charging voltage was 15 kV and the maximum current 48 kA. The current rang for five half-cycles (200 μsec), after which time the series ignitron extinguished.

After breakdown a negative $J \times B$ front was observed to propagate for about 20 μsec. This was shown by the voltage monitor signal, which records the integral of the radial electric field discussed in the previous subsection. Measurements of currents, from the magnetic fields produced by them, showed that the longitudinally flowing current feeding this front does not remain confined to a radius close to that of the firing electrode as it does for the case of a positive $J \times B$ front (Sharp and Watson-Munro 1964); this current was found to spread radially across the tube. For times later than 20 μsec transverse current no longer flowed, the current becoming purely longitudinal.

(c) *Limiting Conditions of Hybrid Plasma Preparation*

The hybrid method of plasma preparation depends for its success on the initial formation of a (negative) $J \times B$ front to produce a radial spread of the ionizing current. At low pressures and at high magnetic fields we have found that this spread does not take place and that both the discharge current and the plasma are axial, of a diameter close to the radius of the inner electrode.

We have investigated the conditions under which the negative $J \times B$ front can be propagated. These conditions are obviously dependent on the machine geometry in addition to the neutral pressure and the magnetic field; however, we illustrate with results from SUPPER II which are given in Table 1.

IV. Measurement of the Properties of the Plasma

The formation and decay of the plasma were examined, using a variety of diagnostic methods, as follows.

1. An image converter camera gave information on the gross behaviour.
2. Stark broadening and laser interferometer measurements gave the spatial and time variations of charged particle density.
3. Spectral measurements gave the variations in space and time of the electron temperature.
4. Measurement of the electrical conductivity of the plasma provided an additional check on the integrated electron temperature.
5. The use of Alfven waves as probes gave information on the total particle density, percentage ionization, and average temperature.

(a) *Image Converter Camera*

An image converter camera was used, with the aid of a mirror, to take photographs of the plasma from the stainless steel mesh end of the machine. Pictures of 1 μsec exposure time were taken throughout the life of the plasma from formation to 500 μsec.

In Figure 2 we display a set of photographs taken with an axial magnetic field of 7 kG. From the photographs we can note

(i) a rotating plasma showing signs of considerable turbulence at times up to about 100 μsec;

(ii) evidence of a darker area of less illumination in the volume defined by the inner electrode;

(iii) evidence of the decay from 200 to 500 μsec of the plasma into a central core.

A comparison of these photographs with those presented by Irons and Millar (1965) for a positive $J \times B$ plasma is informative. It will be noted that, while turbulence ceases at about the same time of around 100 μsec, the decay of the hybrid plasma lags about 100 μsec (the extra duration of the axial current) behind the pure $J \times B$ plasma.

(b) *Ion Density Measurements*

The Stark broadening measurements of ion density were made using the method developed by Irons and Millar of our laboratory. Measurements were made both looking across the machine at different longitudinal positions and along the machine

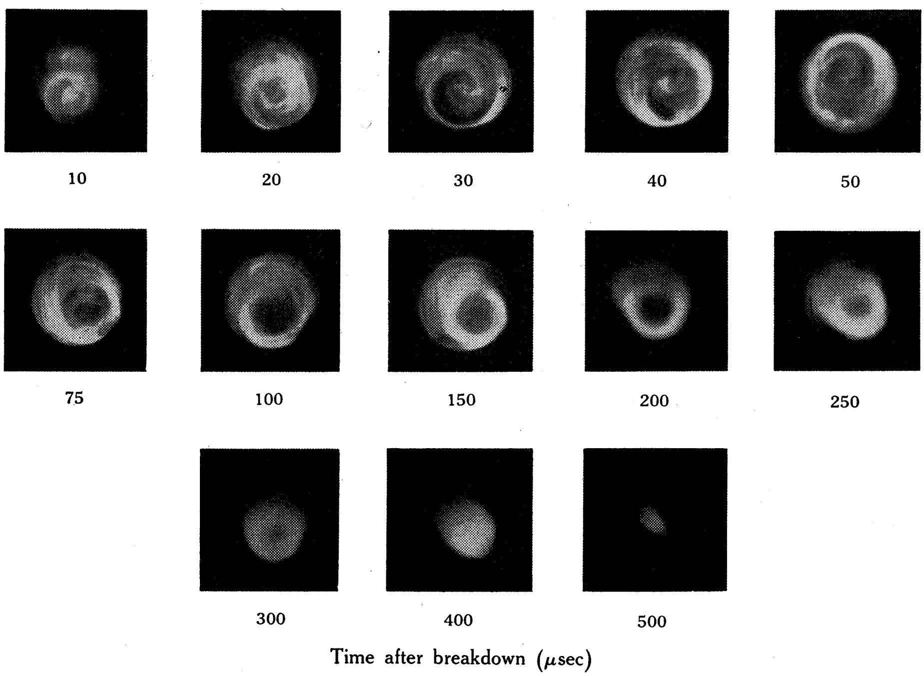

Fig. 2.—Framing camera photographs of a hydrogen plasma prepared by the hybrid method. The neutral pressure was 70 mtorr and the magnetic field 7 kG. The photographs were of 1 μsec exposure and are given for various times after breakdown.

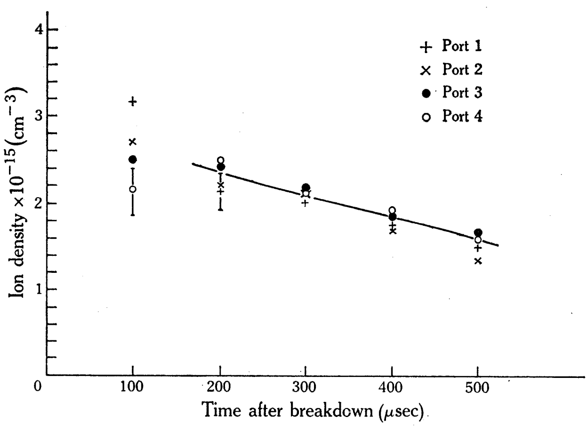

Fig. 3.—Transversely measured ion density as a function of time after breakdown for four different positions along the length of the plasma. Each point is the average of several shots, the results for fields of 7 and 13 kG being combined since they were not significantly different. The error bars shown are typical.

at different radial positions. Ion density measurements looking along the machine were also made using a He–Ne gas laser interferometer (Ashby and Jephcott 1963). Owing to problems with vibration, absolute densities were not obtained in this way. Only density changes were found, and these were normalized to the Stark results at a time of 200 μsec after breakdown.

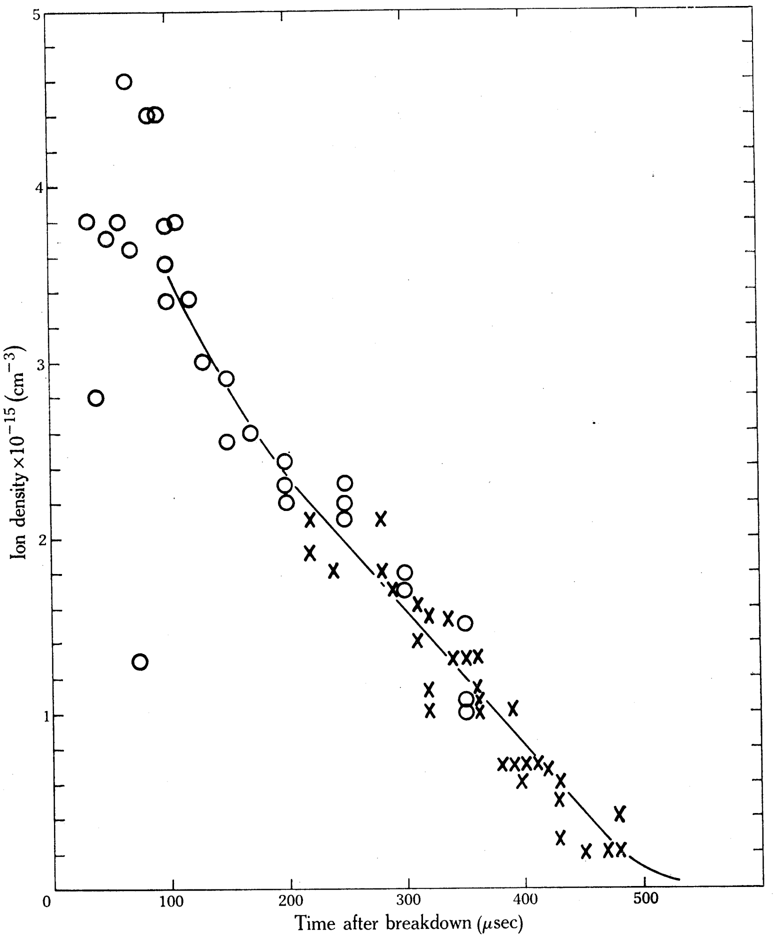

Fig. 4.—Longitudinally measured ion density as a function of time after breakdown for a distance of 6 cm from the axis of the vessel. The results are for a magnetic field of 7 kG, each point representing a different shot (○ Stark results; × laser results). The laser results were normalized to the Stark results at a time of 200 μsec.

The Stark results, giving the longitudinal distribution of ion density, are presented in Figure 3. The ion density is plotted as a function of time after breakdown for each of the four observational ports. The error bars give the maximum shot-to-shot variation. It can be seen that, at least for times greater than 150 μsec after the plasma is prepared, there is no significant longitudinal variation of the ion density.

The results for the radial variation of ion density are given in Figures 4 and 5 for a field of 7 kG. In Figure 4 the results on the variation with time at a particular radial position are given. These serve to indicate the agreement obtained between the Stark and laser measurements and give valuable experimental support to the theoretical model used by Griem, Kolb, and Shen (1962). From these results and similar ones at the other radial positions the radial distribution of ion density at different times can be obtained. These are presented in Figure 5.

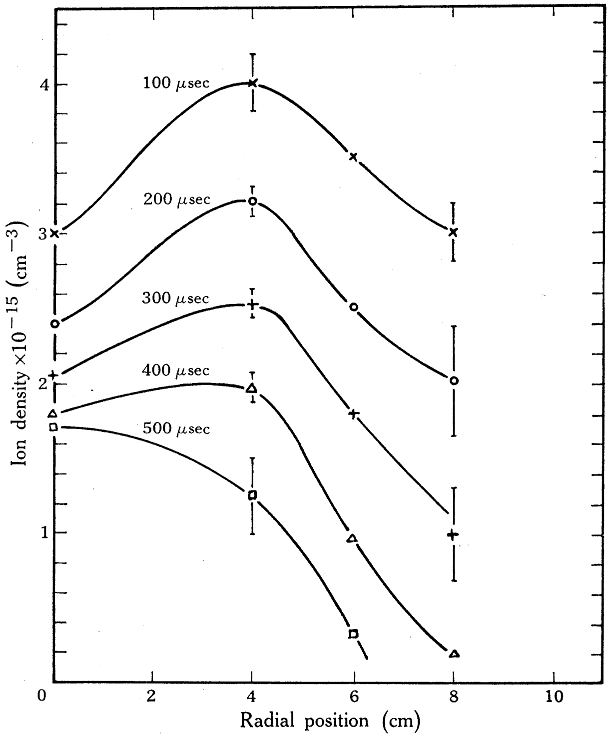

Fig. 5.—Radial distributions of ion density for different times after breakdown. The results are for a magnetic field of 7 kG, and the error bars shown are typical.

A comparison of the results presented here with those obtained for a plasma prepared by the normal positive $J \times B$ process is of interest. In Figure 6 we make this comparison by plotting as a function of time after breakdown the ratio of the transversely measured ion density to the original neutral density. It can be seen that this ratio is higher for the plasma formed by the hybrid process. The superiority of the hybrid process when low fields are used is particularly evident. At magnetic fields lower than 7 kG we have found that this superiority becomes even more pronounced.

(c) *Electron Temperature Measurements*

The electron temperature was measured by comparing the ratio of the intensity in a line to the intensity of a band in the continuum (Griem, Kolb, and Shen 1962). The ratio used was of the Hγ line to a 32 Å interval of continuum centred at 5094 Å.

As with the ion density, measurements were made of both the longitudinal and radial distributions of temperature. Within the errors of about 20%, no significant longitudinal variation of temperature was found. The radial distributions of temperature were found to be similar to those of the ion density. In each case the magnitude of the temperature was about twice that which has been obtained for positive $J \times B$ preparation under similar conditions (for instance, at 200 μsec the peak temperature is about 2 eV). This is of considerable importance, since in some wave experiments an excessive, if not prohibitive, wave attenuation can result from too low a temperature.

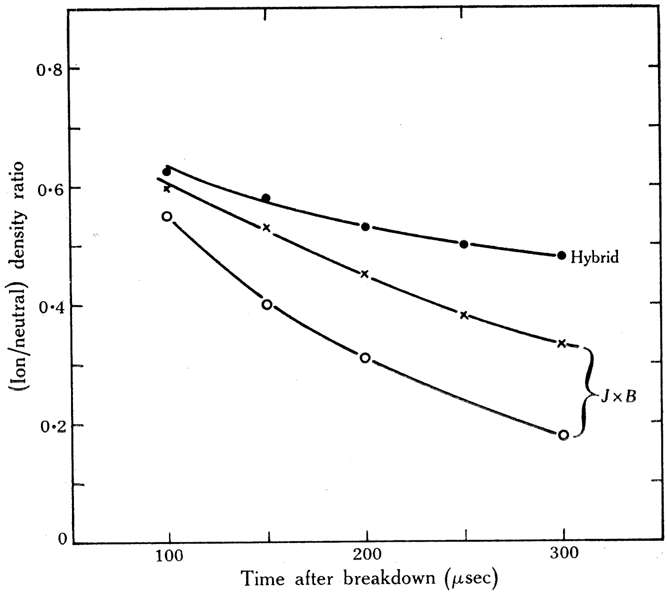

Fig. 6.—Ratio of transversely measured ion density to original neutral density plotted as a function of time after breakdown for hydrogen plasmas prepared by the hybrid method and by the positive $J \times B$ method. The hybrid results are those of the present paper (neutral pressure 70 mtorr, magnetic fields 7 and 13 kG), and the positive $J \times B$ results are those obtained in SUPPER II for neutral pressures and magnetic fields of 70 mtorr and 13 kG ($\times$) and 90 mtorr and 9 kG ($\bigcirc$).

(*d*) *Electrical Conductivity Measurements*

By use of matched resistance dividers connected to differential amplifiers, the voltage between the sending electrode and the stainless steel screen was measured. This voltage is given by

$$V = IR + I\frac{\mathrm{d}L}{\mathrm{d}t} + L\frac{\mathrm{d}I}{\mathrm{d}t}. \tag{1}$$

If damping is neglected it can be shown that, at both current zeros and current extrema,

$$L = \frac{V}{\partial I/\partial t} = \frac{V}{\omega I}. \tag{2}$$

Using the measured values of V, ω, and I, at different times, we find that for both current zeros and extrema $L = 0 \cdot 4 \pm 0 \cdot 05$ μH. This value is consistent with the calculated value for a transmission line of length $1 \cdot 7$ m (the length of the machine) and ratio of outer to inner radii of 3, namely,

$$L = \frac{\mu_0 l}{2\pi} \ln(b/a) \tag{3}$$

$$= 0 \cdot 34 \ln(b/a)\ \mu\text{H}$$

$$= 0 \cdot 4\ \mu\text{H} \text{ when } b/a = 3.$$

Assuming L has this same value for all intermediate times as well, then $\mathrm{d}L/\mathrm{d}t = 0$, and one can hence obtain the resistance R from the ratio V/I at a current maximum, where $\mathrm{d}I/\mathrm{d}t = 0$. The measured values of the conductances obtained in this way are given in the second column of Table 2. The conductances given in the third column

TABLE 2

CONDUCTANCE VALUES

Time after Breakdown (μsec)	Measured Conductance (mho)	Calculated Conductance (mho)
60	62	—
105	42	59
145	26	33

of the table have been calculated from the measured radial electron temperature distribution discussed in subsection (*c*) above and the Spitzer (1956) resistivity value

$$\frac{3 \cdot 9 \times 10^4}{T_e^{3/2}} \text{ ohm cm,} \tag{4}$$

where T_e is in degrees Kelvin.

The agreement between these values gives considerable support to the spectroscopic observations.

(*e*) *Alfven-wave Diagnostics*

In our plasma density and temperature range, torsional magnetohydrodynamic waves have propagation characteristics that permit estimates of total particle density (essentially from the low frequency velocity), electron temperature (from low frequency attenuation), and fractional ionization (from the attenuation–frequency curve).

The theoretical dispersion relations and the experimental methods used in our laboratory are fully discussed by Brown (1965). For the purposes of the present paper we shall limit the discussion to the diagnostic results.

For the field of 7 kG we examined the velocity and attenuation at three frequencies ($0 \cdot 25$, $0 \cdot 49$, and $0 \cdot 93$ Mc/s), all substantially below the ion cyclotron frequency of 11 Mc/s, and at three points of time after breakdown (100, 150, 200 μsec). When we fitted the results to the calculated (KDF9 computer) curves of Brown, we obtained the results given in Table 3.

These density and temperature figures are lower than those resulting from spectral and laser measurements. The discrepancy has been observed by other workers with plasmas produced both by the $J\times B$ process (e.g. De Silva 1961; Brown 1965) and by the hybrid method (Brown and Watson-Munro 1966). In all cases, however, the experimental results have been interpreted in terms of a theory in which it is assumed that the plasma is uniform in the radial direction. The effect of such non-uniformity is at present being examined in this laboratory.

TABLE 3

PLASMA CHARACTERISTICS FROM ALFVEN-WAVE PROPAGATION

Time after Breakdown (μsec)	Total Density $\times 10^{-15}$ (cm^{-3})	Electron Temperature (°K)	Percentage Ionization
100	$1\cdot4\pm0\cdot4$	$1\cdot4\pm0\cdot2$ $\times 10^4$	60 ± 10
150	$1\cdot6\pm0\cdot4$		
200	$2\cdot1\pm0\cdot4$		

V. CONCLUSIONS

A hybrid method of plasma preparation in which both radial and axial currents are used has been described. It depends for its success on the initial formation of a negative $J\times B$ front and is hence not suitable at high fields or low pressures. It is a particularly suitable method at low fields and, as such, is a useful supplementary process to the normal positive $J\times B$ method. It results, in general, in higher plasma densities and temperatures than obtained with the positive $J\times B$ process. Its use gives greater access to the plasma, since radial probes can be used without grossly modifying the preparation process. A possible disadvantage of the method in some experiments is the presence of large axial currents long after breakdown. This can be overcome in general, however, by performing these experiments at the zeros of the current.

VI. ACKNOWLEDGMENTS

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